UNIVERSITY OF SCIENCE AND TECHNOLOGY IN CRACOW

FACULTY OF ELECTRICS, AUTOMATION, COMPUTER SCIENCE AND ELECTRONICS,
INSTITUTE OF DRIVE AUTOMATION AND INDUSTRIAL DEVICES.

PhD THESIS

M.Sc. MICHAŁ WIDLOK

Advanced methods of galvoscanner position control with integrated power supply module

Supervisor:
dr hab. inż. Andrzej Senderski,

Cracow, May 2007

Summary:

Galvoscanners are very fast and accurate electro-mechanical devices that are used to angular position control of a given element. Today available torque and rotation angle is limited, however new devices are developed rapidly and the situation is constantly changing.

This paper presents new idea of galvoscanner position control that can be used to various applications: target tracers, material processing machines or medical imagers. Designed position control system has been build and verified with real galvoscanners (LSK 040EF) proving that the ideas and used algorithms are correct. Finally a special controlled power supply module have been added to drastically improve electrical efficiency of the system. The power supply module also have been build and verified in reality.

Presented control system has been designed with extensive use of computer simulation and data visualization software. Author formulated functional mathematical model of galvoscanner that was needed to perform accurate simulation. The model was verified with real galvoscanner in steady state and in transients achieving very good accuracy.

Additionally a special programming device (ICSP- In Circuit Serial Programming) that have been designed during research is presented in appendix. This device is used to reprogram ICSP capable ICs using ordinary PC computer. Designed programmer is very universal and can be used to most of programmable ICs if only a appropriate software driver is provided

Formulated model along with real control system is universal and can be used with many different galvoscanners on the marked. Gathered experience and knowledge will be very important for future authors work, in designing military marine electronics systems.

AKADEMIA GÓRNICZO-HUTNICZA
IM. STANISŁAWA STASZICA W KRAKOWIE

WYDZIAŁ ELEKTROTECHNIKI, AUTOMATYKI, INFORMATYKI I ELEKTRONIKI

ROZPRAWA DOKTORSKA

MGR INŻ. MICHAŁ WIDLOK

ZAAWANSOWANE METODY STEROWANIA POZYCYJNEGO GALWOSKANERAMI ZINTEGROWANYMI Z MODUŁEM ZASILANIA

Promotor:
dr hab. inż. Andrzej Senderski,

Kraków, Maj 2007

Streszczenie:

Galwoskanery są bardzo szybkimi i dokładnymi urządzeniami elektromechanicznymi służącymi do kontrolowania pozycji kątowej danego elementu. Obecnie osiągane kąty obrotu i momenty obrotowe są stosunkowo niewielkie, ale nowe urządzenia są cały czas opracowywane i sytuacja stopniowo ulega poprawie.

Rozprawa prezentuje nowe metody sterowania pozycyjnego galwoskanerami, które mogą być wykorzystane w wielu docelowych aplikacjach jak: układy śledzenia celów, laserowe obrabiarki czy urządzenia medyczne. System sterowania pozycyjnego został zaprojektowany, wykonany i sprawdzony z rzeczywistymi galwoskanerami (LSK 040EF) dowodząc, że zastosowane idee i algorytmy są poprawne. Dodatkowo zaprojektowany został specjalny, sterowany moduł zasilania, który znacznie poprawił sprawność energetyczną całego systemu. Moduł ten został również wykonany i sprawdzony w rzeczywistości.

Prezentowany system zaprojektowany został z wykorzystaniem symulacji komputerowej i pakietów wizualizacyjnych. Autor sformułował matematyczny model funkcjonalny galwoskanera, który był konieczny do przeprowadzenia symulacji. Model ten został sprawdzony z rzeczywistym galwoskanerem zarówno w stanach ustalonych jak i dynamicznych osiągając założoną dokładność.

Dodatkowo w załączniku przedstawiony został zaprojektowany specjalnie dla celów badań programator ICSP (Programowanie Szeregowe Wewnątrz Układu). Programator może w łatwy sposób zmieniać ustawienia programowalnych elementów scalonych, używając jako źródła danych zwykłego komputera PC. Programator został tak pomyślany aby był w stanie programować dowolne układy, jeżeli tylko jest dostępny odpowiedni sterownik programowy (driver).

Sformułowany model wraz z realnym system sterowania pozycyjnego są uniwersalne i mogą być użyte do sterowania i symulacji dowolnych galwoskanerów dostępnych na rynku. Zdobyte podczas pracy doświadczenie będzie bardzo cenne w dalszej zawodowej pracy autora przy projektowaniu elektronicznych systemów dla Marynarki Wojennej.

Table of contest

Introduction

Galvoscanners are concurrently the fastest and the most accurate electro-mechanical devices used to control rotation angle of a given element. Available power and torque is limited now, but fast development of galvoscanners as well as control systems for them might change this situation in near future. In the begging galvoscanners use was limited to laser light shows and simple medical imagers, however today they are used frequently in many different areas. Galvoscanner, also called torque motor has two special properties over the entire working range [1], [2]:

1) Torque is proportional to the applied current
2) Torque is independent of the rotor displacement

Today main applications of galvoscanners are: Military (target tracking or marking), Medical (laser-based BioMedical applications), Material processing (laser marking, machining or drilling), Laser imaging (laser show or light show systems), Semiconductor processing (micro-machining applications such as memory repair).

Galvoscanner are known for about 30 years, but unfortunately availability of scientific publication or even detailed technical data-sheets is very limited. Manufacturers treat galvoscanner and control systems parameters as top secret data, further reducing general knowledge about this subject. During research author found only a few schematics of very old position controllers and some main parameters of galvoscanners. In fact the most helpful informations was found on non-commercial web pages in forms of FAQs or system descriptions.

Unfortunately galvoscanners are still very expensive and very sensitive to control system malfunctions. They and can be damaged in very short time just because of badly tuned control system or even random electrical noise influencing control loops.

Increasing importance of galvoscanners as well as almost total lack of scientific publication about them forces author to start research work that is presented in this paper. Because galvoscanners are extensively used in military applications, where dedicated, application specific control system is required, this research would be very useful for future author's work (author is a designer of marine military electronic systems).

After collecting some available informations author decided split research work to following sections:

1) Collect all available publications, technical data and other informations about galvoscanners and controllers for them (Chapter 1)

2) Formulation mathematical models of galvoscanners that could be used to simulate complete control system (Chapter 2.1, 2.2)
3) Measure parameters of galvoscanners used in research and create a measurement procedure (Chapter 2.3, 2.4)
4) Verification of models (Chapter 2.5, 2.6)
5) Design and build laboratory control system for galvoscanners (Chapter 3)
6) Investigate power efficiency of the system, trying to increase it as much as possible (Chapter 4)
7) Experimentally verify design ideas and real control system (Chapter 5)
8) Summarize results (Chapter 6)

To complete the research (especially points 2, 4 and 5) a special laboratory stand have been created that consist of:

- PC with real-time operation system and simulation/visualization software
- ICSP devices programmer (designed by author) presented in Appendix 1
- Measuring and data logging equipment
- Low noise high-efficiency ZVS-CV power supply (designed by author)

Original achievements

1) Formulation of the new control structure characterized by application of position reference block cooperating with modified PID position controller and dependence of supply amplifier voltage of position reference
2) Formulation and verification mathematical model of galvoscanner that can be used for computer simulation of new control systems and position regulators. On the basis of this mathematical model, a ngSpice version have also been created and experimentally verified. Author haven't found any information about galvoscanner's modeling in available literature.
3) Design and building of real, laboratory research galvoscanner control system that enables to test variety control system configurations, and that could be tuned for different galvoscanners and applications.
4) Modification, design and building of controlled ZVS-CV power supply for the control system, that meets particular requrements. This supply reduce output power amplifiers loses several times due to output voltage dependence of position reference. Also EMI reduction has been achieved by special resonant inductors that allows zero voltage switching in all modes of operation.

1. Addressed problems, recent state of research

1.1. History of galvoscanners and technical background

In present technology quite common task is to control position, or rotation angle of the given element. In the case of linear position movement, linear motors or standard electrical motors with mechanical equipment are used. Usually control of rotation angle is accomplished by electrical motors with encoders and regulators, but now in some special applications by galvoscanners. Galvoscanners have some advantages over any other devices, because of their short response time and very high accuracy. However they are not suitable to drive heavy loads (large moment of inertia), but this drawback might be reduced in short future.

The magnetic circuit for "moving iron" galvoscanner have been disclosed in a United States Patent [2]:

Patented Nov. 22, 1949
2,488,734
Dynamo Transformer
Robert K. Mueller, Newton, Mass.
Application March 7, 1946

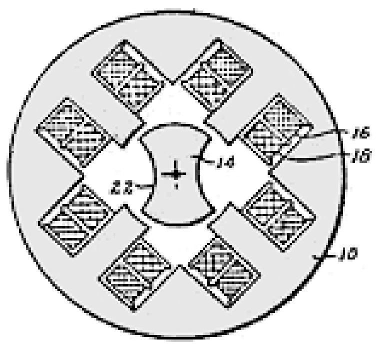

Figure 1.1.1. Dynamo transformer from Patent 2,488,734

It shows the dynamo transformer (presented on Figure 1.1.1) also called torque motor with two special properties over the working range (10-20 degrees) [1], [2]:

3) Torque is proportional to applied current
4) Torque is independent of the rotor displacement

Presented galvoscanner consist of rotor made of magnetic iron (14) and stator (10) with two electrically separated windings (16, 18) wound over the poles. Today "moving iron" galvoscanners have similar construction to the "original one" - differences are mainly in construction of poles, and using pernament magnets instead of double windings. All this modifications allows better linearity and much greater torque available from the device.

For very long time galvoscanner was only a "technical innovation" without any practical use. The situation have changed when good and accurate position sensors and solid-state position controllers become available. Galvoscanner companies started to integrate position sensors and some other control circuits directly into the device, and produce dedicated controllers [3]. This made the technology more available to normal users, but even now commercial systems are expensive and not enough universal. One of the first really good commercial system - “Interscan” (for laser shows) was build in 1976 by General_Scanning_Inc. and Inermedia_Systems_Corp [4]. Total system costs, the laser source with digital laser path controller were about 45000$.

After a few successful applications of such systems galvoscanners was finally found as a good solution to number of problems. Soon military and medical projects (with very high budgets) effectively stimulate fast galvoscanners development, especially miniaturization and improvements in control electronics. This reduce the costs of commercial systems making them more available to normal users and designers. However the prices are still high and companies don't give much technical data with theirs systems. Today galvoscanners are known by many names: optical scanner, galvanometer, galvo (slang), or simply scanner. In this publication we will stick to “galvoscanner” as the most popular and widely known.

