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experiments in machine vision and image processing

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Introduction

In short

That visual phenomena are elusive is widely acknowledged; what this elusiveness entails, far less so. This is particularly true when it comes to political regimes and socioeconomics. The long-standing debates on the ways of seeing and its relationship to governance, capital, and technology have barely focused on the mildly ill-defined character of the visual tasks. Although the elusiveness has been elaborated by twentieth-century philosophers, it is not precisely due to its slippery nature that vision has been considered a dangerous supplement to culture studies (Jay, 1993; Mitchell, 2002a). It is the seductive power of images and the oppression of the gaze that have shaped the mainstream of visual critique and its surrounding practices.

The elusiveness of seeing has not deterred pioneering AI research from placing vision at the forefront of its efforts. It was initiated under the assumption that rich and direct signals could be parsed into data streams with relative ease. In doing so, computer science has successfully configured the operational machinery of the gaze. By the end of the 20th century, it convincingly presented landscapes and views of battlefields as reduced to the mediated and reassembled components of computational AI systems. Whether this strategy was an ingenious choice poses a problem in itself. Either way, reining in its speed, ubiquity, and spectral variants, seeing has established a basic channel through which industry-owned machinery have attempted to govern the excesses of life around them.

Proving that machines can relate to the external environment through complex statistical models was a tremendous and fascinating achievement. Yet despite the value of this pursuit, the claim that computation alone can master the intricacies of technical vision soon turned out to be premature. The elusive and ill-defined nature of the task has confronted researchers with the limitations of computational essentialism and revealed the multiplicity of modes that are indispensable for connecting AI to the external environment. Studying this variety lends legitimacy to the proposal of a niche field of visual studies as a means of understanding the current sociopolitical agenda.

This book addresses classical themes in the study of visual regimes and algorithmic governance. In doing so, however, it does not elaborate on the power of the gaze nor the eloquence of images. It starts neither from examining the impact of machine learning models, nor from the composition of datasets. The accounts presented below will tie machine vision to the collectives that tend to work with coarse-grained matter rather than with computational tasks. Exploring techniques aimed at mitigating the inverse nature of seeing in image analysis, photometry, and visual communication design will illuminate AI-compliant domains of visual culture. Bringing them to the fore, I offer a study of sensory environments in the making. The idea is to think of machine vision as an earthbound technology. Its uniqueness lies in uncovering the astonishing, sometimes perplexed, alliances that are inscribed in the emergence of future political orders.

My main motivation for shifting the reader's attention towards the elusiveness of vision is then that operational AI systems cannot function without rearrangements made in front of the cameras and sensors. From this arises the double account of this book. The first is to show how the proliferation of vision systems catalyses the emergence of one-of-the-kind sensory environments. The second investigates whether the amplification of those environments pertains to terrestrial politics, and how it redraws the boundaries for more-than-human relatedness and the governance of the commons. A specific case of visual studies then provides the evidence for why a critical reading of cultures and politics in the era of machine learning needs to engage with computational interstitials, exploring the cracks and joints and bringing forward what resists being seamlessly integrated into a totalising, homogeneous computational modality. It reveals that these rearrangements are amplified by advances in material engineering and information design.

In what follows, I set out to demonstrate that the terrestrial nature of vision technologies develops into new aesthetic vocabularies, becomes both a subject and an instrument to economic colonialism. It calls for vigilance against the technological destabilisation of access to light and direct sensory information. While putting the focus on emerging design opportunities, it indicates a counterbalance to the proliferation of advanced computational systems. The questions of tactics, design, and a renewed politics of the commons will organise much the following discussion, but before I proceed to the merits, let me present this book's research principles in some more detail.

The research principles

In its main parts, the proposed study relies on the meta-analysis of selected research and engineering projects. The selection has been guided by the community of practices and the conceptual background of the collectives engaged

in engineering visual techniques. I have started to investigate these by participating in collaborative projects and teaching programmes (both as a student and researcher) in the environment dedicated to science and technology at the AGH University of Krakow, where I am based. As a researcher-curator in the field of image technologies and media art, I have relied on the observations of art restoration laboratories and curators linked to the media art scene. This book's general approach to the study of technology builds on the legacy of Ludwik Fleck's investigation of thought collectives (Fleck, 1935/1979) and the Central European traditions of research in the history of technology and material culture[1].

At the time of writing, I was fortunate to be aware of the first book-length scholarly studies on machine vision, embedded in a cultural anthropological context. Among them are takes on some of its theoretical concepts (Parikka, 2023) and creative practice (Zylinska, 2023), as well as studies based on media ethnographic or intellectual history research (Dobson, 2023; Rettberg, 2023). The arguments of these works indicate that there is some consensus on a gradual de-objectification of the human gaze rearticulating either agency, aesthetics, or power relations within contemporary societies. The nucleus of this transformation is voiced differently in each of these studies. James E. Dobson offers an intellectual history of machine vision, discussing the genealogies of the field by working on a critical analysis of its core algorithms. Jill Walker Rettberg, on other hand, will be of special interest to readers who wish to track ethnographic research positions and discuss the construction of social relations in an everyday environment infused with machine vision systems. Approached from the media studies perspective in the works of Jussi Parikka, machine vision accelerates Harun Farocki's much-vaunted concept of operational images to the scale of a complex theory. The author puts imaging systems at the centre of his narrative and compiles actor-networks that relate the light practices of astronomy, data repositories, and visualisation. Joanna Zylinska's study places creative practice at the centre. With reference to creativity, the author poses the question of the actuality of photography and reflects on it by developing the concept of the book's titular "perception machine." Narrated in different sensibilities and literary voices, machine vision has been encountered among the ideas that are reshaping classical themes in the humanities towards algorithmic procedures and more-than-human ontologies.

Not unlike the aforementioned monographs, I initially conceived the following inquiry in relation to the commitments of algorithmic visual culture studies. In reference to the investigation of practices brought about by the breakthrough

[1] By this, I primarily mean studies in science and technology published in the *Quarterly Journal of the History of Science and Technology*, edited since 1956 – at L. & A. Birkenmajer Institute for the History of Science of the Polish Academy of Sciences, Warsaw. For further exploration of the topic, see Trojanowska (2022) and Zamecki (2020).

in generative models and image recognition with neural networks, I have followed the debates around machine gaze and operational images (Azar et al., 2021; Farocki, 2004; Paglen, 2014). With computational logic at the centre of the investigation, I reviewed arguments and technical system theories formulated in the context of research on surveillance, automation, and military technologies (Andrejevic, 2019; Chamayou, 2015; Dobson, 2023). I also observed the scope and vitality of discussions on new forms of operational, calm, or networked images (Cox et al., 2021; Dvořák, Parikka, 2021; Gustafsson, 2019; Mackenzie, Munster, 2019; Moskatova et al., 2021; Rothöhler, 2021; Rubinstein, 2008; Veel, 2012) and confronted debates on machine creativity and aesthetics (Broeckmann, 2020; Bunz et al., 2022; Zylinska, 2020).

But it would be hypocritical of me to voice my relationship to visual culture studies only in positive tones. I was also haunted by a sense of tediousness and inadequacy that I shared with those seeking to open visual culture to the current debates in the humanities. Despite valuable insights from a number of contributions shifting the theoretical discourse towards concepts of operational images and instructive observations on sites of networked imagery, I have found that the merit of the vividly transforming field seems constantly to elude comprehension. The problem is that in committing to keeping its eye on film, photography, and recommendation engines, visual studies loses the force and direction of its argument, as a domain eventually recognised as a mangle of practices and craftsmanship, a set of better or worse implemented systems. Learning from this mess can be exciting, but sour remarks on the "prosthetic" function of the topics warrants attention. It was evident that visual studies deserved renewed intellectual engagement, not least because its mingling of cloud expertise on reflectance properties, image classification, and segmentation techniques (once reserved for specialised laboratory-like zones) extrapolates onto the more common areas of logistics warehouses, road systems, and industry facilities.

Approaching the present study's position, I gradually became more critical of the tendency to place images at the centre of debates on algorithmically transformed visual culture. What appeared crucial instead was the need to outline the principles through which AI, and algorithmic systems in general, relates to the external environments. As vision has been identified as the primary means of such relations, the discovery of technological principles amounts to a valuable contribution from the field of visual studies. A substantial shift needs to be made in order to adequately capture the issues of the present techno-ecological era (Bińczyk, 2018; Stiegler, 2018). Machine vision appears as a dangerous supplement to the general discourse of algorithmic governance mostly because it is not limited to operational imagery and continuously campaigns for a sensory, material, and enmeshed understanding of the problems it works on. Getting more vigilant about the operational image's paradigm, but also subversively intrigued by the

massive evidence on "invisual" visuality, I decided to acknowledge my study's substantial caveat: this is not a book on images. Instead, I discovered what I was looking for in the history of technical experimentation, landscape planning, and the massive uptake in current material engineering. In these terms, I consider the following study as a contribution to a materialist facet of showing seeing. While doing so I also propose that the following analysis is a proof of concept for visual studies being capable not only of narrating machine vision in its own way, but also of providing arguments for contemporary debates on ecopolitics and post-human relatedness. Accordingly, this book's arguments in visual culture will be vastly supported by the neighbouring fields of design and geohumanities[2].

The study of principles shaping the relation between the algorithmic domain and the living world beyond it puts the present book in dialogue with selected positions in media studies. A rich body of academic inquiries considering the evolution of media environments includes positions that create space for reflection on the relationship between media and environment. Among the reference points, I would specify Sean Cubitt's *The Practice of Light*, broadly recognised for entangling the digital domain with the discourse on media materialities: light-sensitive photographic emulsions and printing inks of the Old Master's workshop (Cubitt, 2014). Printing enabled by light sensitivity is then the principle derived from Cubitt's matter-oriented approach to visual technologies. A distinct proposition comes from locative media studies in which context Anna Nacher's *Locative media: The hidden life of images* (Nacher, 2016) interrogates how the objects of visual culture are embedded in hybrid landscapes. Characterising the titular life of images in terms of nesting (pol. *zagnieżdżanie*), Nacher invites us to think about the direct

[2] As the exploration of this study's domain implicitly required thinking about environments, I turned to the scholarship that investigates the proliferation of new forms of mobility and geolocation techniques while developing a non-representational approach to contemporary visual cultures (Amin, Thrift, 2002; Anderson, Harrison, 2011). Departing from this vantage point, I propose to consider the intersection of architecture and automation studies as a critical reference for visual culture debates. In the concluding parts of this book, I will combine the exploration of design and engineering with collections highlighting the rise of automated and human exclusion zones. Starting from the cases featured in the *Automated Landscapes* volume edited by the Nieuwe Instituut in Rotterdam (Bedir et al., 2023), this study considers the non-human conditioning of architecture and the discussions around it. In order to differentiate between the debate's perspectives, I will refer to speculative architects' proposals, including a set of essays edited by Liam Young (2019). Corresponding with Young's collection is the research problem formulated by Benjamin Bratton (2019) as a complex ecology generating "the incentives to hide, to scan, to camouflage, to self-display, and to trick the world into seeing things not as they are but as they could be or should be" (p. 20). In this context I engage with the author's theoretical positions, namely the adulation of self-governance, the planetary scale, and the AI conditioning machine landscapes (Bratton 2016). I refer to these bodies of work in the second part of the book.

connotations with natural habitats and the fixed action patterns observed among biological species. The principle of visual culture objects being nested or anchored in a specific place or site offers an alternative take on fusing computational procedures and environment into a multilayered postmedia landscape. Imprinting matter with light and embedding images in landscapes marks a point of departure for further discussion on the ecocritical relevance of visual studies.

A further incentive to engage in the discussion on relatedness arises from the reading of media archaeology, including the recent contribution by Abelardo Gil-Fournier and Jussi Parikka. *Living surfaces: Images, plants, and environments of media* connects with contemporary theoretical frameworks of an ecological approach to media studies (Gil-Fournier, Parikka, 2024). As the authors elaborate on an affinity between the photosensitive surfaces of photography and the light-fed tissues of plants, it becomes of primary importance to specify ways to link the computational/virtual and the material domains. Gil-Fournier and Parikka (2024) respond to the problem with reference to the concept of ground truth, naming it as an approach that characterises both geographical and environmental sciences, and remote sensing (pp. 147–150). Derived from the potentialities of grounding the connection between machine vision and the environment, their account is made possible by the constant collecting, comparing, calibrating, and modelling of data (p. 147). In line with this view, the whole line of argumentation focuses on ground truth being embedded in a mass of images (combined into maps and AI training datasets) rather than on material environments being formed and recomposed in relation to algorithmic developments (pp. 143–147). Aiming at a comprehensive study of techno-environment relations, I take the propositions on ground truth calibration and data collection as a starting point for debate. The current book's opening chapters will present an argument for organising vision technologies around the principles of ill-posedness and image processing.

In terms of scope, the proposed study inserts computation between other styles of thinking that amount to a historically intensified constellation of epistemology. In this, I build on the concept of the post-digital articulated by David M. Berry in reference to Heideggerian stances: as the condition which is "both an aesthetic and a logic that informs the re-presentation of space and time within an epoch that is after-digital, but which remains profoundly computational and organised through a constellation of techniques and technologies to order things to stand by" (Berry, 2015, p. 45). In that sense, the following contributions collect the voices of conceptually engaged researchers who still wait to be recognised by visual studies or by historical reviews of science and technology. I propose to revisit historical projects on physics-based machine vision propagated by Berthold Horn, the contributions to optical image processing of Pierre-Michel Duffieux and André Maréchal, as well as the teachings on sensory physical phenomena by Marcel Minnaert and his co-researchers. I believe their contributions not only fit into an account on machine vision, understood as

a more-than-digital technology, but also guide us to the universe of designers and engineers who have established new interconnections between technics and the environment. Their inputs urge us to look at those who, besides studying appearance, have taken up the study of the physical qualities of things; besides thinking about material objects, they have attempted to think with matter; and crucially, besides taking care of representations, they have become concerned with the accountability of the systems they construct. I put the latter in dialogue with those who work on chemical reactions, with pigments, soils, and raw materials. Therefore, the following chapters will uncover matter-oriented approaches in computer science.

A key research decision was to approach the histories of image processing and machine vision in terms of technical experimentation. This is an experimentation different from those devised for chemistry or physics, though not inherently downsized to casual demonstrations of technical system design (Brooks 1991b, p. 1227). Drawing upon the new experimentalists' frameworks, I understand it as a long-term collaborative effort, invested in a process of system stabilisation to produce an epistemic thing in Rheinberger's sense, or a phenomenon in Hacking's sense. Adopting observations of scientific activities, I conceptualise vision as an effect that is actively stabilised within technical systems (Hacking, 1983, pp. 229–230; Rheinberger, 1997, p. 80)[3]. From here, I would argue that image processing, photometry, and materials engineering serve as avenues through which technical forms of vision can be transformed into new phenomena, including sensory, economic, and aesthetic orders. I propose then that the experimental systems in question are not technical achievements in the purest sense. Rather, I suggest thinking of them as the ensembles that operate on the edge of chaos and evoke the conflation of epistemic and technical processes. Respectively, in the first part of the book I will consider system stabilisation: operations that impose a series of fine-grained adjustments and attunements either at the level of instrumentation or method. In the second part I will look at how lab-scale solutions are renegotiated when the technologies mature and become implemented on a larger scale. As we move from one line of experimentation to another, we will eventually track the process of adaptation and attunement, which is expressed through a series of trade-offs made to stabilise a vision system.

[3] In these terms the approach presented in the following study contrasts with the understanding of artistic experiment as defined in reference to the 1960s creative engagement with computers. Ian Hacking's account underlines experimentation as a long-term process of stabilisation for a given phenomenon under inquiry; however, in the introduction to their essay collection *Mainframe Experimentalism*, Hannah B. Higgins and Douglas Kahn emphasise the opposite: the arts ascribe value to unpredictability in experimentation. They reference John Cage's views on artistic experimentalism, concentrated on an "unpredictability of outcome, which could be based in new technology or virtually any other process that removed the author's choice from the composition process" (Higgins, Kahn, 2012, p. 3).

Additional arguments for framing machine vision within the new experimentalist perspective are how the computer sciences have approached the problem since their inception. In a famous technology debate initiated by James Lighthill in 1973, John McCarthy held the position that AI is a science that requires experiment to carry it out (BBC, 1973, 38:40–39:30; see also McCarthy, Hayes, 1981, pp. 2–3). The view of computer vision's genuinely experimental nature prevailed in the early developments of the discipline. Considered as messy and ill-defined, the research evolved by patching vision together with a range of assistive technologies, constantly meandering into the vagaries and forks of ill-defined phenomena. This mood has been evident since the earliest debates on image processing as well. It echoes through the teaching and accounts of the pioneering contributions, just as the lack of preexisting theory reverberates in academic teaching and professional curricula. Manuals only make passing reference to the conceptual background of the discipline (Gonzales, Wintz, 1987; Rosenfeld, 1976; Sonka et al., 2014)[4]. However, it is precisely these troubling "ways of seeing" as discussed by the humanities (Azar et al., 2021) that have made the synthesis of "vision science" perpetually problematic. The best twentieth-century scholarship embraced that intricate art of interpretation, which Peter Galison suggestively characterises as "borrowing bits of theoretical ideas, pieces of craft knowledge about film and optics, and portions of experimental knowledge" (Galison, 1997, p. XX).

From science and technology studies I will also borrow the analytical concepts of this inquiry. To navigate through a wealth of empirical research, I will follow the discourse on the concerns and constraints of vision experiments rather than their assumed aims and goals. Both concepts are understood here as local researchers' lemma: subsidiary, intermediate arguments for proposing specific solutions, policies, or materials. Using those, the presented study will be guided not by the problems solved during the projects, but by the problems that became apparent during this work: ill-founded reverse engineering problems, misleading assumptions on the study of form, unverifiable principles of visual field organisation, etc. The selection of examples shown below assumes that a community of concerns and constraints link projects developed by distant epistemic cultures.

I propose to consider concerns and constraints as the engines of socioeconomic games taking place at the core of research life. Neither term is new to the study of science. Apart from Bruno Latour, Peter Galison was probably the earliest to theorise the discourse of constraints in his 1995 essay devoted to scientific practice. Galison's (1995) constraints are the perfect tool for a historian mapping the distinctiveness of scientific subcultures and explaining the coordination taking

[4] The only exceptional in this context is David Marr's computational theory of perception (Marr, 1982/2010).

place between them despite a lack of shared views (pp. 16, 18). With constraints he marks the endpoints of scientific inquiry and "the boundaries beyond which inquirers within the community find it unreasonable to pass" (p. 14). His account on experimental physics takes much insight from observing how constraints arise, how they are administered, and how they expire. However, once limited to constraints, an insight into the domain of technics could be unnecessarily distorted. To paraphrase one of the author's caveats: rigorous scientific cultures obsessed with avoiding the limitations imposed by their internal conventions block the path to walk freely in the space of design. Acknowledging the unorthodox nature of technical commitments brings us to the inclusion of a complementary concept.

The post-constructivist approach to science and technology has managed to acknowledge the importance of scientific procedures that are chosen to be important, nurtured, and delivered by scientific communities. A radical take on this program was formulated by Latour when he put forward the idea of rethinking the "matter of facts" discourse in terms of "matters of concern" (Latour, 2004, 2008). This proposition stems from discussions on the renewal of critical discourse in philosophy. In the 2004 outline, Latour uses the concept of concern as a way to empower a new type of scientific realism[5]. A few years later, he wrapped up the concept in his *Spinoza Lectures*, using the same metaphor of theatre machinery to lay down the argument that a matter of concern is what becomes apparent once one adds a matter of fact to its whole scenography "much like you would do by shifting your attention from the stage to the whole machinery of a theatre" (Latour, 2008, p. 39).

In the context of the following study, I look on Latour and Galison's propositions as both adapting to and shaping their historical context. While I believe that Galison's understanding of constraints reflects the spirit of experimental science in the second half of the 20th century, Latour's lectures capture a profound shift in thinking about the political and socioeconomic responsibilities of research communities. Matters of concern are thus proposed as a concept that embraces a new rationality in epistemic cultures. In that sense, I suggest the concept to articulate not the opposite, but the reverse of Galison's proposition. I propose to consider concerns and constraints in their dynamic interplay and observe how they are passed forward across disparate projects in the empirical sciences, technology, and design.

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[5] Where he expresses the position as follows: "The question was never to get away from facts but closer to them, not fighting empiricism but, on the contrary, renewing empiricism. What I am going to argue is that the critical mind, if it is to renew itself and be relevant again, is to be found in the cultivation of a stubbornly realist attitude – to speak like William James – but a realism dealing with what I will call matters of concern, not matters of fact" (Latour, 2004, p. 231).

In closing the introduction to the research principles, I will leave a few general declarations here in brief. Regarding the timeframe, I propose a study of entangled history, rather than a consideration of a predefined future. What I find particularly relevant is to think of the future as an intruding *avenir* rather than a more or less fixed *futur*; that is, as a continuation of the present (Chaunu, Legrand, 1979). In the chapters below I will try to move from the realms of the past to the flow of the present becoming. Furthermore, in terms of technical concepts and definitions, unless specified otherwise, I derive them from the STEM encyclopaedias circulating in anglophone academic networks and teaching curricula. In that vein, I understand machine vision as an interdisciplinary field which explores the possibilities of physical sensory systems that exist not only in the form of statistical models, but foremost as embodied and localised entities, devised and built according to a specific design approach. The same applies to image processing, which I treat as a minor sub-discipline of computer science. Both concepts are now subsumed into digital technologies, combined with the computational approach, based on internal representations and derived from machine learning. In line with the intention of the present study, I will propose a reformulation of the understanding of both fields in the following chapters.

Reader's guide

As the argument of this book seems somewhat circuitous, a reader's guide may be helpful. In the thematic inquiries of the first part [Chapters 1–4 "Experiments"], I foreground the voices of engineers and scientists engaged in research projects in the second half of the 20th century. Here we move along the selected strands of inquiry informed by discourse on limitations, ill-posed problems, and the concerns shared by vision inquiries. As the first chapters elucidate the emergence of ephemeral laboratory-scale vision environments, the preliminary characteristics of vision environments are presented in the interim summary. The interim summary is intended to bridge observations of the ephemeral vision ecosystems with the perspectives of culture studies gradually introduced to the second part's chapters. In the second part [Chapters 5–7 "Manifestations"], we examine the broader relevance of the observed phenomena. Through the subsequent chapters, we follow the tensions brought about by the technological shifts in human inhabited areas, terrestrial zones, or secluded industry spaces. My aim here is to examine in what terms visual technologies should be considered as a substrate for catalysing long-term changes in local environments and power relations with special emphasis on ecopolitics and the question of commons. Below, I guide the reader through the chapters' aims and scope in more detail.

Two opening chapters elaborate on the relations between vision technologies and physical environments. The first chapter is an introduction that maps engagements in image processing from a broad perspective of visual practice. It elucidates historical transitions between different modes of visual resources transformation, highlights the technical diversity of image processing, and discusses the interconnections between its various pathways, shaped by developments in optics, computation, and photochemical techniques. The transitions between those modalities are problematised with the help of three case studies. The first places information theory at the centre of the analysis and extends its range by examining examples of visual experiments probing the concepts of calculable aesthetics. The second recalls a modality that relied on processing images by optical means. The third presents an analysis of the various forms of photochemical processing, emphasising the crucial role of this modality in bringing up ecological traces in the technologies of vision. A principal focus of this review is the question of historical reconfiguration in methods of image technology. Once the field has been mapped, the following thematic account provides a foundation for understanding the early developments in digital image processing within the context of twentieth-century empirical research.

The second chapter argues that recent developments in vision technologies are driven primarily by the constraints imposed by the underdefined or ill-posed nature of the problems they aim to solve. The chapter examines the role of research projects in unravelling the environments organised by light and complex optical models. The history of ill-posed and reverse problems in vision engineering provides a retrospective account of the evolution of research developments exploring the physics of image formation. Subsequently, the topic of scene recognition in computer science is addressed, with reference to the expertise derived from empirical investigations in astronomy and astrogeology. It is proposed that the empirical investigation of planetary surfaces is pertinent to the discourse on machine vision insofar as – in contrast to the utilisation of high-level semantic categories – physics-informed methodologies have demonstrated the potential of low-level interpretation. Qualities (such as colour, texture, surface shape, and reflectance) have been perceived as a means of circumventing the semantic order of things and of embedding the perceiving subject directly in fields of energy and the lumps of matter. Against this background, the chapter highlights computer science discussions on the instability and lack of unique solutions in reverse problem solving. The case study demonstrates the interdependence between algorithmic and environment-oriented approaches and vision technologies.

Chapters 3 and 4 continue to demonstrate how the ill-defined task of vision technologies is managed with expertise in visual communication and multispectral imaging. The chapters specify how the stabilisation of computational systems was achieved by their attunement to the material environment conditions. The

third chapter moves to algorithmic traits in research on wayfinding, ergonomics, and merchandising. It undertakes a review of the challenges resulting from the optimised visibility of fiducial signs and landmarks. The discussion begins with an examination of historical curricula that proposed the provision of visually designed solutions that are pertinent to the environment. A review discusses the efforts to parametrise the clients' gaze and engineer lines of sight for both machines and humans. The examples illustrate how visibility has been achieved by modifying external signals to align with the limited perceptual capabilities of subjects, whether biological, human, or technical. The fourth chapter begins with reminiscences of geophysical projects that captured large terrestrial structures in the extended visual registers. It discusses machine vision materialities, with pigments and paints matched to the broad-spectrum sensitivity of cameras and lenses. The study brings forward nascent approaches to material design, making new sense from reflectance, gloss, emissivity, the degree of polarisation, dynamic properties, and broadband or multispectral signatures.

The interim summary elaborates on the scales and rhythms characteristic of a technological complex under discussion. Manifestations of sensory environments form the topic of the second part. The chapters that follow contrast terrestrial models of vision technologies with classical takes on automated landscapes and machine mobilities. The aim is to discuss the study's relevance to the politics and agencies of contemporary visual cultures. The observation shifts beyond the laboratories and asks about the emerging industry standards, technical interventions, and architecture. The manifestations are composed of three studies, gradually approaching the question of technological regimes and ecopolitics.

As the debates on visual regimes are organised around the issues of agency and control, the fifth chapter sets out to speak about the performativity and action patterns characteristic of technicised vision environments, and asks what kind of technical agency is enabled by the environment-oriented approach presented above. From the redistribution of agency, the inquiry moves to the redistribution of space, and the sixth chapter focuses on physical arrangements, indicating the alleged entanglement of sensory and computational practice. The final chapter concludes the study with ecopolitical references by matching the observed sensory reconfigurations with the selected postulates of current debates on climate science and algorithmic governance. The final part presents observations on how technologies rearticulate the politics of the commons. Here, I argue that with the mass proliferation of automated environments, points of friction and power asymmetries arise, not from oppressive surveillance and normalised pattern recognition algorithms, but primarily from the treatment of sensory communication as a commodity, granted and distributed through the privatised channels of technological service providers. In this sense, the chapter aims to pose a series of questions that outline a future discussion for visual studies and design agendas.

What is at stake?

With the following contribution, I argue that vision engineering deserves renewed intellectual engagement. The diagnosis I dare to formulate insists that today's key technological debates should be framed around not one, but several technics; not only those dependent on perception as abstracted into data, but also other much more earthbound technologies relying on the direct conflation of material and sensory qualities. Due to the terrestrial character of the latter, it is critical to raise awareness among those who are gathered along the technological assembly line: engineers and designers searching for photosensitive components and filters, devising algorithms, and solving foundational problems. At stake here is not just the monitoring of recent technoscientific developments, but also the renegotiating of territories, and understanding how the spatialisation of more-than-human habitats is changing their tropes under the pressure of technical materialities. In that sense, an inquiry into the universe that has emerged over the decades of vision engineering translates directly into the aesthetic and socioeconomic issues at play at the time of writing. As my proposition is to work with earthbound visual cultures, my call for the renewed politics of vision becomes a call for the renewed governance of the commons.

FIRST PART / experiments

1. On image processing

The algorithmic challenges of machine vision attract the attention of artificial intelligence research and critical code studies, but it is hard to get anyone's mind around a subject as mundane as image processing. Image processing is a foundational technology for machine vision. It is a subfield of computer science, established during the 1960s to provide methods for the controlled transformation of digitised material. During its first decades, it provided a number of procedures to compress, filter, and segment image content. Its uptake was proportional to the proliferation of digital imagery, peaking in the 1990s. At the dawn of 21st century, however, as a research domain it seemed to lose some its verve, at least in the minds of some concept-oriented researchers. It was at this time that Azriel Rosenfeld, a pioneer of the domain, concluded an encyclopaedic entry on the advancements, acknowledging that image processing could still be exciting providing work on collaborative JPEG, JPEG-2000, and MPEG standards, getting access to high-capacity computational architectures, and turning towards a broad spectrum of civil applications (Chellappa, Rosenfeld, 2003, p. 629). It is not surprising, then, that a generation of younger engineers described image processing, in anecdotal statements, as a field in which an academic researcher could at best count down to their retirement, knowing that the next breakthroughs would be introduced by private investors and the IT industry. In this, they were actually quite right. However, since the world is not a machine-readable place, extensive transformation of visual matter has necessarily been positioned at the crux of the digital domain. Consequently, layer by layer, frame by frame, neural networks and image segmentation algorithms crunch and convolve terabytes of visual data.

The image processing of Rosenfeld and Chellappa (2003) takes place in a digital domain: "Computers [as they initiate the entry] are used to process images for many purposes. [Therefore] image processing is the computer manipulation of images to produce more useful images" (p. 595). This equation of computers and processing makes the transformation of visual matter *signum temporis* of the digital transition. In the wake of generative AI, the ubiquitous transformation of the image content is taken for granted. It may then be useful to temporarily set aside

this assumption of self-evidence. A way to do so leads through thinking of image processing not as a historical manifestation of the digital age but as a principle of contemporary visual culture. A principle not invented but grasped and naturalised by the practice of computer sciences.

In this chapter, I propose to reintegrate the concept and definition of image processing. The work relies on bringing back together the scattered modalities of visual technologies and revising their complacency. As a starting point, I will take an average one-liner on image processing in the context of STEM that refers to the manipulation of image content data in a digital system. For example, the McGraw Hill *AccessScience* repository defines it is as: "The computer manipulation of visual data to solve a problem" (Umbaugh, 2024, p. 1); or Rosenfeld and Chellappa's aforementioned paragraphs in *Encyclopedia of Physical Science and Technology* (2003, p. 595). Often, computer manipulation of images is accompanied by other operations like "image display, restoration, enhancement, and classification" (DeFries, 2013, p. 389). Similarly, one to the the AI-generated definition in *ScienceDirect* offers that image processing refers to the manipulation and enhancement of digital images using computer software (Carter et al., 2022, p. 135). From this point on, we will map the central techniques of today's machine vision systems in their broader contexts.

A basic definition

Approached via generic definitions, it seems that processing is all the achievement of computer science. However, zoom out from that point and we begin to come to terms with an important phenomenon: the constant transformation of visual matter is more than a cog in the algorithmic systems. Computational culture has accelerated the hitherto latent component of visual technologies by enabling images that are neither frozen nor fleeting. This mezzanine level of visual culture, I would say, is not precisely an inert flow of hallucinated representations. It is rather a slightly destabilised, wobbling object, adjacent to Benjamin's study of technical reproduction, to Deleuzian themes of difference and repetition, and to Flusserian philosophy of time and history in media (Benjamin, 1935/1968; Deleuze, 1994; Flusser, 2011; Leslie, 2015; Poster, 2011). An example would be a latent pattern emerging on photographic paper carefully exposed in the darkroom, or an image of a diatom synthetised in the microscope's lenses and mirrors, or even a painting by an Old Master that has had its varnish dissolved in a restoration studio. For now, I would just suggest that the importance of processing techniques is limited by the discursive tradition that entrenches technological cultures in their specific modalities. I therefore propose to consider image processing as a cultural technique and argue for rewriting its characteristics from STEM discourse.

What would such a renewed approach achieve? The importance of image transformation has grown with advances in computer science, and the computational paradigm has colonised thinking about what processing material is and how it might be done. After decades of development, its generic definitions have become almost entirely equated with digital methods. Unlike their 1970s predecessors, contemporary textbooks on computer vision barely mention the viability of optical information treatment (Gonzales, Wintz, 1987; Sonka et al., 2014). The demise of analogue photography has erased the associations with darkroom-developed film, latent images, and retouching from popular discourse. However, while silicon technologies have colonised most of the discourse on image transformation, photochemical reactions, optical setups, mechanical and even physicochemical interventions are still being efficiently used to manipulate the content of images with a view to their intended applications. The latent, tenuous coexistence of these methods has been reported without much reflection. For example, if one refers to the third edition of the *Encyclopedia of Physical Science and Technology*, the diversity of modes is revealed in the entries on optical image processing, partially coherent processing, photographic processes and materials, to name but a few (see Chellappa, Rosenfeld, 2003; Francis, 2003; Mirsalehi, 2003; Vincett, Sahyun, 2003). However, one would look in vain for any intention in these lists to show processing as a multimodal technique that goes far beyond the concept of information or signal. For the rest, see theories of computational culture (Berry, 2015; Berry, Dieter, 2015; Cramer, 2015; Parisi, 2021) eager to sniff out a trail through this thicket and challenge the transparency of the dominant narratives by asking: what does this coexistence indicate? Is it merely the result of layering apparatuses in the order that media archaeology reveals? Or should we consider image processing modalities as interdependent and complementary?

As a first step, it would not even be particularly difficult to configure a new perspective on the ubiquitous transformation of images, not least because it is considered a benefit of more than one technical system. In the case of optics and photochemistry, it serves as proof of the field's excellence. Here too the encyclopaedia entries concur:

> OPTICS has been critical to every scientific and technological revolution, beginning with Copernicus down to microelectronics and telecommunications. Optical instruments continue to be used to magnify both the images of distant galaxies and the subwavelength features in biology and microelectronics. Optical imaging systems are used both to enhance visual observation and to acquire, process, or transmit images by photography, videography, or digital electronics. (Young, 2003, p. 645)

The ubiquity of digital image transformation also serves as a means of comparison with other domains: "A modicum of image processing is built into all photographic

materials and processes, owing to their limited response characteristics, as well as the way in which they are employed […] Much more sophisticated image processing can be carried out with digital imagery" (Vincett, Sahyun, 2003, p. 131).

There is a wealth of media studies that allows us to trace the subtle affinities between the computational and material components of imaging (Leslie, 2015; Zielinski, 2008). Those are well recognised for revealing the kinship between Rembrandt's black inks, Hollywood film tapes, and light shining from mobile phone screens (Cubitt, 2014). However, with its otherwise suggestive insights, the field remains predominantly object-oriented: focused on images, films, blackness, light, pieces of code, types of filters, and tending to consider records of compressing, deteriorating, restoring, and retouching images as a rather loose set of practices. With the subsequent account, we seek to reaccentuate this approach by framing concerns of divergent technical cultures.

An exercise in interweaving the practices of methods and crafts – long treated as distinct – may prove illuminating. An integration could start by anchoring image processing in the broader context of science and technology, characterising it as a relatively recent cultural technique that generates a set of procedures designed to destabilise a visual object and elevate it to a new form in a limited, controllable way. Next, we could develop the historical narrative: image transformation has occasionally been viewed as an undesirable phenomenon in the context of nineteenth-century photochemistry and art restoration, where the original problem amounts to stabilising the reactions of a photosensitive material (pigments, varnishes, and coatings) applied for image making purpose. Furthermore, we can relativise the contributions of image transformation modalities that have been observed so far by adding that the practical domains of photography, microscopy, and computation have provided techniques for controlled image transformation.

Such an overview of STEM encyclopaedic entries is still not particularly revealing, but may yet be useful for weaving together the histories of what are often seen as parallel modes of vision technology. One argument for it would be to show the interdependencies and illuminate the relationships between distant, often competing, technological cultures that contribute to the field. Another is to monitor how alternatives have been cut off and to highlight cases where certain solutions have been ignored. Such a post-constructivist approach to making the history of science requires counteracting the process of erasing technical knowledge, creating the impression of accumulation, purpose, and the need to use hegemonic solutions (Bińczyk, 2013, p. 242). Taking both arguments into consideration, I propose to consider a few project experiments that reveal how links are forged between what are largely deemed independent modes of technical action: digital, optical, and photochemical processing.

Information aesthetics

Let me start with a relatively unknown experiment in the field of information aesthetics[1]. The case comes from the well-recognised circle of the Hochschule für Technik Stuttgart, where in the late 1960s Max Bense (a proponent of the calculus universalis and an animator of generative art), half-heartedly but with hope for future discoveries, reported on the assignment of beauty ratings to two drawings by Rembrandt[2]. As was typical of Bense's research, the idea was to validate the intersubjective judgement of the drawings against a standardised aesthetic measure. He called the test a "Rasterentropy" calculation. Facsimiles of the originals were superimposed with standardised grids of 240 elements. Participants rated the contrast of the shades of light and dark within each grid tile on a scale of 1 to 10. These values were then used to calculate an aesthetic score for each image according to the Birkhoff formula $M = O/C$, where the aesthetic measure (M) is the quotient of order (O) and complexity (C). The game, played by a group of art historians and philosophers in Stuttgart, was designed to test whether the value of a Rembrandt could be predicted from the ink coverage distribution calculated using information theory concepts.