There are two types of galvoscanner control systems: open loop and closed loop, each with many variants or modifications.

An overview of typical galvoscanner closed loop control system is shown on Figure 1.1.2.

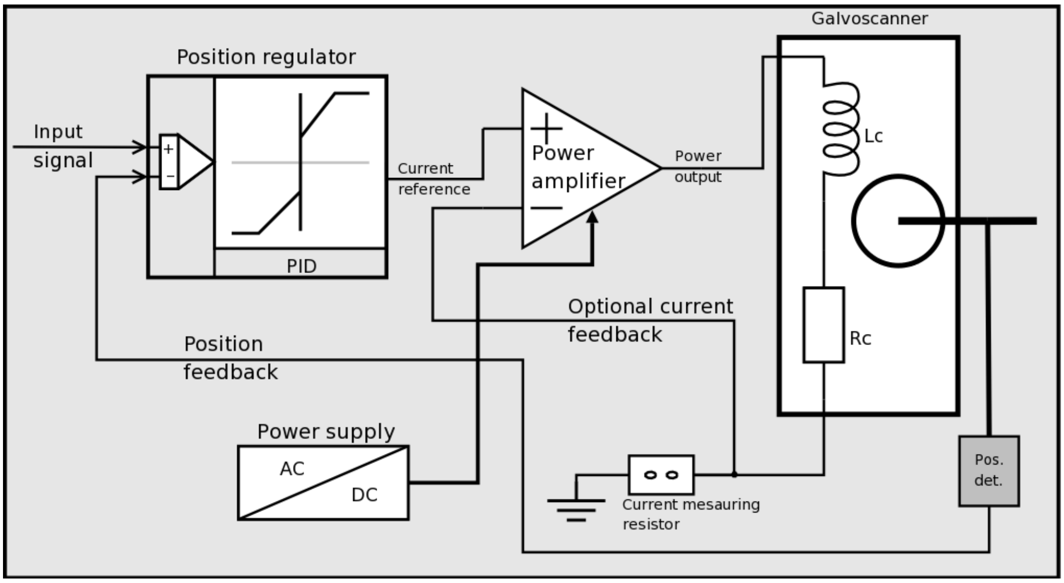

Figure 1.1.2. Typical closed-loop galvoscanner control system block diagram

“Position regulator” is a low-level, closed loop subcircuit that detects and minimize position error of the rotor. “Power amplifier” is a power circuit that powers the coils, according to the signal from position regulator (sometimes performing a current control as well). “Controller” is a full system consisting of position regulator, power amplifier and possibly other circuits to suit the given application.

Open loop galvoscanner will always have some limitations, that are often unacceptable for most of the applications. There are three main types of the open loop galvoscanners:

9) ordinary open loop galvoscanners
10) resonant galvoscanners
11) torque motors

Open loop galvoscanners are very similar to normal devices, except that they lack the position sensor.

Resonant galvoscanners are tuned to resonate at a given frequency, when fed with adequate signal. Frequency of the input signal have to be fixed (equal to resonant frequency), and by varying the amplitude we can change the peak to peak rotation amplitude. Such devices have been used in “Interscan” projector to create special effects.

Torque motors are simply electro-mechanical devices with fixed rotor (or with very small rotor movement) that can create constant, well controlled torque.

1.2. Galvoscanners applications

Main applications of galvoscanners are:

1) Military – mostly in target tracking or marking. The system usually consist of a head with the approximate position controlled in traditional way (with electrical motors for example), and high speed and very high accuracy galvoscanner systems that finally track the target. This dual system is needed because galvoscanners have limited rotation angle.
2) Medical – laser-based BioMedical applications, galvoscanners offer the positioning accuracy, speed, and size that are ideal for compact, system designs used in dermatology, ophthalmology, confocal microscopy and analytical applications.
3) Material processing – laser marking, machining, drilling and welding systems have achieved very high marking speeds and precise laser processing performance in small and large beam diameter configurations using galvoscanners.
4) Laser imaging – laser show or light show systems for discotheques and public clubs.

These sometimes does not have closed loop drivers and are usually made very cheaply. However in this area very high accuracy or speed is usually not needed.

5) Semiconductor processing - micro-machining applications such as memory repair and laser trimming, as well as mask and wafer inspection applications depend on galvoscanners to consistently deliver very precise and stable positioning.

Most of these applications use galvoscanners to perform some kind of laser or light path control by using mirrors. Others use them for precise tool manipulation or positioning. This publication will concentrate on closed loop systems that are used in most of the applications from target-tracking to material processing. In fact, almost all closed-loop systems needs the fastest and the most accurate position control that is possible.

Laser shows might not be the most important application of galvoscanners, but the idea of controlling laser light path with two mirrors is very important because many other devices works in very similar way.

Laser shows systems usually consist of high power visible laser (form 200 mW in rooms to 4-10 W in open areas), and a path controller [5]. Such controller usually drives three galvoscanners: first is used as a dimmer (beam interrupter), second and third are used to control the beam path and have small mirror mounted on it's shaft. Laser beam reflects from the second mirror to the third and then is directed to the output window.

If galvoscanner's shafts (and thus the mirrors) are mounted perpendicularly. The beam direction can be controlled in two dimensions, by turning the mirrors. If the galvoscanners and their position controllers are fast enough it is possible to create steady images on the screen, or with high power lasers even on clouds. Figure 1.2.1 shows recent path controller used in modern laser show equipment. Path of the laser beam is marked with red line. We can see how the laser beam going out of the beam interrupter, reflects from two constant mirrors, and finally reaches two control galvoscanners mirrors which control output beam position.

The beam can be controlled in many different ways to produce the image, but only two basic modes are used today. They are:

- raster scanning (Figure 1.2.2)
- vector scanning (Figure 1.2.3)

Each of them can be realized in two ways assigned respectively to case (a) and case (b). In raster scanning laser beam travels over all possible points in the image area (pixels) according to lines showed on Figure 1.2.2.

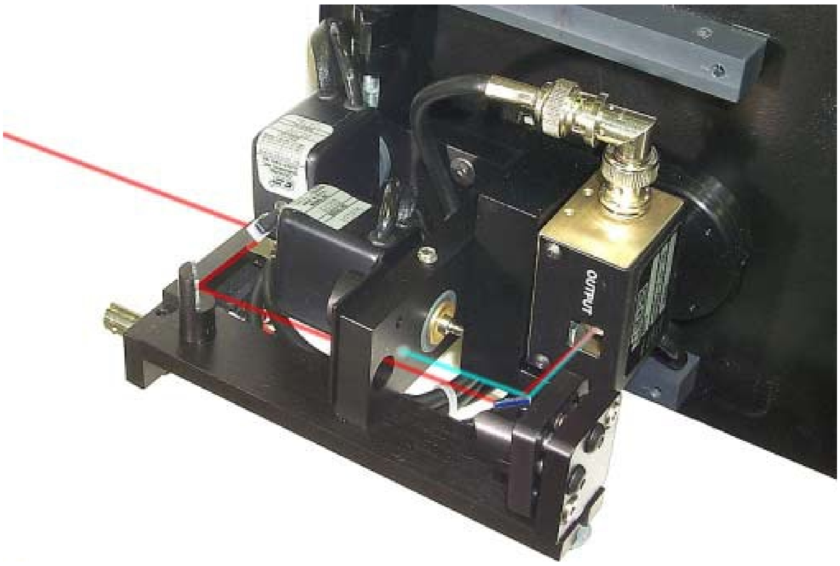

Figure 1.2.1. Recent laser path controller with beam interrupter

At dark points of the image the beam is interrupted. The image is crated like in the TV set. The only difference between case (a) and case (b) is the way that the beam goes. In case (a) active lines are horizontal, while the others are blanked completely. In case (b) all lines are used to display points of the image.

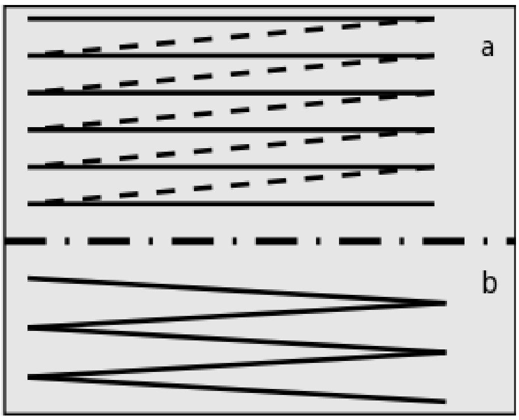

Figure 1.2.2. Raster scanning method for image projection

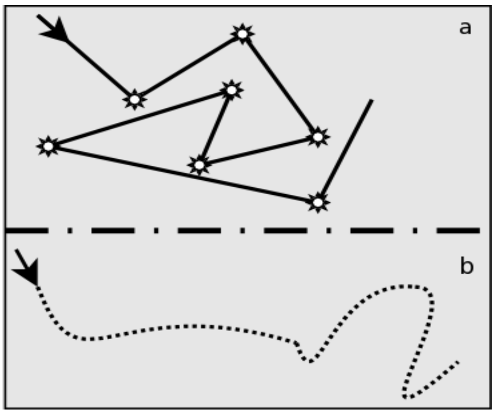

Figure 1.2.3 Vector scanning method for image projection

Raster scanning shown on Figure 1.2.2 case (a) does not require closed loop position control, but require very fast beam interrupting system. Second way, case (b) is a bit better because it can use laser power more effectively. This way also allows to use resonant galvoscanners.

However taking into account that typical image created by the system has much more dark areas, we can see the laser will be off most of the time. It means that even very high power lasers will create dim images, and generally it is a waste of power. We should remember that high power lasers that not use laser diode bars can not be turned on and off quickly. That's why usually beam interrupters are used instead of switching the lasers.

In vector scanning laser beam goes through all bright points of the image area according to specified algorithm. Generally the beam is stopped at bright points (case a) or track bright lines at constant speed (case b). In both cases laser is interrupted between two points or two lines and should move from one bright area to the other at maximum speed.

Vector scanning can create images even without beam interrupter but needs very fast and accurate closed loop position controllers for galvoscanners. As shown on Figure 1.2.3 case (a), laser beam is controlled to stop on given points, or to track a given line with approximate constant velocity all the time - case (b). Both of these methods need different regulator settings to get best performance from the system. Vector scanning are considered as standard for laser shows (ILDA), and there are even special file formats for images, and test images for controller tuning.