The detailed report on this hastily arranged, pre-digital humanities project held an astonishing conclusion that the meticulously processed images differed in score, with $m_1 = 0.0076$ and $m_2 = 0.0167$, respectively, which did not correspond to an intuitive assessment of the participants, who found m_1 more appealing (Bense, 1968, p. 40). In the face of such unsatisfactory results, the experiment was subsequently repeated after a participating art history expert pointed out that the edges of m_1 had been trimmed a few years after it had been painted. The argument was that, since the reproductions in question did not reflect the artist's intention as regards the distribution of blurred shapes in the picture plane, the calculated m_1 (cropped) and m_2 (integral) samples were incoherent. Once the m_2 edges had also been cropped, Bense adds with disarming honesty, the calculations then reflected the intersubjective judgements of the participants.

Aside from the results, the experiment illustrates Bense's approach to information aesthetics, which, as Christoph Klütsch would argue a few decades later, emerged independently of the mainframe experimentalism of his fellow campaigners such

[1] The strand of creative experimentation that references Claude Shannon's information theory and the teachings of cybernetics has been observed by art history and media theorists preoccupied with the origins of generative arts. Among the preeminent examples of this movement, the studies enumerate attempts at scientific visual research enabled by French art collective Groupe de Recherche d'Art Visuel (GRAV), or New Tendencies in Zagreb (Broeckmann, 2016, pp. 134–149; Klütsch, 2012; Rosen, 2011, pp. 27–43).

[2] M. Bense reports on the case in a collection of essays edited by Hans Ronge (Bense, 1968, pp. 39–41); experiments with Old Masters were also mentioned in Bense (1965).

as Friedrich Nanke, Georg Nees, and even Abraham Moles. According to Bense, it was a serendipitous historical coincidence that brought number-crunching machines within reach of philosophers concerned with the idea of a calculus universalis, and allowed aesthetics to shift from a descriptive-explanatory to a prescriptive-generative mode (Klütsch, 2012, p. 248). What the Stuttgart case has in common with the emerging digital culture is a concern with the informative value of an image. It also shows that Bense, a philosopher, performs the contradictory elements of order and chaos, mathematics and art, applying Maxwell and Shannon's theories to Rembrandt's sketches and hoping that the computations would eventually reveal an aesthetic logos. In this sense, his structuralist determination, combined with a meticulous counting of shades, anticipates much of the latest developments in AI vision technologies. Attempting to calculate the raster entropy of an Old Master's work prompts participants to reconsider the delineation of image boundaries and to calibrate the grids applied to them. In this sense, the Stuttgart experiment captures the affinity of future digital work with all the recognisable instances in which image planes were discretised by Nipkow disks and captured by flying-spot scanners known from the early television era[3]. Since 1950, digital technologies have reduced the material image to information, but Bense's case is a reminder of how close it remains to the blunt, mechanical crushing of objects. Taking this case as a starting point, I will turn to the domains of technical practice.

Optical setups

It was an image formed by a wave of light, not merely a bit of information, that initiated theoretical inquiry in the long-established field of microscopy. At about the same time that grids were being applied to the subtle gradations of Rembrandt's sketches, the illuminated bodies of microalgae were being used to calibrate the acuity of open-ended optical systems. Twentieth-century microscopy provides descriptions of complex procedures for the automated identification of objects. In those terms, the review by Silverio Almeida and Guy Indebetouw presents the state of the field in the 1980s. It is a comprehensive introduction to a branch of optics that originated some hundred years earlier in the works of Ernst Abbe. The review contains a list of practical applications, one of which refers to a classical task in taxonomy and marine environment research:

[3] Improved models of flying-spot scanners were postulated in a foundational paper on "Experiments in processing pictorial information with a digital computer" published by researchers at the National Bureau of Standards in Washington D.C. (see Kirsch et al., 1957, p. 227).

> One would like to develop a rapid optical method for both identifying and counting diatoms [microalgae]. […] Since the diatoms are phase objects, the first step in their identification was to convert them into a suitable input format for the optical processor. (Almeida, Indebetouw, 1982, pp. 73–74)

Due to their characteristic structure, diatoms have served as standard specimens for microscope tests. Hence automatically counting the fine outlines of *Pleurosigma angulatum* – using the method described by Almeida and Indebetouw – became one of the model objects for Ernst Abbe's engagements in founding the field (Masters, 2020, pp. 45–46, 74, 75). In the 1870s, Abbe, a physicist and future partner of the Carl Zeiss optical company in Jena, set out to explain the mechanisms of image formation in optical instruments. He proposed formulas for the magnification limits of microscopes and the optical conditions that a lens must satisfy to form a sharp image (the so-called Abbe Condition). The later history of Abbe's contributions shows that at the basis of image formation theory – further developed by his younger co-researchers (such as Czapski, Köhler, and Siedentopf) – was Fourier optics (Gross et al., 2005b, p. 241). Later experiments in the field explored the possibility of building optical correlators – devices that took advantage of beams of light travelling through labyrinths of prisms and lenses for the purpose of information processing[4]. When Almeida and Indebetouw addressed the community of experts on Fourier optics, Abbe's inquiry became a classic point in the philosophy of science.

In his study on scientific realism, Ian Hacking evokes Abbe's famous investigations while arguing that there is a fundamental difference between macroscopic and microscopic vision, between looking at Jupiter's moons through a telescope and observing microorganisms with a system that (as Abbe notes) works like a diffraction synthesiser (1983, 1985). Concluding on the incommensurability of macro- and micro-object observation, Hacking (1983) suggests that the long-standing rejection of Abbe's theory reveals a tricky assumption about the processing and vision of real-world objects.

[4] Fourier optics has enabled an understanding of various physical phenomena in terms of frequency analysis. It provided a theoretical basis for the broader practice of signal processing. Named after Joseph Fourier (a French physicist who in the first decades of the 19th century worked on equations modelling how a quantity such as heat diffuses through a given region), the theory turned out to be useful for a study of signals propagating not only in devices such as microscopes, but also in communication systems that proliferated in the 20th century. Fourier optics then became proof of concept for common principles that can be applied to the transformation of images both in electrical (i.e. composed of wires, amplifiers, and sensors) and optical ensembles (devised like microscopes and all sorts of other optical correlators of lenses, prisms, and blends that filtered beams of light). A comprehensive introduction to the research on physical image formation in microscopes initiated by Abbe and the ensuing development in optics is included in the works of Goodman (1996, 2005b), Gross et al. (2005a), Masters (2020), and Zalevsky et al. (2015).

He explains:

> If you hold […], that what we see is essentially a matter of a certain sort of physical processing in the eye, then everything else must be more in the domain of optical illusion or at best of mapping. On that account, the systems of Leeuwenhoek and of Hooke do allow you to see. After Abbe even the conventional light microscope is essentially a Fourier synthesiser of first- or even second-order diffractions. Hence you must modify your notion of seeing or hold that you never see through a serious microscope. (pp. 196–197)

With this challenge of modifying the notion of seeing, we arrive at one of the major alternatives to the digital mode. Hence it was well before the mid-20th century, I believe, somewhere between the research and development of the Abbe–Zeiss company and the mainframe labs of places like the Technische Hochschule Stuttgart, that machine vision first became achievable. Since the moment when Abbe asked why images of marine plankton fuse into a blurred microscopic spot, optical processing has moved from system analysis to system synthesis, providing techniques for image enhancement, periodic pattern extraction, and image correlation. By the mid-20th century, it also seemed that optics offered a viable fusion between communication theory and the physics of light.

Studies in optics reveal this shift when they refer to works of Pierre-Michel Duffieux (a French physicist who applied Fourier integrals to the process of image formation) and to André Maréchal and Paul Croce for the construction of basic experimental systems which thereby founded Fourier optics (Almeida, Indebetouw, 1982, pp. 43–46; Duffieux, 1946/1970; Hawkes, 1983; Maréchal, 1966). Maréchal and Croce's (1953) double diffraction, or 4f, setup allowed for the transformation of an image by controlling the distribution of light in the pupil of the apparatus with masks or filters (Fig. 1). This was followed by the introduction of laser light with its coherent beam, together with techniques for making spatial filters, and the major improvement in 1963 represented by Anthony VanderLugt's holographic-like method (VanderLugt, 1966). At the very least, operating between Abbe's condition of vision and Shannon's theory, researchers in optical processing went on to develop significant expertise in pattern recognition.

In the early 1960s, there was much enthusiasm about Fourier optical systems, as they seemed to offer a promising alternative to digital computers. Even decades later, advocates of optical computing deemed the method capable of processing massive amounts of information in parallel with the speed of light (Ambs, 2009; Stark, 1982, p. XIII). Optical processing of images relies on their transformation from the spatial to the frequency domain, and the basic procedure was

demonstrated by early trials in image enhancement at the Institut d'Optique at the Université de Paris. André Maréchal and associates, running their 4f setup experiments, sought to establish a method of fixing distorted – double-focus – photos. In that process, once the light had propagated through the lens, the image it carried was transferred to the frequency domain. The transformation – which can be explained using Fourier harmonic wave propagation equations – directed low-frequency features of the image toward the centre of the spectrum, redistributing high-frequency traces around it. Filtering methods have since been mastered to manipulate images by eliminating selected frequencies, which could lead to the extraction of periodic signals from a random noise, the elimination of periodic noise from the image (such as halftone or raster), contrast enhancement, or image blurring (depending on the suppression of the selected frequencies) (Almeida, Indebetouw, 1982, p. 68; Goodman, 1996).

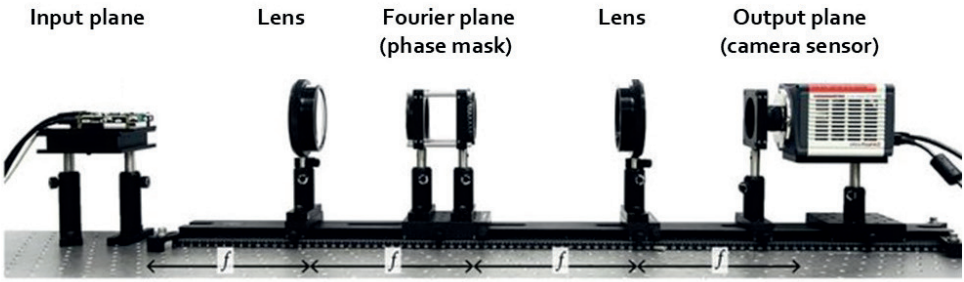

Fig. 1. Implementation of a 4f scheme (after Chang et al., 2018)

Moreover, a correlation between the input and the reference images seemed possible, while the output signal strength could reveal the similarity of the signals. However, since optical correlators were not programmable, contributions to the field relied on inventing, adjusting, or reconfiguring a suitable apparatus, in contrast to algorithm-oriented digital image processing. While the basic 4f setup offered by Maréchal and Croce in 1953 could easily have been adapted for image enhancement and filtration, experiments in pattern recognition required a more developed architecture. When a popular variant of this architecture was proposed, it changed the feasibility of certain problems. In 1966, Goodman and Weaver outlined an architecture for a joint transform correlator (JTC), a setup designed to perform pattern recognition (Ambs, 2009, p. 2). Here, apart from frequency domain filters, an additional plane was included to match the original image against a reference pattern. That is the procedure described in the aforementioned 1980s review.

Alongside high accuracy in the diatom recognition task and a number of other practical applications, the Almeida and Indebetouw introduction to optical filtering enumerates various limits to optical processing as well concerns regarding how to make the systems work. In the early 1980s, although a few special-purpose optical correlators had been constructed and marketed, most of them, the study warns, were "still in the laboratory stage, with little resemblance to what might be called an engineered prototype" (Almeida, Indebetouw, 1982, p. 65). Indeed, the optical processing applications required complex hardware systems to be configured each time; the research report includes a diagram of the impressive setup. The authors list several studies which aim to eliminate the technical issues that could potentially degrade the setup's performance. Such issues include: imprecise filter positioning; filter vibration; the effects of deformations of the filter's substrate (plates or films); the effects of vignetting, dirt, speckle, or spurious reflections on the optical elements adding to this practical design of beam splitters; *in situ* filter processing; and last but not least an automated output analysis (pp. 67–68). Despite the enumerated vulnerabilities, the 1980s presents a domain that lacked neither technical invention, nor theory, nor potential applications. However, with complaints about the unjustified price of basic setup components like lenses designed to perform a Fourier transformation, the field lacked the industry-level development of high-quality, configurable components.

What might be relevant for tracing the interdependencies between alternative processing cultures is a recurring criticism articulated by the proponents of a digital approach. The consensus was that optical processing was useful when the information was optical and that no electronic-to-optic transducers were required (Ambs, 2010, p. 10). By the 2000s, enthusiasm for optical pattern recognition had almost evaporated. Leith's account on the propagation and neglect of the solutions underlines that while optical devices upgraded slowly, computing made a fast leap forward in their efficiency and speed (Leith, 2000, p. 1300). Moreover, the integrity of optical processing was brought into question, with open acknowledgment that researchers in physical optics had developed their methods for analysing and synthesising optical data-processing systems based, as VanderLugt (1966) puts it, "on *ad hoc* approaches, intuition, and educated guesswork" (p. 1055). When the sidelining of optical computing was completed with a major industry shift, digital technologies, despite struggling with their own problems on the basis of limited computational power, argued that the prospect of speed-of-light parallel computation had been over-hyped.

Indeed, having attracted considerable interest on the feasibility of direct image processing, the field raised hopes for the growth of a versatile new technology. The ambition of computer science was to work on a general level. This led to a rupture between industries that had previously been open to exchange. Over time, the discourse on optical computing has evolved into one of the optical-digital

economy, where, as Leonid Yaroslavsky puts it, digital signals are considered a general equivalent in information handling, in the same way as money is a general equivalent in economics, and optical pulses deprived of their physical carrier have gained the value of "purified information" (Yaroslavsky, 2011, p. 398). As we move along the timeline of the debate, there is a telling reversal in how the sides have changed places. In the 1980s, lenses were seen as a component that could revolutionise pattern recognition by giving it super speed and super resolution (Stark, 1982). In later decades, however, the fusion of optics and electronics has been seen as a revolutionary stage for experimentation in optical devices such as telescopes and microscopes. By 2011, computers were seen as devices that extend the capabilities of optical systems, not necessarily the other way around, and old proponents of optics-to-digital conversion boasted about the adaptability and programmability of computers, stating that: "No hardware modifications are necessary to reprogram digital computers to solving different tasks […] This feature makes digital computers also an ideal vehicle for processing optical signals since […] they can adapt rapidly and easily to varying signals, tasks and end-user requirements" (Yaroslavsky, 2011, pp. 397–398). The above debates suggest that what had been conceived of as a technique for image enhancement and optical pattern recognition accelerated into a quest to use light waves to perform Boolean logic operations.

With time, optical methods shrank to a laconic reference put forward in academic textbooks on image processing curricula. Eventually, the presiding feeling was that there was nothing significant that computers could not do. Even a Fourier transformation – the effect that generated so much demand for 4f setups – turned out to be feasible with the algorithm proposed by James W. Cooley and John Tukey as early as the 1960s (Cooley, Tukey, 1965). By the very nature of things, academic teaching on digital imaging has not delved into the subtleties of what was once claimed to be its alternative. But what would visual culture be like if optical correlators had a stronger presence in the imaginary of computer science? If one were to try to make an argument for optical processing, it could be an argument for image integrity. Optical correlators have been criticised for offering only limited possibilities for image manipulation, but what is limiting in one culture of experimentation is compelling in another. Abbe, Zernike, and their followers were concerned with controlling the emergence of image artefacts. They did so in experiments that Hacking (1981) later selected as the best examples of scientific realism towards entities. However, in the introduction to Fourier optics in Goodman's handbook, this understood reality of transformed signals was no longer an issue.

Another benefit from a broader recognition of Maréchal and Croce would be an insight into the very nature of processing. Unlike computing, which focused on central processing units, optics configured multi-module systems, open-ended structures, and setups that allowed light to propagate through lenses and prisms,

in and out of the system. Thus, just as Max Bense's once-dilettantish experiments make palpable a strange affinity between scissor-paper works on Rembrandt and the core of information theory, tracing back all the peculiarities of optical setups indicates a paraphrasing of Hacking's observation: there is a tricky assumption in thinking about machine vision that it should only work through a centralised processing unit. Vision happens within the decentralised systems, between modules of sparsely arranged setups. Optical processing shows how much can be achieved through such open structures. Similarly, it challenges digital processing as the definitive way for image processing technologies. The wave of light could be used as an information carrier, but image processing did not have to be forced entirely into the framework of Shannon's theory. Presented in this way, neither conclusion seems to promote an integrated discourse on image technologies. Taken together, however, both disclaimers create the space to consider technological cultures that transform visual resources without engaging computational architectures and signal processing theorems.

The chemical imprint of matter

Chemical processing flourishes when it combines its waves of light with matter. The domain of non-computational, matter-oriented image processing lingers in the shadow of photography. A hint of its existence appears in Tristan Tzara's (1922/1992) passage:

> When everything that called itself art was well and truly riddled with rheumatism, the photographer lit the lamp of a thousand candles and step by step the light-sensitive paper absorbed the blackness of several objects of use. He had discovered the momentousness of a tender and unspoilt flash of lightning, which was more important than all the constellations designed to bedazzle our eyes. Precise, unique and correct mechanical deformation is fixed, smooth and filtered like a head of hair through a comb of light. Is it a spiral of water, or the tragic gleam of a revolver, an egg, a glittering arc or a sluice gate of reason, a subtle ear with a mineral whistle or a turbine of algebraical formulae? As the mirror effortlessly throws back the image, and the echo the voice, without asking us why, the beauty of matter belongs to no one, for henceforth it is a physico-chemical product. (p. 100)

With these vibrant phrases Tzara champions Man Ray's photograms – photographic images made without a camera. Esther Leslie weaves the fragment from *Champs Délicieux* into an account on the revolutionary load of photography in Walter Benjamin's writings (Leslie, 2015, pp. 15–16). All the way back in the 1920s, experiments with direct photography marked a departure from the medium's

foundational myth – the reversal of the story of active light penetrating passive matter. As Leslie (2015) writes:

> This process provides the chemical imprint of matter in all its new and revolutionary beauty. Matter has come to voice, and it speaks of itself. The most precise mechanical act produces something quite magical, just as it is material, physical and real, and, furthermore, it is owned by no one. This is not property. It is an art of "luminous values" in "passionate progress" that no modern art, no painting, can halt. (p. 16)

Notions of "voicing matter," the "art of luminous values," and "revolutionary beauty" will lead us back from the philosophical plateau to the discourse of science and technology. The materialist's praise of technology extends to practices long relegated to the second line of photographic reflection: laborious chemigraphic processes, artisanal tricks inherited from the arts of etching and lithography. If photography has always been about permanence, about capturing and immobilising a fleeting glimpse, then chemigraphy would be about the transformation of latent, outsized, imperfect images. Materialist interpretation breaks through media studies and STS discourse on photography, but even when steps are taken in this direction, the focus on the practice of light prevails (Cubitt, 2014; Pavlidis, 2022, pp. 81–162). Voicing matter becomes possible not only by foregrounding photographic experimentation *per se*, but primarily by teaching material culture studies and tracking the histories of glitter, phosphorescence, or the chemistry of colours (Leslie, 2005, pp. 95–117).

In introductory teaching on the principles of contemporary photography, chemistry is a problematic component. It can be attached to the past tense of photography and presented as a field that "gave photography a boost" (Pavlidis, 2022, p. 9), but even in classical introductions to the photographic arts, chemistry is placed in the process in a number of ways. Not to stray too far from the basics, transformation is underlined in accounts such as William Henry Fox Talbot's *The Pencil of Nature* from 1844:

> During the brilliant summer of 1835 in England, I made new attempts to obtain pictures of buildings with the camera obscura; and having devised a process which gave additional sensibility to the paper, viz. by giving it repeated alternate washes of salt and silver, and using it in a moist state, I succeeded in reducing the time necessary to obtain a picture with the camera obscura on a bright day to ten minutes. But these images, though very beautiful, were very small, like miniatures. (Talbot, 1844/2010, p. 9)

The photographic processes mastered by Talbot elicits the intuition that image technology is not just a flare of magnesia illuminating the camera lens, it is also

a corporeal, wet process spread over many stages and apparatuses. It is not fleshy, it does not work on portable devices. It is a processing that functions in distributed architectures.

A good example of a multi-stage technological process is that of chemigraphy. In the early 20th century, it converged into a method in which matrices were interchangeably retouched, varnished, exposed to light, halftone filtered, and etched. It emerged from the mangle of practices that fused photographic-like engagement with the craft of printmaking. Some insights into this workflow as it was arranged in the time of Walter Beniamin and Man Ray were captured in a 1930 documentary film *Het grafisch bedrijf* (van der Wal, 1930). Characteristically the theme that introduces the chemigraphic practice focuses on the organisation of the multifunctional studio (compare Schraubstadter, 1892, pp. 13–24) (Fig. 2). The camera walks us through a cramped workshop, backyards filled with water basins, chemical baths, and darkrooms. The journey starts at the retouching desk. The following shots show a photograph of a jazz band musician being transformed within a multistep rework procedure involving aerographs and fine brushes. During this process, the contrasts are changed, the background is erased, and the contours of the details are heightened. Having employed traditional techniques of image-making, the workshop proceeds perversely to blend almost every technique known to the history of image-making.

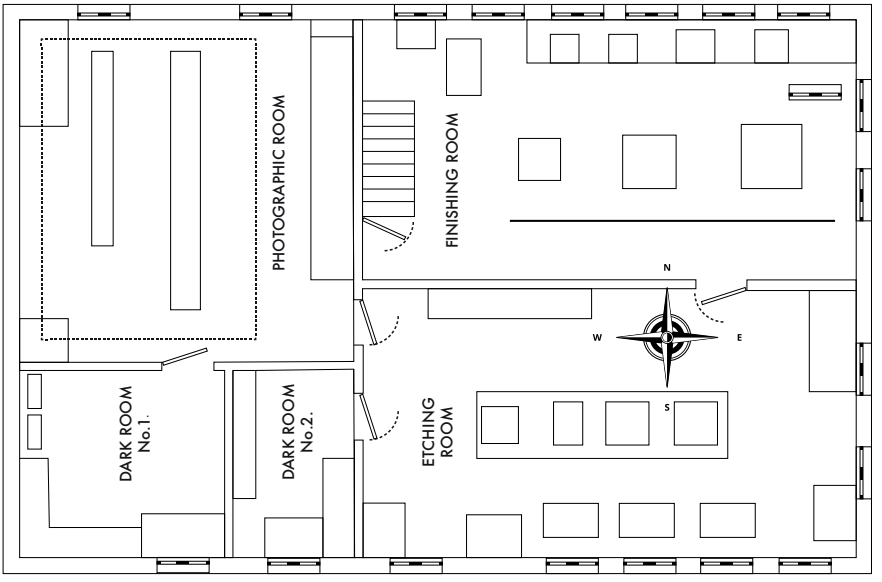

Fig. 2. A multistage process enabling image transformation manifests in the organisation of the chemigraphic studio: from retouches to the input picture, to photographic reproduction, processing, and transferring the image onto printing matrices. A plan of a studio (after Schraubstadter, 1892, Figure 1)

What can be learned from this? It appears that chemigraphy employs photosensitive varnishes – possibly a Syrian asphalt (which, by the way, has for a long time served as a component in vernix covering the acid-digested plates of etchers)? In the chemigraphic workshop, this substance is exposed to light to harden and mask the plate before the acid bath. Technicians apply halftone filters, discretising the image plane to create an illusory gradation of grey. Scene after scene it becomes evident that by the mid-20th century these complex practices had become routine in the polygraphy industry and ultimately became infused with digital technologies that increase control over the production process. Elements of chemical image processing are practised in fields related to material science, testing refractive surfaces, dyes, and pigments.

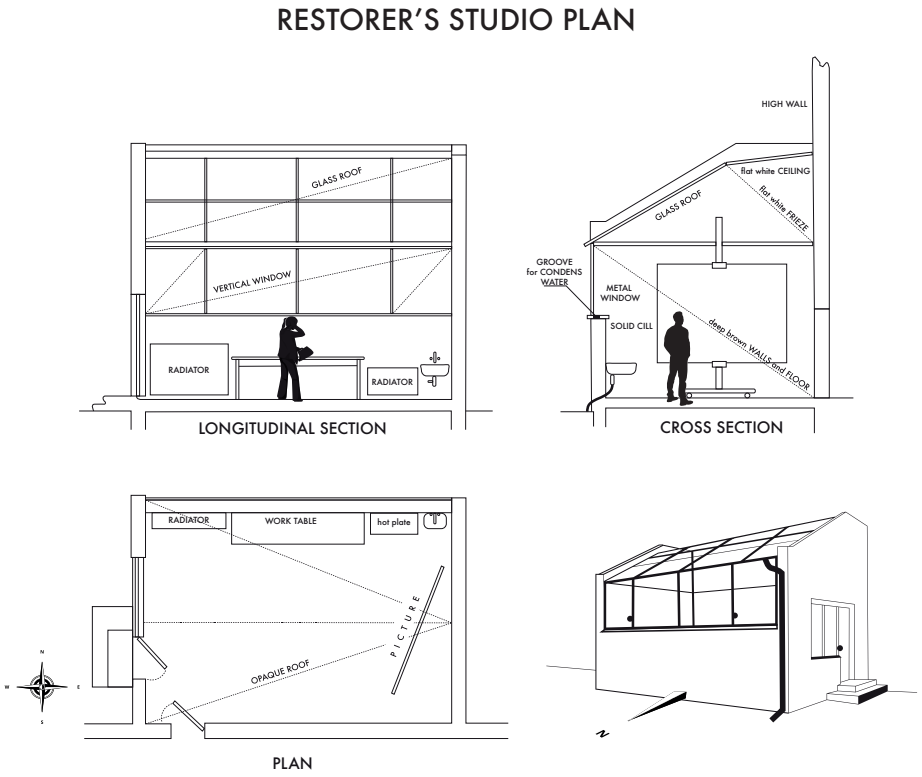

Fig. 3. A detailed recommendation to optimise the environment for inspecting Old Masters' paintings includes orientation towards north, proportions for open and covered ceilings, and wall paint colour. A restorer's studio plan (after Ruhemann, 1969, p. 70)

Could the efforts of chemigraphy serve as proof of concept for what I am trying to construct in this chapter's exploration? They render palpable an extended, multistage process, that comes with alterations to material structures, that

changes the physical conditions of the film and produces matrices and prints, but does not take the form of a centralised system. From the chemigraphic workshop of Schraubstadter, the observation should move to the art restoration studio sketched by one of the field's most influential figures, Helmut Moritz Ruhemann. Ruhemann's case of painting restoration supports a number of processes, some of which duplicate the work of chemigraphy, while others remain specific to the discipline. Restorers' studios aim to bring back the transparency and coherence of faded pigments, disintegrated varnishes, and films by exposing the painting surface to chemical activators (like in Pettenkofer's process). For this purpose, not only the workflow, but also a physical space becomes a carefully devised environment. Ruhemann (1969) details the requirements for lighting conditions and wall surface colours for successful operations on paintings.

In the ideal studio envisioned in *The Cleaning of Pictures* (Ruhemann, 1969), materiality, light distribution, and space are combined into a craft of image transformation. The passage emphasises that powerful light is more important for the sharp observation of museum objects than strong magnification. He renders the arrangement of the interior in great detail:

> High side windows are imperative for a restorer's studio, if possible, joining on to a low top light and running along the whole length of the wall. But the top light must not extend over the whole of the studio roof: one third or half of it away from the side window should be opaquely covered. Light coming from every side is useless for restoring and creates distressing reflections. The walls must be painted dark and matt. Very dark coffee brown has proved more agreeable than black. (On this colour pictures look surprisingly well).
>
> In artificial lighting the restorer must also have the most powerful available, provided that excessive ultra-violet radiation is avoided. The window panes should all have an ultra-violet filter. Where this is not yet installed, the pictures should be covered when not being worked on. Fluorescent lighting has one disadvantage: it is too diffuse for certain jobs and, like the conventional studio top light, not concentrated enough. For anything to do with the surface texture of a picture, such as puttying, treatment of flaking and for varnishing, a small concentrated source of light is needed of which one can clearly see the reflection on the surface of the picture. Also, for observation or retouching of fine detail a stronger, better-focused lamp is necessary. (pp. 70–71)

With its one third of the roof covered with opaque material and "very dark coffee-brown walls," the description echoes advice from the Old Masters on how to choose a studio with windows exposed to scattered northern daylight. An insight into this kind of working environment offers a valuable reference point

for the exploration of astronomers' observatories and robotics laboratories presented in the following chapters of this book. But prior to advancing further, it may be instructive to briefly reconsider the surface of the Old Master's painting illuminated by "a small concentrated source of light."

With all its passion for configuring both technological workflows and specially arranged interiors for this purpose, with all its expertise on historical and laboratory methods, art restoration provides a radical example of processing technologies. The effects of light, oxidation, and uncontrolled reactions between the components of pigments or varnishes force slow but obvious changes on the surfaces of paintings, polychromies, and frescoes. Twentieth-century experts working on museum collections have excavated a number of the historical practices of painting surface alterations, enhancing surface tones with colour varnishes or darkening patinas. Expertise in art restoration demonstrates how relative is the assumption that an Old Master's work is a purely painted, integrated, and ever-stabilised object. Their debates remind us that routine practices like light filtering and colour scale equalisation are part of a painter's craft; artists themselves used varnishes and glazes to deepen image tones and filter the light reflected from the picture's surface. Most interestingly, they recall a number of practices that destabilised the material image's surfaces. These included eighteenth-century Venetians softening the surfaces of paintings to copy them with tracing paper. In declaring themselves as acting against time-induced natural processes and secondary interventions, art restorers have contributed to deepening our understanding of the Old Masters' craft and the long history of image processing.

Fierce debates in art restoration have often concerned "unacceptable" treatments, which highlights the tensions between the historian's cabinet and the restorer's studio. Such was the case in "the cleaning controversy" that occurred between 1947 and 1965, after the National Gallery in London exhibited some of its recently de-varnished paintings (Maclaren, Werner, 1950, pp. 189–192). During the Second World War, the Gallery undertook a series of interventions to clean part of its collection of Old Masters' paintings. Some of the work was carried out under the direction of Ruhemann, who had found refuge in England from Nazi Germany. These interventions stirred up major controversy in the world of art history, which was regularly reported in *The Burlington Magazine* correspondence and commentaries from 1940 to 1965. Disputes reached the public when the Gallery exhibited the noticeably changed Old Masters in 1947[5].

[5] The 1947 *Exhibition of Cleaned Pictures* was the museum's response to intense commentary on the newly reestablished permanent display of Old Masters in the partly ruined building of The National Gallery. Sheldon Keck traces the history in some detail, quoting excerpts from complaint letters sent to *The Times* between October 1946 and May 1947 by viewers surprised by the cool and bright palettes of the paintings presented next to the unrestored pieces of the collection (Keck, 1984). For the voices in the debate on the ground of art history, see Gombrich (1963).

The cleaning controversy that resonated between the walls of Ruhemann's studio, has divided those who saw avoiding intervention as a guarantee of the image's authenticity from those who thought it possible to attain the image's original appearance through positive research and active treatment. A laboratory was founded at the Gallery, in addition to the studio, based on a suggestion from the committee investigating the case in 1947 (Weaver et al., 1950, p. 132). The Gallery invited Ernst Gombrich, then head of the Warburg Institute, to inspect their new laboratories. Somewhat irritated, he responded in his 1963 paper on why he would not accept, saying that such a visit can teach the historian no more than a visit to an operating theatre can instruct the layman in medicine (Gombrich, 1963, p. 93). He has defended art history's right to critically assess the procedures developed by experts in chemistry. This same tension can be sensed also in Ruhemann's late work. By the end of his career, he – who himself introduced the method of removing varnishes to the National Gallery – argued that all laboratory findings need practical verification and that the scientist was "not immune to wrongly interpreting facts" (Ruhemann, 1969, p. 135). During the decades that shaped its identity, art restoration was not alone in distinguishing between the scientific approach and direct sensory experience (Gritt, 2013; Jones, 1962; de la Rie, 1987).

Scandent technologies

Having completed a lap round the territories of visual culture, I will return to the principles introduced at the beginning of the chapter. Regarding the aforementioned examples, I favour an approach that emphasises distributed architectures and the multimodal character of vision engineering. Therefore, an integrated definition could be formulated as follows: as a relatively recent technique, image processing has been developed in optical, informational, and photochemical variants. It facilitates the emergence of distributed, scandent-like systems, where processing is enabled through the configuration of versatile instruments and modules, including solid-state sensors, prisms and lenses, chemical activators, and sophisticated light sources.

For the study of vision technologies, the proposed approach has at least two implications. First, it acknowledges their key challenge is not in improving algorithmic methods, but rather in developing new design paradigms and enabling ecosystems of relation that integrate into environments in which vision emerges as a major resource, a pool of commons. As so much depends on the careful configuration of otherwise versatile elements, design has a prior importance for vision technology as it can lay foundations and elicit the most valuable contributions. Furthermore, the proposition implies a type of nature-technology

relatedness at work here. The proposed characteristics fill a gap in technical discourse that fails to address the systemic, long-wave, ecological character of their interventions.

While using terms like trailing or scandent technology in a not entirely figurative manner, the characteristics suggest that image processing results in a specific type of intervention in what is perceived as a material arrangement not only of optical processing ensembles but also of the art restoration or chemigraphic studio. With chemigraphy and optical setups, processing took the form of distributed practices. Importantly, the distributed systems observed here are characterised by specific dynamics, as they do not load the landscapes with heavy infrastructures, but instead inconspicuously latch onto the painted studio walls, cling to the darkrooms of chemigraphic workshops, coil around laser beams, or tilt toward northern daylight. Observing the inconspicuous propagation of sensory systems is no less important than observing the intrusive behaviour of infrastructure-laden or heavy, extractive industries. Inconspicuous expansion into the sensory environment, as I will argue further, is both an instrument and a subject of technological colonisation.

In the following chapters, I will take this definition out of the abstract confines of the encyclopaedia and embed it in the histories of research and practice that have given rise to the technomaterialist variants of machine vision environments.

2. Physics-based vision is mildly ill-posed: engineering trials and the empirical investigation

The previous chapter explored ubiquitous image processing routines. It argued that state-of-the-art vision techniques would be best understood as a collaborative process distributed between a range of agents operating in photochemical, optical, and digital domains, rather than as a swift digital procedure. What follows is an exploration of the empirical research that aims to elucidate the constitution of digital image analysis and machine vision. From this vantage point, we will argue that the machine vision constructed through engineering trials and empirical scientific investigations is characterised not only by a free trajectory through a number of modalities and agents, but also by becoming earthbound, dependent on material arrangements made in front of the camera lens or the observer.

Below, I propose to discuss a line of research concerned with the physical conditions behind image formation. The review will intertwine historical developments in computational methods and their related investigations in photometry. Central to this account will be the history of a fractious project to create visual AI by using non-trivial optical models that overcome the innate deficiencies of computational systems. The strands of research that I would like to bring together, each in their own way, assume the meticulous specification of the investigated objects either in terms of their position towards light, their shape, or the reflectance properties of their texture, etc. The technicalities vary: in one case the work evokes a sophisticated variant of film-set building. In another, it relies on references to objects such as reflectance maps, devised to calibrate computational procedures. What will be important here is to observe how managing the precarities and unknowns of visual inquiry has forced distant research cultures to act through the embeddedness of their work with the specific, laboratory-arranged environments.

Understanding the physics behind image formation

Few machine vision engineers have openly criticised their field for developing new domains while disregarding peculiarities of the phenomena under consideration. In a short MIT AI Lab report from 1978, Berthold Horn states that machine vision should not be considered a simple extension of AI experiments. The methods invented for symbolic or linguistic operations, he claims, need to be revised to treat visual matter (Horn, 1978). As vision deserves investigation in its own right, Horn's proposition is to reach beyond geometry-based, trivial models of imaging optics. He posits that image interpretation should no longer brush aside features that have physical significance, but should focus on the intrinsic properties of objects, like luminosity, texture, colour, etc.

The idea of studying physical image formation came to computer science from photometric research. Gazing at the lunar surface, astronomers were in an excellent position to solve the non-trivial optical models behind image formation. It was a lemma of extraterrestrial photometry – that matter interacts with light predictably – which has lent much methodological soundness to the stemming branch of computer science. The work of selenographers reverberates in paragraphs of the first edition of Horn's (1985) *Robot Vision*, where he outlines the connection as follows:

> There was much interest in determining the shape of the surface features of the moon from telescopic images taken from the earth, at least until we could send probes, and finally people, to the vicinity of our rocky satellite. Since the libration of the moon, as well as the ratio of the radius of the earth to the distance between the two bodies is small, we always see the moon from essentially the same direction. Thus, binocular stereo can be ruled out as a viable method for recovering surface shape in this instance. Astronomers used shadows to estimate the relief of crater edges above the surrounding terrain. (p. 267)

Horn's physics-oriented computer vision adopted the photometric system of language and mathematical formulas. Like planetary satellite researchers, the future author of *Robot Vision* built his early investigations on light-scattering models that were dependent on physical parameters, such as the porosity of the optically active upper surface layer, the albedo (the maximum reflecting power of the material), and the degree of topographic roughness (Buratti, Thomas, 2009, p. 372). These models were essential for predicting brightness variations as a function of the observer's position, the light source, and the object.

There is remarkable beauty in Horn's passage as it subverts the narrative of technology it speaks about. The planetary gaze, the gaze from nowhere, the stare of a thousand satellites orbiting the Earth, is an emblematic figure of automated super-senses. Marshall McLuhan was among the earliest to argue that, with the first loop of Sputnik in 1957, Earth – enveloped by a human-made device – became a scene for the all-encompassing performance a "single sound-light show" (McLuhan, 1971, pp. 528–529). The theme has been taken up in Benjamin Bratton's account on satellites that configure themselves into a global theatre, creating a shell of pan-Earth cinema that captures the totality of the human condition (Bratton, 2019). In a monograph on politics for the future, Latour (2018) argues that marvelling at the view of a distant planet is contradictory to the terrestrial awareness of those who land on the Earth's surface. The lunar disc of Horn's introduction seems to interlink the "gaze from nowhere" with "a machine stare." This impression, however, begins to dissolve when one looks more closely at the methods and models underlying it. The planetary figure evoked by Horn was not a warp of hyper-vision fantasy, nor a label for trans-human technologies. The Moon, observed by earthly species, head-up from the ground – which, on the cosmic scale, means always from more or less the same place, always from more or less the same angle, and also always "as if" with one eye – is not a celestial body like any other. It is an extension of our terrestrial environment and, in the moment, distorts the perception of this environment through a specific light-scattering behaviour. Lit by a distant sun, it appears almost flat due to the specific properties of its surface. This fortuitous imperfection, debated already in Galileo Galilei's *Dialogue*, persistently directs the work of engineers to avenues that reveal the inevitable embeddedness of the sensory systems. Once Berthold Horn chose lunar observation as the starting point for his physics-based machine vision, he entered a specific territory: one that stretches between the ridges of the ocean's tides and the dusty craters of the Earth's satellite.

A strand of research that leads to this point runs through space exploration prearrangements in which a planetary model is rendered on the scale of a machine. Satellite surveillance missions were often the opening case in histories of digital image processing. However, a less explored part of the history considers what computer science has learned from this encounter with the until then, and still long after, remote experimental cultures. This is especially pertinent to the period of the American and Soviet space race, when, as the authors of one review later put it, lunar "astronomers became witnesses of a great invasion of allied sciences" and "the moon had become the subject of geology and other inquiries" (Shkuratov et al., 2011, p. 1327). Computer engineers became familiar with the expertise of lunar astronomy through the teams working on unmanned spacecraft missions. Engaged in one of the 1960s

cosmic surveillance programs, the Jet Propulsion Lab popularised a set of findings that were critical for understanding how the brightness of the lunar surface relates to the topography of the earthly satellite. Optical measurements of the Moon provided a reliable reflectance model that used to interpret the photographs taken by probes sent on a collision trajectory with its craters (Willingham, 1964, pp. 1–2).

A strand of investigations that led to the MIT AI Labs starts with the astronomical observations pursued in European observatories, extending from Kharkiv to Strasbourg, and most importantly Utrecht's Sonnenborgh. In the course of this research, the puzzling flatness of the appearance of the lunar globe was explained, and the features of the topography and geology of the Moon were detailed. From the variations in brightness under changing illumination conditions, photometry investigated the geometrical and physical properties of the Earth's satellite (Minnaert, 1961, p. 213). Within a long-established network, photographic plates of the lunar disk circulated along with the scales, atlases, and calibration methods. A 1960s introduction to the Moon's photometry by Vasiliy Grigorievich Fessenkov provides some insight into this research and its commitments right at the start of the lunar race. His introduction emphasises an otherwise common declaration to use, as the author puts it, "instrumental means which would be sufficiently precise to permit objective measurements to be made" (Fessenkov, 1962, p. 100)[1]. After the development of direct lunar surface photometry and its specific matter-light interaction characteristics in the 1960s, observatories were roughly at the moment when an opportunity had been created to invert the problem and treat meticulously calculated reflectance curves as coefficients to elaborate on the details of lunar cartography.

The chapters of *Robot Vision* specify the contributions of Utrecht's Sonnenborgh Observatory – at the time famous for its empirical approach to the investigation of optical phenomena. One of the points of reference was Sonnenborgh's method for recovering three dimensional shapes from the variations of the image intensities. The method informed Horn's major contribution to the computational part of machine vision – the shape from shading algorithm (Horn, 1970). In these terms Horn refers to a 1951 study by Johannes van Diggelen in which he successfully demonstrates how the topographic relief of a lunar mare can be determined from a single, uncalibrated photograph. His analysis of photographic resources advan-

[1] Among the particular challenges of such measurements, astronomers listed determining the absolute and relative brightness of lunar maria, mountains, and planes, which would allow for an assessment of the reflection index of light for every detail of the Moon. Another problem mentioned is the interpretation of such indices "by their comparison with different terrestrial substances, with a view to obtaining some insight on the micro-structure of the lunar surface" (Fessenkov, 1962, p. 100).

ced the already exorbitant standards of lunar topography: he specified the shape of two apparently smooth regions of lunar maria, quite notably located near the Moon's terminator.

Following the standard procedures of photometric investigation, Utrecht converted the photographic plates into transparencies. As his source, the Dutch astronomer used a selection from of the 74 images taken at the Yerkes Observatory in the summer of 1946 (van Diggelen, 1951, p. 423). The densities of a transparency could then be measured by microphotometer, most probably a piece constructed for the Utrecht Observatory by Jakob Houtgast (1948). Such a procedure, however, required the original plates to be calibrated at the moment of image capture. As not all of the Yerkes plates were properly calibrated, the visual work at Sonnenborgh proposed an entirely general method, independent of both the photographic density curves calculation and the special cosine law that indicates the ideal orientation to diffuse the reflecting surface towards the observer's line of sight (van Diggelen, 1951, p. 285)[2]. The cues for calculation of the uncalibrated photos of lunar maria were derived from two assumptions: the liminal location of the surveyed terrain, placed near the Moon's softly occluding terminator; and all the lunar mare being filled with a material of the same reflective behaviour. Characteristically for the analytical approach of computer science, Horn (1970) finds van Diggelen's method "heuristic," but nevertheless follows him and the later contributions of Rindfleish, who systematised mathematical formulations for lunar topography, thus opening up a series of attempts in the more general use of photometric formulas (Rindfleisch, 1966; Willingham, 1964).

Another Sonnenborgh author referred to in the context of computer vision is Marcel Minnaert – van Diggelen's senior co-investigator and a prominent figure in empirical photometry research. Best recognised for the Utrecht *Photometric Atlas of the Solar Spectrum* (Minnaert et al., 1940) – a classic spectrophotometry reference – Minnaert proposed simple reflectance functions that refined a photometric model of the Moon. In particular, he proved that a puzzling light-scattering

[2] The special cosine law mentioned in van Diggelen's work is Lambert's optical cosine law, published in 1760 in *Photometria* by Johann Heinrich Lambert (a German mathematician, astronomer, and physicist otherwise known for the early formulation of the Beer–Lambert–Bouguer law, which explored the observable relationship between the absorption of light and the nature of the material through which the light is traveling). Lambert combined his mathematical studies of light intensities and absorption with practical experiments, for which he constructed early hygrometers and photometers. To the vocabulary of optics Lambert introduced the term *albedo*, meaning "the reflection factor of light off a surface" (Krebs, 2008, p. 328–329). Lambert's range of research resonates with the scope of studies combining idealised optical models with the situated exploration of atmospheric phenomena arising from the interaction of light, humidity, and surface materials.

behaviour that makes the lunar sphere look so flat in sunlight can be explained by an equation that obeys the constraints of the Helmholtz reciprocity principle. In *Robot Vision*, Horn (1986) presents Minnaert's contribution – that approximated material in the maria of the Moon – in the form of a reflectance map, which he discusses as a fortunate-convenient case for the unambiguous recovery of shape from shading (p. 221).

When computer science turned its attention to planetary satellites, it did not intend to deepen the knowledge of astronomical observatories. Rather, it intended to further generalise the methods of photometry into practical solutions for autonomous engineered systems. Instead of calculating the characteristics for specific objects, *Robot Vision* recommends relying on cases that reflect light in a regular, and therefore easy to model, way (Fig. 4). Hence, astronomer's lunar soils were supplemented by a pair of perfect opaques (that is Lambertian) and perfect reflective (that is mirror) surfaces. The formulation of Horn's famous shape from shading algorithm took on finding the shape of a smooth, opaque object from a monocular image, given the knowledge of the surface photometry, the position of the light source, and other auxiliary information (Horn, 1970)[3]. To resolve common ambiguities of a shape's recovery, his pioneering study proposed a method to iteratively reconstruct the shape along profiles that used characteristic lines of the object. The algorithm relied on partial differential equations that linked image intensities to the orientations of surface patches. In practice, however, the method turned out to be all about resolving the interpretation's ambiguity. As the image patches' orientation could not be decoded without external references, Horn coupled his algorithm with reflectance maps, two dimensional planes which presented the distribution of light reflected from lit-up spherical objects of a given surface type. When the maps could not give unambiguous answers on patch orientation – since they related to a single image intensity value with an infinite number of points, amounting to a map of an ISO-brightness curve – a method was proposed to compile a few differently lit-up images into one source of interpretation. Away from the fortunate use-cases, physics-based image interpretation has fuelled the debate on the ill-posed and inverse problems of machine vision. Here, and in other terms, the perfect imperfection of the lunar disk has teased the acuity of technological procedures.

[3] A comprehensive introduction to the early version of the method, along with its limitations and the referenced example of the human face curvatures, was published in MIT Artificial Intelligence Laboratory's Technical Report No. 232 (Horn, 1970; for a brief discussion on the reflective properties of matt coatings and human skin, see pp. 128–131).

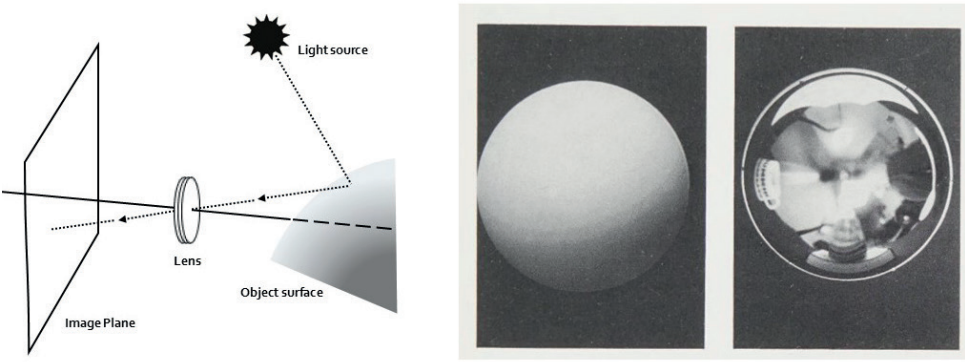

Fig. 4. *Robot Vision* is illustrated with a set of figures that introduce the building blocks of the physics-based approach to vision promoted by its author; here are two from the first chapter. On the left: a scheme to represent image formation. The caption states that in some cases the process "could be inverted to extract estimates of the permanent properties of the surfaces of the objects being imaged" (Horn, 1986, p. 8). On the right: an illustration with "perfectly matte and perfectly specular surfaces," the idealised cases demonstrating that the image of an object is greatly influenced by the reflectance properties of its surface (Horn, 1986, Figures 1-6, 1-7)

The photometric research setups

As far as the study of material properties is concerned, the lines of research in physical vision and planetary photometry have developed in opposite directions. After establishing the methods for topography of the lunar maria, Johannes van Diggelen exerted much effort to empirically determine the porosity of the upper layer and the degree of roughness for materials that might exist on the lunar surface. In computer science, the engagement in non-trivial models of physical image formation evolved towards the use of simplistic reflectance maps and generalised models of earthly environment. Whereas astronomers deepened their expertise in light scattering behaviours of all sorts of soils, grains, and flakes, their engineering counterparts strived to attune robotic lab cameras to a collection of clay pottery and mirror-like artefacts. As I will go on further to demonstrate, handling the precarities and unknowns of those explorations, reveals an intriguing interdependency between the environments and performance of the engineered vision systems. With this intention, I will retrace some of the technical arrangements of MIT's machine vision lab and the Utrecht observatory setups built for the investigation of lunar soils.

When confronted with the question of consistency of the lunar surface, Sonnenborgh asked the Geological Institute of Utrecht University for samples of volcanic ash and powder collected from the historical eruptions of Vesuvius (van Diggelen, 1958/1964, pp. 97–98, 103). This choice was guided by the results of previous studies, which showed that the laboratory-deduced characteristics of volcanic ash were closely related to the polarisation curve of the telescope observing the lunar surface materials. Most notably, instead of performing complex calculations to test previous theories of the Moon's surface, the researchers set out to compare the material samples in a series of empirical trials. The photometrists' solution to the problem was a direct investigation of the ash samples illuminated at 0° and 45°. Further research of the lunar microstructure followed, involving the preparation of a reference set that would allow the reflectivity of samples to be compared with each other (Fig. 5). Measurements were calibrated by covering the flat surface plane with highly reflective magnesium oxide powder. For some part of the test, drilling special cups in metal plates of 134-mm diameter rendered the structure as predicted by previous research (van Diggelen, 1958/1964, p. 127; Tschunko, 1949). Next, the samples were illuminated to measure light reflectance intensity changes at specific angles. The values registered for goniometric measurements of terrestrial materials were then compared with curves obtained from prior investigations of the Moon. Apart from providing new sets of data, these comparative studies raised new questions on the complexity of light-matter interactions and prompted the consideration of new coefficients and conditions like the sample's porosity.

Some chapters in van Diggelen's (1958/1964) publication give an idea about the technicalities and concerns in these investigations. As he reports:

> [...] we have compared three different ashes with the four standard points of the moon defined earlier in this work. For the differences in the albedo, a rough reduction was made by assuming the value 100 for the radiance of all ashes at g = 0° and the first standard point […]. We now see […] that not all the ashes have the same lunation curve. When the albedo has a high value, the shape of the curve near the full moon is mostly somewhat steeper; it reaches a higher value for the second, third, and fourth standard points. (p. 113)

The ambiguity of the results leant weight to considering not only the type of material but also the conditions in which it was eroded, since the scattering properties of terrestrial ash are affected by the weather and humidity. The gravitational difference between the Moon and Earth was also significant, since loosely packed ash seemed to fill lunar models better than when they were pressed together. To model backscattering behaviour of the lunar soil's loose structures, Utrecht

researchers traced the illumination profiles of such relatively exotic materials as spongy lichen *Cladonia rangiferina*, which in the Netherlands was wrongly called "reindeer moss" (van Diggelen, 1958/1964, pp. 139–143)[4].

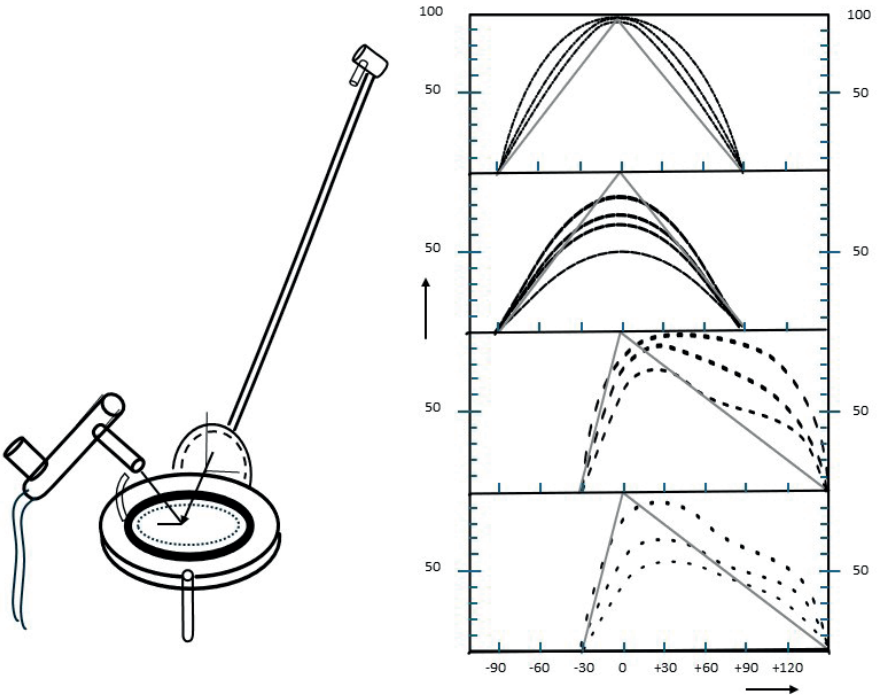

Fig. 5. The Sonnenborgh goniometer, described as an "apparatus for measuring the reflecting power of ashes," and the measurements plotted in form of the "lumination curves for different volcanic ashes." Origins of the samples are detailed as "Vesuvius sand, 1830, Vesuvius sand, 1894, Vesuvius ashes, coarse, 1906; Asama Yama ashes, 1901, Vesuvius ashes, fine, 1906" (after van Diggelen, 1958/1964, Figures 95, 101)

Considering all the enumerated details of the carefully devised experimental set-up, one may than ask: once machinery was put on the move and the outcomes registered in a series of abstract curves, what was the aftermath? Has this work in lunar surface photometry led to any technical or epistemic objects? Firstly, the

[4] The meticulous inquiry did not remain inconclusive. During the preparations for the Moon landing, the research, instead of *portraying* the surface as a rocky desert, developed more tactile-like micro-vocabularies of "deep dust" and "fairy castles" (Hapke, van Horn, 1963). Besides the purely practical relevance of this prediction, it would be fair to claim that the trials conceived in the domain of photometry and optics eventually became aware of weight, compactness, and even the erosion conditions that play a role in framing the problem.

research resulted in an otherwise impossible accumulation of samples sent to one place from geological institutes, biological labs, and other more mundane warehouses. Hence, lunar photometrics has produced unique corpora of materials with specific optical properties[5]. Sonnenborgh was neither the first nor last place where the investigation of planetary satellites devoted such efforts to collecting this variety of materials that could fit the observed photometric behaviours. Extensive tests were conducted in advance of the lunar programme (Mutschal, 1966, p. 3; Orlova, 1956), and the Utrecht observations, first published in *Recherches Astronomiques de l'Observatoire d'Utrecht* in 1958, were soon re-edited by NASA in 1964. A parallel project directly investigating lunar soils was conducted at the Center for Radiophysics and Space Research at Cornell University, where Bruce William Hapke and Hugh van Horn tested more than two hundred different surfaces, recombining rocks and minerals, both in solid and powdered forms, with glass beads, metallic and non-metallic whiskers, vegetation (such as grasses, lichens, and mosses), and artificial surfaces, such as wires suspended over plates (Hapke, van Horn, 1963, p. 4547).

Another, more daring, argument would be that with photometric research some concrete models of Moon-Earth universe came into being. Test samples were situated in controlled light environments. For investigation purposes, a locally constructed measurement device – a photogoniometer – must have been installed in Sonnenborgh's rooms between the other astronomical apparatuses. It was an open structure, staging proper light spectacles every time its 12-volt lamp travelled in a regular orbit around the sample (van Diggelen, 1958/1964, pp. 97–98). With each cycle, a photomultiplier tube registered the amount of light backscattered from the spread on a disk located in the centre of this mini universe. To eliminate stray rays interfering with the measurement, the area surrounding the disk was blackened. With each trial, a little radiant zone lit up in the dusky studio, a toy universe inside Sonnenborgh's halls[6].

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[5] Characterised in some cases as: "orthotropic [materials], which satisfy Lambert's law – at least for the angles of incidence between 0°–40°; [or] reflecting ones, with maximum of intensity in the direction of the regularly reflected ray; [or] completely rough ones with a maximum of reflection in the direction of incident ray and mixed ones with two maxima in the directions of regularly reflected and incident rays" (Fessenkov, 1962, p. 125).

[6] As an aside, it is worth adding that the construction of toy/model environments was characteristic of knowledge formation of the Utrecht Observatory. Marcel Minnaert was the co-founder of a widely recognised physics education programme. The programme encouraged students to learn by operating and manipulating natural effects using home-made instruments and outdoor observations. His popular classic, *Light and Colour in the Outdoors*, was designed to guide them through light and colour phenomena that can be seen in the open air. In each case, the explanation links the observation to the physics and chemistry behind it. However, to be introduced to light and colour by authors like Minnaert is not only to observe, but also to be taught how to

The robotic labs setups

This visit to 1960s astronomical observatories prompts debate about how the precarities and unknowns of visual research were solved by algorithm-oriented computer vision. Here I will further refer to inquiries which followed Horn's program on physics-based image analysis (Horn, Winston, 1976).

The drive to understand the physics behind image formation brought to the surface fundamental issues in the reverse interpretation of images – how to reconstruct three-dimensional shapes from two-dimensional intensity patterns. In this atmosphere, the early 1980s working group on closed-loop robotics at MIT was continuing research on the shapes of objects inferred from grey-level intensities captured in camera registrations. A practical task related to this problem was to attune an autonomous system to pick cogs from a bin of parts viewed by a camera-eye robot. The research pursued a range of trials that situated image analysis as an operational setting for productive industrial systems (Horn, Winston, 1976). The ensuing method has been called a "photometric stereo" (Horn, Ikeuchi, 1984, p. 102; Ikeuchi et al., 1983, 1986; Winston, 1983). When inventors demonstrated it to the readers of *Scientific American*, they took the opportunity to declare that "for the practical applications," machine vision did not have to attain the "admirable capabilities of biological vision" (Horn, Ikeuchi, 1983, p. 5).

But as I will go on to argue, the weight of practice brought down the excitement through speculation that the case was fairly misleading. Putting physics-based vision through practical trials created a challenging situation. Namely, it forced AI research to step beyond its algorithmic essentialism. Unlike matter-oriented astronomy, the computer sciences intended to interpret objects while using a highly autonomous model of vision – one that is intentionally detached from any environment around it. When engaged in debates on ill-defined or reverse engineering problems, AI researchers would first provide further computational solutions. This in turn has favoured paradigms that are further generalised and detached from the world-out-there for the much-awaited vision intelligence. With a physics-based approach, the issue of reverse interpretation of shapes, as Horn put it himself, has been considered as mildly ill-posed. Even though the methods

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construct visual phenomena. When he writes about rainbows, for instance, he does so with instructions on how to build a suitable evaporator in order to obtain drops of a size that scatter the light of the spectrum. He also gives instructions on how to look for rainbows, stating that the phenomenon can be observed "in a direction of 42° from the antisolar point and preferably against a dark background" (Minnaert, 1974/1993, p. 192). Whether or not such an introductory or holiday book primed those pursuing projects in a research institute years later is a matter for the biographers. Nevertheless, training in how the visual environment is arranged enables engineers to explore the relationship between a visual system and the external world.

necessary for removing ambiguity in machine images were attainable, the load of computation necessary to endorse the indirect problems of vision turned out to be significantly high. Alas, the debt incurred by capitalising on the serendipitous case of lunar disk observation needed to be paid.

The history of photometric stereo brings me to the main point of this chapter: when the real world came into play and demanded attention, how were vision technologies organised? Why did astronomy not have to use complex mathematical models to infer the properties of lunar regolith? What must be proposed to stabilise a machine system with all the assumed perfect Lambertian reflection models, all the objects immersed in a super-transparent atmosphere? To understand the groundbreaking developments in "stereo vision," attention must be given to the experiments that MIT's AI Lab research has embedded in operational machine environments, particularly in industrial robotics.

Although nested under the computer sciences, "photometric stereo" had much in common with the approach of the lunar surface researchers. First, as in the case of Sonnenborgh, the visual exploration assumed that some change of position was required in the technical setup. Likewise, in both cases, the idea was to "see" specimens by moving the source of light rather than shifting the position of the viewer/camera eye – as would happen in the case of a typical stereometric inquiry. Next, both astronomers and computer scientists worked with reflectance maps. Published by Robert J. Woodham in the 1980 issue of *Optical Engineering*, the "photometric stereo" assumed acquisition of several (usually three) monocular images (Woodham 1980; Ikeuchi et al., 1986). These needed to be taken under different lighting conditions while holding the same observation point. In that procedure images would not need to be combined directly by computationally heavy processing (Fig. 6). What was sufficient to constrain uncertainties about the object's surface orientation were image radiance maps – calculated at a lower computational cost. Sensitive to changes in radiance, photometric stereo vision revealed three-dimensional shapes; on the same basis it could inspect textures and scratches, or detect minor surface deteriorations, etc. Finally, both photometry and photometric stereo required the setup of a controlled light environment. However, where in the research on soils and other materials illumination techniques seemed quite natural, for computer science the lights installed above a camera-arm robot were evidence of bending the standards of algorithmic purism. This is why I find the transition from photometry to machine particularly illustrative: non-computational techniques have been invited into AI research, not merely because they mimic (as in brain sciences), or even compensate for the algorithmic complexity of the task. Developments like photometric stereo result from the consistently ill-defined nature of visual tasks. Vision's inherent elusiveness is evident even at the technical level.

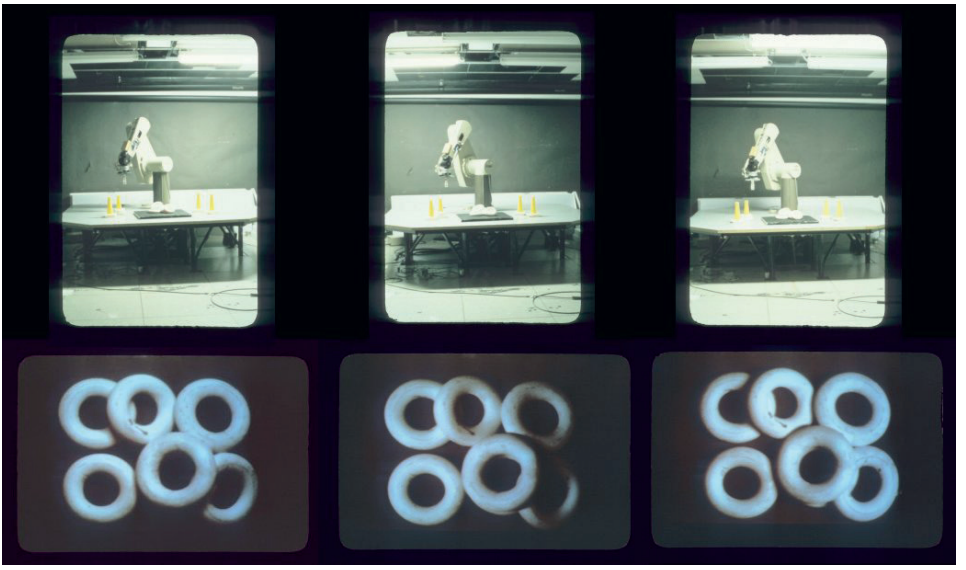

Fig. 6. Lighting up one after the other, three lamps above the robotic arm bring out the shape of objects captured by the camera – the arrangement enables an implementation of the photometric stereo method (Ikeuchi et al., 1986, Figures 1, 2)

Photometric stereo was implemented for the camera-arm setup, providing a solution to the "bin of parts" challenge (Horn, Ikeuchi, 1984), but how did this research unfold? In his 1983 report on MIT AI's development, Patrick H. Winston takes note of Horn's work on the image-irradiance equation – the aforementioned shape from shading algorithm. As information obtained directly from the images was rarely unambiguous, the laboratory searched for a way out of this ill-defined task. Winston's (1983) report details: "examined [was] the use of supporting information from silhouettes, edges, and rotational symmetry, showing how to arrive at unique solutions in some cases" (p. 45). However, the most important addenda was in supplementing the work of the shape from shading algorithm with cues derived from so-called reflectance maps (Horn, 1977, 1979). Reflectance maps were technical images informing the algorithm about the relationship between surface orientation and image brightness in the registered image. Notably, maps were not a transformation of the image seen by the viewer but operated somewhat independently being a trace of radiance pattern emerging in the scene (Horn, 1977, p. 207). Horn (1977) calls them strange images of the world surrounding the object. One of the ways to plot them, notes the introductory paper, is to take measurements directly from goniometer-mounted samples (much like in the case of photometric trials mentioned above). Another was to draw a map indirectly from an image of an object of a known shape, for example a sphere. Horn's implementation required taking yet another path: calculating the map of an object

of unknown shape, in which case the position of light sources and the surface material properties needed to be given (Horn, Sjoberg, 1979, p. 1770). Calculating reflectance maps thus became an important point of further exploration. When Robert J. Woodham proposed a photometric method for determining surface orientation from multiple images, physics-based vision was prepared to accept the idea. One did not necessarily need to operate on data heavy images directly; it is reasonable to take cues from reflectance maps and combine them in order to constrain the ambiguities of scene interpretation (Woodham, 1980, p. 141).

Woodham's proposition insisted on stepping back from simulating all illumination and reflectance conditions *in silico* to constructing them *in vitro*. Just as the first meeting with photometrics opened up physics-based or "early vision" (as it was termed later) to the study of radiance and light-scattering behaviour, so their second crossing gave researchers the courage to oust mathematical purism and argue that computation was not enough to claim that one has a practical method at one's disposal[7]. This argument opens a 1980s dissertation supervised by Horn, whose author, William Michael Silver, was appointed to devise an experiment that would bridge the gap between the theory and a practical method (Silver, 1980, pp. 44–45). His work got closer to the work of photometrists, for instead of analytically assessing the brightness value associated with different viewing configurations, he took on an empirical study of models of the surface microstructure in relation to the surrounding light sources (Horn, Sjoberg, 1979). Thus, like photometry, the robotic lab started to construct their own small universes of light. Silver (1980) called it a studio, or – a bit of a stretch – a sealed light chamber. As he specifies:

> A cube one meter on a side, containing four sealed light chambers such that holes can be drilled for the precise placement of point sources. The chambers surround a peephole in the center of one side of the box, thru [*sic*] which a camera may view a scene on the far wall. A cloth bag fastened to the peephole is held around the lens of the camera, so that stray light cannot enter the box. The inside walls of the box are painted flat black, to eliminate illumination by reflection. (p. 47)

So, to the photometrist's orbital, planetary-like goniometer, robotics adds a blackened box in which a collection of tint-painted wooden spheres are suspended. With the suppression of stray light, the exact positions were made to provide nearly ideal conditions for measurements. The question of how to design lookup

[7] In the context of computer science, early vision was used to define stages of vision that preceded the cognitive processing of visual information. Included here are image capture, preprocessing, and visual information coding. This relies on a predefined physical model that organises mathematical expressions phrased into algorithms (Watson, 1990, p. 61).

tables for object intensities, and how to get the surface depth from a gradient were the point of the experimental work.

A sort of light environment – a luminous zone – that emerged from those experimental setups extended to the scale of a room. The photometric stereo method was enabled by three lamps operating with an industrial camera-arm[8]. Switched on one after another, the lamps illuminated objects for a fixed camera's eye at different illumination gradients. Thus, triple lighting became part of how hand-eye manipulators picked through a bin of parts. Curiously enough, the authors of this study did not expose the assistive facet of photometric stereo vision when speaking to the general public. Rather, they advertised the setup's agility, stating that photometric stereo could readily be applied to a factory setting since it required no special lighting conditions; they emphasised that extended sources of light could be placed in almost arbitrary positions, if the grey-level calibrations were made after the lights were fixed in their spots (Horn, Ikeuchi, 1984, p. 111). However, as one delves further into the somewhat more detailed reports, the design decisions described by Ikeuchi, Horn, and their co-researchers become more complex. Fluorescent lamps are recommended, since these sources "can increase the range of normals [*sic*] which the photometric stereo method can handle" (Ikeuchi et al., 1983, p. 7). Moreover, point sources should be constrained, meaning that the surface normal directions illuminated by each of three sources would be distinguishable. Furthermore, the light sources need to be placed at a sufficient distance from the machine as the method assumes that "a given light-source is constant over the points of the field of view" (Ikeuchi et al., 1983, p. 7). Thus devised, the photometric stereo became a building block of machine vision, together with its complementary technique of structured light (Forbes et al., 2021). From that point on, one can expand the list of recommendations, enabling the flawless operation of industry setups, and follow the practice on solving the issues like: suppressing accidental shadows cast by the machines and/or persons nearby, or securing perceptual comfort or technical norms for a setup constantly switching the lights in a shared operation space, and so forth.

With the photometric stereo implementations, physics-based vision returned from mathematical abstraction to the grounded conditions of real, functioning ensembles. A vision technique, thus conceived, required a number of design decisions that affected both the method's performance as well as the perceptual conditions and accessibility of the immediate surroundings (Silver, 1980, p. 45). Ambient light suppression and general lighting conditions remain key points in the integration of industry systems. Lights flickering around robotic setups can

[8] A limitation of scaling is implied by Woodham (1980), as he notes: "Unfortunately, since the sun's path across the sky is very nearly planar, this simple solution does not apply to outdoor images taken at different times during the same days" (p. 142).

be considered as no more than an assistive technology – a temporary, contingent component installed for some critical case needs. The weight of this turn toward material arrangements, however, becomes evident in the concluding section of this chapter's investigation, which debates the ill-posed problems of early vision, and pits the likes of Horn and Woodham against their counterparts inspired by the brain sciences.

Lines of ambiguity, inverse and ill-posed problems

The practical developments described above pertain to a major problem of which twentieth-century engineering was only just becoming aware. That is, the ill-defined nature of sensing: a visual stream, whether captured by a monoscope camera eye or perceived by a living creature, does not carry signals that render the world unambiguously. This in turn results in a notorious inadequacy in the ill-posedness of methods proposed by engineering. In the first half of the 20th century, the theory of ill-posedness climbed the technical agenda, also forcing the computer sciences to acknowledge their engagement in classes of problems that were recognised as intractable, lacking either stable or unique solutions. Theory therefore predicted not only the emergence of issues like those that bothered the inventors of the shape from shading algorithm; it also stressed that the recovery of external world properties (the measurements) would need to become insanely precise. Arbitrarily minor errors arising from instability in the measurements, it claimed, could lead to hugely significant errors in the solutions. Alas, almost every attempt to expand the boundaries of visual, aural, and other types of sensing would then oblige engineering to navigate through inevitably messy and ambiguous environments.

The example of perception inference has also been used to show that ill-posed problems are, in fact, inverse problems concerned with determining the causes of a desired or observed effect (Engl et al., 1996). In terms of procedures, ill-posedness is therefore often the vice of inverse tasks. Where a direct problem would be one of modelling physical fields, processes, or phenomena in mathematical physics, an inverse problem is often one of control theory, the theory of pattern recognition (Kabanikhin, 2008). The latter then clarifies an interplay between the direct approach – applied when setting up the soil samples in Utrecht and the painted spheres at MIT for observation – and the inverse track – taken when computers and astronomers matched their radiance curves and intensity maps to specific instances of texture or form. Its initial iterations, like the "bin of parts" selection or recovering 3D shapes from a single photo, were treated as inverse problems.

The problems of uniqueness and stability of solutions have dominated the discourse around physics-based and early vision since shortly after the first systematisation of the method. Ill-posedness has featured in the research around photometry as well, but there it has remained unframed. Proponents of a physics-based approach have been aware that cases like lunar topography present a fortunate case in calculating the shape of objects, and that the uniqueness of results achieved by researchers like van Diggelen would not pertain to the case of perfect Lambertian surface in the studies of Horn (Horn, 1970; Horn, Brooks, 1989). Shape from shading and the combination of reflectance maps were brought in to fix ill-defined problems, or to put it more straightforwardly, to dispose of ill-posedness. But could ill-posedness be regulated in the virtual domains?