1.3. Recent state and available publications

Galvoscanner are known in the industry for about 30 years, but unfortunately casual user situation didn't change much in that time. Even if galvoscanners and their electronics are improving, they are still not very popular and widely known. Essential scientific and technical knowledge is carefully hidden by leading manufacturers. It is caused by hard competition between them from one side and by growing importance of the military applications from the other. Lack of accurate technical data and almost total lack of scientific publications on this subject is meaningful trouble in research. Companies usually sell their devices without much technical data, and with dedicated controllers that can't be used with different brand galvoscanners.

Today only a few companies in the world actually produce galvoscanners. One of the most innovative (and most expensive) galvoscanners are made by Cambridge_Technology [6]. General_Scanning or LSK are known too. Figure 1.3.1 shows 6220hb “moving coil” device (measuring 5cm in hight). Compare the size of the mirror, to the size of galvoscanner itself. Such proportions (big mirror with small galvoscanner) is possible only with moving-coil technology.

It is characteristic, that controllers needed by almost every system have similar construction, and typically are dedicated for one, specified application only. Tunings available for designer are limited, and sometimes even the procedure is not given in the manual. It is important that inappropriate controller, or badly tuned controller can easily damage connected devices making all system useless. Even worse, such crashes are very hard to track, and debug accurately.

Figure 1.3.1 Cambridge Technology 6220hb moving coil galvoscanner

Companies almost never give the schematic or even accurate description of theirs better position controllers, and sometimes all this devices seems to be “secret” because of marketing considerations or military restrictions. System produced for commercial applications are not suitable for research work.

Available technical info is limited to a few schematics of very old position controllers, and some main parameters of galvoscanners. Manufacturers usually don't want to even give full description of the product, stating that it is factory only data useless for the customer. Some descriptions, schematics, and sometimes even FAQs can be found on the Internet [5]. These articles are usually written by designers or galvoscanner's specialists, and posted to discussion groups. However this publications are hard to find and the noise on the discussion groups is very high. Some literature can also be found on www pages like LaserFX [7], however it is usually devoted to laser shows only, or ILDA specifications.

1.4. Area of interests

Main problem considered in this work is how to achieve good position control quality and high efficiency of the whole galvoscanner system. Requirements of good position control and high efficiency are important for further galvoscanner technology development, especially for military applications, where equipment has to be reliable, accurate and miniaturized. Unfortunately to get better position control properties higher dynamics of the controlled system is needed which worsen energy efficiency of the whole galvoscanner system. The solution will be searched in control structure as well in parameter optimization of its elements.

Figure 1.4.1 shows block diagram of the laboratory system designed by the author, that will be used during research. Presented system is different from typical ones used in the industry, but it is very well suited for research work. It can be used as image projector (Chapter 1.2, point 4), for target tracking (point 1) and many more other applications where precision control of position is required (points 2,3,5). Different applications only change demands placed on different blocks, while the main idea stays the same.

Conventional, two mirrors laser beam path controller was used as a galvoscanners load, because it could be quickly realized in hardware. In fact it is laser imaging device, that can produce very effective results when used with higher power visible laser. Projected image quality is also an approximation of the system performance (speed and accuracy).

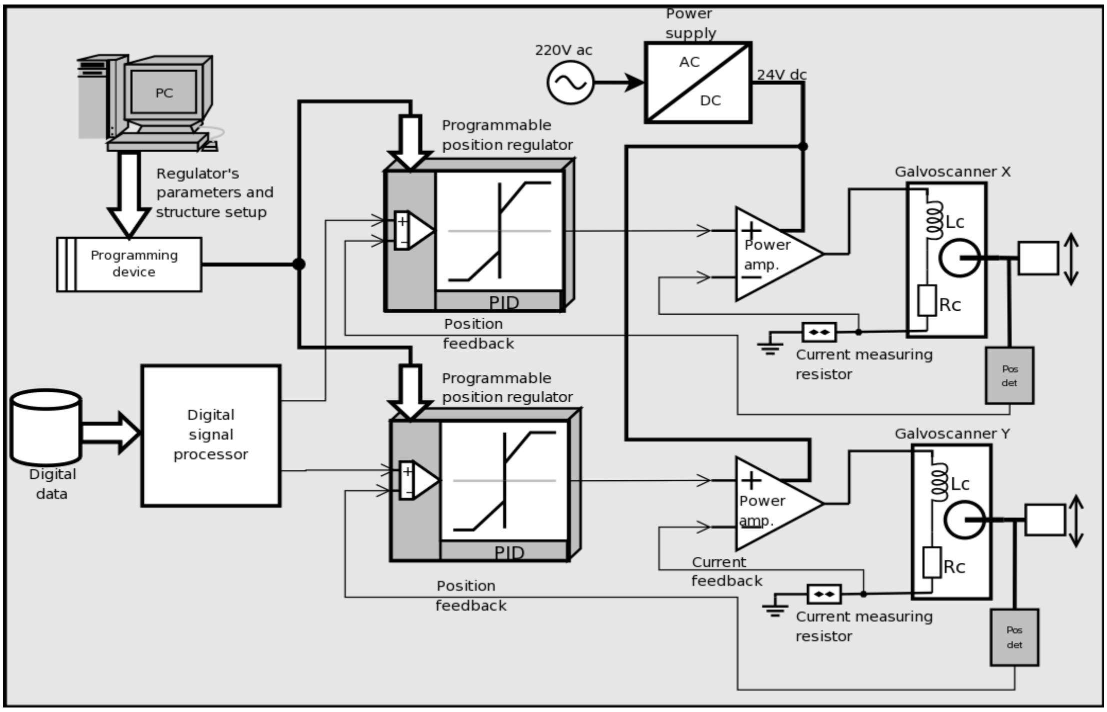

Figure 1.4.1 Block diagram of galvoscanner control system used during research

All of the blocks shown on Figure 1.4.1 were needed to create usable research system, however for some applications they could be integrated in miniature, or application specific integrated circuits. Of course image projection requires a specific, dedicated to it tuning of control loops, usually different other applications. Generally in the research much attention have been paid to adjust and verify system parameters caused by different demands which depends on given application.

All blocks presented on Figure 1.4.1 are described in more detail in following chapters, now it will be given only the main idea of theirs function:

- PC computer is used for changing parameters of programmable analog regulators, preparing digital data for digital signal processor and overall control tasks (Chapter 3.2, 3.3).
- Programming device is connected to PC parallel port and outputs data using JTAG interface that is used to program ICs in position regulators (Appendix 1).
- Position regulators are fully programmable analog devices, that can be programmed to any basic regulator (P, PI, PD, PID) and even to non standard or combined type. For most research work, advanced analog regulator, with non standard characteristic were used (Chapter 3.2)
- Power amplifiers amplify the low level signal from position regulators, and also serves as current regulators. Maximum output voltage is +/-24 V, with 4 A peak current (Chapter 3.3 and 4.1).
- Power supply converts 230 V AC line power to 24V DC, needed by power amplifiers. This block is also controlled from DSP or PC to reduce the losses in power amplifiers (Chapter 4.2).
- Digital signal processor or PC is used to process digital data before it is actually send to D/A converters, and then to position regulators. By this processing it is possible to reduce response time of galvoscanners and increase accuracy of the system (Chapter 3.2).

Thesis of research work:

Using digitally formed position reference signal and reference supply voltage signal depended on predicted time voltage curve based on position reference signal, enables to achieve required position control quality and high power efficiency of galvoscanner control system.

1.5. Galvoscanner construction and theory of operation

Today galvoscanners come in a few different types, but only two of them are relevant. These are “moving iron”, and “moving coil” constructions. Other were “moving magnet”, or combination of the basic types, however they don't gain approval because of inferior performance and other problems. “Moving iron” and “moving coil” galvoscanners have simple mechanical construction, and can be made with very high tolerances, what greatly improve response time and accuracy. Position controllers for these two types also have similar structure, but have to be tuned differently.

Author also found out that in old recorders (with ink pens) often use galvoscanners. Those devices were similar in construction to the “moving coil” type, however the details are different. The devices tested by author was able to achieve about 2ms step response time, and needed about +/- 50 V power supply to achieve it. Maximum coil currents have been estimated to about 4 A. They were about 4 to 5 times greater then LSK devices used in this research work.

1.5.1. Moving iron galvoscanner

Because of lower costs and better availability “moving iron” galvoscanner is concurrently the most popular. For example General_Scanning G-120DT galvoscanner is shown on Figure 1.5.1.1 below [3]. This scanner is well know from quite long time, and it is often used as a reference to compare other devices. It's parameters however, are not very good in today standards. Device presented on the figure has average sized mirror mounted on the shaft and rather complicated connector. There is no common standard defining such connectors and almost every company uses it's own one so quick substitution of different brand galvoscanners is not possible. Normally there are 5 to 7 pins needed to control galvoscanner in close loop mode:

1, 2) Main coil

3, 4) Position sensor power supply

4, 5) Differential position sensor output

6, 7) Optional temperature sensor

It should be noted that this is probably the first really popular device with parameters, that are good enough for most of the tasks. It is also rather robust (in the galvoscanner's standards) and usually long lived. Many of these devices can be found on surplus marked today, however they are still harder to find then one could expect. Also almost every company that makes galvoscanners have some of this kind in the offer.

Internal parts of moving iron galvoscanner are shown on Figure 1.5.1.2.

Figure 1.5.1.1 General_Scanning GD-100PD galvoscanner outlook

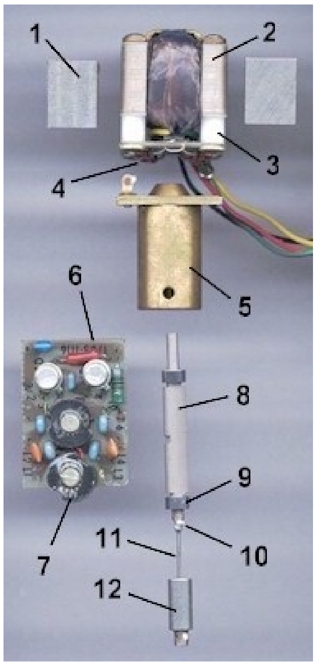

Figure 1.5.1.2. GD-100PD internal parts

Galvoscanner from Figure 1.5.1.2 consist of:

1. - Alnico magnet
2. - Stator laminations
3. - Plastic spacer
4. - Position detector board
5. - Hub ½" diameter
6. - Oscillator board
7. - Ferrite transformer
8. - Rotor
9. - Lower bearing
10. - Solder joint
11. - Torsion bar
12. - Sleeve

Both rotor and stator laminations are made form soft magnetic iron. Stator is sometimes made of isolated plates like transformer core to reduce losses. Coils are wound over the two stator poles, as shown on Figure 1.5.1.3. The torsion bar is needed to electrically ground the rotor and also to bring it back to the neutral positions when the device is off. If the coils are unenergized, rotor is kept in neutral position by the magnets and torsion bar.