While it has been claimed that there is no universal method for solving ill-posed problems, the focus has been put on studying the properties and regularisation of methods that could approximate unstable mappings, transformations, or operations (Kabanikhin, 2008). Such was the proposition in the debate that went through MIT's AI Lab in the late 1980s. It concluded that:

> The review of early vision […] shows that certain regularisation techniques can be useful for a correct and sound 'solution' of many vision problems. The key idea of all regularisation techniques is to introduce *a priori* knowledge – or constraints – which have to satisfy the solution. Therefore, we will have different solutions according to the assumptions we have made, that is our *a priori* knowledge about the world. (Bertero et al., 1987, p. 45)

But should this *a priori* knowledge be set by a software engineer working on the level of algorithms? At computer science laboratories, going virtual seemed the default solution, especially when the discussion on ill-posed problems was brought to the table by researchers oriented toward the exploration of brain-inspired AI[9].

[9] Operating somewhat independently of a brain-like AI paradigm, Horn first proposed to solve inverse problems by integrating various cues about surface orientation in the work of algorithm. Shape from shading will remain ill-posed, he stated, unless one takes advantage of the hints given by the distribution of intensities on the object's boundaries/limbs and uses the reflectance extremes (that is, observing a surface normal – a ray or a vector that is perpendicular to a given patch of surface). Furthermore, the uniqueness of the solution might remain unachievable if each intensity point of the image is treated independently, as unrelated to its neighbours. Alternatively, one could think of the object's components as related (applying the integrability method) or "assume that the surface is relatively smooth" (applying the regularisation method, the least-squares minima) (Horn, 1977). The latter provided an instance of setting *a priori* assumptions in the virtual realm. However, the solutions produced by iterative schemes while achievable, he warned, were also not quite accurate as "methods that enforce integrability can get stuck in local minima in their search for the global

There was then some consensus in the debate around machine vision, broadly agreeing that the problems it dealt with were mildly ill-posed and that the solutions could be worked out. To tackle ill-posedness, additional constraints were introduced. Here, a conceptual split emerges that will inform the analysis that follows. To solve ill-posedness, some thought in terms of information theory and the abstract language of mathematics, arguing that the reduction of errors in the data can significantly improve the solutions. For approaches like physics-based vision, an answer would preferably be not only robust against data noise but also physically correct (Bertero et al., 1988, p. 876). Further, some branches of engineering would look for solutions outside the algorithmic position. Crucially, the vision research explored above acknowledged that a decision regarding the appropriate stabilising method could be made judiciously from purely mathematical considerations. Neither the photometric stereo nor light chamber exercises would happen if intervention into the physical environment was not the *a priori* that puts the algorithm on the right track. The introduction of a computational vision system requires a radical lash, notably concerned with suppressing ill-posedness not only through algorithmic operation, but also by interfering with the machine's immediate surroundings.

* * *

Research in planetary photometry and AI robotics guides an historical inquiry such as this to an ephemerid universe emerging around vision research. The universe that has been both discovered and constructed. It has been constructed as a set up for photometric tests, made from blackened boxes, lamps, soil samples, and goniometers. It has been discovered with the development of physics-based vision and following the attempts to repair its ill-defined nature. What one can observe while following the strand of research from one domain to another is that within those universes, light was supposed to define objects, cut off their boundaries, and limit the range of the machine's operation. And light did its duty: a technical sort of vision came into being when goniometers lit up the soil samples and when the robot's arm was guided under the set of flickering lamps. Once photometry fused with algorithmic operation, self-contained computer vision transformed into machine gaze.

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extremum, and methods that do not enforce integrability inherently trade off increased surface smoothness against departures from the exact match of the shading information" (Horn, Brooks, 1985, p. 13). When the algorithm got stuck in its search for the extremum, the fragmentarily reconstructed shape interlaced with what were initially called lines of ambiguity.

It also became clear that it was the moonlight as observed and measured by astronomers, rather than the generalised light of physics, that was glaring at the core of vision technology. Although the initial intention of physics-based image recognition was to use nontrivial optical models, it was eventually proven that the amiably generalised models of a perfect Lambertian, translucent universe were not sufficient to capture the peculiarities of visual inquiry. Further constraints – debated in the ccontext of ill-defined and ill-posed problems of vision – turned out to be inevitable and, aware of this, *Robot Vision* is illustrated with telescope views of the lunar disk, indicating not only the origins of the field but also its character. This is not to say that visual technics have turned the selenographers' experience into a profound theorisation. For the following decades, the computer sciences considered ambient light, atmospheres, fog, or dew, much like phenomena that transiently manifest in empty cartesian space. Nevertheless, it is photometry rather than optics that has proffered state-of-the-art technics like structured light measurements (Forbes et al., 2021), regulated frequency lighting, and the implementation of lidar technologies. Being oriented towards practical gains, functional machine vision focuses on light-flooded zones – much like those observed by marine biologists in the upper layers of ocean.

The next chapter explores how this bonding with the environment is replicated on another level of technical interventions. It turns to domains that tackle the ill-posedness of visual guidance in a much more literal way, and therefore solve it by setting the signs systems, mastering techniques of wayfinding and visual persuasion. Approaching algorithmic processing and distributed vision systems from that angle, the inquiry tracks the histories of minute technical objects and observes the rise of technicised vision in the development of fiducial signs, tags, and pictograms.

3. When environmental problems arise, new signs are created: auxiliary technologies of vision

In order to explain the physical bounds of machine vision in more detail, we'll move to another part of twentieth-century technological inquiries. The previous chapter set out to explore the tensions between the computational facet of machine vision and the physical phenomena behind image formation. The current one focuses on the relations between the work of algorithms and visual communication design. The main point is how assistive visual systems (fiducial signs, pictograms, etc.) have moved from supporting human readability to structuring environments for machines. I will trace how techniques, once intended to make environments accessible to humans, are now subtly reorganising environments in ways that bypass human vision altogether, raising new political and ethical issues.

The following passages problematise the processes of sign reproduction and sign display by looking at experiments in "readable-for-all" and "navigable-for-all" spaces. The inquiry aims to expose the flourishing of auxiliary techniques (such as wayfinding or visual information design) that provide support for complex visual tasks. I propose to examine examples of research and development from visual arts, merchandising, and systems engineering. The case studies introduce the concerns and constraints connected with the deployment of standardised pictogram systems, parametrised package design formulas, and quick response codes. In its concluding part, the chapter will look at scenarios for the integration of human- and machine-interpretable communications into a common landscape.

The topic I will engage with can be considered an extension to the study of optimising visual communications for human receivers. Known as human factors engineering, it evolved in fields ranging from television broadcasting and digital image compression to human-machine interaction design. The domains have used a variety of metric apparatuses borrowed from the field of psychology. Eye-trackers, tachistoscopes, colour probes, and mainframe computers were configured to incorporate technical signals into a human-in-the-loop system.

Experiments in visual optimisation have emulated conditions under which images would be circulated. A product of this research has been a stream of images compressed and coloured according to both the capacity of the media channel and the perceptual conditions of the viewer.

The engineering of human measures and formats has been little explored in media studies. Jonathan Sterne and Dylan Mulvin have made a substantial contribution to this topic by tracing in detail how the perceptual technics of colour television broadcasting relied on Weber–Fechner's idea of a logarithmic perceptual response (Sterne, Mulvin, 2014). In their conclusion, they point out an appealing interdependence between the practice of image optimisation and the work of economy. Sterne (2012) elsewhere uses the term perceptual technics in order to "describe the process of creating surplus definition and transforming it into perceptual capital" (p. 51), asserting that "through perceptual technics, a company can economize a channel or storage medium in relation to perception" (p. 51). This vision of burgeoning psychotechnics converges with those outlined by Friedrich Kittler, who claims that "everyday reality itself, from the workplace to leisure, has long been a laboratory in its own right" (Kittler, 1999, p. 160). From this perspective, new questions arise. If an economically warranted demand initiates a selection mechanism, how deeply do the effects of this kind of processing reach? Is it possible that the little-examined engagement with optimisation determines which types of conventional signs are removed from general use, and which proliferate?

Signs and environments

To begin, it is worth reflecting on a general statement from the field of 1960s visual communication. Martin Krampen – an alumnus of the Ulm School of Design, member of the Commission on International Signs and Symbols' (CISS), and researcher involved in devising a comprehensive sign production method – argued at that time: "[when] environmental problems arise, produced by technological or other developments […] signs or symbols are created, often anonymously and tentatively, to communicate about these problems" (Krampen, 1965, p. 19).

With this claim, Krampen (1983) introduces an original view on the development of international sign systems. In the 1980s, elaborating on the topic he emphasises that: "technical developments generally bring with them changes in the environment, and that new environmental situations bring new dangers that must be posted with signs [and explicitly] enlargements of the sign repertory are a result of sudden changes in the environment caused by sudden advances in technology" (p. 32)[1].

[1] It might be important to note that this idea, much endorsed by information design, of making signs and considering communication environments in terms of signs and signals meets a fervent critique in mature versions of James J. Gibson's ecological theory.

Krampen (1983) attributes the action in this technically elicited cycle to labour forces and anonymous individuals. In practice, however, the process of sign conventionalisation (in which he participated as a member of international committees and as an academic teacher) relied primarily on the initiatives of local authorities and the professional expertise of design artists. In his extended study on the evolution of traffic signs, he writes about their diachronic development from the visual communication perspective, using "icons of the road" to present conflicts and tensions that occur in the process of what he calls the socialisation of the sign system (p. 1). His theory claims that tension and conflicts in the communication sphere grow as the initially restricted system gains more and more authority.

What is specifically relevant to the present inquiry is that in the decades that followed a number of auxiliary solutions were developed in order to ensure that visual signs would prompt the desired reaction from the human observer. Within those campaigns, methods for the design and evaluation of road sings, pictograms, and trademarks were mastered by art schools and international committees. Historians of visual design indicate that during the 1960s sign languages become a topic of public interest, and the professional status of graphic designers profited from the open debates on standardisation projects. This relied on a specific assumption that, in an increasingly internationally orientated world, visual symbols would become core elements of communication, surpassing language barriers (Middleton, 1963, p. 12). Fifty years later, the topic has almost disappeared from public discourse along with the 1960s formulas to unobtrusively

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In his early essays, Gibson (1954) stays somewhat in dialogue with Charles Morris's semiotics and attempts to theorise pictorial perception in terms of surrogates; but the concept of surrogates and signs evaporates from the great ecological metatheory in the latter decades. In *The Ecological Approach to Visual Perception* – first published in 1979 – Gibson (1979/2015) leaves no doubt as to this shift, stating: "The ambient stimulus information available in the sea of energy around us is quite different [from signs and signals]" (p. 56). For this he develops a series of arguments, including one that asserts that the images and sculptures (former *surrogates*) "do not provide firsthand experience – only experience at second hand" (p. 56). The theory turns therefore toward "the information for perception [which] is not transmitted, does not consist of signals, and does not entail a sender and a receiver" (p. 57). With his characteristic eloquence, the author argues that "the environment does not communicate with the observers who inhabit it. Why should the world speak to us? The concept of stimuli as signals to be interpreted implies some such nonsense as a world-soul trying to get through to us. The world is specified in the structure of the light that reaches us, but it is entirely up to us to perceive it" (pp. 56–57). This radical approach detaches the great Gibsonian theory of visual perception in the environment from the design and engineering engagement of shaping visual environments. Despite a number of common areas of observation (including ambient light patterns, atmospheric phenomena, surface reflective behaviour, etc.), the relationship between stimulation and stimulus information is expressed otherwise.

regulate the flow of airport traffic and the operation of interfaces as guided by visual icons. Nevertheless, for some time now, a new layer has been covering these familiar systems with machine-readable signs. The semi-autonomous zones of logistics warehouses and autonomous traffic are making use of lines-of-sight to integrate their complex functionalities. New signage is there introduced, often in parallel to previously developed conventions. These auxiliary techniques of vision, this time devised with a machine interpreter included in the setup, seem to be a concern of technical engineering rather than of visual information design. However, their ubiquitous appearance eventually prompts design-like issues, such as: what do machine-readable sign systems construct within environments? What relations do they involve?

The background against which Krampen spoke about this co-emergence is of specific importance. Since the 1960s, a number of auxiliary techniques of visual communication have been proposed in the context not only of roads and general traveller information, but also of the proliferation of newly established systems for self-retail markets and visual advertising. The archives of international committees and working groups on visual communication hold records documenting the intense development of specific methods. These can be traced through projects undertaken on the occasion the Olympic games and world fairs, within open calls and surveys from The International Council of Graphic Design Associations (Icograda), the international organisation for railway companies in the Western world (Chemins de Fer), and UNESCO working groups on road signs standardisation, to name just a few (compare Bakker, 2012, p. 38; Krampen, 1969). The relation of design to cybernetics was discussed at postwar design schools, including the influential Hochschule für Gestaltung (HfG) Ulm (Leopold, 2013).

Within the design network, comprehensive methodologies for visual communication have been in high demand. Conceptually oriented professionals rushed to specify methods of sign production, evaluation, and display (Brugger, 2024; Krampen, 1969; Mackett-Stout, Dewar, 1981; Szolginia, 1980). In the 1960s, the movement was focused on forming pictographic systems that would allow communication independent of linguistic and cultural barriers; it reflected design primarily in terms of semantic interpretability. Wibo Bakker's study of the networked community gives some insight into the scale and effects of those activities. The inter-institutional cases include the Icograda–Ulm collaboration: a major research project carried out by the committee in 1968. To elaborate on a system of pictographic information for international travellers, Icograda recruited Krampen as a creator of the sign production method. The methodology produced signs by devising tests in which respondents drew pictograms for specific expressions (e.g. ticket sales, departures). The work covered 63 verbal expressions and was tested with 3000 international air travellers, groups of university students, and

military men in Germany (Bakker, 2012, p. 43). The first findings of the research were published in a special edition of *PRINT* magazine in 1969 in the form of a list that contained short recipes for the visual design of pictograms. For example: "Air arrivals: plane heading down with or without arrow (nose pointing B or L) Air departures: plane heading up with or without arrow (nose pointing B)" (Krampen, 1969, p. 63). While creating the list, the Icograda–Ulm project determined the semantic interpretability of a sign at the beginning of the design process. The next recommended step was to work on a sign's legibility and visibility, as considered during the project's evaluation.

The work on legibility has been broken down into a number of techniques that adjusted idealised designs to what was called environmental stress and visual competition. A popular way was to cut, blur, and disassemble the original sign in order to devise experiments assessing its vitality – a good Gestalt – and whether it could withstand a number of adverse conditions. The stress test could then include splitting the image, perspective viewing, undulating surface reproduction, three-dimensional relief emphasising lines through light, focus manipulation, and movement (Krampen, 1965, pp. 27–29) (Fig. 7). Basically, a designer was supposed to imbue the sign with a certain robustness. Likewise, when Krampen elaborates on signal strength in relation to trademark design, he claims that good design will protect a project against stress conditions, whether trademarks are applied in very small sizes (on letterheads) or in large ones (on the walls of office buildings or factories). Resilient Gestalten will be equally well perceived when in motion (on trucks or vehicles) and from different angles (lateral as well as frontal). A well-designed trademark must be able to stand up to what Krampen calls the "noise" of other symbols around it in different circumstances.

Among the priorities of good form design, some held greater importance. Notably, within visual communication design, distance-visibility and glance-visibility became prime evaluation measures (Mackett-Stout, Dewar, 1981). The question of recognising an icon exposed only for a very brief period of time was explored in a number of trials. The test scenarios vary in the detail, but various scattered quotations give some hint as to the general framework and impact of such efforts. Some, for example, established the legibility of standard pictograms by presenting them slightly out of focus for a fraction of second. As described by Mackett-Stout and Dewar (1981), Icograda pictograms were tested with a group of students, displayed for 40 milliseconds, resulting in a reporting error rate of 40–50% (p. 144). Others – like tests of road signs – could include variants conducted either on the road with a driver as an interpreter, or in the laboratory using scaled signs. The road tests assessed the speed-reaction time factors. In the laboratory setting, versions of signs were exposed under different lighting conditions.

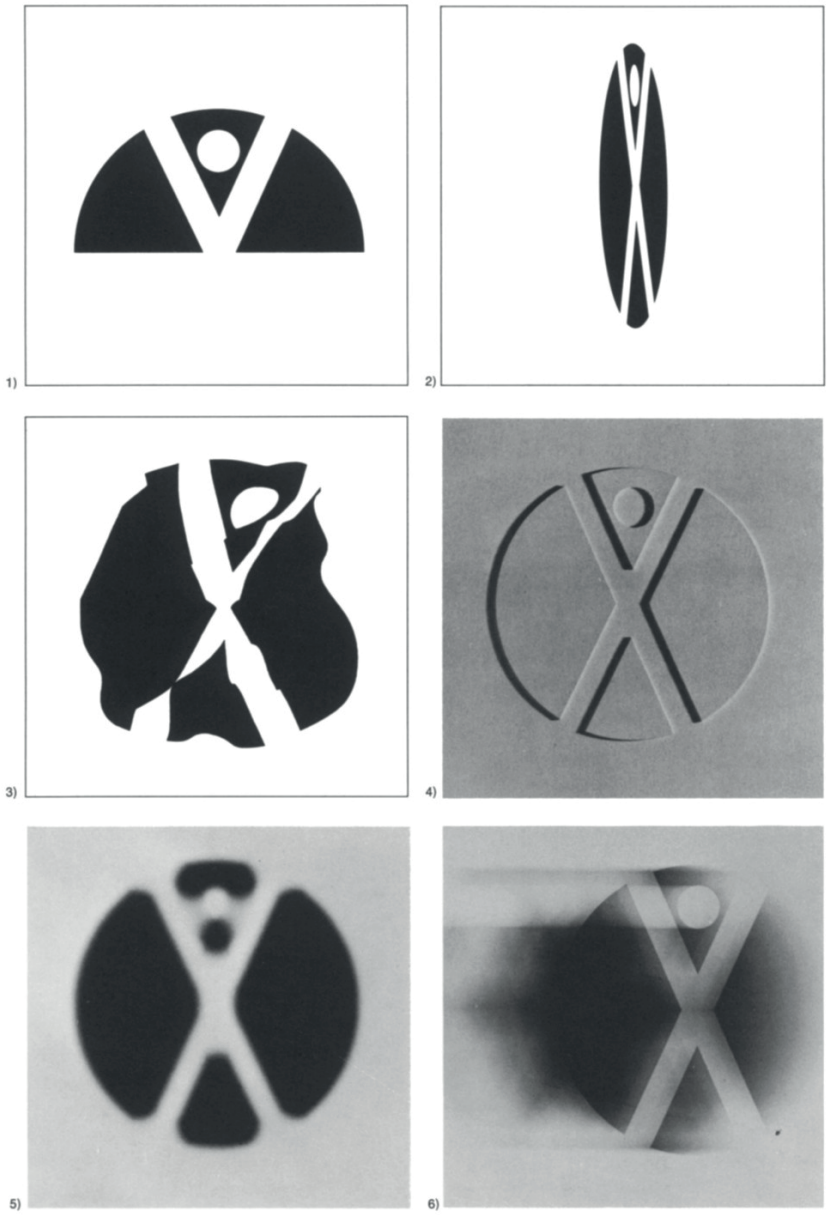

Fig. 7. Analysis of "configural vitality" by Ernst Roch: 1) split image; 2) perspective viewing condition; 3) situational change including undulating surface; 4) three-dimensional relief emphasizing lines through light; 5) and 6) manipulation of focus and movement. Roch's design was proposed for the 1967 international world's exhibition *Man and His World*. Krampen uses sthe case of Roch's design process to illustrate commonly pursued legibility tests in his essay theorising visual design methods of the 1960s (Krampen, 1965, p. 29)

Statistical data were presented in the form of perceptibility or legibility curves (Krampen, 1983, p. 118). This process of assessing legibility has been integrated into academic training. Industrial design departments like those founded in the Eastern Bloc's fine arts academies, have set up visual laboratories to perform parametrised experiments on student diploma projects connected with workplace safety signs, merchandise, or traffic.

One could object here by saying that the deployment of a method does not amount to the deployment of an assistive technology. Intuitively, the more parametrised the evaluation techniques become, the more technological benefit they seem to carry; a characteristic which was not necessarily desirable among the representatives of fine arts academies. Indeed, within the international movement there were mixed attitudes towards the deployment of tightly parametrised techniques. As a rule, visual information designers allowed for the possibility of testing parametrisation but were far from absolutising it. This includes Krampen (1983), who stated that mere empirical testing cannot provide the best solutions and claimed that the discussion on road signs should keep their focus on design issues (p. 120). Comparing the voices coming from different parts of the design community, one needs to admit that there were specific social terms at play here too. Some endorsed parametrisation to claim the generative-like or objective character of their work. This was, for example, the case of the 1970s professional generation from Central Europe, especially those who represented the industrial design institutes established a generation earlier throughout the Eastern Bloc. Looking for their place next to the established professors' studios, younger teachers and diplomats were often keen to declare that the evaluations of their projects needed to be as objective as possible (Otręba, 1976, p. 33) and insisted on using ergonomic and anthropometric research, rather than theories of design teaching. On the other hand, the heuristic approach taken to achieve a good Gestalt was often criticised for giving the impression of being educated guesswork. Here, this attitude becomes a bit complicated as it shifts to a professional meta-level. Probing a good Gestalt does not necessarily require back-end technology, so to speak, to assist in making a sign system on a designer's desk; rather, it became a call for more of the front-end technologies of vision – such as pictographic sign systems. In other words, an assistive technique – such as a wayfinding sign system – was intended to be a contribution that could go from the studio into the wild. So, moving on to the next area of inquiry, it is convenient to summarise the role design has ascribed to itself in the process of establishing new environments.

At this point, it is worth highlighting the next step in the adjustment of human-centred techniques to algorithmic processing. The splinter debates and standardisation practices referred to above remind us that, in the second half of the 20th century, the design community paid much attention to pictograms, visual techniques of wayfinding, and directing traffic in complex technological environments. From

around the mid-1960s onwards, the way in which these systems were developed was guided by the professional expertise of the visual arts. These, in turn, were prepared to use more or less structured methodologies for the creation of good form and were concerned with selecting signs in terms of their trans-linguistic and trans-cultural communicability. Parametrised methods of evaluation were accepted in this activity, but refrained from making them absolute – the popular tachistoscope's measurements of reaction times to signs were not independent techniques in themselves, but something like their derivatives. Returning to the previous chapters' view, the distributed, trailing, and situated character of image processing challenges the design processes of those collective bodies (sign systems) with new aims and goals. To complete this overview, I will contrast the work of visual communication with the practices developed in the fields of merchandising and systems engineering.

From design boards to tachistoscopes

The work of 1970s visual designers drafting new projects according to Gestalt principles has often been tested with the use of tachistoscopes. Taking their name from the Greek *tachistos* (rapid) and *skopein* (to view), these instruments control the duration of exposure to visual stimuli. The swift display of images, signs, and chunks of text during experimental psychology tests has been a feature of the discipline since its nascent decade in the 1850s (Benschop, 1998). Rutch Benschop in her critical history of the method notes that, being widely adapted as a temporal magnifying glass of psychology, tachistoscopes only meet with critique occasionally due to the atomisation and impoverishment of the perceptual conditions; this, quite notably, came from the part of Gestalt representatives and J.J. Gibson's theory of ecological perception (Benschop, 1998, p. 24). Media studies, on the other hand, has demonstrated the cultural impact of tachistoscopes in the history of the persistent, but empirically unrectified, techniques of subliminal marketing (Acland, 2012). On a more general basis, it was then probable that twentieth-century visual information was encouraged to construct signs that could be perceived in the blink of an eye.

At this point, the historical inquiry into visual communication extends into a sparsely documented domain. While art students secluded in the interiors of academic laboratories tested their unique, not-for-public-release diploma projects, the neighbouring field of merchandising was setting up selection mechanisms that would standardise the view of supermarket shelves, bookstores cabinets, and gas station self-service coffee machines. Commercial visual labs could take the quite voluminous form of experimental environments that dissected the investigated process in every detail. One of the industry's most distinctive experiments was in emulating the self-service retail point. As a new type of self-service

retail became popular in 1960s Europe, readers of *Le Monde* were informed of a new laboratory based in Paris – the IRVEC (Institut de Recherche Visuelle et d'Étude du Comportement) – which offered expertise on packaging[2]. This expertise was in determining which elements of type, shape, or colour in a particular project should be redesigned to attract the customer's attention. Offered by the IRVEC or ORSEM (Office de Recherches, Sondages et Études de Marchés), such expertise was either drawn from the laboratory or based on the perpetual study of points of sale (*Le Monde* 16.11.1961). The institutes set up special self-service markets equipped with microphones, cameras, and timers. The customers' behaviour in the test shops was observed through Venetian windows, recorded, and counter-evaluated with a series of surveys. It was often from this field visual laboratory that formulas disseminated to design schools and art academies. In ORSEM's case, its records were transferred behind the Berlin Wall to the Central European region and found their re-implementation at the Academy of Fine Arts in Krakow.

Professional literature on merchandising provides some insight into the testing techniques. The French edition of Maurice Cohen's *La Vente Visuelle* presents self-service arrangements in the context of Paris' IRVEC. The manual – one of the popular examples addressed to marketing specialists – shows the kinds of visual identification formats that could be developed, based on a list of tests issued by ORSEM. The list enumerates visibility and legibility tests, spontaneous attraction tests, the measurement of legibility thresholds, apparent size tests, the measurement of legibility angles, and the measurement of visibility as a function of light source intensity (Cohen, 1974, p. 34). The methods did not imply any commitment to a specific design approach, presumably leaving their clients free to configure the test or to rely on their own expertise.

Although the records avoid theoretical inclinations, they give some indication of the scopic regime behind the experiments. It was a regime concentrated on sign competitiveness, rather than concerned with good Gestalt. The tachistoscope was then not only a primary testing device but also an embodiment of a more general merchandising concern. Testing aimed at excluding "irrelevant" components of the design[3]. Some merchandising professionals focused their attention on assessing the graphic design against swift viewing conditions, also testing a product in terms of the apparent size of the packaging, and – not least – the lighting design of the venue. Parametrised laboratory trials analysing the syntax of shapes and colours were expected to define the proportions and formats, all in service of anchoring the images in customers' minds. Products piled up in self-service shops were to be adjusted to the easily

[2] In the following years, the company operated under the acronym IRSEC – Institut de Recherches, Sondages et Études Commerciales – see *Bulletin officiel des annonces civiles et commerciales* (1972, p. 20718).

[3] This set of practices relates to a much-debated idea of subliminal advertising; for a brief account of doubts regarding its impact (and even possibility) as well as its cultural context, see Acland (2021) and Broyles (2006).

distracted gaze of consumers. The 1960s tachistoscopes therefore embodied not only a parametrised approach to design, but also a fantasy on the hyped-up consumerist urban metropolis. According to that vision "the blink of an eye" has become a measure of things, a basic rule for assessing which version of a traffic sign, a pictogram, or a package design is best suited to a hectic environment.

In *La Vente Visuelle*, Cohen (1974) describes the visibility and legibility tests in IRSEC laboratories as follows:

> Ces tests ont pour bout de déterminer la facilité de la rapidité avec lesquelles chaque élément peut être vu ou lu par le public. Ils sont réalisés à l'aide des tachystoscopes qui permettent soit des projeter une image sur un écran (tachystoscope à projection), soit d'exposer la maquette elle-même, tachystoscope à vision réelle à des temps brefs allant de 1/500e de seconde ou 1/100e a 1 seconde. (p. 34)[4]

He continues on a test of "spontaneous attraction":

> Ces testes sont réalisé en moyen d'tachystoscope à vision réelle et permettent de déterminer la puissance de l'impact spontané des conditionnements étudiés. Les maquettes sont exposées par paire, chacune aux extrémités du champ visuel du sujet interviewé. De la description plus ou moins riche des conditionnements exposés, pendant un temps très bref, on détermine la maquette qui a le plus attirée l'attention de sujet. (p. 34)[5]

And on measuring legibility thresholds:

> En confrontant les résultats de ce test à ceux du test de visibilité et de lisibilité, il est possible de déterminer la part de la connaissance antérieure intervenant dans l'identification d'un conditionnement. (p. 34)[6]

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4 In translation: "The purpose of these tests is to determine how easily and quickly each element can be seen or read by the audience. They are carried out using tachistoscopes, which either project an image on to a screen (projection tachistoscope) or expose the model itself, the real-view tachistoscope ranges at short times from 1/500th of a second or 1/100th of a second to 1 second."

5 "These tests are carried out using a real-vision tachistoscope and make it possible to determine the strength of the spontaneous impact of the studied packaging. The models are displayed in pairs, each at the far ends of the visual field of the interviewed subject. On the basis of a more or less detailed description of the exposed packaging, it is possible to determine in a very short time which model has attracted the respondent's attention the most."

6 "By comparing the results of this test with those of the visibility and legibility test, it is possible to determine the proportion of prior knowledge involved in the identification of packaging."

These short passages suggest experiments devised according to the framework of psychophysics, rather than Gestalt. However, with commercial services' merchandising mission, the classical traits of experimental psychology are compiled into something more than just generic data gathering. A few details in Cohen's laconic descriptions offer more insight on this. Firstly, the enumerated flicker exposure rates of the object, although not unprecedented in psychological trials, are exorbitant in terms of the physiology of human sight. At its short span of over 100 Hz, the flicker exceeds the optimal average sensitivity of the human eye, given that contemporary clinical studies state that the eye in the frequencies between 50 and 90 Hz starts to fuse flickers of visual stimuli into one continuous signal, with only some capacity to distinguish between steady and modulated light up to 500 Hz (Mankowska et al., 2021). Next, such a tachistoscopic vision was supposed to construct not merely a good – read *resilient* – Gestalt but to amplify "le puissance de l'impact" – the impact force. Finally, the procedure was designed to determine the "connaissance antérieure intervenant dans l'identification d'un conditionnement" – a sort of prior knowledge (either memory or maybe some contextual stimuli) – involved in identifying the packaging. Altogether, the merchandising laboratories of *La Vente Visuelle* promised something more than a testing methodology for technical design faculties: it was promising a technique for predicting the scores of superfast persuasive visuality. The example of IRSEC includes an auxiliary technique that not only promoted trans-linguistic, common communication, but also worked through forceful sign competitiveness.

Inherently, positions such as those in Cohen's merchandising manual, as well as the services offered by industry subscribers, have circulated with only limited impact. However, one only has to look to studies on speed and media more broadly to see how well the niche examples fit into contemporary paradigms of visual culture. Both the philosophy of technology and critical media studies have examined the problem of accelerated perception in a broader context. Within the framework of media studies, Kittler points out how tachistoscopic vision contributes to the discursive networks of the 20th century (Kittler, 1990, p. 252). Juxtaposing media apparatuses, he pairs the tachistoscope with the film projector, presenting both as displays that are contradictory to their mode of operation. Charles R. Acland refers to Kittler's perspective in his historical study, *Swift Viewing: The Popular Life of Subliminal Influence*. While demonstrating the ubiquity of subliminal viewing techniques in twentieth-century visual culture, Acland (2021) details its rudimentary variant – a technique of unproven effectiveness for displaying subliminal advertisements. Promoted in the 1950s by American marketing specialists, this technique aimed to influence US cinema audiences to order larger quantities of Coke and popcorn by inserting images between the frames of a film. In one chapter, Acland shows how widespread the belief in this technique's effectiveness had become. The observations on short-time exposure match with the current

chapter's observations on the flourishing of specific types of vision assistive technologies[7]. Finally, a third approach from the perspective of the philosophy of technology gives context to the laboratories like those once installed in Paris. Specifically, with its ambitions for rapidly noticeable design, the universe of merchandising fits into the landscapes of Paul Virilio's study, *The Aesthetics of Disappearance*. Where Virilio (1980/1991) introduces the reader to the concept of "picnolepsy" – the epileptic state of consciousness produced by speed – tachistoscopes fit in as devices that ensure the aesthetics of disappearance, complementary to the technologies of film and the military industries. Altogether, media studies and the philosophies of technology confirm that experiments of the kind described by *La Vente Visuelle* were well-positioned in the logic of their time.

Fleeting and imaginary, tachistoscopic design presents itself as the product of a specific historical moment. Soon enough, history would brush away the subliminal marketers, IRSEC professionals, and Icograda debates, bringing new visual regimes to the stage, this time connected to the narratives of the digital era. During the wave of Internet expansion in the 2000s, studies on ubiquitous and physical computing considered this expansion in terms of software, or rather everyware. Proposed in Adam Greenfield's seminal book, everyware was expected to induce new interaction paradigms which, according to his prediction, "in countless ways will disrupt unwritten agreements about workspace and home space, the presentation of the self and the right to privacy" (Greenfield, 2010, p. 3). The turn has brought huge excitement around the idea of smart, customisable, maker-made designs that would eventually compose themselves into complex networks. Nevertheless, they were not the designers who finally looked seriously at machine-readable systems, and they are not the designers who now have a decisive say in how machine-readable signs are installed in common, or public spaces. How does the practice of machine-friendly design recompose visual communication standards? Answering this question requires an investigation into how wayfinding and fiducial sign systems have been modified by the vision of machines trailing under the ceilings of shops and warehouses.

From tachistoscopes to quick response codes

The importance of auxiliary vision technologies becomes even more pivotal when one realises how the standards for optimising places – such as self-service shops and logistics centres – have changed with the introduction of automated vision systems. When a machine-readable environment is arranged, the accelerated

[7] As part of his argument, Acland (2021) elaborates on the history of tachistoscopy, from psychology laboratories to areas such as merchandising and education; see *Swift Viewing* (pp. 63–87).

vision of self-retailing gives way to the slower, even somewhat lethargic operations of industrial cameras. The machinery installed in logistics centres and shops freezes objects in static, hours-long streaming.

As an example of such an environment under construction, I propose to take one of the Fraunhofer-Institut für Fabrikbetrieb und -automatisierung (IFF)'s R&D projects. Launched in 2016 by the Magdeburgian unit, the IFF offers solutions in the optimisation and automation of logistics hubs. The technical report provides a bird's eye view of the warehouse, thereby introducing some of the issues of the future of work:

> The giant facility of a major supplier that manufactures modules for several carmakers resembles an anthill. Forklifts and entire convoys are constantly driving through the warehouse with boxes and pallets and setting down the items in a seemingly chaotic system. Seconds later, they are moving again with new loads, which they bring to the spot where the items they contain are processed further. New deliveries from the global supplier network are constantly arriving at the building's loading ramps where they are introduced in the warehouse management system. Finished modules have to be readied for shipping. (Schulze, 2016, p. 31)

The intervention is all but minimal. In IFF's communications, the warehouse is an asset in itself. As such, it should be kept from being moved, redesigned, or extensively rebuilt. Rather, it should be optimised safely. The authors emphasise that what IFF offers is "tailoring the system." The ethos of this kind of automation allows a change to be made only if it meets a well-defined criterion (e.g. speeding up the process, saving energy, or reducing the workload). As processing the features of natural objects on an industrial scale is commonly considered too intensive, the IFF project decided to apply assistive technologies, using ARTag markers. Easily extracted from a CCTV stream, these markers allow the encoding of a limited amount of information only. Then, correlating the images with specific observation points, it is possible to locate the parcel assigned to that load and follow the vehicle's route. The ease of implementation provides an argument for line-of-sight solutions. While the radio signals from RFID antennas have been discouraged as they are disrupted by the metal structures of storage shelves and brackets, the markers perform robustly under a constant stream of ceiling lighting. IFF-like automation lies not in groundbreaking fusions, but in the ability to provide a cascade of trivial improvements to seal the system. The umbrella term "Smart Environments of Industrial 4.0" often covers a blend of technologically conservative programmes. This reluctance to make radical changes paves the way for auxiliary technologies that can be seamlessly integrated into the existing infrastructure, thereby capitalising on past investments.

Decades after the internationalisation of sign languages, the abstract labour forces of Martin Krampen's account have produced the semi-automated facility within which an engineer now places a set of pixelised tags to be tentative cues for the camera surveillance. If one connects a number of implementation cases with tests in the development of tracking methods, AR, and machine vision marks and fiducials, a cascading technological shift illuminates the actual construction process of what might be considered an augmented, navigable-for-all landscape. New systems latch onto the existing infrastructures, hanging on the pre-installed camera capacities and existing processing pipelines; or they are recommended as compositions of "ready to use" and "cheaply available" components. In the cases of navigation and vision control proposed in the above-mentioned project, such improvements often amount to introducing machine-readable tags, markers, and lines that integrate the work of algorithms into the blobby and ill-defined surroundings. The proposal from Magdeburg was then to improve the navigation system in logistics centres by introducing a special form of signage that could be read by cameras monitoring events in the warehouse. Their markers took the form of 10 cm × 10 cm black and white panels mounted on the roofs of vehicles carrying parcels to be unloaded at ramps through the warehouse (Borstell et al., 2013, 2014)[8].

In form, most of a guidance system's functional tags are reminiscent of the QR codes introduced into industrial applications in the mid-1990s. Quick response codes – now commonly used for guiding autonomous units – were developed from barcodes by Masahiro Hara, an engineer at the automotive company Denso in 1994 (Sugiyama, 2021). Hara's innovation enabled easy scanning for managing inventories of automotive components. The worldwide recognition of the QR formula soon reached automation and robotics where the 2D pixelised tags became a standard solution for positioning and localisation in machine-navigable environments. By the 2010s, prototype testing spaces at Boston Dynamics and the MarsYards bore these characteristic markers. In Industry 4.0, research with QRs proceeded in projects deploying logistics solutions in limited areas, such as transport hubs and factories. Marking the warehouse vehicles, as described by

[8] In reference to pixelised tag formulas, a concern from a *leitmotif* of visual culture theories has gained some attention with the mass proliferation of satellite images and mapping, especially Google's 2005 freely accessible 3D model of Earth (Salari, 2020; U.S. Geological Survey, 2007). Around the 2010s, the thresholds of visibility were deliberated by a few media theorists considering the conditions of early 2000s image infrastructures – compare the collection on resolution in media introduced by Casetti and Somaini (2018); see also Salari (2020). One prominent example comes from the visual essays of German artist and media theorist, Hito Steyerl's *How Not to Be Seen: A Fucking Didactic Educational. MOV File* (2013). Moving in a playful manner through her ways of disappearing, Steyerl presents the resolution tablets placed on the ground to calibrate the satellite imaginary. The objects are *photo calibration targets,* positioned for aerial inspection of the Earth's surface.

IFF, offered the possibility of quickly processing the signal picked up by industrial cameras, tracking the vehicle's route, and locating the items it was carrying in the facility's vast labyrinth. Combined with load counters, depth cameras, and an RFID reader system, the arrangement provided a complete tracking system for the objects and people being moved. The six months of warehouses testing described in IFF's brochure formed the basis for selling their systems to major logistics companies (Schulze, 2016).

The IFF project was proposed at a time of intensified testing for the development of augmented reality signage. It was one of many projects to test and develop new types of touchpoints connecting the algorithmic realm with ill-defined objects of the real environment. A few years later, some economically minded reviewers of the technological scene came to see these technologies as a breakthrough, enabling the transition from the digital domain to an era of fusion linking the metaverse with areas of hard reality (Agha et al., 2022; Ang, 2021). Artists and designers leapt to using tags creatively almost immediately, but the topic remains underexplored within media studies. To introduce some of its technicalities, it is useful to recall a niche but coherent series of reviews comparing the performance of machine-readable tags, which have been constantly growing in number since the 2010s (Botta, Quaglia, 2020; García-Ruiz et al., 2023; Garrido-Jurado et al., 2014; Jurado-Rodriguez et al., 2022; Morar et al., 2020; Olson, 2011; van de Wynckel et al., 2024) (Fig. 8)[9]. The reviews highlight that the 2010s generation of passive markers (as already mentioned) was derived from barcodes and bi-directional QRs redesigned for autonomous vision.

When IFF proposed their solutions, the field comprehensively discussed the constraints and implementation problems related to this kind of augmented reality system. Among the primary issues were some of the markers' physical forms. One was that tags needed be read at a distance comparable to ten times the diagonal of the board. Another was that, due to the light sensitivity, markers are configured from contrasting black and white fields, and less frequently from strong RGB channels. The markers' shapes were proposed according to their functional constraints: for object localisation, square tags were considered the most useful as they seemed easiest to calibrate in-camera by setting different position angles. Hence, engineers recommended regular shape sets with six degrees of freedom, permitting an extensive list of unique characters (a large dictionary), although a few authors found it more convenient to encode their dictionaries using methods structured as rings, circles, or even blobs. The materials used to make the physical

[9] A comprehensive review of indoor detection shows that artificial markers are used as detected features, instead of "real object features," while the maker/camera position is used as one of three basic types of environment data along with image feature databases and 3D models (Morar et al., 2020).

tags were also taken into account, with research conducted into special layers for cameras operating beyond the visual band. Some have stressed how demanding it can be to maintain these specific coatings. All in all, the first decades of the 21st century saw the emergence of a new auxiliary technique, this time dedicated to machine vision environments.

Fig. 8. Three examples of sign systems capable of generating fiducial patterns designed to be quickly located by machine vision systems (Botta, Quaglia, 2020)

Reintegration of the sign systems and the unlimited identity space

Large pixel squares that jump out at the viewer like a portal to *Minecraft* are immediately perceptible to both humans and machines, but only technical equipment is capable of reading it. The introduction of machine-readable tags therefore brilliantly incorporates a posthuman model of relationships and the environment. Easy to notice, yet illegible for humans, tags are a stark reminder that there is no common language of signs, and no norm that satisfies the demands of diverse sensibilities. Such discrepancies in visual communication can have far-reaching effects. A twist in the short history of the field followed as developers began to work with such uneven, conditional visibility, assuming that the physical mark should be integrated not only into the system with which it communicates, but also into the surroundings in which it is physically situated. This is usually announced under the theme of sign customisation or unobtrusive sign design (for a comparison of various tag embedding methods, see Agha et al., 2022; Dogan et al., 2022; Getschmann, Echtler, 2021; Jurado-Rodríguez et al., 2021; Snyder et al., 2018, p. 4). The approach charges the field with a range of socially and economically relevant issues and moves it back from MATLAB code to the maker's studio, from logistics' hubs to leading articles in *Forbes* magazine. From the cultural studies perspectives, attempts in making unobtrusive tag systems are of special interest,

as they raise a number of questions not only on the proliferation of technological touchpoints, but also on the potential conflicts that are disguised by claims on well-designed and readable-for-all technical environments.

Sign customisation and unobtrusiveness is being approached in several ways. One tendency is to transform a marker into an "aesthetically plausible form," which frequently comes down to a commitment to dispose of the characteristic pixelised arrangement. This approach lays the ground for projects that consider topographical solutions for tag development. These could incorporate a marker into a template such as a company logo or use a generative pattern as a basis for the sign structure. Hiding machine-readable content within an existing graphical form has been tested by a group at the University of Cordoba, a prominent contributor to the field. Cordoba's primary invention is the widely used ARuco open-source library, which allows fast interpretation of the most common tag types in high-resolution camera recordings: they include ARTag, APril Tag, and the native ArUco (Kedilioglu et al., 2021). Among their subsequent propositions is a method for making templates that allow markers to be point-inscribed into a deliberately shaped logo (Jurado-Rodríguez et al., 2021). The output of the process is therefore a series (dictionary) of similar-looking logos, each of which may contain a unique machine-readable code. The points of the marker are determined for a shape (logotype) based on the set of shape invariants. This method uses pattern matching algorithms developed from David Lowe's scale-invariant feature transform (SIFT) algorithm and its later optimisations.

Another illustrative example of the project that commits to fusing machine-readable and human-plausible forms comes from representatives of the design and maker's scene. From their research on hacking and the customisation of everyday technologies, Christopher Getschmann and Florian Echtler propose devising markers in the form of soft organic patterns that spread all over the surface of the observed objects. Seedmarkers, as they've been named, are on the one hand consistent with the mechanics of generative algorithms, but on the other are subject to evaluation by human authors. Taking into account their functionalities, Seedmarkers can be read as one-way non-iteration graphs (Getschmann, Echtler, 2021). The creators of this project found a visual equivalent for the graph structure in the Voronoi formula and recommend such an alternative to the pixelised structures of QRs as organic, referring to the patterns found in animal fur, bubbles, foam, etc. An approach they describe entails the dissemination of new aesthetic forms like fractal trees. Thus, the production of fiducial signs (which allegedly has the advantage of rendering objects interpretable by both machines and humans) reinstates the earlier search for vital forms with the search for unique patterns. The erstwhile paradigm of simplicity and semantic interpretability that led designers to dispense with the details in pictograms can be replaced by one that favours basic generative rules.

Schemes for Voronoi patterns or logotype customisation communicate a moderate, inclusive approach to sign systems design. They aim to construct an environment in which humans remain aware of where markers are being located and are, at least supposedly, invited to decode their content. From the human perceiver's perspective, unobtrusive customised markers imbue the existing sign systems with new types of objects. By contrast, assistive technologies design considers another, more radical model of seamless sign integration where the unobtrusive turns into the inconspicuous. This alternative is to integrate machine-readable markers into their surroundings in such a way that they become unnoticeable by a human perceiver. Inconspicuous signs are currently achieved by combining materials with special optical properties; that is, either those that reflect light outside the frequencies recorded in the visible band (e.g. near-infrared), or those for which subtle changes in the reflectivity render a kind of optical fingerprint detectable by image-recording devices (a so-called physical unclonable function). Developed during the last decade, projects for signs invisible to the naked eye are still few in number, but they seem to meet the requirements for mass implementation, being low cost, easy to implement, and well-adjusted to the current trends in commercial electronics design.

Quite a few propositions for human invisible tags are founded on the assumption of further proliferation of mass-produced near-IR cameras and the commercial availability of emissive paints and coatings. In this framework, a group of researchers at MIT CSAIL have tested a complete workflow for 3D-printed, near-infrared visible markers. The system is intended to work on interior-scale environments where signs like ArUco or QRs are detected by IR modules up to a distance of 250 cm with minimal near-infrared illumination (Dogan et al., 2022, p. 1). Among these types of projects are also those arguing that the larger-scale transformation of current sign systems is inevitable in specific domains like autonomous driving. From the transportation safety division of American company 3M comes a project stating that the next generation of traffic signs will "be done in a way that meets current specifications and would produce no significant change in visible appearance of current signage" (Snyder et al., 2018, p. 4). The developers propose to adapt existing traffic sign systems by applying a machine-targeted message in a near-IR band directly onto the surface of traditional traffic signs. In infrared tag design, commercially available materials are used that are characterised by having high transparency in the visible spectral region (380–780 nm) and low transparency in the near-IR spectral region (780–1,500 nm). The idea is to apply an IR-visible QR tag onto a traditional traffic sign, without disturbing the luminous visible transmittance (380–780 nm) of approximately 92% while providing an approximately 90% near-IR contrast. Some of the contributions came from research into functional materials and proposed sophisticated microstructures to enhance the visibility of machine-readable signs. The crystals promoted by researchers from the University of Luxembourg are in this vein (Agha et al., 2022). Their inquiry spec-

ifies several scenarios for the use of so-called cholesteric spherical reflector (CSR) markers made from a thin layer of crystal beads and shells. These fine-grained cholesteric liquid-crystal displays (ChLCD) are moulded into the form of spherical reflectors characterised by a specific optical behaviour. The beads can form a layer largely imperceptible to human vision, and light is selectively retroreflected from their complex helical structure making them exceptionally easy for cameras to detect regardless of the background (for details, see Schwartz et al., 2021). The authors promote ChLCD and IR coatings as simple, low-cost machine vision technologies that would allow the computational requirements of analysing the environment to be reduced.

Taken together, from discrete interventions in Industry 4.0 warehouses, down to customised, human-plausible, and eventually inconspicuous versions of machine-readable markers, these elements herald a scopic regime evolving beyond the accelerated vision of late modernity. But what kind of vision is this? Authors exploring the particular properties of ChLCD crystals and IR coatings admit that not every technical affordance should be realised on a full scale, and some may turn out to be less competitive than others. It is also not assumed that visual modality will be the only one to assist with the interconnection between material entities and the work of algorithms – RFID tags, digital twins, and other techniques are constantly combined in multilayered systems. However, the idea of information-rich landscapes has gained enough attention to acknowledge that variants for building touchpoints between technology and environments are not inconsequential in terms of their wider impact. To frame new solutions in the larger picture, it might be important to note some of the arguments presented for developing ever more variants of machine-readable signs.

There is some consensus in technological discourse when it comes to imagining how the ubiquitous deployment of machine-readable markers could reorganise the world around us. Firstly, it states that the technology allows goods and commodities to be tracked not just after they have been produced, sold, and distributed. It offers more efficient linking of the tagged items to their digital twins, as allocated in the metaverse. It is assumed that markers readable from the distance of surveillance cameras could contribute to the creation of new types of merchandising based on the tight matching of unique stock identifiers and customers' preferences. Furthermore, some peculiar qualities of materials like ChLCD crystal – that are unique in their pattern of light reflectance – provide the prospect of using tags as a sort of unclonable fingerprint for a product. Unique identifiers could then make it possible to track specific items while they are being used or borrowed, and while they are being machine-separated in recycling plants. Unclonable identities could serve to tighten the controls on the distribution or disposal of unlicensed or forged products: in other words, it could tame both unauthorised sales and uncontrolled dumping. Overall, efficient and inconspicuous tagging could

create an unlimited identity space in which lifelong tracking of specific objects would be possible without much investment in computational power. Here, the first conclusion would be that assistive technologies of vision would provide new scenarios for surveillance by enabling this unlimited identity space.

Considering what has been said about the capitalist exploitation of perceptual surplus in twentieth-century media, one might expect that the unlimited identity space would primarily be an economic construct – made to circulate commodities and control unlicensed production. Yet, concerns over the inconspicuousness much endorsed by engineering specialists have their unpredictable reverse in the issues already being signalled by vernacular discourses on advanced technologies. The problems could be fairly basic in nature, but the extent of the apprehension over inconspicuous systems can be seen by those who have observed operations in militarised or restricted conditions. For example, those who followed social media communications in the weeks following the 2022 escalation of Russian aggression against Ukraine may have come across a transient conspiracy theory which, although false, revealed a certain logic on the emerging state of public sign systems. A series of reports circulated about reflective tags and markers spotted on several public buildings in Kiev and other Ukrainian cities. It was feared that the markers would provide easy targets for drones and artillery attacking the capital. From the images posted online, some commentators have made a good point that the markers in question had most probably been left by surveyors and scanning companies. It is doubtful that even military-grade equipment could operate efficiently on the basis of such markings. Nevertheless, the anxious reaction to their presence reveals that tagging and landmarking are recognised as part of potentially adversarial tactics. On the other hand, strategies based on new kinds of land mapping for hybrid warfare do not seem entirely misguided. What seems relevant to this story is that the mere fact of placing machine-made, and therefore potentially unreadable, markings in a shared urban space was itself, and not for the first time, a potential violation of the general principles of public sign accessibility. Machine readable signs can feed on carriers unaware not only of their content but also of the very existence of the sign. In light of this, the reiteration of assistive technologies is no longer about post-privacy. The tension evoked by the ubiquity of coded sign systems adds to the previous caveat a concern for safety and well-being in an unobtrusively tagged habitat.

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What then does the study of sign systems add to the outline of the universe looming behind vision experiments? The present chapter argued that auxiliary technologies administer limited perception capacities, not only in the case of

humans but notably in engineered entities. Following this observation, the transition from human-centred design to machine readable systems implies a variety of scenarios resonating with discrepant standards of direct (human) and machine perception. The transition seeks to recapture a set of minor techniques which have fostered the operation of visual environments over a number of decades. The techniques involve the deployment of fiducial signs or other types of markers (calibration signs, pictograms, road signs, QR-tags, etc.) and the optimisation of such signs in terms of their legibility. Altogether, the exploration above advances the inquiry into machine vision with three conclusions.

The first observation is that assistive techniques originally introduced in the context of 1960–1970s design are currently being proposed as a cheap and effective way to improve visual communication in near-automated zones. This is because fiducial signs and tags reduce the complexity of interpretation processes by introducing expressive messages and landmarks (e.g. road signs, tags) into ill-defined, messy environments. The inquiry does not supply evidence to argue that signs and tags are of transient utility and that the techniques should perish as algorithmic systems mature. Otherwise, the proliferation of these techniques in human-readable contexts (merchandising, visual design) suggests that the complexity of communication favours investment in the development of assistive technologies. Secondly, signs infuse a physical quality into the operations of algorithmic systems. Despite being lightweight or even unnoticeable, assistive technologies are of material order. Interestingly, engagement with their material aspect has deepened in recent projects which situate markers in relation to the laboriously implemented autonomous agents (be it delivery units, crawlers, or unmanned vehicles equipped with visual systems of specific sensitivity thresholds, etc). And finally, the inquiry here shows that assistive technologies actively incorporate the visual regimes. In the examples of projects such as airport communications or self-service shop packages, sign systems are carved out according to specific techno-mythologies, be it a vision of accelerating or of trans-lingual global modernity. Their proliferation makes it possible to establish not only points of contact between the technical sphere and its surroundings, but also to impose behaviour that is rooted in locally dominant cultural scenarios.

Altogether, the assumed characteristics of the machine-vision universe should incorporate a class of light material objects. These objects (tags and signs), made to relieve the computational work otherwise necessary on the side of the algorithms, are also indispensable for the appropriate functioning of general communication landscapes. Presumably technical and of secondary importance, signs and tags are by no means neutral in their operation. Available in many variants, they become agents modifying the patterns of contemporary visual culture.

4. It's not if they're looking, it's if you let them see: multispectral design

This chapter further prepares the arguments for engaging with feedback loops that exercise power and control over vast areas of land. But it is no longer about visibility as communication, nor about visibility as a function of complex optical models. Rather, it is about sensory capacities and, ultimately, aesthetics that arise from the material aspect of visual technics. What follows is a discussion of pigments, coatings, and materials, and the manipulation of the physical work of surfaces. Abrupt as it may seem, the progression from material signs to materialities does not depart from the genealogical exploration of machine vision pursued thus far. While the previous chapters made it explicit that the environment is integral to distributed machine vision systems, the last implied the emergence of visual regimes that are increasingly designed for machines. At this point, I would argue that the technologies discussed above, from pictograms to fiducial markers to near-infrared tags, not only enable visual communication as such, but foremost redistribute it, gradually displacing human perceptibility from the scene. A careful reader might add that with this kind of design, the world isn't just becoming more tagged, it is becoming less visible to those not equipped with the right sensors and interpretative engines. Does this mean that the inquiry has provided substantial evidence for techno-determinist, a-human futures? The following chapter approaches the problem on the basis of the argument that the world, in its material complexity, acts on its own. Engineering the properties of matter such as gloss, emissivity, and low observability then regulates who or what is seen and under what conditions. Thus, to conclude on the machine universe, the following chapter will wrap up the initial hypothesis that machine vision develops by overcoming the ill-defined nature of the tasks it aims to achieve with a final disclaimer: the redistribution of visibility cannot be done entirely in favour of technical systems.

The following chapter discusses how techniques of remote sensing refine the matching of pigments and paints with broad-spectrum sensitivity cameras and

lenses. The materialities of vision technologies will be analysed here in reference to research in material engineering – a rich field of experimentation making new sense of reflectance, gloss, emissivity, and the degree of polarisation observed in the multispectral signatures of objects and surfaces. The idea is that while fiducial markers remain central to integrating the virtual and real realms, the specific properties of surfaces meanwhile work as "amplifiers" and "sensitisers" which attune technical systems to their surroundings[1]. Below are selected strands of engineering inquiries on retroreflective coatings, carbon nanotube production, and low observability materials intended to complement the previous characteristics of vision environments with new elements.

The study of multispectral signature design proposed here gets into dialogue with the concept of invisual culture. In one of the introductory essays on operationalised (read: imperceptible) imagery, Trevor Paglen suggestively claims that the history of pigments, dyes, and inks belongs to the realm of the fleshy human eye, as distinct from machine-readable cultures that transfer images to imperceptible mathematical models (Paglen, 2019)[2]. This claim emphasises the contrast between two areas in the history of vision divided by the rise of the machine gaze. Expressed thus, the theory of invisibility implies that a revolution is in the air not only because "machines can see" but also because their peculiar sensorics compete with the carnality of the biological gaze. Despite its somewhat overly elevated tone, the claim seems justified when it develops into an account on the crisis of representations and the proliferation of operational images, etc. Indeed, in some sort of shortcut, the historical volume of fleshy painting seems to dissolve under the action of the digital substrate. But does the machine gaze really invalidate the corporeal realm of colours, pigments, and other sensual formulas? In this context, fields such as multispectral design provide intriguing counterarguments.

Engaged with the world extending in front of the camera's eye, I will argue that machine vision grows a flesh of its own; and that, once the concept of invisible visuality takes its central position in the analysis of visual culture, the as yet under-discussed paths of spectral signatures design will shed light on the

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1 For the alternative use of the terms compare Neimanis (2017, p. 55) and Paszkiewicz (2021, p. 9).

2 In his introductory paragraphs, Paglen (2019) writes: "Our eyes are fleshy things, and for most of human history our visual culture has also been made of fleshy things. The history of images is a history of pigments and dyes, oils, acrylics, silver nitrate and gelatin – materials that one could use to paint a cave, a church or a canvas. One could use them to make a photograph, or to print pictures on the pages of a magazine. The advent of screen-based media in the latter half of the 20th century was not so different: cathode ray tubes and liquid crystal displays emitted light at frequencies our eyes perceive as colour, and densities we perceive as shape" (p. 24).

emerging materialities of visual environments. Inseparable from the history of pigments, spectral signatures design is not only not taking away the materiality of the visual world, it is in fact making it heavier, adding specific concreteness to it while transforming dyes into surfaces, paints into coatings, and pigments into nanomaterials. These materialities play a crucial role in establishing the new visibility regimes. Such regimes pertain first and foremost to engineered systems: remote-sensing satellites, drones, and cameras surveying vast pieces of land. However, being physically enmeshed, the matter is not only interpreted by dedicated machinery but is also sensed by a number of biological and human actors. One objective here is then to observe how materials regulate the algorithmic work of machine learning models. Another is to establish how vision materialities reorganise relations within the broader class of natural ecosystems.

Posthuman philosophies have done their best to demonstrate the potential of vibrant matter. In these terms, Jane Bennett bases her account of the political ecology of things on a critique of the idea of matter as passive stuff (Bennett, 2020, p. VII). Her concept of vital materiality refers to ontologies nested in the discourse of philosophers like Epicurus, Hobbes, Spinoza, and Nietzsche, and assumes that vitality is "a force to be reckoned with without being purposive in any strong sense" (p. 62). However, synthetic ecologies of specific dyes and surfaces are still poorly understood and vaguely discussed in the context of visual culture. In complement to the study here – the inquiry into the materialities of vision – are the precedents in selected analyses of film and photographic techniques. Among the body of work addressing the problem from the media studies perspective, is an account on the practices of light and black materialities of visual media by Sean Cubitt, in which he successfully fuses the domain of representations and its physical embodiment (Cubitt, 2014, pp. 21–42, 80–95). Machine vision studies can use such a continuous model to track the emerging materialities of remote sensory systems. An alternative to this would be an approach that presents new materialities through the process of substitution.

The process of substituting natural surfaces and coatings with their engineered equivalents became a central topic in Esther Leslie's study of the chemical industry. Leslie's (2005) account on synthetic nature concentrates on scientific breakthroughs in chemistry taking place in 1840s continental Europe. The author poses a question on what happens to art and aesthetics when natural resources are remade synthetically by chemists. Recognised for her sociomaterialist approach to Walter Benjamin's writings, as well as the deployment of Marx and Althusser's theories for the broader revision of cultural transformations, Leslie interprets dyestuffs – synthetically acquired colours – as industrial objects and a means for creating exchange value (p. 11). Ahead of her time, Leslie's contribution has been welcomed as an unorthodox invitation to study how the chemical industry transforms nature (Nieto-Galan, 2007). The materialist turn in ecocritical studies creates an opportunity to include the history of dyestuffs in a broader debate

on the redistribution of agencies in more-than-human ecosystems. The model of substitution implies that the materials debated in the present study could also be considered in terms of the exchanged commodity.

Embedded in the contexts mentioned above, pigments, surfaces, and materials reconnect the recent debates on visual culture with reflections on the agency of matter in the posthuman environment. Having outlined some theoretical references and conceptual background, I will go on to unpack the material engineering of visibility.

Extended registers of vision

To elaborate on the emerging materialities of visual culture, two issues need to be emphasised. Firstly, that current vision technologies enable the examination of a range of physicochemical properties of the objects under study. Secondly, that somewhat contradictory to the algorithmic operations that dissolve the long-established system of images, machines are born into the realm of sensing a lot more than the strip of a rainbow perceived by the human eye. In most technical environments, the extended range of sensors provides the opportunity to operate within the ultraviolet, near-infrared, and far-infrared frequencies (Fig. 9). Such capabilities exploit the distinct spectral signatures of materials in these regions – the fingerprints of matter – first understood in the famous experiments of Gustav R. Kirchhoff and Robert W. Bunsen in 1859.

Spectral 'signatures' entered scientific discourse after Bunsen and Kirchhoff observed, using a spectroscope, that the flame of burning sodium salts produced two narrowly spaced emission lines at wavelengths corresponding to its characteristic yellow colour. The position of these lines indicated the presence of sodium in the flame (Hellman, 1968, pp. 20–21). In the following decades, the spectral signatures of specific materials became accessible through remote-sensing systems. Common in astronomy, the method reached new scientific communities in the 1970s when large-scale projects connected Earth remote sensing from satellites like the Landsat Multispectral Scanner System (MSS) with specific terrestrial ecosystems and components of landscapes mirrored in the analysis of extended spectral bands (Schowengerdt, 2007, p. 3).

At that point, new research communities were provided with a large quantity of images cutting through regions of Visible (V), Near-InfraRed (NIR), Long-Wave and Mid-Wave IR (LWIR, MWIR), down to Short-Wave IR, and microwave, as well as radar wavelength ranges. Described in various separate chapters on the history of science (Goetz et al., 1985; Rast, Painter, 2019), imaging spectrometry and earth remote sensing constitute the ancestry of most of the sophisticated visual techniques employed today.

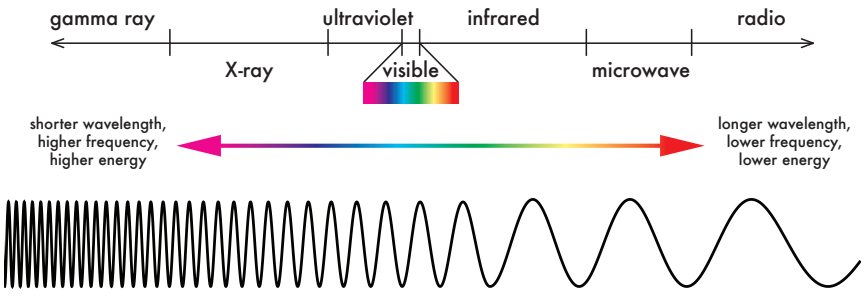

Fig. 9. Electromagnetic spectrum comparing wavelength, frequency, and energy (after NASA's Imagine the Universe, 2013)

Excitement about measuring the spectral signatures encourages specific ways of thinking about the sensory qualities of objects. Applied geophysics set out to map vegetation, soil, and rock through the range of spectral signatures. Some become discernible "in the solar-reflective region by its reflectance as a function of wavelength, measured at an appropriate spectral resolution", others through the temperature and emissivity in TIR, or surface roughness in a Radar region (Schowengerdt, 2007, p. 13). To put it another way, projects like Landsat popularised a new way of speaking about Earth structures, from now on discerned by the interplay between their materials' emissivity and reflectance in specific sensory ranges. Along with multispectral signatures, categories that have so far not been used – except in specialised descriptions of physics – permeated the discourse on vision. The experience of light split by the Newtonian prism is completed with measurements of albedo or references to Max Planck's perfectly black body.

Imagine a scenario in which a graphic designer has a colour space, as known in computer graphics, supplemented by reference tables of reflectance and emissivity: tables like the ones compiled in number of contexts (Emissivities of Common Surfaces, 2024; Gavin, 2024; Memari et al., 2014; NASA Space Math, n.d.; The Engineering ToolBox, n.d.). To the RGB of liquid crystal displays, work with spectral signatures adds two more indices. The first is where the reflectance degrees and albedo values differentiate surfaces, thereby placing freshly fallen snow and river sands at the top of the list, while leaving moors, deciduous woodland, and asphalt at the bottom. Those lists indicate that asphalt is like paper, presenting their close emissivity values in the infrared, and make them in some way superior to poor emitters such as polished gold, aluminium, or silver. Silver stands here in contrast to human skin, and so forth. Some vague sense of aesthetics is at stake in the game it seems. Proliferating in research papers, industrial specifications, and general publishing, these lists indicate a new space that is emerging as a result of common measurement practices. References to emissivity and reflectance convey their own as yet unexplored sensory orders.

name	wavelength range	radiation source	surface property of interest
Visible (V)	0.4–0.7 μm	solar	reflectance
Near InfraRed (NIR)	0.7–1.1 μm	solar	reflectance
Short Wave InfraRed (SWIR)	1.1–1.351 μm 1.4–1.8 μm 2–2.5 μm	solar	reflectance
MidWave InfraRed (MWIR)	3–4 μm 4.5–5 μm	solar, thermal	reflectance, temperature
Thermal or LongWave InfraRed (TIR or LWIR)	8–9.5 μm 10–14 μm	thermal	temperature
microwave, radar	1mm–1m	thermal (passive), artificial (active)	temperature (passive), roughness (active)

Fig. 10. The primary spectral regions used in earth remote sensing as presented by Robert A. Schowengerdt in *Remote Sensing*. In composing the table, the author emphasises the complexities of spectral imaging, showing that the boundaries of some atmospheric windows are not distinct, and small variants in these values determine their accurate interpretation (after Schowengerdt, 2007, Tables 1–3)

In the context of geo-surveillance, some spectral signatures are easy to decrypt, while others remain misleading (Figs. 10, 11). Geophysics benefits greatly from a fortunate contrast between the signatures of large terrestrial structures[3]. A general variable, such as vegetation, produces a high reflection in the near-infrared channel, while remaining low on the red edge of the visible spectrum. This makes vegetation-covered areas easy to distinguish from deserts and bodies of water. Furthermore, as a forest's reflectance changes rapidly between the red and infrared bands, for bare soil the change is insignificant. Again, compared to soils and plants, bodies of water are characteristically non-reflective in the near-infrared band (Schowengerdt, 2007, p. 14). Limitations and ambiguities in the reading of observed structures, on the other hand, are routinely exploited by military industries. Camouflage typically seeks substitutes for natural structures that can provide the backdrop for warfare. In state-of-the-art techniques, materials are selected to make the masked object similar to its background in not just one but several registers of visibility. The desired effects are then developed through the choice of coatings and surfaces, guided by their resonance in selected wavelengths (Park et al., 2021). Much observed in the context of military concealment, this expertise in multispectral signature management also finds its way to influencing developments in machine vision technologies.

[3] Schowengerdt (2007) notes, however, that "although this desirable situation is often reached in practice, it is also often foiled by any number of factors" (p. 13).

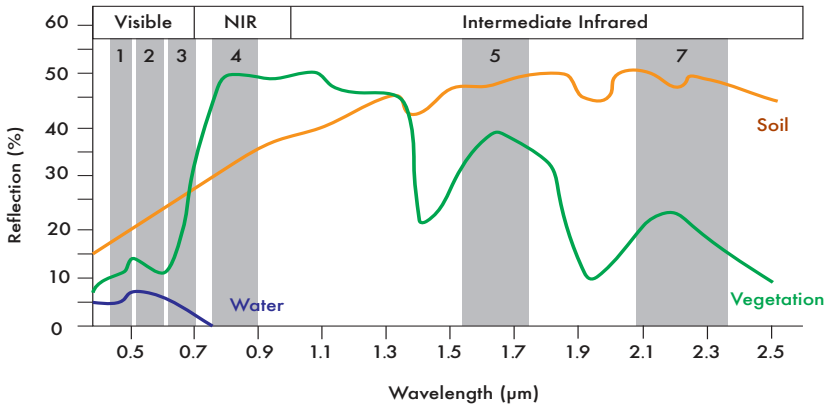

Fig. 11. In contrast to the complexities shown in Figure 10, a plot of spectral signatures for soil, vegetation, and water represented against the LANDSAT-7 channels demonstrates the potential of the method. Numerous versions of this plot have been reprinted, showing that vegetation has high reflectance in the near-infrared channel 4 and low reflectance in the visible red channel 3. This makes it possible to distinguish between vegetation and bare ground. The difference in reflection between channels 3 and 4 is smaller for the bare ground, while it changes rapidly for the vegetation (after al-Azmi, 2017; European Space Agency, 2014; Siegmund, Menz, 2005)

A dictionary for the multispectral vision environments

Until recently, it would not have seemed viable to make spectral signatures a topic for the broader design discourse. For most of its history, the concern with the material properties of dyes, coatings, and surfaces has been limited to specific professional engagements. This state of affairs has been changing for several reasons. Firstly, being a prominent element of military stealth technology, multispectral signature management has reappeared on research agendas owing to the new warfare strategies of the past two decades (Åkerlind et al., 2015; Ålund, 2021; Cederquist et al., 1993; Kastek et al., 2009, 2012; Nyberg, Bohman, 2001). The 2020s especially have seen a new wave of interest in advanced forensics and concealment techniques. Much of this surge is due to the escalation of Russian aggression in Ukraine, where remote-sensing technologies are reported to be key drivers behind the renewed construction of battlefield awareness (Jersblad, Ålund, 2021).

The notion of spectral design features in a paper by Andersson et al. (2014), researchers otherwise connected with the Finnish National Defence University

and Swedish Defence Research Agency[4]. The authors describe it as the ability to create desired optical responses from surfaces by choosing suitable materials and effects (p. 2). In this context, design is presented as a conceptual part of signature management technology (Åkerlind, 2015). Along with a few publicly known instances of contemporary concealment techniques, warfare remains the most straightforward example for the development of machine vision materialities. But that does not mean that it defines its character or qualities. New vision materialities do not grow on the battlegrounds; they are produced in urban spaces and bundle along roads and traffic lines. The parallel advances in civil infrastructure engineering indicate that the concept of spectral signatures has already become commonplace in large-scale technical engagements.

Designing multispectral signatures has been catalysed by the rush for large-scale infrastructural innovations. Chief among these are those connected with vehicle-to-infrastructure communication and the development of assistive driving systems (Babić et al., 2022; Burghardt et al., 2021, 2023; Mihalj et al., 2022) where engineered surfaces and specialised pigments are being tested against automated vision systems. Furthermore, spectral signatures have become an indicator of the future orientations of construction. The industry remains the largest sector for multispectral research, due to their involvement in the debates on sustainable urban ecosystems. Linked to the problems of energy harvesting and loss, civil engineering has built up an impressive body of research on emissivity. In the mid-1970s, the fuel crisis led to the development of glazing films and coatings that could guarantee the thermal insulation of buildings. Likewise, glass technology was introduced that could keep heat inside the building. Developed in the laboratories of companies like Philips, low-emissivity coatings have been used in the subsequent decades without being especially linked to any visual practice (Gläser, 2008). However, when specialised infrared cameras were converted into mundane devices in the construction builder's toolbox, the special emissivity properties of materials were widely deployed and also constantly inspected. Overall, in a slow and messy process, the number of technical improvements unintentionally creates possibilities for the spectral surveillance of machine vision. The veil of secrecy over military engagements and patented products is not conducive to a comprehensive study of the field. However, the three areas mentioned above allow us to speculate on a few sorts of materialities that indicate the transition to new chapters in the history of visual regimes.

Suppose one wanted to create a dictionary for multispectral vision environments. What would it comprise? What kinds of materials and material agencies indicate the supposed revolution? One way would be simply to take the rea-

[4] Considering communication of spectral signatures technology to the general public at the dawn of the 2020s (compare Bevziuk, 2023; Jersblad, Ålund, 2021).

dy-made lists of colour spaces, reflectance, and emissive properties and mash them up in a bricolage of recipes and designs. Organised in this way, the dictionary would accurately reproduce the physical extremities of contemporary ecosystems. It would elevate the contrast between black and white to the contrast between highly emissive tar on the motorways and super-reflective covers of the Arctic snow. It would show the interrelation between the chemical composition of chlorophyll and the spectral signatures of vegetation areas and shift red into the centre of the sensory space: extending downwards to the thermal frequencies. It would invite us to recognise red as the colour – a spot marking the boundary between the non-colours of black and white. Even when based only on fixed or generalised values, such a dictionary of multispectral vision environments is an intriguing resource. More than a collection of examples, it would provide a unique reference to the study of matter and sensitivities enmeshed in competing and colliding ecosystems. It would also, however, expose the residual elements of multispectral vision that are enmeshed in ecosystems for their own reasons and propagated somewhat independently of the evolution in current visual systems. At that point, the dictionary would reflect more the 1970s universe of geo-surveillance projects than the 2020s presumptions on the revolutionary turn in visual culture. I would refer these also to Leslie's model of evolution in paints and dyes, providing the opportunity to compare asphalts and moors, glass and ice – pairs of substitutes and natural materials. But what about the continuity model in that case? I believe one can propose successors to the media archaeology of inks and silver halides, and I'm convinced that to extend the list of materialities of machine vision one needs precisely to investigate the areas where spectral signature management has become a topic of interest. These include the aforementioned: military concealment, road infrastructure, and construction building. From this, I suggest that candidates for the machine gaze aesthetics would be: retroreflective surfaces, carbon nanotube coatings, and aluminium flakes. Below, I present some arguments for each of them.