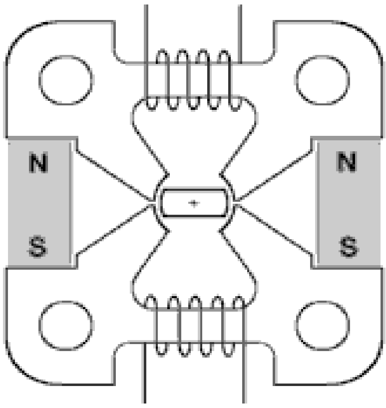

Figure 1.5.1.3 Moving iron galvoscanner - rotor in neutral position (coils off)

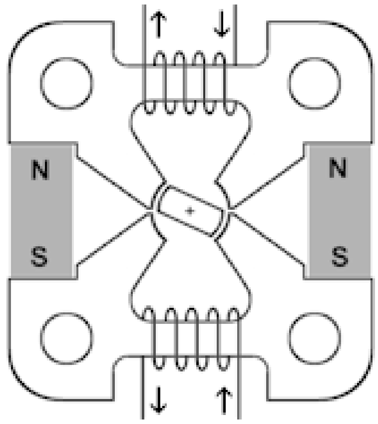

Figure 1.5.1.4 Moving iron galvoscanner - rotor displaced (coils energized)

When current flows throw the coils, rotor align itself with stator poles as shown on Figure 1.5.1.4 below. The operation is quite similar to the “variable reluctance” stepper motor. The main difference is that galvoscanner is optimized to work with very small rotation angles, and has only one phase.

It should be noted the rotor torque is constant and proportional to the coils current and its direction over all available working angle. Such galvoscanners are very robust because they don't need any moving connections, or rubbing elements. Only part susceptible to breakage is torsion bar. Because the coils are wound over the stator, it is easy to remove heat from them, so the scanner can operate with very high speeds and loads without the danger of overheating. The iron rotor is has large mass and it limits the maximal attainable galvoscanner speed. Also the torque is lower then in the “moving coil” galvoscanner at similar current.

1.5.2. Moving coil galvoscanner

Moving coil galvoscanner (shown on Figure 1.5.2.1) is completely different from “moving iron” type. It consist of pernament magnets, that form a magnetic field similar to that created in DC motors [6]. The rotor is formed form single, very stiff coil that is mounted inside this field.

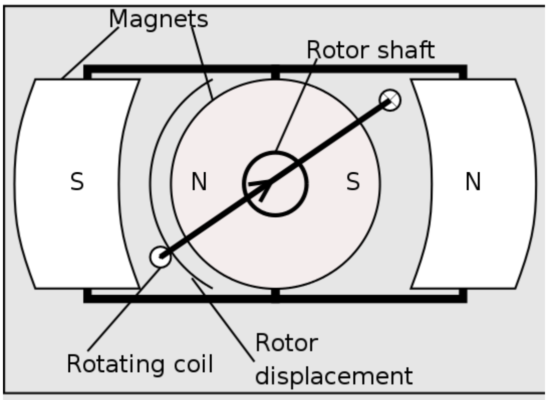

Figure 1.5.2.1 "Moving coil"
galvoscanner block diagram

In general this galvoscanner operates similarly to the DC motor without a commutator. The coil is connected by flexible wires not by brushes, and it has only a few turns. There is no working iron in the rotor so it is much lighter then the rotor in "moving iron" type. Very strong magnetic field created by magnets enables this galvoscanner to produce high torques.

Some problems with this galvoscanner arises from connections between coil and input terminals – because they have to survive very fast and frequent moves. Also the coil construction is endangered to high temperature and forces during operation. This type of galvoscanners are not as robust as "moving iron". They must be used with very precise and reliable controllers, because they can be destroyed very easy. If the maximum rotation angle is exceeded the torsion bar and coil connections can be broken making the device useless. The rotor coil have small thermal constant and is sensitive to overheating, even if maximum peak current is never exceeded. Good controllers for "moving coil" scanners usually have a few different protection circuits, and sometimes even a thermal model of the scanner's coil to prevent overheating.

Both types usually have a torsion bar mounted between rotor and stator. This bar is generally thin, elastic metal wire (similar to high tone piano string), that serve two functions. It centers the rotor during turn off, and it provide grounding for it. Presence of torsion bar also cause, that constant current is needed to keep position that is out of neutral because it works as a spring. It also prevents the rotor from exceeding maximum rotation angles, what is very important especially in "moving coil" galvoscanners.

Closed loop scanners always have an integrated position sensor mounted directly on the rotor. Such sensor is typically capacitive type, that outputs two differential current signals, that are proportional to the rotor angle. The accuracy of the position detector is very important because in many application there is only position feedback. Today there are scanners that have position detectors working with micro-radian accuracy (0.01% of full scale), and with response time in micro seconds range.

1.5.3. Modes of operation

Both “moving iron” and “moving coil” galvoscanners can be used in three different modes of operation. Each mode requires slight modifications of the galvoscanner construction, but the main electromagnetic system stays the same [8]. The modes are:

- Closed loop operation (Figure 1.5.3.1) – very fast and accurate, but need position sensor and special controller. Galvoscanners don't need a torsion bar, but it is always mounted to serve as a electrical rotor grounding, and to center the rotor in the case of input signal lack. This mode is the most complicated and used in high-end (the highest performance) systems.
- Open loop operation (Figure 1.5.3.2) – torsion bar has to have well defined parameters, but position detector and closed loop driver is not required. This mode is used in less demanding applications. Approximate position is controlled by the value of input current.
- Resonant operation (Figure 1.5.3.3) – the rotor mas and torsion bar stiffness is controlled during the production, to achieve given mechanical resonance frequency. Such galvoscanner can by driven by very simple driver that only outputs desired frequency, as a sine or square wave signal. Because of the mechanical resonance rotor angle is always changing sinusoidally. This mode is limited to raster scanning applications and not widely used today.

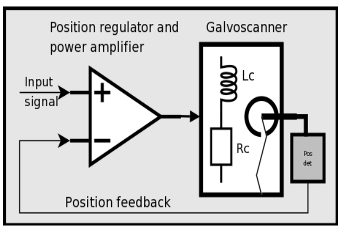

Figure 1.5.3.1 Closed loop operation mode

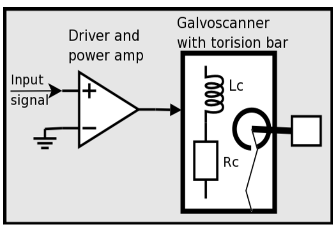

Figure 1.5.3.2 Open loop operation mode

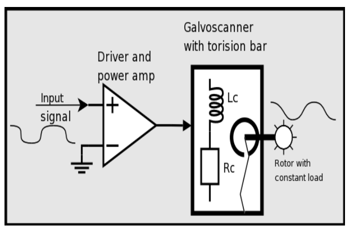

Figure 1.5.3.3 Resonant operation mode

In fact closed loop mode can be used to all applications, while other modes are typically dedicated to only one. Closed loop controller can also be tuned to suit different scanners with different loads, what is completely impossible with other controllers. Following research will concentrate on closed loop mode, that surly will be the most important in currently developed applications.

The choice of galvoscanner itself is more complicated because there many different types on the market designed with different applications in mind. For example a device for material processing needs very accurate position sensor and must be able to move large mirror, while speed is secondary concern. On the other hand target tracking application don't need very high accuracy of position sensors (because feedback must be taken form camera that sees the target) but high speed is a must. The prize might also be a problem for developers with limited budgets.

For this research author chooses LSK moving iron, closed loop galvoscanners because they are originates form Europe, have good parameters (as for moving iron galvoscanners) and have affordable prize.

2. Formulation and verification of mathematical models of galvoscanner

2.1. Choosing of the simulation model and environment

Galvoscanner is a complicated object with nonlinearities and some very special and uncommon properties strongly depended on construction details being technological know how of the manufacturers. These “features” make modeling and simulation a difficult task, especially if the models have to be accurate. It is difficult to find anything about scanner simulation in the available literature and in Internet too. Manufacturers rarely use simulation to design their drivers - they can bear one or more destroyed devices during testing. A casual user is not able to do so at all. Then accurate models and good simulation environment is very important. Main reason is that a mistake that could be easily found during simulation can destroy the galvoscanner. Also it is obvious that to change the configuration of the driver is much simpler to do on the PC screen then in the real world.

Because of complicated construction and lack of detailed mechanical parameters it is very hard (or even impossible) to create accurate mathematical model of galvoscanner. Fringing flux, magnetic permeability of stator core and rotor or internal parts dimensions are not know – to measure these parameters it would be necessary destructively disassemble the device. In this situation author had following possibilities:

6) try to formulate and verify exact model based on general physical laws
7) try to formulate and verify simplified functional model
8) to resign of model formulation, to resign of simulation research and limit to experimental research verifying theoretical considerations.

The first possibility is the best one, but exceeds assumed limits of the work. The third possibility could be expensive, as it was mentioned above and not necessary the shorties way to get satisfying final result, So author decided to follow the way implicating from the second possibility.

2.1.1. Simulation environment

Modeling electro-mechanical objects like galvoscanners can be done with Spice, Scilab [9], Matlab [10] or others. Every such simulation tool has its own limitations. In galvoscanner's case is important to take into considerations detailed dynamic and static properties of electronic devices applied in the control system. It is caused by relatively high galvoscanner dynamics and specific operation its control and supply devices.

For example real output power amplifier behaves differently when load is heavy, then it would without load. Maximum output voltage swing is other thing that should not be forgotten. Even worse – output voltage is normally depended on the current in real world. Such interactions are usually nonlinear and very hard to accurately simulate with high-level equation orientated programs like Matlab or Scilab. On the other hand such problems virtually does not exist when using ngSpice with real (not behavioral) semiconductor models.

Electric circuit simulation program (like ngSpice or similar) seems to be the best choice for low-level amplifier and position regulator testing. NgSpice is not able to model mechanical systems directly, what is needed for galvoscanner model. Shaft, load or torsion bar are mechanical parts that can not be ignored. The best solution is using of well known electro – mechanical analogies. Table 1 will summarize them.

Table 1. Electro-mechanical analogies.