Retroreflective surfaces, black coatings, and aluminium flakes

Conceived for clearly defined applications, experiments in multispectral signatures are usually combined with several areas of state-of-the-art technologies. One such combination evokes the minor field of retroreflective surfaces engineering. Retroreflective surfaces and coatings are characterised by backscattering light at a narrow angle towards the light source. A common experience of this would be the glow of a traffic sign reflected straight back in the direction of a driver manoeuvring car headlights. The narrow reflection angle of a retroreflective surface

differs from the omnidirectional scattering of Lambertian clay-like surfaces and from the well-defined reflection of mirrors. Controllable light-scattering behaviour pairs well with automated vision systems as it does a lot to keep surface patterns unified and legible, undisturbed by casual ambient illumination. To put it another way, when lit by a beam of light, backscattering surfaces respond in a dazzling patch of evenly luminescent colours – quite agreeable for reading a sign quickly and easily. Observable in nature as the effect of a dew drop sitting on velvet strands of grass, retroreflectivity joined the repertoire of meteorological optics only quite recently. Some explanation of the phenomenon had already been proposed in 1874 by Eugen von Lommel, but its name – sylvanshine – was coined in 1994 by A. B. Fraser in a paper reporting on the bright glow seen on the dew-covered leaves of certain tree species when lit by nothing but headlights (Fraser, 1994; Mattsson, Cavallin, 1972; Nilsen, 2004). The relationship with traffic sits at the crux of retroreflectivity technologies' history.

In the realm of safety measures, retroreflectivity has largely replaced Lambertian-like surfaces – a model and a concern for vision technologies developed up to the 1970s. Such is the case with more recent work on communication systems, where the detectability and visibility of signs have been given the highest attention. The second decade of the 21st century has seen a number of pilot projects aiming to find the extent to which the old formulas of infrastructure-to-human traffic communication can be adapted for infrastructure-to-machine protocols. When these questions have been addressed in regional studies conducted in Sweden, Croatia, and 3M in Michigan (Babić et al., 2022; Burghardt et al., 2021, 2023; Mihalj et al., 2022), the authors emphasise the need for controllable light reflectance in addition to making suggestions on maintenance, problems of sign occlusion, and the enlarged sizes of signs and road markings. Road infrastructure investments have made retroreflective surfaces and coatings viable for use on a mass scale, in turn making them ubiquitous beyond this specific use.

Retroreflectivity is being analysed for machine learning systems and automated detection methods. Wanting to stay ahead of technological change, commercial solutions suppliers like the R&D laboratories of Swarco in Vienna, are already testing their microcrystal bead components against assisted driving systems. Otherwise known for Swarovski's faceted stones and shiny jewels, the company makes most of their income by supplying glass components – crystal beads – for road infrastructure paints and coatings. A study from the Vienna lab details how minor irregularities in the surface improve its visibility in machine vision systems: water droplets flow faster off an uneven surface, allowing car-mounted lidars to independently detect the flash of light caused by the headlights of a vehicle approaching from the opposite direction (Burghardt et al., 2023). Comparable research has also been made for high-visibility safety apparel. Following ISO's 2013 regulations, retroreflective surfaces have become ubiquitous elements of

safety clothing. Since industry workers' vests and gloves are covered with strips and patches, vision-based tracking systems have been trained on image recognition models that take retroreflective surfaces as a fast and reliable indication of a human presence. Initially the method was recommended for recognition only in extreme operational conditions (Mosberger et al., 2014), but the ubiquity of safety measures and the physical affordances of retroreflectivity have helped make lidar and camera-based machines sensitive to these select components in the urban landscape and general work areas.

To the soft glow of microcrystals, one should add the velvety textures of carbon. Black surface engineering is the next area linking up with the advent of automated vision systems. At first glance, the industry of superblacks does not seem to pair with visual technologies on a scale comparable to universal safety measures. The industry of black coatings is characterised by a variety of applications, ranging from thermal control baffles to radiometers set for the precise measurement of power in optical wavelengths (Lehman et al., 2018). The coatings emit energy intensely enough to create high-quality blackbody sources. In the technical context, blackbodies are a useful reference point for characterising the behaviour of other materials (Brandt et al., 2008)[5]. Selected sorts of black paints are being tested to measure the temperature of heated objects using thermal cameras. Being uniformly black over a very broad wavelength range – from the visible to far-infrared (FIR) – these specific dyes are applied to surfaces either as a permanent coating or as a small test spot to measure their radiance temperature against that of the uncoated surface (Brandt et al., 2008). The current utility of superblacks for spectral vision systems therefore lies in their calibration capacities – a quality that may not necessarily create high demand for these materials but is sufficient to propagate their use along with omnipresent visual-thermal and mid- and far-infrared detectors.

Furthermore, vertically aligned carbon nanotube arrays (VANTAs) have made a specific contribution to new vision materialities as they have also become a sort of ambassador for spectral design. This is primarily due to a breakthrough in the first decade of the 21st century. The interest in materials of negligible reflectance came not only from the chemistry of paints and dyes, but also from the theoretical modelling of several types of surface diffusers. In the 1990s, the technology relied on a theory predicting that delicate, rough, low-density nanostructures could provide the desirable properties (Garcia-Vidal et al., 1997, pp. 4289–4292). The research reported that different sorts had been considered, including metal

[5] According to definitions made for technical use – as not all objects and materials radiate infrared energy equally – a blackbody presents an emissivity of 1.00, as it is assumed no other material is capable of radiating more thermal energy at a given temperature. In contrast, an object with an emissivity of 0 emits no infrared energy and can be considered a perfect thermal mirror (see Brandt et al., 2008).

soot derived from gold or silver (Lehman et al., 2018). Eventually, the extremely low index of refraction was achieved with nanotubes of carbon (Yang et al., 2008). Yang's vertically aligned carbon nanotubes (VA-CNTs or VANTAs) garnered much attention as a material capable of absorbing light at an order-of-magnitude stronger than commercially available low-reflectance carbon dyes. Around 2009, an ultralow diffused reflectance of 1×10^{-7} created a new standard for black surface technologies (Yang et al., 2008). In the course of what was called "a race for superblacks," technologies of carbon nanotubes heralded the invention of a genuine spectral material that perfectly absorbs light and perfectly emits thermal energy. Designed primarily to absorb stray rays around black-boxed optical instruments, new blacks have not only gained status as a cultural meme in technical journalism and social media, but have also become a subject of interest for artists and designers working with sophisticated pigment combinations since the 2010s. Patented products have occasionally been linked to renowned studios, a prominent example being the superblacks attributed to Anish Kapoor's work *Descent into Limbo* (1992), where nonreflective surfaces were used to create the effect of a dark cave dissolving the objects submerged within it[6]. Public recognition of the technology initiates a discourse on spectral signatures beyond the purely technological context.

A third industry that defines the spreading machine vision materialities is the aforementioned low observability engineering. To a further degree than in the other two areas, low observability (LO) concerns materials in reference to their surroundings, and in doing so it aims neither to boost nor calibrate the field of vision. The priority is to conceal objects by making them indistinguishable from their background. Developed for military purposes, the field was originally focused on technologies for camouflaging large units such as aircrafts and marine vessels against radar detection (Galati, 2016, pp. 269–271; Nicholas, Strattan, 1996). As warfare tactics became occupied with night-vision googles, thermal infrared cameras, and multispectral sensors, the requirements for concealment started to be sketched anew, subsequently covering thermal regions, infrared, and visual regions. In the rhythm of the post-2000s arms race, advanced technological camouflage has sought new types of spectral invisibility.

The limited availability of source material on developments in the military industry prevents a detailed survey. However, some of the LO issues associated with introducing advanced vision systems can be roughly outlined by looking at the work published by military academies and the research grant topics funded at technical university departments. A timeline of those studies suggests that first the expected target's characteristics were outlined. The research publications

[6] The original version predated the VANTAs innovation; for a discussion on the use of nanocarbon tubes paint in Kapoor's work, see Chambers (2021).

of the 1990s sketch the thermal and IR signatures that enabled the detection of soldiers and military equipment on smaller scales (Cederquist et al., 1993). Prepared merely for detection purposes, these standard characteristics were used as references in propositions for the valuation criteria in the spectral design of camouflage in the 2010s (Åkerlind et al., 2015; Andersson, 2014; Park et al., 2021). From another vantage point: public promotional sources that military industry suppliers used to publish on a daily basis have recently added "multispectral concealment solutions" to the professional jargon, catalogues, and business communications (Bate, Smatana, 2025; Bevziuk, 2023; Jersblad, Ålund, 2021; *The Economist*, 2018; Ukrainian World Congress, 2024). Eventually the topic of so-called new situational awareness – constructed by ubiquitous, thermal, IR cameras carried by drones and operated not only by the army, but also by non-state and paramilitary actors – has become a recurrent theme in press and military reports from the frontlines of the 2020s (see Bevziuk, 2023).

It should be emphasised that LO technologies select their materials against specific models of the environment and viewing conditions. The multistage selection process develops from these models, arriving at detailed characteristics for the coatings, surfaces, and textiles. As a general position, the initial characteristics of the background – called the "operational environment" – are envisioned as roughly sketched models, typically of green vegetation areas, deserts, or arctic landscapes. Working from the specified model, the research formulates the desirable characteristics of the materials in more detail. From this, standards and recommendations for potentially good concealment rates are specified. Standards are essential both for state military tenders and the organisation of supply chains. This results in a somewhat problematic detailing of otherwise general characteristics. Quantitative descriptions of spectral signatures can then state, for example, that for a chlorophyll vegetation area, the spectrally selective reflectance of the surface should be less than 15% in the visual spectrum, with specific percentage ranges for the reflectance of green (45–60%), brown (10–25%), and black (5–10%) in the near-infrared band (Andersson et al., 2014, pp. 4–5). Auxiliary, qualitative specifications would recommend materials for a chlorophyll-like background response, characterised by low gloss, a low degree of polarisation, being non-destructive for the radar spectrum, being controllable for multiband detectors in the optical spectra, and so forth (Andersson et al., 2014, pp. 4–5). In this case, one specific problem is achieving a low infrared emissivity of around 0.4–0.6, as human bodies and operating machines are usually hotter than their background. It is through such selective procedures that specific types of materials could be matched or engineered for military-scale use.

Endeavours to produce invisibility effects demonstrate the complexities of matching the desired surface properties to the state of an intended effect. A perfunctory survey of the field reveals the uncertainties and concerns of trying to cope with the

task of concealing objects through extended registers of the spectrum at the same time. The basic limitation starts from the laws of physics, according to which the reflectivity and emissivity of a material are interdependent. No values for reflective and thermal (emissive) signatures can be easily controlled for one physical object over the entire visual and mid-IR (MIR) range. In most cases, the setting of an important parameter in one register results in random effects in another. For example, fabrics which scatter microwave frequencies of the electromagnetic field (acting like a faraday cage) are coated with silver. This, in turn, gives them an intense reflection of visible light – they shine, hiding the objects behind them. Matt, light-absorbing coatings (as in case of nanotube blacks) can hide someone in the sunlight and blacken their image in IR night goggles, but will generally be good emitters, revealing immediately the hot spot of a body in thermal vision. So, while it may be possible, for example, to select uniform fabrics that will reduce elevated body temperatures discernible by thermal vision, it will be difficult to find ones that match the desired thermal signature without treacherously shining in daylight or infrared. The limitations described along with the state-of-the-art proposals imply that universal solutions for low observability materials are practically unachievable.

Due to its specific cascade of procedures, low observability is characterised by a variety of solutions. More than in the case of the other engineering fields, it does not necessarily advance work on the specific qualities of materials, but rather a hunt for an optimal effect attained through a composition of surfaces, colours, metastructures, or textiles. Such a composition is then enmeshed in a specific culture of material design. Actual prototyping favours materials devised for high durability, produced not merely by the cheapest technologies suitable for mass production, but of a quality guaranteed by military industry suppliers. Therefore, if any one specific item should be added to a dictionary of the new materialities of vision, it would be difficult to pick a favourite. If pressed, I would favour technologies that use neither carbon nor crystals, but aluminium. Various forms of this material circulate in the prototypes of military spectral signatures management. Aluminium flakes and alloys are recommended as a component in paints and resins designed to conceal soldiers in bands ranging from the visual to the thermal infrared, VIS to TIR (Andersson, 2018, p. 62; Andersson et al., 2014, p. 14; Shirke et al., 2024, p. 3; Yan et al., 2020). The popularity of aluminium is seen in the fact that, when used in various forms, it allows us to combine the desired spectral behaviours of dyes and paints in VIS and NIR with low-emissivity properties in TIR. Hence, low observability completes the proposed shortlist of machine vision materialities with reflections of silverish aluminium flakes.

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Genealogies of multispectral design present the matching of vision techniques with specific sorts of materials. As a long-term process it starts with nineteenth-century experiments in spectrometry, leading through projects in remote sensing, and into research and development projects in specific areas of material engineering. Within a shorter time frame, from the 1970s Landsat projects to contemporary R&D tests, the study of spectral signatures has contributed several developments to technical discourse. Primarily, it has constructed its own entities and articulated its research with a vocabulary of green vegetation zones, battlefield armour-covered human beings, and sylvanshine leaves. Next, it has placed the newly constructed entities on lists and indexes arranged according to specific material properties, thus creating new types of documents and portraying the sensory properties of structures and objects. Here, circulated in a variety of contexts, from scientific research to commercial product specifications, the indexes have organised the materialities according to specific values, of which emissivity in thermal ranges and reflectivity in solar light have become the most frequently used. Eventually, spectral signatures research has showcased specific materials as desirable points of reference due to their perfect retroreflective structures or blackbody-like objects. Aggregated into larger dictionaries, these spectral entities provide the basis for experiments and trials concerned either with selective solutions for enhanced visibility or propositions for concealment techniques. Retroreflective surfaces, carbon nanotube coatings, and aluminium flakes complete the proposed inquiry with a short list of machine vision materialities. A longer dictionary should include a broader class of synthetised and selectively observable surfaces and coatings – materials defined by the methods of spectroscopy and remote-sensing projects.

The scale and variety of engagements described above implies that multispectrality forms a current running through contemporary visual culture parallel to the processes of image operationalisation. This current brings about important effects in sensitising visual systems to specific types of materials. Furthermore, it elevates the importance of physical properties, like thermal reflection or the emissivity of surfaces in various spectra. It can be argued that, along with the proliferation of adequate sensory equipment, multispectrality reveals new realms of aesthetics and consolidates specific visual procedures. In such a context, spectral signatures become not only a prominent analytical procedure, but also a concept suitable for a general understanding of scopic regimes.

The emergence of a new discursive space and concerns about multispectral design provides new arguments for the study of relations between vision technologies and the environment. At the beginning of the present essay, a premise was offered that the special properties of surfaces work as "amplifiers" and "sensitisers" which attune technical systems to their surroundings. The claim suggested the ability of matter to dominate and impact on the evolution of technical systems.

This hypothesis stood to some extent against a vision that was outlined in the previous chapter – that of assistive technologies colonising the environment with alien, machine-readable tags and marks. The review presented here replaces the colonisation scenario with some kind of story of mutual attunement. Vision systems and materialities adapt to each other grudgingly. Discussed above, the cases of the automation industries and of military concealment allow us to argue that there are some materials that seem to propagate under the dictates of machine vision technologies: retroreflective surfaces are useful materials for the machine vision industry, and researchers in low observability argue that military concealment adds utility to the development of advanced materials for spectral design in signature management applications. However, the propagation of specific cameras and sensors prompts sophisticated compositions of special property materials in selected domains only, while cues and affordances provided by spectral signature studies are plentiful. Hence, it is not an arms race triggering the invention of ever more sublimate invisibility cloaks. It is already the spectral characteristics of the structures around us that instruct the selection of sensitivities and sensors eligible for visibility and concealment strategies. All told, in the relations between vision technologies and nature, multispectrality admits the agency of matter.

INTERIM SUMMARY /
sensory environments in the making

Towards the earthbound visual cultures

Before moving on to the second part of this book, let's wrap up the observations on the universe emerging behind MV experiments. In the opening chapters, I have argued that vision technologies in the 20th century started to generate their own synthetic, self-sustaining, and vaguely adaptive worlds: work studios, darkrooms, photometric test sites, etc. The subsequent observations implied that computer science, despite its ambition to absorb the sensory process entirely into the virtual realm, has not made those universes shrink. On the contrary, confronted by the ill-defined nature of the visual task – the elusiveness of vision – computation has caused those humble setups to proliferate and take on most intriguing and sophisticated forms.

The previous chapters' explorations have reported on the proliferation of a specific technological complex, and we have explained why this complex is weaving its way through advanced sensory engineering with such impetus. It was demonstrated that the reliable performance of machine vision systems depends heavily on offloading the interpretative work of algorithms onto the external environment. This led to the argument that machine vision is not simply applied to the world, but rather relies on a specific sort of scaffolding – through signs, fiducials, and calibrated surfaces that help the machines to stabilise perception, reduce ambiguity, and act with confidence. Cases discussed in the second and third chapters provided insights into human-readable signs that are adapted for machine detection, the use of calibration markers and fiducials, and the integration of illumination techniques that augment legibility across diverse environments. Nevertheless, machine vision is not restricted to solving the limitations of computational systems. Hence the inquiry shifted in the fourth chapter to how material properties themselves are engineered to cooperate with automated perception. Here, it explored the domain of multispectral sensitivity and spectral design, where pigments, gloss, emissivity, and reflectance are manipulated so that surfaces actively amplify or suppress machine readability. From retroreflective paints to near-infrared coatings and physical, unclonable functions, these developments show that vision systems are increasingly shaped not just by what is added to the environment, but by what the environment becomes itself. Taken together, these chapters demonstrated how the visible world is being reconfigured through both assistive technologies and engineered materials, creating new visual regimes in which what is seen depends on who or what is doing the seeing and how the world is manipulated to better serve the technical solutions.

At this juncture, the technical operations compliant with algorithmic vision development can be identified. I propose that they are: distributed structures, light zones arrangement, sign systems, and multispectral ordering. These operations indicate that the computation which made technical universes proliferate in various new forms is, at this time, dependent on more than mere technical setups. The closer we move to photometric stereo, wayfinding, or spectral signatures management, the more it becomes apparent that computation pairs with specific sorts of zones or places through which vision can happen. Therefore, approaching the second part of the study, I would argue that the supposed technical extensions and assistive technologies are of primary importance. Whereas photographic vision developed setups, the algorithmic vision of the 21st century cultivates environments.

What I will insist on is discussing machine vision in terms of earthbound, light-dependent environments. Being light responsive, digital cameras dwell in their "light environments" – much like marine species floating in diurnal cycles through the upper layers of the ocean. The optimal light conditions of technical ensembles are then designed in detail (Jahr, 2017). Expertise in implementation informs how light frequencies correlate with task performance: for instance, using blue for the detection of details and cracks, and red for general object capture. Illumination itself provides references for shape recognition: structured gratings projected onto the surface allow us to determine their characteristics. Rays create the barriers that trigger alarms and help avoid collisions, etc. In the computational digital era, carefully devised machine photic zones offload much of the complex algorithmic task and serve as an elegant solution for guiding movement through complex surroundings. However, the refinement of illumination patterns brings about the first set of design problems. These pertain to ecologies of light, intersecting with the establishment of vision machines. Every terrestrial ecosystem – be it sunlight cast across a body of water, or an artificially illuminated movie set – has its own residual patterns, and all these zones are being constantly destabilised, compromised, and transformed both by natural and human-induced interventions. With a new element in this composition – such as vision technologies may introduce – the existing imbalance will change. Minor in scale as they are, these alterations might be problematic, because they are on a collision course with the light arrangements invented and maintained for the last hundred years through specific practicalities and aesthetics. With their characteristic demand for stable, artificial, and (in their own manner) regular illumination, the emerging machine environments may be nothing like the *ad hoc* operational areas preestablished by previous technical revolutions.

As the systems become earthbound, sensors entwine with tags and markers haphazardly pasted on walls, furniture, products, and even packages. All those ele-

ments are usually light, small-scale, replaceable, easily dispersed, and always belong to someone, being there in the service of a third party, not making sense for most living creatures, integrated for the stakeholders' own purposes. That horizontal distribution of interconnected components is no less important than planetary-scale surveillance, where a diadem of satellites looks down on the Earth from stratospheric heights. The poetics of satellite systems forms a separate genre of contemporary ecophilosophies. It appears in posthuman glossaries under the theme of the planetary gaze – the gaze from nowhere, spinning down from the sky onto the details of streets and gardens. By contrast, the earthbound systems discussed here are somewhat modest cousins of these space technologies. Trailing with their vines, they are no longer attracted to the upper layer of starlike orbit but to the most vibrant parts of inhabited environments. This slow, uncontrolled, disposition indicates the terrestrial vectors of vision politics. It penetrates a thin layer of the planet within which all life happens. This is a critical zone, extending from root tips up to the tops of the highest trees; the critical zone which becomes a philosophical lieu of interest by the intervention of the ecohumanities debating the prospects for a renewed politics of Gaia (Korintenberg et al., 2020; Latour, 2017).

All those modifications and shifts however are rather gentle compared to the changes that spectral ordering seems to induce. The operation anticipates the posthuman character of visual cultures. Spectrality gains momentum with the proliferation of off-the-shelf devices operating in extended electromagnetic ranges – cameras and bolometers. Spectral ordering insists on considering non-human seeing, on debating the multilayered realities perceived by animals, machines, and human beings. But this is just part of its potential. Spectral ordering introduces a new understanding of how surfaces and materials are matched, how they gain in contrasts and gradations. Constructed over the course of many repetitive measurements, I proposed that indexes organise a sensory space in the same way colour does, except that they incorporate hitherto niche orders of emissivity and reflection. Within those spaces, human skin is put in contrast with polished aluminium, while paper appears comparable to asphalt. The design potential for this ordering is unquestionable and not only on the speculative level. By the same token, the specific materialities of machine vison emerge.

Altogether, the earthbound systems indicate a shift in visual culture – from digital commands and satellite signals to embedded, spectral intelligences interwoven with the very materials and atmospheres of earthly life. Even though the construction of this intelligence does not triumph over its algorithmic counterpart, it compensates for its limitations. In the forms observed above, visual technologies grow into realms that recombine concrete sensory registers with habitable environments.

The legitimacy of addressing the vision as environment problem

The approach elucidated in the present study seems to be highly underrated in the discourse of both technology and visual culture studies. Technology's ambition is to build autonomous systems. This in turn positions sensorics not as a tool for making connection with but rather gaining independence from the machine's surrounding. Elsewhere, and for reasons of their own, visual culture studies focus on the autonomy of images and the power of the all-piercing gaze. Conversely, the argument presented here is that recent technological developments reveal the growing importance of vision environments. These are not passive settings, but actively constructed, selectively tuned spaces in which vision takes place and from which new kinds of relatedness emerge. Below I put forward some arguments for encapsulating exploration in the concept of the visual environment.

The first argument would be this: more than one industry has expressed its ambition to reinvent a sensory act and has ended up developing a pro-technical sensory environment. From the calibration of machine-readable markers, to the maintenance of an automated production line, or advanced stealth techniques, vision is less an event between a subject and an object, and more an orchestrated condition, a spatial, material, and technical affordance that enables certain perceptions while excluding others[1]. To emphasise this shift from seeing as relation to seeing as co-evolving, an example comes from the visual media industry. Independently of machine vision inquiries, unique technical ensembles have long been arranged in front of cameras, on movie sets and in photographic studios. The refinement of those systems is reported in a study of cinematography by Richard Blank. This concise history of film and light depicts the situational plan in a few lines:

> Anyone visiting a film studio to watch filming will be amazed by the sheer number of spotlights, lamps, lighting fixtures which are standing around among the scenery and which are arranged, moved, positioned 'somehow' without one, as a layman, being able to recognise any kind of system. When someone has come to see the actors working, he will soon become inpatient. The setting up of the light takes time, a long time, far longer than the work with the actors. (Blank, 2015, p. 13)

[1] I thank Denisa Kera for proposing this formulation, which I have adopted here.

Anyone who disregards the rules of set lighting will prove to be a dilettante, adds the introductory chapter (Blank, 2015, p. 10)[2]. Such cinematographic environments appear sparsely in terms of the theory (Baxter, 1975; Samlowski, Wulff, 2009), but they are plentiful in practice-based research and professional expertise (Blank, 2015; Nevill, 2021) (Fig. 12). From Eisenstein to Lars von Trier, an awareness of the subtle relations between the technics of the movie set is a *sine qua non* of mature cinematographic expression.

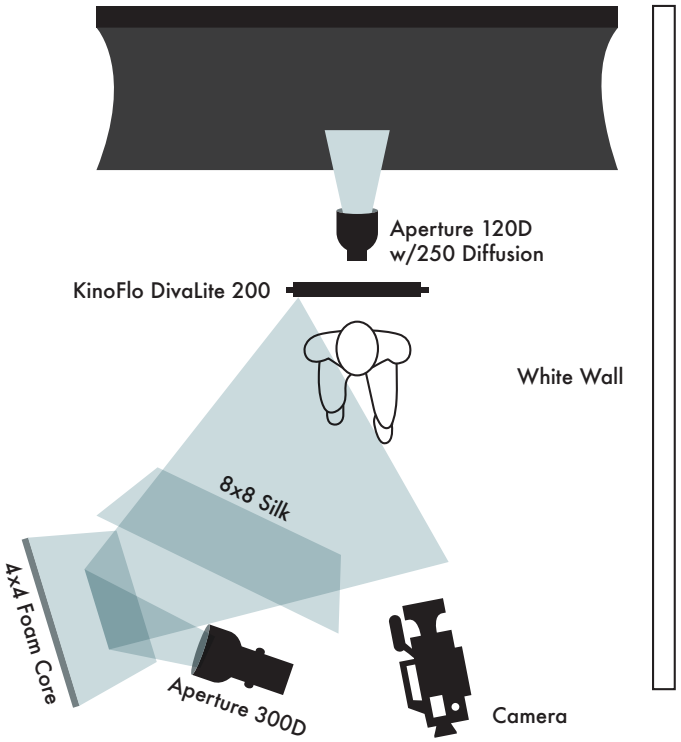

Fig. 12. Spotlights and lamps illuminating the movie set: light sources, reflective and diffusive surfaces form into a sort of vision environment. Arrangements of specific setups have become a theme in professional blogs and manuals (after Reynolds, 2020)

[2] For the purposes of visual studies, Blank (2015) proffers a rule book of cinematographic craft and declares that it is universally valid and rarely contested. He argues that questions about light go beyond the scope of technical matters. Cinematography is concerned with producing the illusion a specific geographical location, time of the day, and surface materialities. Among *Film & Light*'s interviews, Blank quotes Hollowood operator Vilmos Zsigmond, who admits that he constructs his movie-set daylight other than it is in California, preferring the scene as it would be in Sweden or Ireland, "where the sun travels low around the sky even in the summer months" (p. 14).

Another example that adheres to the validity of the concept comes from light engineering. Only recently this domain has brought into focus man-made light zones, manipulating streetlights and signal systems that have been around long enough to have become transparent elements of everyday infrastructure. A well-thought-out approach to light technology emphasises the relevance of vision environments by raising concerns about the interdependence of nocturnal ecosystems and artificial lighting at night (ALAN) (Fig. 13). Studies on the politics of light pollution started with a stipulation that radical steps are needed to disburden aquatic and terrestrial habitats from particular biological stressors (Longcore, Rich, 2004). Long campaigning for broader recognition, the research has laboriously collected evidence on how artificial lighting alters the life cycles of biological species, influencing hunting, migration, and navigation patterns[3]. It is only recently that lighting engineers have responded to the call by translating this environmental science expertise into design processes (Pérez Vega et al., 2021; Sanders et al., 2021; Zielinska-Dabkowska et al., 2023). Design approaches of technical disciplines pursue alterations in large-scale systems.

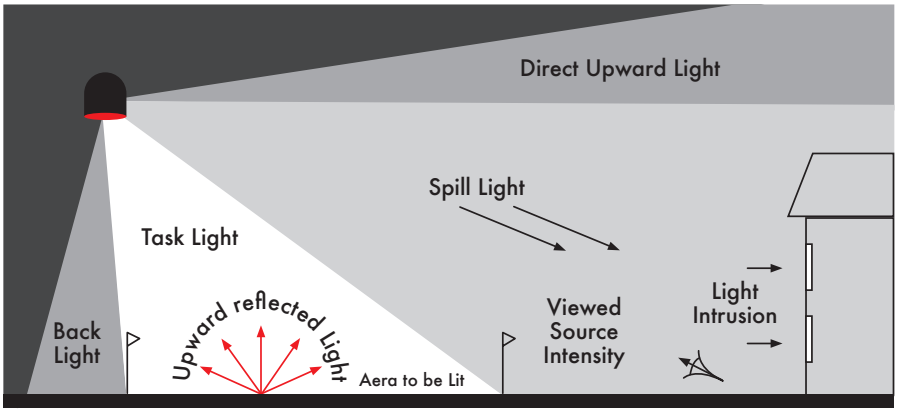

Fig. 13. Schemes and diagrams demonstrating the circulation of light in physical environments include those presenting artificial light in urban spaces, often presented in the context of nocturnal ecosystems and artificial lighting at night studies (ALAN) and urban landscape design (after Ciriminna et al., 2015, Figure 3)

[3] Ecologies of darkness emphasise the breadth and strength of biological impacts (Eklöf, 2023). They call for outdoor artificial lighting to be reinvented in terms of its timing, intensity, and spectrum. The question of how significant these burdens are for the overall state of ecosystems warrants a separate discussion. Ecological discourse suggests its own arguments for rethinking the technology of light environments.

So, there is also substantial conceptual work going on behind light tech: that is, in rephrasing hybrid geographies. The involvement in nocturnal ecologies brings a set of examples that renew the imaginary of artificial light systems. The agenda includes the critique of iconic buildings and monuments such as the 9/11 Memorial Tribute in Light, embodied in sky-high beams that affect the routes of migrating birds. In Europe, there is a tendency towards rethinking illuminated heritage sites that are shrinking the hunting areas of night species. With the 2010s manual *Stadtbild Berlin Lichtkonzept Handbuch*, technical norms for light engineering were filtered down through collaborative initiatives between ecologists and urban architects, working broadly towards a safe, energy efficient, ecological city. Advisory boards like the Senate Department for Urban Development and the Environment (Senatsverwaltung für Stadtentwicklung und Umwelt) have declared new alliances in the by and large human-centred "parliament of things" (Berlin Lichtkonzept, 2011/2015, p. 9)[4]. The catalogue extends to tourist resorts on the Mediterranean and industrial platforms on the North Sea where residues have deregulated marine life cycles. When collected in this way, the LED glows of heritage sites and industry facilities become evidence of a specific sort of intervention – one that creates knots and ribs in a complex sensory fabric which interconnects otherwise distant creatures. In this case, light engineering not only fosters the sensory complex of its own kind but also becomes a testing ground for posthuman sensory politics.

As a second argument, I would emphasise that models of sensory environments have proved essential for understanding the behaviour of autonomous agents – living creatures of all kinds from marine plankton to humans.

Sensory environments are integral to most influential theories of the twentieth-century life sciences. Once biology had provided evidence on how illumination patterns intertwine with the lifecycles of tons of marine plankton and coral reefs, one of the most insightful continuations to this approach came from James J. Gibson's ecological theory of perception. He incorporates specific articulations of sensory phenomena. The approach radically dispenses not only with the representations nested in the Helmholtzian model of sensory experience but also with discourse derived from the psychophysical perspective. In their place, Gibson (2015) holds on to the terrestrial perspective, arguing that it is applicable for the phenomena's scales and sensitivities:

> All these facts about moving bodies and about the transmission of light, sound, and odor [*sic*] in a medium are *consistent* with physics, mechanics, optics, acoustics, and chemistry, but they are facts of higher order that have never been made explicit by those sciences and have gone unrecognised. The science of the environment has its own facts. (p. 14)

[4] On Berlin and other urban lighting design regulations in collaborative frameworks, see Pérez Vega et al. (2021) and Méndez et al. (2024).

In the late 1970s, ecological theory was not the only realm thinking in terms of terrestrial rather than information-based models of behaviour. Just about the time when Gibson's groundbreaking approach was spreading through perception studies, the sunlit bodies of oceans were composed into the maverick CLAW hypothesis – a seminal model that served the philosophical discourse of later decades. This study of the sea encapsulated the concept of photic zones: upper layers of the ocean penetrated by sunlight, animated by the diurnal migrations of plankton. These are zones where photosynthesis takes place. Since the dawn of marine ecology, the study of living light environments has been at the heart of research. The CLAW hypothesis has followed the observation of changes in reflection, albedo, and the photochemical reactions of marine plankton (Fig. 14).

The four authors whose names give CLAW its acronym initially described a possible negative feedback loop between oceanic phytoplankton, atmospheric sulphur, cloud albedo and climate (Charlson et al., 1987). They showed how clouds accumulate over the ocean surface causing the water to cool and the phytoplankton to decline and re-grow in a stable way. Originally, CLAW was therefore about the ecosystem's undisturbed, natural feedback loop; later, the anti-CLAW hypothesis described in James Lovelock's *The Revenge of Gaia* outlined how that can change due to human intervention. The anti-CLAW theory proposed that the (human-induced) rise in temperatures switches the negative feedback loop to a positive one, triggering the climate catastrophe (Charlson et al., 1987; Lovelock, Margulis, 1974)[5]. Hypotheses like CLAW and its much-debated reverse understand light not only as an active component in instigating photosynthesis. Marine ecology research further conceives of light as a resource administered by terrestrial ecosystems: blocked by cloud cover, backscattered by aerosols, shimmering with soft opacity through bodies of water.

Finally, I would argue that after decades of implementing sensory systems, engineering needs to critically revise its assumptions about the gap between the external world and technological structures.

In engineering discourse, the techniques for situating a project in the external world have been constantly played down. This tendency is especially evident in the interdisciplinary research on AI, machine vision, and robotics. While vision technologies not only detect but also shape a machine's surrounding, robotics remains devoted to the concept of autonomous systems, denying that environments should ever become a field of intervention. Even while introducing the situated approach to artificial intelligence – which in most uses of the term indicates the tight coupling of an autonomous object and its surroundings – control systems engineering insists on an approach that makes machines respond directly to messy and unpredictable areas (Brooks 1991b, p. 1227; Siciliano, Khatib, 2016, p. 308).

[5] In the anti-CLAW scenario, upper layers of a body of water are not lit up by light mirrored from the clouds but are intensely heated by sunrays falling on the ocean.