Electrical variable	***Mechanical equivalent***	***Electrical unit [SI]***	***Mechanical unit [SI]***
Voltage	Rotation speed	$[V]$	$[\frac{rad}{s}]$
Current	Torque	$[A]$	$[N \cdot m]$
Capacitor C	Inertia	$[F]$	$[kg \cdot m^2]$
Inductor L	Spring	$[H]$	$[\frac{N \cdot m}{rad}]$
Resistor R	Dynamic friction	$[\Omega]$	$[\frac{N \cdot m \cdot s}{rad}]$
Voltage source	Rotation at constant fixed speed	$[V]$	$[\frac{rad}{s}]$
Current source	Constant torque load	$[A]$	$[N \cdot m]$

It can be seen, that it is possible to simulate almost all mechanical parts using ordinary electrical elements. It is only a matter of interpretation of the results. Of course all parameters in SI units have to be provided, what can be sometimes problematic and prone to errors.

2.2. Formulation of galvoscanner simulation models

2.2.1. Mathematical model of the galvoscanner – differential move equations

Galvoscanner is a quite complicated device, that is hard to accurately describe in mathematical terms. Magnetic circuit is complex (refer to Chapter 1), and manufacturers rarely give any detailed data to the user. Accurate dimensions, magnetic properties of rotor and stator materials, number of turn in the coils and so on are simply not known by the user. Some of this information could be gathered by (destructive) disassembly of the galvoscanner, but some would still be problematic.

In available literature and even in Internet there are not any descriptions of mathematical models (basing on electro-mechanical devices theory) that would take into account complicated distribution of magnetic fields in the galvoscanner. There are even no examples of and any other models of galvoscanners, that could be helpful during research. Because of these reasons author decided to create functional galvoscanner model basing on physical characteristics of the device. Galvoscanners are build on the basics of the "dynamo transformer" [2], and theirs main properties are summarized below [1]:

- Torque is linearly proportional to the applied currents
- Torque is substantially constant over the range of the motion (+/-10 to +/-20 degrees maximum typically) for which fringing effects are negligible
- Torque produced by the current will rotate the rotor until it is balanced by the opposing torque of the torsion bar and/or load

For more detailed discussion on construction and theory of operation please refer to Chapter 1.

Basing on these properties differential equations can be formulated for the galvoscanner's state variables:

$$T_E = TRC \cdot I_C(t)$$

$$T_E - \left(T_{TB} + T_{FR}\right) = RIN \cdot \frac{d\,\omega(t)}{dt}$$

$$U_C(t) = CR \cdot I_C(t) + CL \cdot \frac{dI_C(t)}{dt} + BEM \cdot \omega(t)$$

$$\omega(t)=\frac{dPos(t)}{dt}$$

$$T_{TB}=KTR\cdot Pos$$

$$T_{FR}=FR\cdot\omega(t)$$

where:

T_E -	Electrical torque (created by coils)
T_{TB} -	Torsion bar torque
T_{FR} -	Mechanical friction torque
I_C -	Coils current
CR, CL -	Coils DC resistance and inductance
BEM -	Back Electromotive force
TRC -	Torque constant
KTR -	Torsion bar constant
FR -	Mechanical friction constant
ω -	Rotor angular velocity
Pos -	Rotor position

It can be seen that galvoscanner equations are similar to the pernament magnet DC motor, except the torsion bar torque. If the rotor excursion is below it's maximum the system is highly linear and it is possible to apply Laplace transform to it. Transformation of the previous equations let us write:

$$T_E(s)=TRC\cdot I_C(s)$$

$$RIN\cdot\omega(s)=T_E(s)-\left[T_{TB}(s)+T_{FR}(s)\right]$$

substituting for T_B and T_{FR} :

$$RIN\cdot\omega(s)=T_E(s)-\left[KTR\cdot Pos(s)+FR\cdot\omega(s)\right]$$

$$I_{CL}(s)=\frac{U_C(s)-\omega(s)\cdot BEM}{CR\cdot\left[1+s\cdot\frac{CL}{RL}\right]}$$

$$\omega(s)=s\cdot Pos$$

2.2.2. Galvoscanner model block diagram and transmittance

Using equations from previous chapter block diagram of the galvoscanner model (Figure 2.2.2.1) can be created. It is assumed that the input signal is voltage applied to the coil, and output is rotor position (excursion angle). It is also possible to watch rotor angular velocity and coils current.

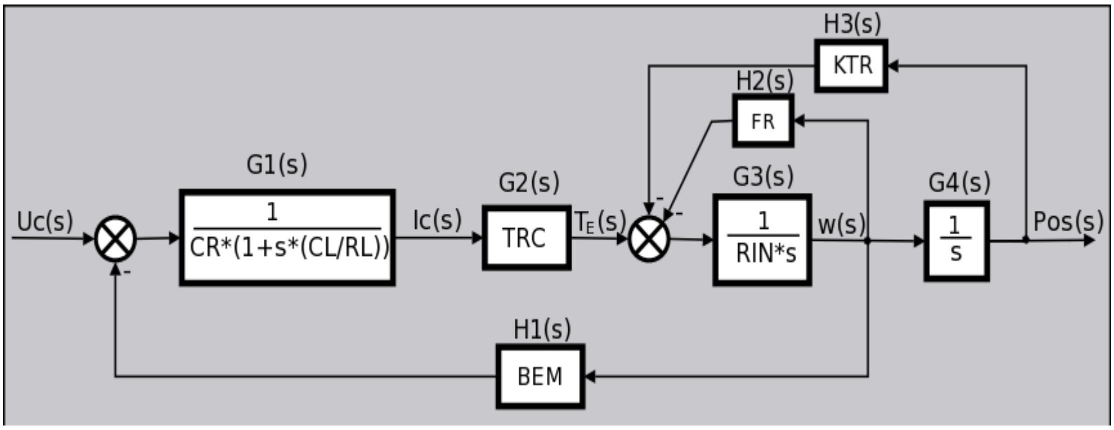

Figure 2.2.2.1. Block diagram of the galvoscanner mathematical model

Using this diagram the model's transmittance can be created. Reduction of blocks G3(s) and H2(s) to G5(s) gives:

$$G5(s)=\frac{\omega(s)}{T_E(s)}=\frac{G3(s)}{1+H2(s)\cdot G3(s)}$$

After substitution for G3 and H2:

$$G5(s)=\frac{\omega(s)}{T_E(s)}=\frac{1}{FR\cdot\left[1+\frac{RIN}{FR}\cdot s\right]}$$

Further reducing blocks G5(s), G4(s) and H3(s):

$$G6(s)=\frac{\omega(s)}{T_E(s)}=\frac{G5(s)}{1+H3(s)\cdot G4(s)\cdot G5(s)}$$

Note that transmittance G6(s) is still for ω. It is required because this signal is still used in the model (as feedback from BEM). Again substituting real parameters:

$$G6(s)=\frac{\omega(s)}{T_E(s)}=\frac{1}{FR\cdot\left[1+\frac{RIN}{FR}\cdot s\right]+KTR\cdot\frac{1}{s}}$$

Finally complete model input transmittance can be computed:

$$Gw(s)=\frac{\omega(s)}{U_C(s)}=\frac{G1(s)\cdot G2(s)\cdot G6(s)}{1+H1(s)\cdot G1(s)\cdot G2(s)\cdot G6(s)}$$

Substitution for real model parameters will yield to 3'th order transmittance:

$$Gw(s)=\frac{BEM\cdot(CR\cdot KTR+(CR\cdot FR+KTR\cdot TE)\cdot s+(CR\cdot TM+TE\cdot CR)\cdot s^2+TM\cdot TE\cdot CR\cdot s^3)+TRC}{(CR\cdot KTR+(CR\cdot FR+KTR\cdot TE)\cdot s+(CR\cdot TM+TE\cdot CR)\cdot s^2+TM\cdot TE\cdot CR\cdot s^3)}$$

The model have been simulated with Matlab/Simulink. Figure 2.2.2.2 shows Simulink block diagram of the presented model. Simulink model have been used to verify model behavior (comparing it to real device) and to verify ngSpice model presented below.

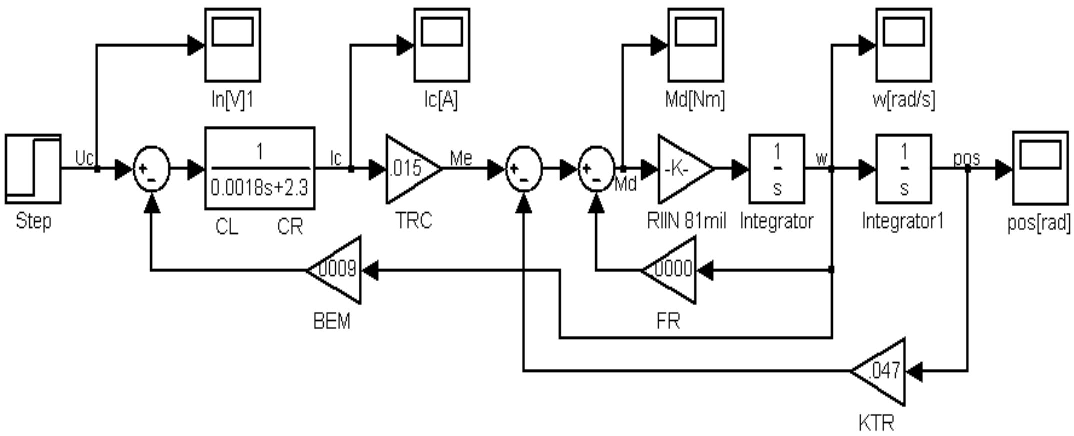

Figure 2.2.2.2. Galvoscanner model implemented as Simulink block diagram

Designing of the real regulator require using of circuit orientated simulator like ngSpice. It was needed for power amplifier, power supply and other circuits design. NgSpice have huge library of transistor, operational amplifiers and other components, so it is possible to create a very accurate model of the full electrical circuit. Fortunately it is possible to implement mathematical model from Figure 2.2.2.2 as ngSpise net list.

2.2.3. NgSpice implementation of the galvoscanner model

NgSpice is a Linux version of very popular Spice circuit simulator [11]. The main idea was to create model that will precisely follow mathematical model created before and let's quickly test many different control methods and check given regulator for (galvoscanner) safety. The model is supposed to determine if wrong tuning or some other errors in real circuit do not cause destruction of the real object. It would be very useful if the accuracy of the simulation will allow pre-setting the position regulator.