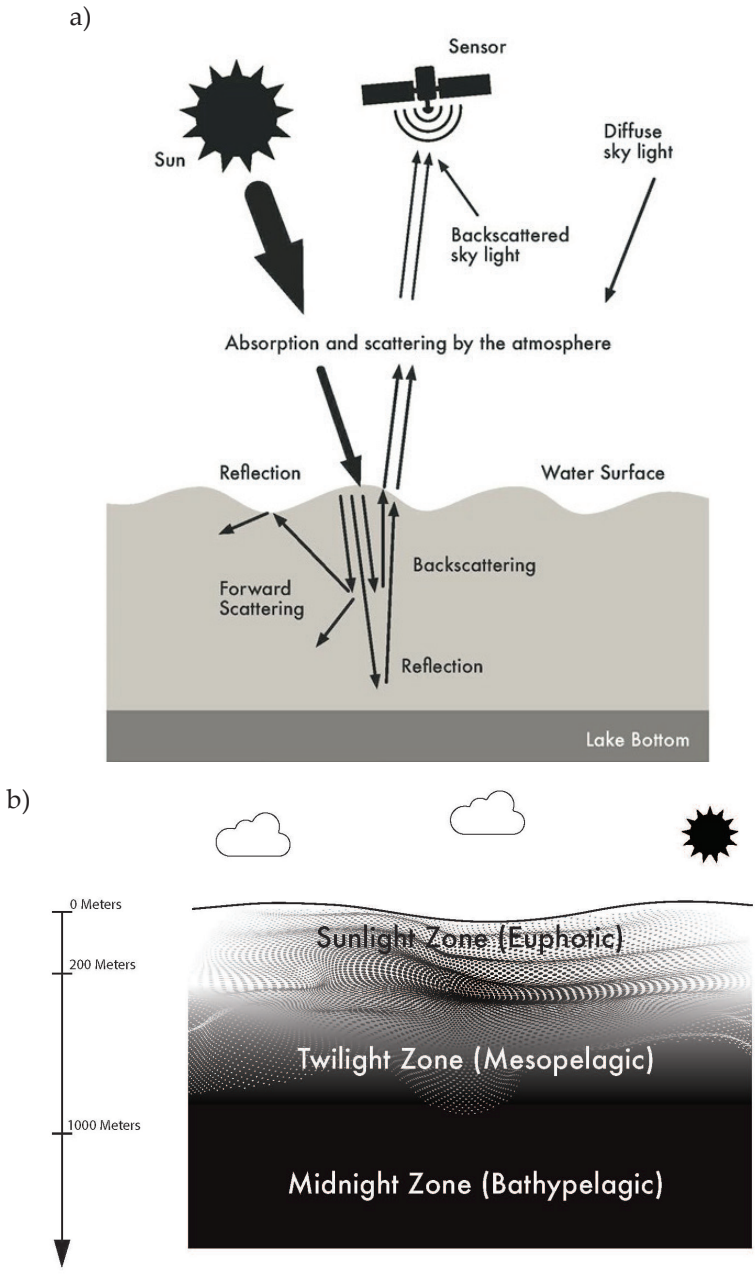

Fig. 14. Schemes and models explaining the complexities of marine ecosystems often include light as a factor regulating the lifecycles of the species. The examples include (a) a representation of how light behaves in bodies of water as a factor in interpreting satellite images, and (b) the photic zone – the sunlit layer of waters which become an ecological niche for plankton photosynthesis (after Laanen, 2013 – Fig. 14a)

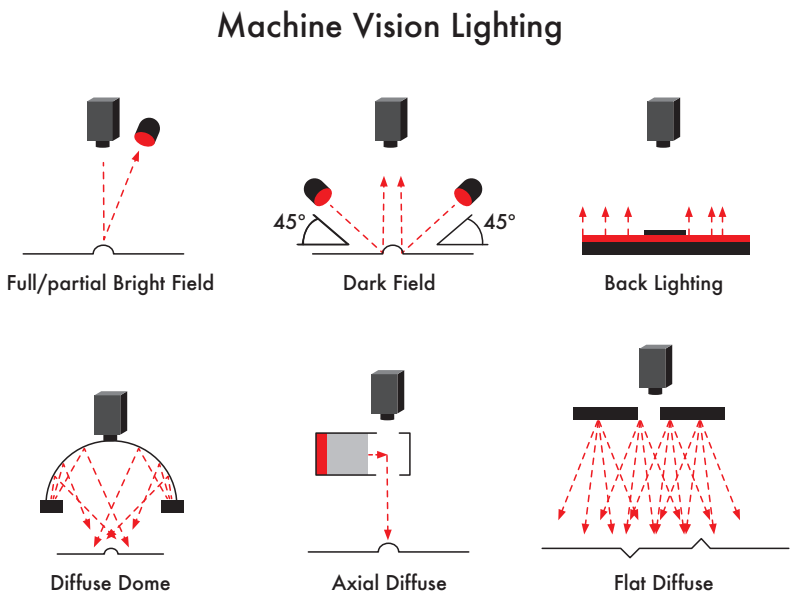

Fig. 15. Techniques like illumination for machine vision systems are enumerated in the context of their implementation (after Hlaváč, 2020)

What drives propositions like those articulated by Rodney Brooks' MIT laboratory is the primary ambition to develop bottom-up, embodied cognition as the predominant form of AI (Brooks, 1991b, 1991b, pp. 14–17; Shakery, Ziemke, 1997)[6]. In this context, thinking in terms of assistive techniques, despite being inherent to machine vision practices (Fig. 15), met very early on with the objection of an intellectual compromise, a malpractice that made the founding systems of robotics

[6] Since the seminal papers of Rodney Brooks representing the renewal of robotics discourse in the 1980s, the term "situated robotics" has been introduced to the discussion on behaviour-based systems, so that situatedness relates primarily to direct, situated interactions with dynamically changing environments. Textbook definitions of the concept tend to consider intervention into the environment solely as an act of fixing it into a static structure. For comparison, see Michaud and Nicolescu (2016), who state that "*Situated robotics* deals with embodied machines in complex, challenging, often dynamically changing environments. *Situatedness* thus refers to existing in a complex, challenging environment, and having one's behavior [*sic*] strongly affected by it. In contrast, robots that exist in static, unchanging environments are usually not thought to be situated. These include assembly robots operating in complex but highly structured, fixed, and strongly predictable environments, specifically engineered and controlled to enable the robot to accomplish very specific tasks. The predictability and stability of the environment have a direct impact on the complexity of the robot that must operate in it; situated robots therefore present a significant challenge for the designer" (p. 308).

work only because of the very careful engineering of their environments (Brooks 1991a, pp. 14–17). It is in these terms that 1980s programs only selectively refer to Herbert Simon's evocative argument of sundials and clocks, the one being a smart and the other a poor choice for measuring time on a rolling ship (Baber, 1989, p. 330; Simon, 1970/1996)[7].

Studies from outside engineering discourse are much less reluctant to claim that recomposed nature becomes the precondition of operation for technical devices. This has been demonstrated by human geographies, which grasped this quality upon the mass manifestations of locative media. In the 2010s, human geographies indicated the rearrangements in vision-related objects: maps, route records, fiducial signs, and landmarks have encouraged thinking about the environment as a locus for visual culture. Processual approaches to imagery, and theories of locative media have all renewed the conceptual framework for theories of space production and placemaking (Cornelio, Ardevol, 2011), the concept of nested images (Nacher, 2016), the posthuman landscape (Bratton, 2019), and the philosophy of critical zones and terrestrial politics (Latour, 2017, 2018). Within the domain of these studies, some authors have moved towards data-driven technology as shaping the sociopolitical order (Kitchin, 2021), while others have successfully introduced environmental thinking into observations of both analogue and digital artistic productions – what in visual culture discourse is termed postdigital aesthetics.

Reporting on the current state of technical infrastructures, most of these insights demonstrate the value of reconsidering technological design and implementation practices. The study of human geographies indicates that sensory systems are highly cohesive with the pipeline for urban development, and the ensuing studies have worked with cities saturated with remote controllable digital CCTV cameras; "sensor networks have been deployed across street infrastructure such as bins and lampposts" (Kitchin, 2016, p. 7). When a technical system stretches and strains for miles into an incoherent (redistributed) infrastructure, a refined concept of situatedness becomes urgent.

Furthermore, the critique of the continued neglect of an environment approach to vision technology converges with the study of performative materiality. The new-materialist philosophies of Karen Barad and Jane Bennett organise major debates

[7] "Sundials perform as clocks *in sunny climates* they are more useful in Phoenix than in Boston and of no use at all during the Arctic winter. Devising a clock that would tell time on a rolling and pitching ship, with sufficient accuracy to determine longitude, was one of the great adventures of eighteenth-century science and technology. To perform in this difficult environment, the clock had to be endowed with many delicate properties, some of them largely or totally irrelevant to the performance of a landlubber's clock" (Simon, 1970/1996, p. 6).

in contemporary humanities by inviting a discussion on the arts and technologies in terms of their material relations and potentialities (Barad, 2007; Bennett, 2020). From the perspective of the humanities, that materialistic turn in visual studies seems to manifest as a dazzling concept. Sensory qualities become a backbone for narratives of the Anthropocene (Baxter, 1975; Nevill, 2021; du Plessis, 2021; Samlowski, Wulff, 2009) and through this turn, environment emerges not only as a component of contemporary politics, but also as a principle for the visual culture in the making.

Altogether, the recent history of technological design from cinematography to robotics shows that environments are increasingly instrumental for developing most sophisticated forms of engineering. From photic zones in marine ecology to controlled testing chambers in automation labs, sensory systems are scaffolded by physical, optical, and political arrangements. In light of the arguments presented above, I propose to validate these engineered visual environments as the primary unit of analysis in machine vision.

Towards the second part of the study

By their very nature, the proposed conclusions suffer from several shortcomings. They remain, however, fragmented, technical, and unscalable. Altogether an ephemeral environment observed on the laboratory scale does not dominate machine vision cultures – it explains its limitations. Our insights are based on historical resources and research papers. However, long-term observations of the subtle interdependencies made possible by the implementation of sensory technologies were barely included.

To critically assess the value of the proposed findings, it is necessary to demonstrate their relevance for the broader context of technoscientific interventions. Thus, the second part of the book is devoted to examining: what is the relevance of the characteristics we've captured? Not only the technical terms, but also the ecological and political qualities. Manifestations of sensory environments are the topic of the chapters that follow. With the aim of discussing the politics and agencies of contemporary visual cultures, the investigation now turns to asymmetries, hierarchies, and conflicts that technical arrangements bring to the fore in local ecosystems. It compares alternative propositions on sensory politics, including those transforming vision into a limited resource and those making senses a collaborative capacity distributed across networks of machines and biological entities.

To progress with assessing the relevance of prior observations, we need to reorder some of the study's framework. The first part followed concerns and constraints organised around selected strands of vision-oriented research. The second will

focus on the intellectual alliances of robotics, AI, and automation, considering them as a domain that has given the most impetus to revising sensory design. They will be approached in three terms: situatedness, internal representation, and embodiment. I adopt these taxonomies after debates on AI development in mainstream MIT-Stanford research articulated in the seminal series of papers by Rodney Brooks and his coauthors (Brooks, 1985, 1991a, 1991b; Pfeifer et al., 2005). In the original context, the focus on internal representation converges with a strong program of AI-oriented machine vision. Highly ambitious in attempting to create universal systems that would infer external conditions from complex world models programmed into their control units, the internal representation approach became subject to critique in the 1980s. These critiques in turn insisted on an embodiment approach, which assumes that machines are above all physical constructs that take advantage of opportunities to experience the world directly through feedback loops enabled by their sensory systems (Michaud, Nicolescu, 2016). Embodiment, along with the third component – situatedness – promotes the concept of machines that, as Brooks (1991b) puts it, "do not deal with abstract descriptions, but with the 'here' and 'now' of the environment that directly influences the behaviour of the system" (p. 1227)[8]. In line with this study's broader scope, the following observation will consider situatedness as an approach that intentionally couples engineered systems with their environments not only in terms of their structure, but primarily in terms of the rearrangement of the physical space.

The second part of this book will step beyond the relative seclusion of the laboratory and go on to explore early manifestations of vision environments. Looking to refine the proposed characteristics of distributed, trailing systems, it will seek insights on the recomposition of agencies, asymmetries, hierarchies, and conflicts occurring along with the proliferation of vision techniques. Our aim is to examine in what terms vision technologies can be considered a substrate for long-wave changes in terrestrial politics. The framework proposed above will serve to assess the relevance of the distributed environment model, and to outline the arguments for an ecopolitical imprint of machine vision as such. In what follows, I apply it to discuss three propositions. The first, on the environment-oriented strategy, is relevant for the development of machines' performativity. Here I will ask whether the approach uncovered by the previous inquiry is compliant with embodied systems agencies. The second, on their specific ecological imprint, is relevant for understanding the transformation of automated landscapes. Lastly, the third debates whether the design practice of vision environments design bears any specific political relevance.

[8] To tidy up the basic references, I will only add that situated interactions have been proposed as complementary to embodied models.

SECOND PART / manifestations

5. Machine performance

Patterns of behaviour, or perhaps more accurately the most attainable patterns of behaviour, illuminate and outstrip the working principles of technological regimes. Being interested in the deep registers of technological shifts, they expose the relevance of the sensory environment concept.

This chapter explores how different models of machine agency (such as representation-driven AI vs embodied systems) reveal the infrastructural requirements and political assumptions behind vision technologies. It asks: what affordances do alternative approaches offer for the design of machine behaviour? Hereafter, the discussion concentrates on machine performativity, by comparing three takes on autonomous systems design. It starts from internal-model-based systems. Arguments for the most attainable behaviour patterns in representation-based systems will come from observations on mobile drone swarms and customised quadruped units. Next, I propose to discuss the affordances for mobile platforms explored by pioneers in robotics who have adopted biology's teachings on tropisms, forced movements, and embodied cognition from Jacques Loeb and Valentino Braitenberg (Braitenberg, 1986; Loeb, 1918). The final part of the chapter will superimpose affordances brought about by the internal representation and embodied approaches onto the classic model of Rodney Brooks' multitasking machine architecture. His architecture will reveal a path through the discrepancies between algorithmic, embodied, and distributed models of the sensorics (Brooks, 1985). Concluding the observations on the most easily implemented machine vision performance, I invite the reader to return to the study's general problem and assess whether the introduction of environment-oriented techniques is indispensable to make the domain fully functional.

From the detection of anomalies to patterns of life analysis

The most hotly debated insights into the redistribution of visual agencies are coming out of surveillance studies and discuss how these relate to broader environmental and territorial logics. Drones have become a matrix for discussing

surveillance systems, and the prominent theoretical proposition for understanding the logic of automated warfare. The development of smart mobile units infuses classical debates on the panopticon with questions on machine/human cohabitation. Recognised as "situational awareness" machinery, drones introduce vision as a central category in military tactics. The technology marks the era of, as Chamayou (2015) puts it, "winged and armed panoptics," where the Gorgon stare of the machine not only disciplines but also annihilates (p. 44).

Chamayou's (2015) comprehensive arguments against automated warfare render palpable the general principles of the mass implementation of machine vision systems. Among the characteristic strategies of drones, the theory details the detection of anomalies and pre-emptive anticipation (pp. 42–45). The author demonstrates that in automated warfare of the 21st century, patterns of behaviour become markers of identity, and military technologies are permitted to interact with individuals and events with a certain degree of generalisation. Tactics, described in relation to military actions taken by the US army in Pakistan in the 2010s, imply that reaper drone missions were calculated based on the pre-emption of dangerous actions (like a suicide bombing or a reunion of militants). The potentially dangerous action in that case could, and has been defined based on anomalies from regular life patterns, as previously defined by the surveillance systems. Chamayou's study demonstrates the flaws of such tactics.

Importantly, the method pointed out by drone theory elucidates some of the technical affordances behind it. It assumes, amid masses of activity, that surveillance images are scanned in order to pick out events that seem pertinent to the security focus. As long as systems are focused on "abnormal" or "irregular" patterns (Chamayou, 2015, pp. 44–45; compare Andrejevic, 2019), surveillance can be scaled to large mega-systems that would otherwise collapse under the flood of data. Hence, anomaly detection advances mass surveillance not necessarily because it is the most reliable tactic, but because it is an implementable automation trick. To combine (not just visual) data to an extent that resembles a total recall project requires persistent vigilance machinery, a 24/7 attentiveness which only automation can provide (Chamayou, 2015, p. 38) Nonetheless, even professional mobile systems acquired through military grants and R&D projects are hardly ever self-sufficient. To circumvent the shortcomings of data processing, automated vision systems make the most of image detection features and behaviour patterns that deviate from the norm.

Uncovered by the study of drone warfare, the operation is not limited to surveillance tasks. The detection of anomalies has made machine vision the technique for product quality control – effortlessly detecting defects, scratches, and cracks on the assembly line. It enabled the efficient construction of the (often contemptuously dismissed) expert systems during the AI winter of the 1970s. Also, quite

unsurprisingly half a century later, it became the strategy for the sluggish commercialisation of autonomous mobile platforms. Therefore, while surveillance engineers are keeping an eye on abnormal behaviour patterns, companies' selling mobile quadrupeds furnished with IR cameras and lidar sensors are bidding to place their robots in stable, even stagnant environments. Boston Dynamics' webinars in the 2020s, for example, make this strategy clear. After a period of prescribed sales and experiments in promoting their flagship product for household areas, the company recommends the quadruped as a platform for mobile monitoring in industrial facilities. The promotional materials cast the machines as inspectors covering the industrial facility's routine, rounding up and reading different sorts of signals (including gauge readings, thermal inspections of machinery, detecting pressure cracks and leaks through acoustic modalities, etc.). These tasks amount to detecting deviations from standard functioning (Frayne, Bhattacharjee, n.d.). Eventually, as in the case of surveillance, the industrial application of machine vision is based on observing deviations from the model operation of the production floor and the machinery's condition.

However important and easily attainable, detection of anomalies does not exploit the full repertoire of the desired computational gaze's performativity. As the *Drone Theory* goes on to demonstrate, it finds a reverse in the procedures of patterns of life analysis. Unlike its somewhat isolated counterpart, pattern of life analysis seems to promise the attunement of (not exclusively) visual systems with their spatiotemporal geographies (Chamayou, 2015). Chamayou's theory acknowledges that the method has precedents in the time-geography diagrams developed by Swedish geographer Torsten Hägerstrand in the 1960s and 1970s (Thrift, 2005).

In the humanities, pattern of life analysis produces multiple interpretations of spatiotemporality[1]. In this respect, the time geographies of Hägerstrand, regarded as a highly original contribution to social theory, focus on migration and mobility. Hägerstrand emphasises the direct interconnections between actants and their environments. Employing a visual mode for capturing migrations, his processes flatten the ontology of the perceived environment. In this way, pattern of life analysis equates humans and other subjects in what can be recognised as a representation of not one but a multitude of temporarily emerging worlds. Where cartographers have found an affordance for uncovering the cycles of everyday life,

[1] Some variants in this vein were deployed in mid-twentieth-century urban studies, including contributions from French sociologist Paul-Henry Chombart de Lauwe. Unlike the horizontal perspectives of Hägerstrand, Chombart de Lauwe's (1964) approach introduces the all-uniting planetary gaze, for his life patterns to present the situated/observed from the on-the-ground itinerary of a Parisian resident over the course of a year, and mark the geographical distribution of atomised social events. Typically of 1960s French structuralists, this approach served as an argument for developing an expansionist discourse on world-scale urban planning and city development.

military strategists have sought those that indicate alleged targets. Critical surveillance studies exposes the perverse logic of automated vision technologies: once they failingly strive to discover complex regularities of life, they end up efficiently targeting its abnormalities. One could argue that, along with the proliferation of machine learning models, spatiotemporal geography enormously boosts the capabilities for charting multi-dimensional patterns of life. However, this performativity is particularly worrying considering that a military pivot is inherent to the internal-model-oriented approach.

Embedded in flat ontologies, vision machinery overwhelmingly performs non-aligned, redundant work. Artificial life cartographers document the vague relations of posthuman environments, where AI systems complete repetitive quality control procedures. This algorithmic work based on endless referencing to an internal model seems overwhelmingly non-exciting before a generation of reaper drones joins in. Here, visual studies exposes a dangerous facet of vision technologies: whenever the redundant operations of sensory systems become entangled in positions of power, the benefits are uneven. Power preys on the paleness of visual evidence. To put it differently, what is being detected is not as important as in whose name the system performs its tasks.

Taxes and redundant sensorics of embodied systems

Having recapped the performance of internal-model-based computation, the next section addresses its embodied forms. This again brings into focus the references to the several domains of research practice. Engineering commonly takes visual and auditory stimuli as mechanisms that allow for simple, direct orientation. The problem is then positioned at the core of robotics, once scrutinised by Azriel Rosenfeld as the smart coupling of sensory and motor techniques. The study of direct response mechanisms is supported by Loeb's discourse in theoretical biology, where *taxis* (the oriented, locomotory reactions of mobile organisms) is differentiated from *kinesis* (the more complex, indirect, instinct-based, and learned explorations of the environment) (Loeb, 1918). Further on, by naming performances which are notably connected to a reaction to light (*phototaxis*), biology instructs engineering that specific modalities can be more beneficial than others – thus guiding action without any trial movements, deviations, or complex decision making (Holland, Melhuish, 1996). It is also acknowledged that, simple as they are, *taxes* can produce remarkably flexible behaviour, affected quite notably only by present events and events in the immediate past in an essentially context-free way. Here, the embodied approach reveals its difference from representation-based strategies. When machines' performance depends on direct

orientation feedback loops, these are defined by the environment in which a technical unit/animal operates. In such a framework, animals and machines need no predefined context or habits, whether acquired from learning or implemented in the form of an algorithm.

In the context of biology-inspired engineering, locomotory used to be introduced with reference to Fraenkel and Gunn's (1961) classification of direct orientation. *Taxes* were then modelled within the context of cybernetics theory, and the problem of why some sensory-triggered behaviour patterns are easily achievable while others are not is elaborated through a series of experiments probing various combinations of robotics design principles. One of common touchstones for such experiments is the concept of Braitenberg's vehicle – a machine-like, life-like entity – lavishly outlined in his monograph, *Vehicles: Experiments in Synthetic Psychology*. Focusing on cognition, Braitenberg (1986) persuasively demonstrates that a quasi-intentional performance can be achieved by adequately coupling sensory and motor elements. He invites the reader to follow his thoughts by promising "It is pleasurable and easy to create little machines that do certain tricks. It is also quite easy to observe the full repertoire of behaviour of these machines– even if it goes beyond what we had originally planned, as it often does" (p. 31). In the experiments with vehicles, a variety of tracking and exploratory patterns are achievable, even with minimal or no investment in computational analysis. Undergraduate courses in robotics often creatively adapt Braitenberg's thought experiment for implementation in student-made toy units, deploying it as a blueprint for understanding the affordances of exploratory behaviour in machines.

The original Braitenberg's machines were set up to perform interactions within an overwhelmingly simplified model environment. The environment was composed of sensory signals: sources of light, spots of temperature, clouds of volatile chemical substances. Braitenberg's ambition was to demonstrate how intelligent, or at best purposeful, action patterns emerge from simple directional movements (*taxis*) and movements that depend on the energy of the vehicles (*kinesis*). When transferred to the physical space, vehicles problematise not only the emergence of intelligent behaviour, but also the interdependence between such behaviour and the environment within which it occurs. Technical implementations of the speculative account pertain to the distribution of signals, their modality, and the boundaries of the test surroundings. One may use these objects to consider what makes specific types of actions attainable and apparently intelligent.

What kind of visual environment must be constructed to enable this mode of machine behaviour? Braitenberg devises a series of machines that will ramble around a clearly defined signal source. Reflex-like, directional movements towards or against the signal are the starting point for the experiment. A signal source (e.g. a hotspot, a light flare, or a gas leak) could be placed respectively in

a water pond, on a hard surface, or even in an interstellar vacuum. The qualities of the medium (a milieu) are not of primary importance to the original account. In the iconic illustrations by Maciek Albrecht, beetle-like units appear on a blank page – an undefined, potentially infinite space that is occasionally characterised as a pond or hard surface. The sequence of examples, as the author himself suggests, is reminiscent of the general cycle of evolution.

What Braitenberg emphasises is the evolution of agents, rather than the co-evolution of agents in the environment. Various sensor-motor couplings are proposed in a series of fourteen models, starting with one motor and one sensor. Made on a blank piece of paper, these Gestalt-like demonstrations give flashes of the subject's aggression, fear, permanent and exploratory love, and so forth, all persuasively specified. For example: Braitenberg explains that so-called models 3a and b assume that some inhibitory reactions are connected to excitatory ones, since the maximum speed of movement occurs when the sensor signal is low. The vehicle speeds up while approaching the source and slows down when close to it. With collateral or cross coupling of vehicle-to-sensor, different sorts of behaviour emerge. Collateral coupling results in movement stagnating once it reaches the source; cross coupling results in approaching and then drifting away from the source. These are identified as permanent and exploratory love patterns. The emergence of exploratory behaviour is not therefore a reflex-like directional reaction toward or against the target/source. It emerges from a combination of *taxis* and *kinesis*, which in turn depends on the nature of the propagated signal. Such a well-prepared recipe seems attractive for an engineer seeking to show that an internal, model-oriented approach to AI might in some cases be replaced by another one.

The issues of environment come to the fore in the experiments' physical implementations. By switching vehicles from the detection of chemical sources in one test to visual signals in other, engineering gathers evidence on how to couple the modality of the experimental implementation with the optimal strategy for completing the task. The problem has been discussed in the case of Achim J. Lilienthal and Tom Duckett's experiments with "smelling Braitenberg vehicles." The authors emphasise that olfactory detection works differently to its visual alternatives. A basic assumption behind their trials on gas leaks states that "unlike visual or auditory stimuli, chemical stimuli are not inherently directional" (Lilienthal, Duckett, 2003, p. 161). In isolated environments of odorant molecules, the distribution is usually characterised by turbulence, which creates many local concentrations of gas near the distribution source. Consequently, an absolute maximum concentration is not usually located near an odour source if it has been active for some time. Experimenting with the slow, turbulent physics of olfactory signals cannot simply replicate doing-things-with-light as light creates an easily detectable spot of highest signal intensity. Testing the Braitenberg models has brought a conclusion that the detection of turbulent gas works best in an exploratory

mode iteratively avoiding the local concentration patches[2]. If based on simple directional movement instead, gas leak detection would become unreliable. With stagnating behaviour, which Braitenberg had previously called a pattern of permanent love, the vehicle would fix on the first maximum gas concentration, eliminating the chance of identifying the source location. By contrast, if Lilienthal and Duckett's detections were devised for a light source, a simple directional pattern would match best. Once the embodied systems are built and set on the move, environment needs to be solved.

Nonetheless, discussions on the attainability of specific visuomotor patterns in embodied systems have not been redirected to the problems of sensory infrastructures and assistive techniques. A 1980s wave of experiments in robotics discovered the affordances of furnishing machines with redundant arrays of sensors, exhibiting multiplied or complementary characteristics. A pioneering study of vision-guided behaviour was undertaken by MIT researcher Anita Flynn, whose PhD dissertation on redundant sensory setups depicts the crude functions of visual technologies (Flynn, 1985). For a start, sensors are matched with a short list of tasks that include mapping, presence and absence detection, and calibration. While asserting that vision cameras are computationally intensive, the study takes into consideration the sensory modalities' affordances and limitations. In these terms, Flynn's design expertise is particularly instructive as it specifies not only the optimal sensor (e.g. sonar is best deployed for detecting local obstacles), but also the limitations of its performance (e.g. due to its relatively wide beamwidth and sensitivity to specular surfaces, sonar cannot meet mapping requirements on its own).

The redundant sensorimotor couplings of Flynn's study have not developed into experiments on the environment's modality. On the contrary, it provided some arguments for assigning autonomy to embodied systems. Using passive sensory arrays has demonstrated methods for the navigation of autonomous micro air vehicles (Fry, 2009). Formed into insect-like compound eyes (Franceschini et al., 1992; Sharkey, 1997; Song et al., 2013), arrays of simple light-responding calls become prototypes for dynamic vision sensors (DVS) – a highly Braitenberg-like technique which reports on pixel-level changes in brightness, instead of capturing standard intensity frames. The method proposes a paradigm shift in relation to the internal-model-based approach discussed in the first part of the chapter (Gallego et al., 2020). Further exploration of this design approach demonstrates that optomotor reflexes provide a powerful model for formulating both technically feasible visual processing and flight control principles (Fry, 2009; Gehrig,

[2] Operating within a defined area the vehicles eventually trace the complex pattern around the maximum concentration at the source and thus indirectly show where the leak might be.

Scaramuzza, 2024)[3]. Embodied models of Baitenberg vehicles and compound-eyes flying machines are then characterised by their specific performance: an asset of easily attainable behaviour patterns, unlike the case of internal-model-based machines like Chamayou's military drones or robots for product quality control.

The concordance

Let's organise the conclusions. To compare the most achievable behaviour patterns, I will recall a set of tasks inscribed into Rodney Brooks' architecture of autonomous system (Fig. 16). The framework was devised to renew intelligent system design by proposing an alternative to the classical representation-based approaches to robotics (Brooks 1985, 1991a). Brooks' intention was to promote engineering of the real-time machine behaviour that, much like in Braitenberg's proposition, resulted from the direct coupling of perception and action. The tasks he lists in the hierarchical order of his multilayered model were to be composed into a cascade of behaviour patterns, starting from mechanistic movement and interaction to "intelligent" recognition or strategic planning. As the simplest of these, Brooks (1985) indicates the ability to avoid objects. With presumably more complex quests layered above that level, a machine was set to "avoid contact with objects; wander aimlessly around without hitting things; 'explore' the world by seeing places in the distance; build a map of the environment and plan routes; notice changes in the 'static' environment; reason about the world in terms of identifiable objects; formulate and execute plans which involve changing the state of the world; reason about the behaviour of objects in the world and modify plans accordingly" (pp. 6–7).

Now, I propose to use Brooks' list to compare the most achievable behaviour patterns in the alternative methods for sensory technologies: representation (or model) based, embodied, and environment-oriented. The aim is then to check how largely downplayed environment-oriented solutions present themselves against the well-established models of intelligence engineering. Approaches based on representation and on direct interaction have both claimed affordances specific to their approach. Neither fully covers the list, but both fit into some parts of the scheme. The internal representation models (as in the case of drone aviaries) fit into the scheme's upper positions: tasks connected with reasoning about objects and detecting anomalies. Anomalies detection – well-grounded in the technical performance of expert systems – can be considered a variant for

[3] Furthermore, the research argues that, when coupled with neurocomputing, the method creates an affordance for low-level feature detection, tracking, and optic flow, as well as high-level vision, including reconstruction, segmentation, and recognition (Brückner et al., 2009; Gallego et al., 2020).

"noticing changes in the 'static' environment." By drawing a kind of bracket, one could link the highly desirable operation of charting patterns of life to the model's highest capability of "reasoning about the behaviour of objects in the world and modifying the plans accordingly." Between those two falls pre-emptive action (as described in automated surveillance studies) as formulating and executing plans which involve changing the state of the world. Statistical models constructed during machine learning complete the register of affordances attainable for the internal, representation-based approach.

Fig. 16. A breakdown of the mobile robot system based on task achieving behaviours (after Brooks, 1985, Figure 2)

And what of the solutions brought about by embodied design? Focusing on the adequate coupling of signal source, sensing, and movement derived from biology has shown that a vision-guided performance specifically enables targeting signal sources (much like in the case of Braitenberg's vehicles moving towards the light in acts of "aggression" or while expressing "permanent love"). Now, a comparison between the most easily achieved and the most desired patterns underscores a critical issue. Embodied, real-time visual systems achieve the tasks from the bottom of the list only under certain conditions. Since the list insists on avoidance rather than targeting, wandering aimlessly around without hitting things, rather than keeping them in the line of sight, a Braitenberg vehicle with one or two "eyes" stemming out of the moving body would be an erratic rather than purposeful agent. This is in line with the conclusions on implementation, where free exploration and avoiding objects do not quite fit with directional tropisms and *taxis* enabled by visual stimuli. Tasks from the foundations of Brooks' list, however, become easy to achieve whenever design involves a redundant array of sensors. With compound eyes and clusters of photocells distributed across the volume, drones can actively explore the space. Interestingly then, it is not the snapshot

vision of cameras but the clever juxtaposition of simple sensors (sonar, photocell, range sensor, IR) that paves the way for activating attitudinal patterns of locomotion and the autonomous exploration of space. Using this low-level experimentation might suggest that *taxis* is an "easily attainable" procedure. A highly simplistic pattern like targeting and following in a visual mode is a directional task, but it is the redundant combination of sensors that allows for exploring the environment. A sophisticated composition of photocells provides the opportunity to achieve the "wandering" level of performance.

The approaches oriented towards internal representation and those that involve designing direct interactions with the environment complement each other in a way that was intuited by the architects of the autonomous systems. What is achievable from redundantly outstretched *taxis* is different from what is obtainable from laboriously tangled internal models. Here one may propose how operations of environment-oriented design fit into this scheme. The proposal could be illustrated as follows (Fig. 17).

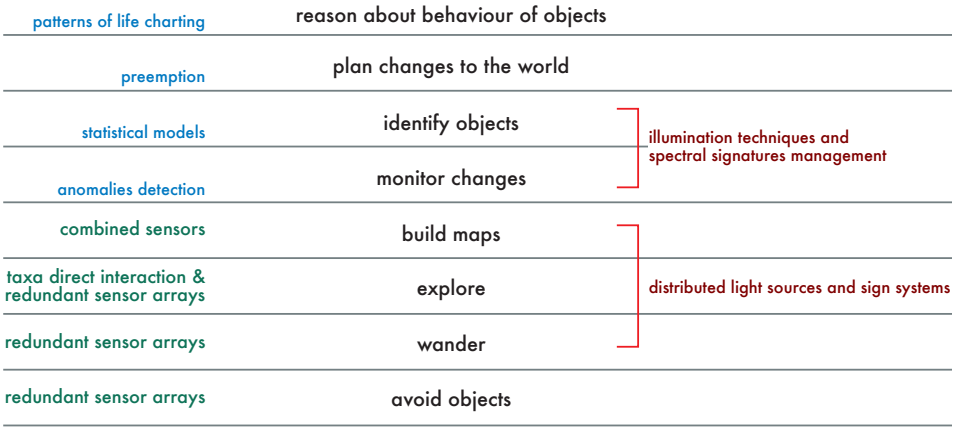

Fig. 17. A breakdown of the mobile robot system based on task achieving behaviours, presented against the solutions most attainable or most characteristic of: representation-based (blue), embodied (green), and environment-oriented (red) design approaches

Affordances of the environment approach would concentrate around the middle layers of Brooks' architecture, the tasks connected with exploratory behaviour and map building. Illumination techniques enable exploration of an otherwise impenetrable landscape. Spectral signatures management, on the other hand, best fits into monitoring changes and objects, or identifying structures. The environment-oriented approach does not seem to offer vision-guided performances that would be otherwise unachievable. However, with its position

halfway up the stack of the list, it offers solutions for stabilising the otherwise erratic or computationally costly performance of two other paradigms. What is of prime importance here is that environment – and only environment designers – can counterbalance the patterns of behaviour imposed by computational logic. Environments are built not just to support seeing, but to let machines see just enough to perform specific tasks. What this mapping then ultimately confirms is that machine performance does not emerge from computation alone, it emerges from bodies and environments constructed to make computation viable. In Brooks' terms, what looks like intelligence in the higher layers of autonomy often depends on external substrata of structured light, marked surfaces, and distributed sensors.

The interventions described in the first part of the book indicate the proliferation of vision environments: not passive settings, but engineered fields of deeply political significance in how they guide the actions of one agent and tame the capacities others. To speak of terrestrial politics, in this context, is not to invoke metaphor, it is to name the material distribution of power in environments increasingly built to accommodate machine perception. To further explore this domain, we'll move to the next point and observe the implementations of automated ensembles on a scale of the landscape.

6. Automated landscapes

Considering the earlier arguments, it can be expected that sensory technologies manifest in the reorganisation of physical space. After all, methods like spectral ordering, illumination, and sign systems are inherent to landscape interventions[1]. Therefore, a sceptic willing to question the relevance of situated systems would be fair to ask for evidence of whether the new sensory ensembles interfere with their surroundings. Are those transformations even discernible? Otherwise, why would anyone even bother with thousands of lamps, acres of retroreflective surfaces, or repetitive traffic signs reinstalled in front of cameras and other sorts of optical sensors, if not precisely because they make a noticeable difference in existing relations? Fair enough. Such a debate on the least noticeable difference may contribute to assessing the relevance of engineered environments for the broader context of visual culture. With this objection in mind, I propose to look at how machine vision is entangled in the manifestations of machine landscapes.

To study a landscape, one needs to go outside, to come out from between the walls and stay outdoors, and perhaps, in the middle of nowhere, feel a bit uncomfortable. But where should one head in search of landscapes of machines and sensors? The explorations discussed below have the feeling of Marc Augé's aesthetics of non-places or the routes of sea logistics traced by Allan Sekula and Noël Burch (Augé, 1992; Sekula, Burch, 2010). The most insightful takes on automated landscapes share this trait. They do not follow debates on human-centred design, future cities, or fantasies about sustainable transport (which has recently been picked up by corporations growing smart mobility services on a civilisational scale); and to a limited extent they only reproduce the digital geography of critical urban studies in how they reveal the building blocks and streams of data organised into mass surveillance systems. It is rather the reverse route that starts from liminal zones. It takes from Augé's non-places, not to explore airports and shopping malls but to identify depersonalised and instrumentalised places that mark the dawn of hypermodernity or, as he puts it, the end of humanity as we know it.

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[1] Landscape has been characterised by the first wave research of visual studies (which considered it an emanation of power) as a central tool in the creation of social identities (Mitchell, 2002b).

Thus, this chapter's proposition is that the study of automated landscapes stretches far beyond metropolitan domains. It grows out of theorisations on geological realms and reaches towards themes like Stack, or the Capitalocene. Whether landscape transformation is expressed in land or laws, real world bodies or speculative debates, will be the topic of the current interrogation. Below, I will lay out my argument in three steps: starting from a critique of the theory of post-Anthropocene trace effects expressed in the context of speculative architecture studies; next, bringing in insights on the non-human conditioning of space provided by the study of automated production zones; and finally, reviewing design politics endorsed by industry players engaged in economising automated systems. Based on these three strands, I will formulate a response to the caveat on the impact of vision technologies on their environments.

The arguments from landscape studies

Positioned within an exquisite design niche, technological landscape studies from the 2010s have provided two seminal collections of writing. Despite their very similar titles, they strike quite distinct tones on the nascent research. *Machine Landscapes* was first published as a themed issue of *Architectural Design* in 2019 and edited by Liam Young, the speculative architect and visual artist. The collection maps archipelagos of human exclusion zones, architecture without people (Young, 2019), landscapes that think for themselves (Bratton, 2019), and machines that communicate with other machines (Paglen, 2019). In the first paragraphs of the editorial, Young introduces the reader to machine landscapes by pointing to faceless cities in the state of Oregon that have been transformed by plots of land developed by big tech companies of the time (Young, 2019, p. 8). Focusing on cloudalist imperia and robotic props from Boston Dynamics and Amazon, Young's collection affirms influential theories on planetary-scale computing and mineral-based AI models, as outlined in Benjamin Bratton's *The Stack* (2016). Furthermore, presented as a cartographic expedition, Young's project invokes mythologies of inventive seaman, familiar from Buckminster Fuller's writing (Fuller, 1969). The revalidated vision of the Fullerian "Spaceship Earth" invites us to chart the traces left by the Anthropocene, the puzzling constructs "not built for us, but whose form, materiality and purpose is configured to anticipate the logics of machine vision and habitation rather than our own" (Young, 2019, p. 10).