Fortunately in ngSpice it is possible to model all “parts” of the galvoscanner separately. This method allow to check what is happening “inside” the device and also ensure that the model will be realistic load for the power amplifier that powers it. Galvoscanner can be broken into four main parts:

- Stator coil
- Rotor with its inertia, torsion bar and friction
- Shaft load – mirror for example
- Position detector

In fact position detector (4) is not really part of the galvoscanner, but it is integrated in its case and every closed loop position regulator needs it anyway. Figure 2.2.3.1 shows how all these parts were modeled.

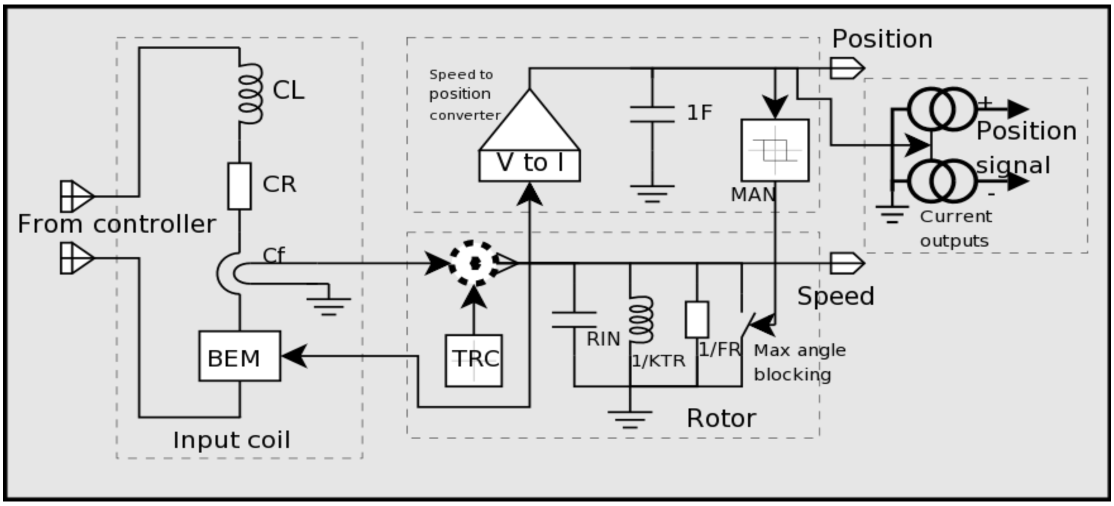

Figure 2.2.3.1 Galvoscanner model implemented as ngSpice schematic

In fact this is exactly the same model as was presented on Figure 2.2.2.1, it is only created by using electrical components (inductors, resistors) based on well known electro-mechanical analogies. Values of all model elements are set according to real device parameters. Input coil subcircuit consists of the coil resistance and inductance

(CL and CR), current sensor (Cf) and controlled voltage source BEM. This source multiples speed signal by galvoscanner BEM parameter creating back EMF voltage. Current measured by Cf (coil current in real object) is an input for rotor subcircuit. Multiplication of this signal by TRC parameter yields rotor torque.

RIN, KTR and FR are mechanical rotor parameters – rotor inertia, torsion rod constant and rotor dynamic friction. Speed output also acts as a load connection point. By connecting capacitors (inertia), inductors (springs) or resistors (friction) we can simulate almost any mechanical load that will be used with real object. Integration of the speed signal (done with V to I converter and unit capacitor) creates rotor position signal.

Additional comment is needed for “Max angle blocking” switch (in rotor subcircuit) and MAN block. These elements allows blocking the rotor when maximum angular excursion is exceeded. Connecting speed signal to ground throw very little switch resistance creates very high breaking torque on the rotor reducing it's speed to zero. MAN block constantly checks if current position does not exceed maximum angular excursion for the given galvoscanner and controls the switch accordingly.

Position signal is converted to differential current signal that match position detector outputs of the real device. Icom and Idif are the most important parameters here. With this model galvoscanner controller can be connected to the differential position detector signals and to the input coil.

The model will act just like the real object (loading the controller's power amplifier and so on) except the situation when maximum rotor angle is exceeded. Real object would became unpredictable (and possible damaged) while the model will just block the rotor signaling troubles with the controller. The model allows to watch almost all internal galvoscanner signals even those that are unavailable for observation in real device. For example real rotor torque during movement can be checked or back EMF voltage can be measured.

2.3. Galvoscanner parameters

To simulate galvoscanner it is necessary to know many parameters of the used devices. Unfortunately manufacturers not always provide even the basic ones except for those that are marketing – safe (or those that are for this or other reason better then competition). One of the best technical data sheets have Cambridge_Technology [6]. Table 3 shows most important parameters and theirs example value taken from Cambridge_Technology data sheet. Other companies usually don't provide all these parameters, and most of them have to be measured by the user.

Problems arises when it is needed to simulate galvoscanner behavior at the end or above its maximum rotation angle. Current – torque characteristic becomes extremely nonlinear and torsion bar behaves unpredictable. Sometimes even integrated position sensors don't work accurate. Of course one can say that it is possible to test real device and then provide some look-up tables for the model. This might actually work, but it means that we have to do destructive test on expensive galvoscanner and even then we get the data only for that model. Tests can be destructive if:

13. Torsion bar would be broken or lost its characteristic
14. Position detector might get destroyed
15. Coil connections would be broken in moving coil galvoscanners

Fortunately exceeding maximum rotation angle happens usually because of some kind of failure only, not during normal work. In this case it is better to assume that galvoscanner get destroyed and there is no need to simulate what will happen next. With such assumption it is enough to test for passing the limits what is rather straight-forward. To protect galvoscanners most of commercial controllers turn off theirs output amplifiers when they detect that rotor is above it's limits. In fact this is not always the best way to react in such situation.

For example imagine that the galvoscanner with heavy load (large moment of inertia) is turned to the one of it's limits at maximum speed. With badly tuned position regulator it is possible that the maximum angle will be exceeded momentary. Without protection the regulator will stop the rotor slight above limit, but when the protection circuits cut the power, large inertia will throw the rotor far above allowed position and possibly break the torsion bar. However, if the allowed position is exceeded because of power amplifier failure, cutting power off is the best possible solution.

Other useful features that could be implemented in galvoscanner model (assuming that required parameters could be obtained or measured) are:

- Thermal model of the coils (important in moving coil devices)
- Real outputs of the integrated position detector (if exist) – suitable for designing low level input circuits
- Saturation of stator core at very high coil currents (only in moving iron devices)
- Special features presented in some galvoscanners, like integrated thermistor, heater, tuning of position detector and so on

During research some effort have been made to create a thermal model and stator saturation model, but finally turned out that it was very hard to check the accuracy of the models. In fact is was not possible to saturate the stator with reasonably safe coil currents in real device. Table 2 shows example value of galvoscanner taken from it's technical documentation.

Table 2. Galvoscanner parameters.

Parameter name	***SI Unit***	***Example value***
Maximum excursion MAN	rad	40^o
Rotor inertia RIN	$kg\cdot m^2$	$0.125\,gm\cdot cm^2$
Torque constant TRC	$\frac{N\cdot m}{A}$	$6.17\cdot 10^4\frac{dyne\cdot cm}{A}$
Max coil temperature Tc	^oC	110^oC
Thermal resistance Tr	$\frac{^oC}{W}$	$1\frac{^oC}{W}$
Back EMF voltage BEM	$\frac{V\cdot s}{rad}$	$108\frac{\mu V\cdot s}{o}$
Torsion bar constant KTR	$\frac{N\cdot m}{rad}$	*No data*
Rotor dynamic friction FR	$\frac{N\cdot m\cdot s}{rad}$	*No data*
Coil resistance CR	Ω	$2.79\,\Omega$
Coil inductance CL	H	$180\,\mu H$
RMS coil current Irms	A	$3.9A$
PEAK coil current Ipk	A	$20A$

Above parameters are taken from Cambridge Technology data sheet [6]. All of these parameters have to be used in the simulation model if one wants to get accurate results. If position detector is also needed, it have to be modeled separate and there is needed additional set of parameters. Fortunately only two are essential for the model:

- Output signal, common mode Icom (example $I_{com}=155\mu A$)
- Output signal, differential mode Idif (ex. $I_{dif}=11.7\frac{\mu A}{o}, SI\ unit[\frac{\mu A}{rad}]$)

Following chapters will present how the parameters were measured for the galvoscanner used in the research. It was LSK moving iron galvoscanner, as was said in Chapter 1.5.3.

LSK 040EF Closed loop galvoscanner was chosen because of it's moderate cost, quite good parameters and because it was produced in Europe. Unfortunately LSK doesn't provide detailed documentation with the device [12]:

- Optical angle 40^o
- Coil resistance $2.3\,\Omega$
- Linearity $\pm 0.2\%$
- Zero drift $0.06\,\frac{mrad}{^o cel.}$
- Wobble $0.03\,mrad$
- Maximum torque $0.028\,Nm$

Response time was given as a set of curves according to mounted mirror size. It ranges from 0.5 ms for small angle to 1.5 ms for maximum angle and heavy mirror mounted. However response time is very depended on used controller maximum voltage and so on. All other parameters have to be measured on the real device.

2.4. Parameters measurements for LSK 040EF galvoscanner

2.4.1. Electrical parameters

LSK provided only DC coil resistance in the data sheet. Paradoxically this is also the easiest parameter to measure, by using technical method ($R=\frac{U}{I}$) or a simple ohmmeter. Coil inductance is much more important for the position regulator, and also harder to measure. Coil inductance for the LSK 040EF was measured using parallel resonant circuit as shown in Figure 2.4.1.1.

Using low-level signal generator (to not move the rotor) and an oscilloscope it is easy to find the resonance frequency of the circuit formed from external capacitor Cr and galvoscanner coil impedance Lc, Rc. Coil inductance can be computed by :

$$Fr=\frac{1}{2\cdot\pi\cdot\sqrt{L\cdot C}} \qquad L=\frac{1}{Fr^2\cdot 4\cdot\pi^2\cdot C}$$

To be doubly sure that the measurement are accurate they can be repeated for a few different resonant capacitors Cr. This will each time give different resonant frequency.

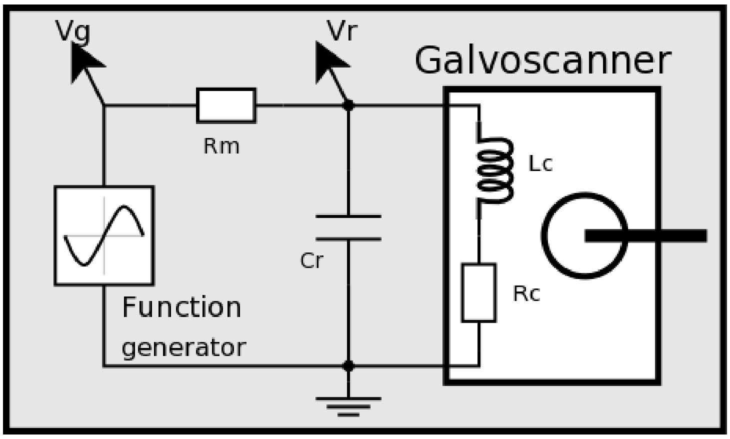

Figure 2.4.1.1. Circuit used for coil inductance measurement

The result can be then averaged. Measured coil inductance for the 040EF galvoscanner is:

$$CL=1.8\,mH \quad .$$

Measurement of some other parameters require precise knowledge of the current rotor position and it's speed. Of course 040EF has integrated position sensor that can be used, but it have to be calibrated first and there is needed some kind of interface circuit. It should keep in mind that almost all position detectors integrated with galvoscanners have low level differential current outputs with large common mode current.

The interface is needed to convert the differential current output of the position sensor to single ended voltage signal that can be connected to the oscilloscope or voltage meter. Also the precise scaling factors have to be known to get the real position of the rotor. Current to voltage converters can be realized using typical operation amplifiers.

Common mode current was measured with rotor in neutral position. Differential current was measured with the rotor moved to maximum angle in two other directions. With this data, position sensor parameters was calculated:

$$I_{com}=114\,\mu A \qquad\qquad I_{dif}=15\frac{\mu A}{o}=859.5\frac{\mu A}{rad}$$

Measurement of Back EMF Voltage was a bigger challenge. This is the voltage that galvoscanner will produce when it's rotor is moving. It is quite similar to the Back EMF Voltage in electric DC motors. Several methods could surely be used, however the most accurate will be to turn the rotor with a known speed and measure voltage that the galvoscanner will produce. Of course the rotor can not be simply turned around – it have to be moved back and forth along its allowed rotation angle. After some tries, two galvoscanners was used with it's shafts connected together. Figure 2.4.1.2 Shows the used setup. One of them was powered with a sine wave while the voltage generated by the other was measured. Integrated position sensor was used to measure rotor angle and speed. Input signal (sine wave powering one galvoscanner) was set to achieve near maximum rotor angle and a few different frequencies were used.

Digital oscilloscope was used to record all possible signals (input signal, position signal and output voltage). Then we can compute the derivate of the position signal (that is rotor speed) and measure the output voltage. Scilab was used to make all the necessary calculations.

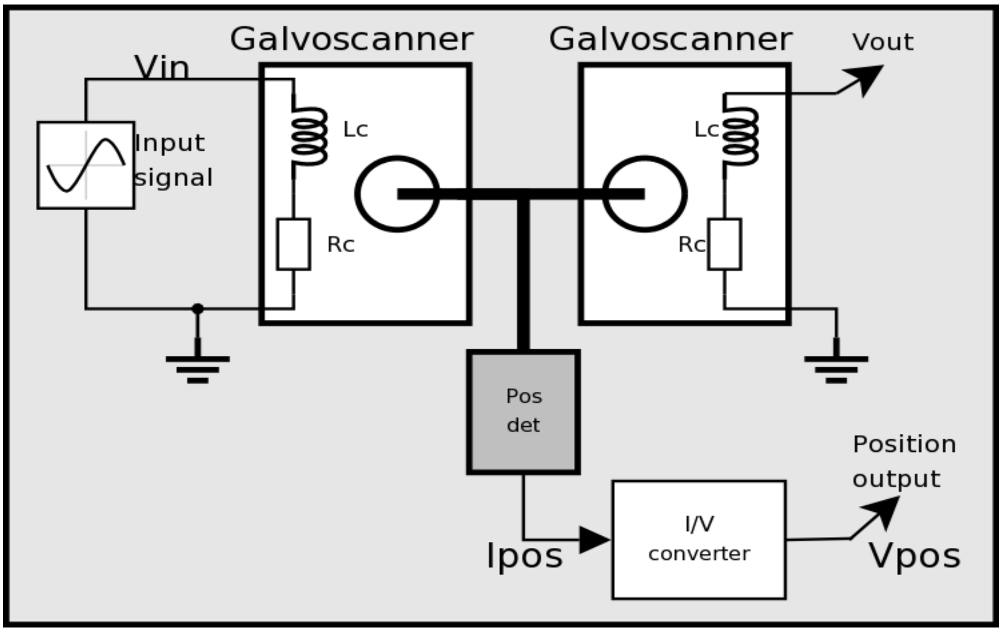

Figure 2.4.1.2. Circuit used for BEM measurement (2 galvoscanners used)

Calculated back EMF voltage is:

$$BEM = 7\frac{mV \cdot s}{rad}$$

It is very small, much less then typical value for moving coil galvoscanners. Such value is caused by galvoscanner construction – moving iron device has magnets and coils on the same core, while the rotor is moving inside the core. It is obvious that magnetic field surrounding the coils changes very little when iron rotor is moving.

In moving iron galvoscanners rms and peak coil current is limited only by maximum coil temperature. In fact peak coil current can be many times grater then rms current, but it is often unpractical to reach maximum value because torque will not increase as much as current. Moving coil galvoscanners are capable of producing larger torque because they don't have saturating iron cores. To estimate the values for the 040EF galvoscanner a few tests have been made:

1) Powering the galvoscanner with sine wave at different amplitudes (with blocked rotor) and measuring it's temperature.
2) Calculating power losses on the coil resistance and temperature rise to get the thermal resistance.
3) Attempt also have been made to check the current which will saturate the core, but in fact it was not possible to reach this values with reasonably safe current values.

Experiments with different current values and different cooling methods gives us some reasonable values, typical for galvoscanners of this size:

$$I_{rms}=2A \quad \text{and} \quad I_{pk}=7A \quad .$$

In reality the coil could withstand peak currents of 10 A or 12 A but this would require of using very high supply voltages. It would be also very inefficient operation because of required power amplifier and power supply.

2.4.2. Mechanical parameters

Rotor inertia is one of the most important mechanical parameter. It determines response time, position regulator tuning and power requirements for the given galvoscanner and load. However rotor mass is usually small compared to connected load (mirror for example). Because of these dependencies rotor inertia have to be measured when the needed load for the galvoscanner is known.

In this particular example galvoscanners will be loaded with small (3x3mm) laser mirrors. Inertia was determined by matching used galvoscanner with very similar model from General_Scanning that has inertia given in data sheet. Construction, mirror mounts and mirrors was the same for the LSK so we can safety assume that the rotor inertia will be very similar. Finally the value have been checked and adjusted during simulation. The value for rotor inertia is:

$$RIN=0.073\,gm\cdot cm^2=7.3\,nkg\cdot m^2$$

Torque constant depends only of galvoscanner construction and is constant in all normal working conditions. It is also quite easy to measure. For 040EF torque constant was determined by energizing the coil with it's maximum rms current and measuring torque on the rotor. Torque measurement in this case is easy because it is static torque. We can block the rotor and connect it by known length lever to linear force measuring device. This is shown on Figure 2.4.2.1 below.

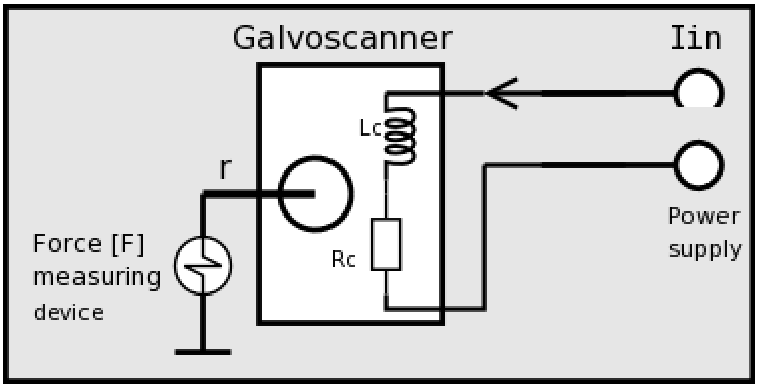

Figure 2.4.2.1 TRC measurement method

Then TRC can be computed as: $TRC=\frac{F}{r\cdot I}$. For the 040EF galvoscanner this is:

$$TRC=15\frac{mN\cdot m}{A}$$

Torsion bar (torsion rod) constant is rarely printed in data sheets. Even Cambridge_Technology does not gives this parameter. Fortunately with small excursions we can assume that the bar is linear and does not change it's characteristic over the time or temperature. Other problem is, if it can be assumed that, the torsion bar behaves linearly over the given rotation range or, if it is needed to use rather more complicated characteristic.

Performed tests did not gave any sure result. Finally it was assumed that torsion bar is linear over all working angle. With such assumptions the torsion bar constant KTR can be measured by determining torque needed to hold given rotor position (out of neutral of course). For 040EF the rotor was rotated by maximum allowed angle and the coil current needed to hold that position was measured. Knowing TRC calculation is straight forward:

$$KTR=\frac{TRC\cdot I_{coil}}{MAN} \qquad KTR=47\frac{mN\cdot m}{rad} \ .$$

Rotor friction and other mechanical loses are so small that it is almost impossible to measure them accurately. These values have to be adjusted during simulation and model verification. With recent technology manufacturers typical use ball bearings for the rotor that create very little friction. Position detector use non contact method, so it doesn't create any losses. Of course additional load can have static friction, dynamic friction and other “features”, but this is completely different task to identify the load. For simple small mirrors, friction is insignificant in comparison to inertia.

2.4.3. LSK 040EF parameters summary

Despite the very limited technical data that comes with 040EF closed loop galvoscanner all parameters required for simulation have been successfully measured. Parameters summary is in Table 3 and Table 4 below.

Table 3. LSK 040EF measured mechanical parameters.

Parameter name	***SI Unit***	***measured value***
Maximum excursion MAN	rad	$0.384\,rad$
Rotor inertia RIN	$kg\cdot m^2$	$7.3\,nkg\cdot m^2$
Torque constant TRC	$\frac{N\cdot m}{A}$	$15\frac{mN\cdot m}{A}$
Back EMF voltage BEM	$\frac{V\cdot s}{rad}$	$7\frac{mV\cdot s}{rad}$
Torsion bar constant KTR	$\frac{N\cdot m}{rad}$	$47\frac{mN\cdot m}{rad}$
Rotor dynamic friction FR	$\frac{N\cdot m\cdot s}{rad}$	$4\frac{\mu N\cdot m\cdot s}{rad}$

Table 4. LSK 040EF measured electrical parameters.