An alternative proposition for understanding the phenomenon comes from research and collaborations between the Nieuwe Instituut in Rotterdam and Delft University of Technology (Bedir et al., 2023). Their inquiries start with observations of non-human conditioning of architecture and develop into arguments published in themed issues of *Footprint* journal and the catalogue of *Automated*

Landscapes prepared for the 2018 *Venice Biennale of Architecture* (Bensi, Marullo, 2018; Muñoz Sanz, Handel, 2019; Muñoz Sanz, Katsikis, 2023). The publications from NI and Delft have evolved into a call to investigate the impact of technological transformations beyond the concentrated areas of human habitation. Co-authors to this program, Víctor Muñoz Sanz and Nikos Katsikis argue that the intense transformation of landscape is best represented not by the human settlements that take up 3% of inhabited land, but by the 70% of the Earth's land surface that is dedicated to agricultural production, resource extraction, circulation, and waste disposal (Muñoz Sanz, Katsikis, 2023, p. 4). The Dutch project therefore stresses not so much the new traits in architecture but the new forms of well-known industrial residues from anthropogenic terraforming. The editors' theoretical basis in not in planetary-scale computing or design programs, but in Neil Brenner and Christian Schmid's understanding of more-than-city landscapes (Brenner, Schmid, 2015). Later, they also probe some major ecocritical perspectives: first Timothy Morton's hyperobjects (Morton, 2013), and then the material-feminist model of partial, situated views (Haraway, 2013). The authors hold up the latter for avoiding the "fallacy of misplaced concreteness" i.e. of mistaking the abstraction for the thing (Haraway, 1997, p. 146; Whitehead, 1967, pp. 50–51). As evidence to this effect, the case study-based insights often combine architectural drawings, participant observations, and archival research. Eco-Marxists at their core, the *Footprint* editors are keen to trace the new materialities of labour. A number of voices in the collections edited by the NI/Delft network also point to the concept of substitution, highlighting the greenhouse as an embodiment of technological substitution for the otherwise self-generating gifts of nature (Muñoz Sanz, Katsikis, 2023).

As both these lines of study are intended to make technological landscapes recognisable, neither of them would outline artificial photic zones or new vision materialities from the outset. Neither Young's nor Delft's collection elaborates on sensory environments in particular. Instead, they situate the conversation in broader debates about lands and territories. Let's summarise their major insights. First, contributing to Young's collection, Benjamin Bratton introduces a reference to his theory of the Stack. Here, landscapes "think about themselves," as Bratton suggestively puts it, while terraforming beyond human control (Bratton, 2019, p. 16). Moreover, it is mineral-based AI that governs the planet. On this point, Stack theory formulates several prominent arguments. It claims that the extraction of Earth's resources is driven by a specifically defined AI – a technology that devours minerals to spit them out in the form of smartphones, LED crystal displays, and other electronics. Secondly, it reminds us that this AI creates a carbon footprint that exceeds even that of civil aviation. This AI manifests itself in architectures that are emblematic of the *Machine Landscapes* study – data depots like exterritorial fortresses the size of small cities. The pivot from cloud capital to rare earth

minerals is found in much of the critical discourse, but it is not about sensing (Crawford, 2021). These three points for thinking about computation as a method for governing and designing the planet dispense with humanity's admiration for acute vision and trained hearing. Operating more on the geological-scale, the Stack digests itself and devours the world around it. Engineered vision environments – the material surfaces and spectral signatures discussed above – would then in this context be symptoms of such a transformation.

However, speculation derived from Stack theory does not come down in favour of scepticism around least noticeable difference; Bratton (2019) indicates that the manifestations of machine landscapes are evident only in subtle traces. Here, his article picks up from Young's editorial, enumerating a set of phenomena that mark the tectonic shift to the post-Anthropocene. Dethroned, as Bratton (2019) puts it, from their privileged position, humans find themselves in a situation of needing to mark "both things that have a name but which have not fully arrived and things that have arrived but which are misarticulated or not even named as such" (p. 16). These traces of technology's formation are dispersed all around us, some in the industry of logistics, some in mobility, others in automation. But what Bratton shows is that one can find enough of them to track a long syllogism linking planetary-scale computation to the organisation of pedestrian zones[2]. Furthermore, in keeping with his dialectical approach, he considers the double potential of such synthetic ecologies: he sees them not only as echoes of the governing simulations, but also as energies that are undermining and will eventually bring down that governance "by their own weedy means" (p. 16). In summary, the theoretical speculation proposes a compelling vision of a ubiquitous yet indirect manifestation of planetary-scale computing through the large-scale structures designed for the convenience of machinery. However, the totality of Stack theory leaves further discussion on the occurrence of such phenomena to those with a more empirically oriented mindset.

Greenhouse industry insights

A socioeconomically grounded approach is offered by the authors of *Automated Landscapes*. Reading through their studies, one finds an argument to claim that it is not a mineral-based AI that is after humans, but the all too human

[2] Yet another argument connecting technology with automated vehicles; as Bratton (2019) states: "In the near term, the design of AV will likely also be governed by liability mandates, which would in turn affect how AV redesigns the cities around them. While the surface area of cities may be opened up by the disappearance of parking lots no longer needed to store individual user vehicles in a suspended state, the definition of 'streets' may change as AVs and the ambulatory humans formerly known as 'pedestrians' are kept at a secure distance from each other. In such a world, human zones may be more park-like, but robots take the streets" (p. 18).

Capitalocene, through which the alliance of biotechnology and AI reorganises acres of land and bodies of water. Datacentres and smartphone factories feature in the Delft case-studies, but it is dairy farms in the Azores and greenhouses in Dutch Westland that form the account's central examples (Bedir et al., 2023, pp. 56–65; Muñoz Sanz, 2023; Rodrigues, 2023). Elsewhere, the urbanisation of largely inaccessible marine ecosystems is the most extreme example of the process (Edwards, 2023). Here, machine vision becomes one of the topics of automated landscapes presented as aligned with sensory systems. Characteristically, this is not the vision of city surveillance cameras or military drones. There is something intrinsically non-hegemonic in this account on sensory systems. Sensors – including optical-photosensors and all sorts of cameras – are set up to harvest the data. However, they perform their work not so much to govern as to keep the entire environment functional. For example, specific end-cameras may connect with an AI model, and the model is sorting plant specimens according to the preferences of prospective customers (e.g. prettier or less showy ones). However, there is a clearly outlined market priority behind such sorting. No planetary-scale AI hides behind the scenes, as AI does not feed on the plants. Instead, in the case of automated agriculture production, the surplus of life is devoured by humans. This study of automated landscapes makes a clear break from the previous perspective, and not just in its choice of philosophical underpinnings. The work on automated agriculture and capital offers legitimacy to not particularly spectacular and not particularly self-sustaining models of technology.

The studies from Delft depict the kind of trailing systems discussed earlier – the sensory systems that need support as they snake their way into the sultry interiors of gardens or under the endless rooftops of warehouses. Only in this case they do not find their support in the rigid scaffolding of lamps and goniometers, but instead latch on to living things. They become bracelets on the legs of livestock (Rodrigues, 2023), they are attached to humpback whales' trunks (Edwards, 2023), they are stuck to plant leaves, or carried on the wrists of human employees (Muñoz Sanz, 2023). Further, the metabolism of greenhouses, as the authors like to call it, is supported by a smart combination of simple touchpoints, including thermostats, galvanometers, vibration sensors. Vision is a component of these mixed modalities with IR cameras and simple photosensors. Again, however, no ambitious manifestation of a complex perception machine seems to be emphasised in this patchwork. Notably, the humid atmosphere of the greenhouse poses a problem for optical systems since the camera lenses fog up and the guiding tags become covered with patches of soil. Despite these inconveniences, spectral signatures can be applied for plant phenotyping (selection of the best specimens for further breeding) and for the early monitoring of inconspicuous changes, like inadequate humidity or plant diseases,

that could potentially ruin a crop yield. Could any of the vison procedures be supplanted by another, more profitable solution? The administrators choosing to submit more and more to hyped-up production rhythms treat vision not as hegemonic, but as a nonetheless viable way of inspection. The consequences of this are a topic for further debate.

The study of the greenhouse industry indicates an unsettling insight. The skilful arrangement of the sensory environment is enough to accelerate lifecycles and short circuit natural selection as a routine part of intense agriculture. Illumination and visual technics are not excluded from this. 24/7 artificial light enhances photosynthesis. Monitoring the plants' multispectral signatures creates a selection mechanism that decides on the specimen's ecological positioning. This transformative section of specific areas of agriculture is still under development. Nevertheless, even the observations made thus far suggest that this is not exactly an indirect trace effect like the post-Anthropocene changes in urban zone planning. These landscapes are transformed directly through the extreme technics of agricultural production, terraformed in vast stretches of fields, with ever cheaper tricks to intensely cultivate small plots of land. Arrays of sensors are distributed to reorganise the metabolisms of automated production, providing a strong case for the immediate manifestation of sensory environments on a large scale.

For the time being, I have found no evidence on agricultural landscapes being rearranged on a mass scale for the purpose of machine vision. However, as machine vision techniques are delegated to decide on the selection of specimens, one may thereby introduce automated plant phenotyping to aid their successful breeding (Bian, 2022). Further, as automated phenotyping becomes routine, there is a good chance that new varieties will become desirable on the very basis that they are in some way easier to handle by ubiquitous vision systems. Would it be too extravagant to breed cube-shaped watermelons? Or standardise low-stemmed trees to facilitate work in orchards? Time will tell. For now, the case of agriculture does not suggest that landscapes are already being commonly reconfigured by sensory systems (except for some highly automated farms), but it also provides a wealth of evidence to discuss how landscape-scale spaces can be transformed in direct relation to vision technologies.

However, landscape studies is not concerned with the problem exactly as the current study has posed it. For now, it is discussed only as either a geoscale technology or a socioeconomic drive, not really as a design concept prevalent enough to shape the asymmetries and arrangements of a piece of land. To be more specific, it is desirable to examine an additional approach: this time from a field that studies automated landscape design through the lens of ergonomics and occupational safety.

Collaborative zones and smart environments

In parallel to the architectural studies on the non-human conditioning of space grows the ethnography of robot collaborative zones and smart environments. Part of its insights stem from expertise in ergonomics, safety measures, and industry-line implementations. A central problem here is how human-allowed and machine-only zones should function alongside one another. In specific cases, the observation of human-centred design couples with the practice of Industry 4.0 implementations tailored and customised to the client's demands (Gualtieri et al., 2020, 2021). Design guidelines for these spaces, insofar as they exist, provide a set of precedents to enlighten the haphazard transformation of twentieth-century policies. Their classic strands, attached to industry-born concepts of work safety, tend to promote policies of human and machine separation – manifested in the construction of barriers, fences, and robust cages. Proponents of automation, on the other hand, challenge this approach with propositions for hybrid workstations and smart environments. Conceived and designed for business stakeholders, these spaces are suitable for observing subtle territorial games that lead to the emergence of corporate industry machine environments and their specific atmospheres.

The integration of purely functionalistic workstations is commonly advocated in the discourse of industrial technology providers such as IEEE or IFF, who nominally argue for both the possibility and the need to create collaborative zones (Grau et al., 2020). In some of the cases discussed in the first part of this book, the politics of autonomous systems has prompted engineers to seek feasible design strategies, arguing for the productivity of fenceless zones. Among the best published examples of this approach is the Hyundai Motor Group public communication, in which the current models are designed to disburden humans of working not only in extreme, hazardous environments (e.g. sending a quadruped to contaminated sites at Fukushima), but also to become part of busy streets in a near-future metropolis (Boston Dynamics, n.d.; Hyundai Motor Group, n.d.). However, industry messaging is reluctant to reveal the complexities of hybrid environments, instead offering the promise of seamless and unobtrusive implementation.

The ethnography of collaborative zones provides indications of how machine vision leaves its mark on physical space arrangements (Bedir et al., 2023). Visual tools reshape the way collaborative zones are structured, and collaborative zones are conditioned by the requirements of vision technologies. The previous inquiry has already demonstrated that illumination patterns, fiducial signs, and tags are indispensable for automated systems to work smoothy. Vision materialities of reflectance, dispersion, and spectral ordering are also common to the design

of work environments. While introducing an affordance such as object targeting or tracking, vision burdens the design of safety measures with the problems of collision avoidance and mitigating the effects of contact. A solution as simple as curtains may remove a physical barrier by creating an immaterial boundary around the machines (Saenz, 2020, pp. 2327–2329), but at the same time assistive technologies of vision (tags, guiding lines, etc.) add a high degree of autonomy to mobile machinery. These in turn create new threads and pose risks on the tracks and paths that guide mobile units along warehouse aisles or production lines. Thus, there is a cluster of well-defined problems to be considered in the context of sensory design and machine zones (Jarota, 2021; Michalos et al., 2015). There is also plenty of expertise in using situated design as a way to integrate autonomous machines into their environments.

Outside the context of high-end factories, the idea of collaborative environments evokes a number of controversies. The proposition to redesign physical spaces for the sake of machines sounds rather extravagant. Among the few voices arguing for this, one is evident in the communications from design communities operating in what deserve to be called smart or ubicomp settings: the SUTD-MIT International Design Centre at Singapore University of Technology and Design and the Department of Architecture at Tokyo Denki University (Mohan et al., 2015; Tan et al., 2016). In a series of prototyping reports, their argument rests on a radical interpretation of inclusive policies, quite surprisingly claiming that accessibility and ergonomic measures should "be extended to cyborgs." As the authors structure their contributions in terms of intervention in response to a growing design challenge, the prototyping includes principles derived from the ways that specific systems operate. The composition is very consistent. Among the specific issues, one finds contrasting colours, avoiding reflective coatings that confuse navigation devices, and positioning infrastructure in ways that enable the automated inspection of human-accessible spaces (Ramalingam et al., 2021). The SUTD/Denki initiative is a unique design programme that assumes quite significant redesign of spaces co-occupied by service devices and human hosts. Being concentrated on hospitals and hotel spaces, it also makes the case for inclusive machine design in ever optimised areas of industry.

A recent debate on the hospitality landscape recognised the vanguard of developments in smart architecture (Leung, 2021; Roelofsen, Minca, 2018; Tymoshchenko, 2023). Balancing optimisation on the one hand and neo-Fordian business models on the other, the hospitality industry deploys a variety of interconnections between sensors, guest behaviour tracking, and experimental design (Leung, 2021; Yin et al., 2023). Tracking devices are central to this paradigm, installed on a massive scale to optimise energy use and service delivery. In this way, hotels embody a specific type of cohabitation zone where tensions arising from granting machine access to the overall shared space manifest in full force. Hoteliers

are keen to introduce the neo-Fordian models with arguments on staff shortages, soaring energy bills, missing keys, and client complaints; they are therefore likely to carry out optimisations that profit the hotel (Tymoshchenko, 2023). But bearing in mind their clients, their strategy will also be to ensure that the automated components of the smart interior do not compromise guests' positive experience. This trade-off between the guests' comfort and the hotel's optimisation manifests in the venue's "atmosphere" – a quality occupying a large share of the overall value of hospitality brands. The delicate interplay between the physical economy and the "atmospherics" of service zones, characterised by Coffin and Chatzidakis (2021) as a Möbius strip, is a long-observed phenomenon (Kotler, 1973). However, it is only the openly tech-centric propositions like SUTD/Denki's that disguise the central dilemma of smart hospitality. That is, automation alters the atmospherics of semi-public spaces in its own inexorable way.

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Taken together, these three topics of landscape studies (mineral AI, non-human conditioning of architecture, and servicescape design) reveal an important idea: vision modifies environments rather than creating entirely new ones. The connection between sensory technologies and spatial design is subtle, but its effects are powerful. Vision technology does not manifest solely in terms of fortified datacentres and flocks of satellites. Properly speaking, these are elements of computing infrastructures, not environments. Datacentres and satellites, like telescopes, radars, and antennas, cut the skyline with characteristic silhouettes, grow firmly into pieces of land, and unfold into powerful views. Computation spreads out into the environment, forming one-of-a-kind, expressive landscapes and panoramic views. The non-computational facet of vision technologies works differently. The work of machine vision is traceable in the non-human conditioning of architecture, whereas sensory technologies evoke subtle changes. They impose new functions on utility spaces, changing hitherto stabilised standards for corridors and passageways, lighting, and furniture design. Furthermore, it turns out that sensory technologies in their environmental embeddedness launch selection mechanisms that unfold not only in built spaces, but also in cultivated pieces of land. In that non-human case, the discreet conditioning of landscape extends to regulating biological cycles and phenotypes with adequate sensory stimulation. This unsettling potential of vision environments persists once the third point of view is taken into account. While the research on the non-human conditioning of space indicates that the interconnections between machine vision and the arrangement of a physical space are subtle, the study on smart servicescapes implies that such subtle interconnections can make a huge difference. It does so

by addressing itself to both non-human and human actors. The closing reflections on hospitality, atmospherics and semi-public spaces have shown that safety zoning and the politics of access are by no means limited to purely "technical" arrangements. Sensory technologies, it seems, can alter one of the most esoteric assets of late capitalism, namely the ambiances. In this case, the inconspicuous engineering of machine vision zones becomes a puzzling design task. It anchors the sensitivity of contemporary visual cultures.

7. On the political aspects of visual culture transformation

The previous chapter traced how environments become visible to machines. Its closing sections signalled that the shift cannot be considered solely in terms of technical advancements; the dilemmas of smart servicescape design indicate that vision environments carry strong economic and aesthetic implications. Following on from this, in the closing chapter I shift from analysing vision systems to reflecting on their symbolic and political resonance. Below I will argue that the proliferation of vision environments is not just a technical development, but a catalyst for a broader sensory reconfiguration process. In this context I set out to demonstrate that such a reconfiguration can serve as an instrument of corporate industry and as a site of potential resistance. Referring to the political plane provides an opportunity to frame the book's original commitments. The proposed reflection weaves together the philosophy of technology, aesthetics, and ecopolitics while holding open a dual reading of vision environments: as both tools of accumulation and a hitherto unexplored pool of commons. The aim is to show how the study of vision environments contributes to a broader political discourse on climate, materiality, and aesthetics.

Making a complement to ecocritical debates

To build a conceptual arc that connects sensory reconfigurations with the propositions for a renewed political framework, I will refer once again to the historically oriented takes in the philosophy of science. Viewed from this perspective, the process of sensory reconfiguration locates cultural developments and technical experiments in a chain of more or less revolutionary rearrangements in observation technologies. The birth of machine vision can then be linked to this thread, following Böhme's account on the technification of perception or Ian Hacking's studies of laboratory microscopists (Böhme, 2012, pp. 124–142; Hacking, 1983). Böhme (2012), in these terms, builds on the commonplace cases of Galileo's telescope observations and the techniques of visualisation in the domain of

reproductive medicine (ultrasonography); he argues that "at issue […] is primarily a transition to a new mode of perception, a shift to the primacy of the (technically mediated) sense of sight away from an intuitive sense of the inner workings of the body" (p. 138). A strong reliance on the instruments of observation, according to the author, is characteristic of the cultures of vision both in the time of Jupiter's moons discovery and the turn of the millennium. This transformation relies on observation technologies that enable more reliable, more acute (in the specific case of the telescope) seeing (p. 18). Such a strong claim about the technicisation of seeing, however, could be somewhat softened by earlier experimentalist studies such as Ian Hacking's. In *Representing and Intervening* Hacking (1983) confronts Böhme's perspective with fervent debates on scientific realism (pp. 21–31). He offers evidence on the culturally bound falsification of tests and skills in the fields of microscopy, and he nurtures a critical distance towards observational technics (pp. 185, 189–191). Both Böhme's and Hacking's studies communicate an intriguing shift in the histories of sensory transformation. To recognise the nature of the current transformation, one needs to suspend the study of optical instruments and laboratory practice and turn to the problems of ecocritical debates.

To a degree somewhat deeper than its historical precedents, the sensory transformation of the current age has proven emphatically earthbound and relational. Becoming an earthbound technology might have been of secondary importance if the experiments and practices discussed above did not speak in their own way to another much looked-for conceptual shift: a campaign to renew awareness of the life conditions on Earth. With that, however, technics speaks as it always has, in the murmur of a minotaur – untranslatable to philosophical discourse. Committed as they have been to exploring the concerns of technical experimentation, constructors and empiricists have stubbornly avoided engaging in a critical assessment of their political implications. Ultimately, it is on philosophy to take the opportunity to redress those positions and rephrase redundant technoscientific accounts into meaningful positions on societal debates.

Does the observation of a conceptual shift in machine vision make it akin to ecopolitics? Yes, and on several counts, I'd argue. The first interface I would propose as particularly relevant here is that of political matter and aesthetics. As there is no politics without sensory orders, in the nebula of contemporary eco-debates there is a party that knows the appropriate aesthetic tone can win the argument. By that, I mean a specific political class – a class of terrestrials who acknowledge this critical juncture in life on Earth, as proclaimed in the late writings of Bruno Latour. Willing to give social resonance to what Isabelle Stenger calls the Intrusion of Gaia, Latour has long sought an appropriate political attractor – a concept that could elucidate the character of the campaign to include arguments from both complex climate science and general politics. Latour has found it in the notion of terrestriality and the concept of critical zones. In response to Gaia's intrusion, the

critical juncture for life on Earth seeks appropriate expression – and here is where a study of sensory orders takes the stage (Latour, 2020; Stengers, 2017).

To give force to the debate, Latour (2020) claims, new ways are needed to speak of the actions in the near-surface layer of the Earth, where most living things reside. In these terms, the campaign to build a new political framework has called for science to attune to the as yet invisible earthbound phenomena, for politics to embrace post-global models of planetary governance, and for the arts to "render us sensitive to the shape of things to come" (p. 9). Of the Latourian project's three tenets, aesthetics resonates most vividly. Decades after Lovelock and Margulis' maverick life sciences theory began to circulate, it is safe to say that Gaia has significantly transformed the aesthetic and iconic codes that convey relations within and with the world. This has been a carefully curated process of the highest quality.

In 2020, the ZKM Centre for Art and Media in Karlsruhe hosted an exhibition on *Critical Zones*, which demonstrated just how much ecopolitics had matured in its self-expression, well beyond the stock photos of Arctic fauna and melting ice floes. Led by a curatorial duo of Latour and Peter Weibel, *Critical Zones* presented a number of proposals on how to address reconfiguration through intermediary extensions and insertions that bridge the gap between living entities and earthly sediments. Scrolling through the exhibition catalogue, one finds the names of authors renowned for their commitment to creatively dissecting the techniques of contemporary culture across several registers. Starting from the scientific, Jennifer Gabrys emphasises the value of inserting monitoring ensembles under the surface of the soil and into the depths of the oceans (Gabrys, 2020). On linguistics, Bronislaw Szerszynski uses his grammar of action in the critical zone to suggest using a middle voice – a "diathesis" – to express the drift of atmospheric and vegetal phenomena (Szerszynski, 2020, pp. 344–349). Donna Haraway's entry on fantasy and science fiction considers narrative, while Latour's engages with the art of spectacle. Likewise, Frédérique Aït-Touati's essay embraces terrestrial aesthetics by taking theatre as the ideal model for the experience of inhabiting. It is Aït-Touati who offers the most straightforward example of how physical arrangements and backstage machinery so often become well-developed sets of techniques that strongly influence cultural dispositions (Aït-Touati, 2020).

The terrestrial project seeks techniques for re-staging the interconnection between the intelligent perceiving subject and the supposedly inert nature in the background. The study of vision environments (illumination techniques, fiducials, emissivity, calibration markers, etc.) has all the qualities to participate in the "staging" or aesthetics of terrestrial politics. Sharing the insights on spectral signatures and retroreflective surfaces, an understanding of illumination techniques develops into a sort of manual for constructing theatrical scenes and machines for such a performance. It could be a revamped version of Marcel Minnaert's *Light*

and Colour in the Outdoors alongside Nicola Sabbattini's *Pratica di Fabricar Scene* (1638). The latter is introduced by Aït-Touati into the ZKM essays as rare evidence of how the arts can manage to bridge the Cartesian gap between a subject and its surroundings (Aït-Touati, 2020; Minnaert, 1974/1993). The study of vision environments in these terms seems much like a set of instructions on how to operate in that middle, terrestrial layer by establishing a sort of photic zones and ordering spectral materialities. Although the immediate goals are different, vision engineering shares many concerns and concepts with terrestrial theatre. Illumination, materials, and surfaces techniques compliant with vision machinery can be easily conceived as an active environment that supplants the imaginary of the perceiving object and the latent scenery. Furthermore, with the observation of superimposed visual regimes and differentiated landscapes, the study of vision environments not only provides ready-to-use design solutions, but also elucidates the character of more-than-human aesthetics and more-than-human relations. In this sense, spectral ordering and illumination techniques convey the ecopolitical ambition to express continuity in all forms of life. Being a catalyst of sensory reconfiguration, vision environments share qualities that, I believe, refine the relevance of the present study to terrestrial politics.

Working with derivatives

The second argument for planting the new political framework in observations of sensory environments comes from the community of existence. The politics of critical zones strives for more than just a new scenography. The theatre of Gaia is not only about continuous space, atmospheric effects, and vibrant materialities. The theatre is conceived, above all, as a common space, a habitat that can support a variety of dialects and sensitivities (see Aït-Touati, 2020). This implies that terrestrial politics seeks a middle ground, rather than the extremities of posthuman sensitivities; to borrow from the language of party politics and democratic institutions, it seeks positions that are more centrist than extremist. Indeed, when it comes to envisioning the Latourian terrestrial class, the "they" who need to be moved and made aware of Gaia's intrusion in the first place, are the same "them" who are gathering in the opera theatres and appreciating the wit of Donna Haraway's *Chthulucene* talks (Coppola, 2020; Haraway, 2016). Where this new societal class – the class of terrestrialists – is concerned, aesthetics is more about art reformulating the senses, than about sensing reformulating the arts. Naturally, terrestrial politics addresses its flow of ideas to human agents. Despite incorporating the earlier and more radically expressed Latourian idea of a parliament of things, it is still more societal agreements and diplomatic protocols that form the basis of these propositions, rather than radical posthuman utopias. Letting nature speak for itself is not the only point here. Consequently, terrestrial discourse attempts to

explore Gaia's aesthetics, alongside the radical projects that pursue direct access to Gaia's own self-expression. In the well-received 2020 exhibition, the rupture of these extreme and moderate attitudes revealed the complex relationship between a carefully balanced societal project and its more romantic cousins, ready to engage only with some radically defined explorations.

Here, the relevance of vision environments becomes salient once again. Studies on sensory technologies can easily take on that radical posthuman temperament, such that many of them delve into the unpronounceable, listening to sounds and chemical signals intercepted from mineral and biological beings, looking for the deeper pulses of matter. The same could be applied to engineering. One motive to study technicised vision, so often repeated in 2010s conferences and research projects, was to understand how machines see. This epistemology of machine vision formed a separate path in the digital humanities (Azar et al., 2021) and contributed a number of major concepts that convey the inner computational mechanics of artificial intelligence. The angle taken in the studies presented above, however, is not concerned with machines' ways of seeing in their proper sense. It is the work on technical realms rather than on technical epistemologies. It observes what might be called the derivatives of technical procedures (like sign systems, calibration methods, emissivity indices, artificial photic zones, etc.). What the present study offers is closer to focusing on machine learning datasets than to a detailed study of the training processes in convolutional networks' hidden layers. By focusing on technical realms, sensory transformation becomes akin not only to experimental creative actions but also to a more general political discourse. Allow me to explain this in more detail.

The work on derivatives begins when one stops reading the sensors and steps back to observe the sensory systems' secondary products. Examining derivatives indicates a set of concepts, notions, and micro-theories that allow us to expand on the common discourse of colour spaces, reflective structures, shapes, and volumes. The approach encourages thinking in terms of metamerism, albedo, emissivity, etc., most of which weave softly into terrestrial threads. Derivatives can be both a tool for commodification and a means of critical intervention. Their material agency and non-computational character creates an opportunity to contradict algorithmic hegemony.

Ecopolitics benefits from the work on derivatives while exploring the community of experience in two ways. The first is when thinking in terms of emissivity, gloss, and albedo meets with aesthetic concepts. Gradually captured in the work of sensory ethnography, spectral ordering has much to offer as it leverages the sensitivities of colours, temperatures, and tones (du Plessis, 2021). Landscape becomes calibrated with land surface emissivity and reflection (Lenton, Dutreuil, 2020, p. 177). With exercises such as pairing human skin with paper and setting

aluminium mirrors in opposition to moorlands, the study of vision environments provides an exclusive boost to the new materialists who are connecting sensory techniques to synthetic natures and pigments to photosensitive materials. Moreover, when the study develops alongside the policies of marking boundaries, fencing, and securing territories, it observes that sensory transformation recasts both cultural pronouncements on the order of systems and the politics of volumes, scales, and measures (Mulvin, 2016). The politics of Gaia implies the invention of new scales and volumetric systems that would decentralise the understanding imposed by measuring everything for the human format (Dutreuil, 2020). The intensity of this process manifests in work on geographies, lands, and territories. Just as the proliferation of satellite geosurveillance animated scholarship on the cybergeographies that defined the era of global positioning systems in the 2010s (Nacher, 2016), so the expression of geography in terms of solids and depths has revealed the work of volumetric regimes in securing vast chunks of planetary governance (Elden, 2013). As explored above, the study of artificial photic zones, machine tropisms, and line-of sight systems offers new insights for the investigation of volumetric politics. Revealing the community of existence, the study of vision environments shifts towards the next stream of ecopolitical debates – one that relates sensory transformation to the capitalist conquest of the territorial outside and the politics of the commons.

Making a complement to the politics of the commons

The idea of the commons bridges reformative programs of terrestrial aesthetics to the critical discourse of ecopolitics. Viewed from such a perspective, sensory reconfiguration serves as both an instrument of capitalist expansion and a site of potential resistance, what eco-Marxists might call the new "commons of vision." Vision environments constitute a resource frontier and a site of potential commons within the logic of the Capitalocene. Here, the reports of sensory ethnographers tighten the correlation between Böhme's aesthetic philosophy and the critical analysis of Jason Moore and Massimo De Angelis.

Starting from a purely empirical position, sensory ethnography asks what kinds of scenescapes are available: "how, where, and by whom the environment is sensed – in short, how life is lived" (Aula, 2021, p. 173). With the research on scenescapes, ethnographers went on to develop theories of the inner outside, the as yet overlooked spaces that blossom between privatised areas. Dressed in the theories of servicescape and non-places, several projects in the field ethnography have focused on the emergence of a new sensory commons (Aula, 2020; Järviluoma, Murray, 2023; Venäläinen, 2020, 2023).

Eco-Marxist formulations are exceptional in how aware they are of the potential of marginal areas, weeds, and scaleless no man's lands for the investigation of major sociomaterial processes. When faced with the technology-driven reconfigurations of the Capitalocene, the notion of the commons is then of primary interest; the approach immediately problematises the otherwise benevolent narratives of sensory communing (Järviluoma, Murray, 2023). The sensory transformation that has taken place with the proliferation of machine vision reconfigures the technological outside, creates new resource pools, and becomes subject to capital accumulation as well as becoming a potential commons at the same time. Ethnographic exploration of the inner outside and sensory commons takes the research beyond the unequivocalness of mechanically applicable theory.

With regard to the theory of the Capitalocene, machine vision would be an instrument of capital accumulation, a technology that enables the appropriation of yet another resource (Moore, 2016). Alternatively, one can consider it another measure to explain the turbulent economic growth predicted in the theories of accumulation by dispossession (Harvey, 2017). Jason Moore's influential theory states: "Capitalism has been able to outrun the rising costs of production by co-producing manifold Cheap Nature strategies, locating, creating, mapping, and quantifying natures external to capitalism" (Moore, 2016, p. 114). The concept of Cheap Natures has glistened through the paragraphs of the previous chapters. Automated landscape studies direct Moore's political insights onto permanently lit-up greenhouses, motorway junctions, warehouses equipped with signs and tags, dimmed smart-hotel lobbies, and retail spaces. But machine vision environments are also conceived in a somewhat different mood. Research on suburban materialities and marginal zones reports on how sensory environments are growing into architecture without people, liminal-, and non-places (Augé, 1992; Young, 2019). Some of the sensory environments are then found among highly commodified and regulated zones, while others are perceived as a form of commons, detritus, often praised for their unexpected beauty. This is when things start to get interesting. Among the concepts that capture the ambiguity of sensory transformations, the study of ambiance is especially evocative. In basic terms, ambiance addresses the creative processes of place-making according to the "dialectics of desire" (Thorsteinsson, 2023, p. 30). As a key figure in ambiance philosophy, Gernot Böhme has become a touchstone for urban planners, architects, managers, and commercial stakeholders (Böhme, Thibaud, 2016). Sectors like tourism and hospitality are keenly interested in the concept. Eventually, the study of subliminal affective qualities takes on a political and economic character (see Coffin, Chatzidakis, 2021; Kazig et al., 2016; Thrift, 2004), and introduces the argument for spending some time with a domain like vision technologies.

In his essay on the topic of the outside, Massimo De Angelis emphasises the need to devote attention to how the commons are being produced and articulated

"among so diverse and place-specific struggles" (De Angelis, 2007, p. 73). De Angelis' commons indicates that the plural "our outside" only differs in practical value from the "out there" wastelands of automated operations. Coming back to Moore's theory, the research on vision technologies elicits a naïve question: to what extent are the sorts of environments studied in the previous chapters – machine vision zones, sensor laden greenhouses – the expressions of vivid Capitalocene expansion? Or are they its limits – as predicted by the theory – the very edges beyond which there is "nowhere to run" (Moore, 2016, p. 114)? It is then interesting to see how work on vision technologies proves the affinity of eco-Marxist positions with their distant cultural reading of the problem. The critique of Cheap Nature clearly fits with the patterns observed in using temperature and light to expand relative ecological surplus (Moore, 2011, pp. 22–24). But, being meticulous here on how sensory technologies create those environments, one should ask what exactly is Cheap Nature in this case? Is it the cultivated field and livestock, or is it the cultivated field and livestock in their environments? Keeping in mind those theoretical nuances, much of the benefit of studying sensory reconfiguration comes from understanding the character of smart zones and machine vision environments, rather than machine vision as a way of seeing. It is precisely in terrestrial terms that sensory environments become a topic worthy of eco-Marxist debate.

The study of the commons renders palpable how the subtle territorial games – the hitherto barely visible patterns of war, dispossession, and inhabitability – that are the subject of this study overlap with subjects of interest for soft powers and economies during the previous decades. From the observations collected in the previous chapters emerges the following premise: vision environments reveal the existence of a sensory pool created mostly for technical use but inevitably blending with preexisting habitats. Managing that pool requires a series of nimble gestures that reconfigures the relations of more-than-human beings. Governing that sensory pool may become an anchor that both enforces and disentangles the hegemonic models of artificial intelligence. Altogether, such an inquiry into the politics of sensory environments becomes the major contribution of visual studies to the wider humanities debate.

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The way to finish this story is not to jump to hasty conclusions. The study of vision is not one size fits all. Very little of what has been explored here provides ready-to-use recipes, but I hope this journey through the history of the research on planetary surfaces and liminal landscapes has rendered some of the contempo-

rary technical logos more meaningful. If it only allows us to shape our arguments on the current complexities of adapting to the new conditions of living on the Earth, it will have been worth the time spent to elucidate them. As an avenue for visual studies, the earthbound technologies of vision present seeing not in terms of power and control but in terms of sensitivities and their intricate multilayered foundations. There is a lot ahead of us that requires vigilance, especially as the politics of *oikos* multiplies and forms into the most dangerous and fantastic nebulae.

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Index of names

Anna Olszewska

Earthbound visual cultures: experiments in machine vision and image processing

This book addresses classical themes in the study of visual cultures and algorithmic governance. In doing so, however, it does not elaborate on the power of the gaze nor the eloquence of images. The accounts presented inside tie machine vision to the collectives that tend to work with coarse-grained matter rather than with computational tasks. By exploring the techniques aimed at mitigating the inverse problems of vision in image analysis, photometry, and visual communication design, this book illuminates the AI-compliant domains of visual culture. Bringing them to the fore, it offers a study of sensory environments in the making.

The idea is to think of machine vision as an earthbound technology. Its uniqueness lies in uncovering the astonishing, sometimes perplexed, alliances that are inscribed in the emergence of future political orders.

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