Parameter name	***SI Unit***	***measured value***
Coil resistance CR	Ω	$2.3\,\Omega$
Coil inductance CL	H	$1.8\,mH$
RMS coil current Irms	A	2A
PEAK coil current Ipk	A	7A
Position detector common-mode current Icom	A	$114\,\mu A$
Position detector differential current Idif	$\frac{A}{rad}$	$859.5\frac{\mu A}{rad}$

Future tests and comparison of simulation and real-live data proves that the computed or measured parameters where correct. The accuracy was well enough to provide useful simulation results. However author still don't know why manufacturers keep most of the technical data “secret” or “factory only” (therms used in one company's reply for author questions about the full technical data).

2.5. Model verification with real device

General idea of model verification is:

- Record the response of the real device
- Prepare the simulation with identical input signals
- Compare the results.

Unfortunately in reality there are some problems. The main one is to create input signals for the galvoscanner without a control system or even position regulator that will be designed after the simulation. It should be noted that it is very easy damage the galvoscanner by simple connecting it to low voltage DC source. Static torque needed to hold even maximum rotor angle is much less then dynamic torque that the galvoscanner can produce. If the DC voltage will be held for a little to long the torsion bar will break or lose its characteristic making device unusable.

On the other side if we limit the voltage to a safe value we will tests only behavior with very small rotor speeds. Of course full tests can be done with position controller but in that case the regulator have to be tuned before the test – what is very difficult and danger for the galvoscanner. The problem becomes a closed circle of dependency: an accurate simulation need to be performed before building real object, but can not be checked if the simulation is accurate enough without having this object working.

2.5.1. Initial, “low power” tests

To perform safe tests that will check if the model does not have any general errors a special procedure was used. First all steady state responses for DC excitations from the model and from the real object have been compared. Then the galvoscanner was connected to the square wave signal generator. The amplitude of the coil voltage was slowly increased to achieve about 90% of maximum rotor angle swing. Then the results (position, and coil current) was recorded on the digital oscilloscope. Then the simulation model was “connected” to identical input signal as the real device and the response was recorded. Finally model and real object response was plotted on the single axis and the difference was computed.

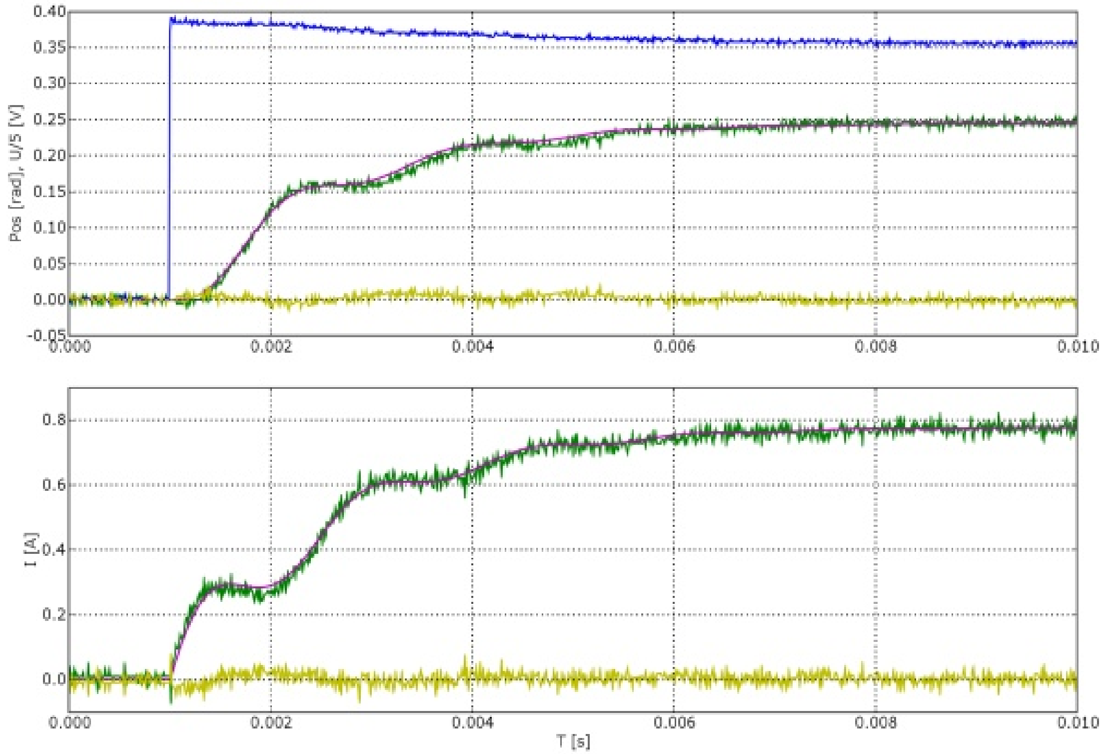

Figure 2.5.1.1. Galvoscanner model tests with small signals. Top – excitation voltage and rotor position, Bottom – galvoscanner current. Blue – excitation voltage, magenta – model response, green – galvoscanner response, yellow – model error

Figure 2.5.1.1 shows the results. Blue waveform on top axes is the input voltage measured on the galvoscanner's coil (divided by 5). Yellow waveforms on both axises are difference between model and the real device response (model errors). Position signal is presented on top axes, while galvoscanner current on the bottom one. Green color is dedicated to real device response, and magenta to model response. During research many tests have been made, however results were always similar. There is one representative sample presented.

Both position and current signals are modeled very accurately, errors are almost pure noise (from the measurement). The only differences can be seen at the middle of the rotor movement, or at begging of current rise. Now we can compute model quality factor, and standard deviation of the errors signals in percents.

For position:

$$MQF = \int \left(Pos_{gal} - Pos_{mod} \right) dt = 12.5 \mu\text{rad} \cdot s$$

$$std = 1.99\,\%$$

For current:

$$MQF = \int \left(I_{gal} - I_{mod} \right) dt = 22.4 \mu\text{A} \cdot s$$

$$std = 2.02\,\%$$

These values acknowledge correctness and good accuracy of galvoscanner model presented above.

2.5.2. Verification of the model with control system

After galvoscanner model initial verification limited to some tests in rather mild conditions, it was possible to make verification in hard conditions that could be realized in closed loop system only.

Galvoscanner current, voltage and position have been recorded on digital oscilloscope. Then model (with some passive components presented in the circuit) have been supplied with exactly the same voltage waveform and the same parameters have been recorded. Sinusoidal, triangle and square position reference have been tried during tests.

At first author wanted to compute Model Quality Factor and error standard deviation for this tests (as in low power tests) but because of limited memory on the used oscilloscope it was impossible to do it accurately. Computed quality factors was depended mostly on size of recorded signal and selected time window, not on used reference signal. Finally it was clear that simulation model have not reached steady state because much longer recorded signal was needed to achieve this.

Sinusoidal reference is the easiest for the regulator and model - simulation results are indistinguishable from recorded. Waveforms for square and triangle reference are presented on Figure 2.5.2.2 and Figure 2.5.2.2 below. On both figures blue waveform is the galvoscanner voltage, green is the recorded current (top) or position (bottom) and magenta is the simulation result.

Small differences in the current waveform (Figure 2.5.2.1 top) are not caused by inaccurate model but, by short simulation time - the model was not in steady-state yet as was stated earlier.

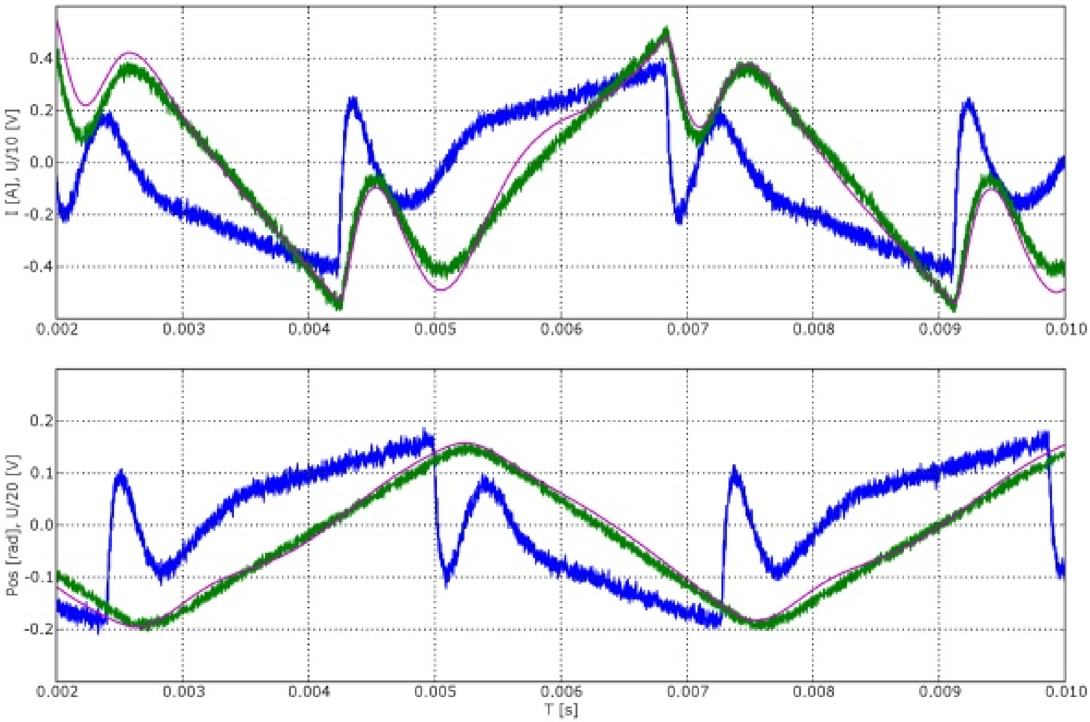

Figure 2.5.2.1: Model tests with large signals (triangle reference). Top – voltage and current, Bottom – voltage and position. Blue – excitation voltage, magenta – model response, green – galvoscanner response

The only way to fix this was to record much longer signals, however then the resolution of the plots was to low. The same problem can be seen below on position signal with square reference (Figure 2.5.2.2 bottom). Next slope on the same figure (at 8-9th ms) is simulated correctly.

Please note that the voltage on the galvoscanner reaches +/-20 V in peaks, while to hold the rotor at maximum angle in steady state about 1.7 V is needed. Such big difference causes problems in power supply and output amplifier cooperation and became an inspiration to formulate modified control system structure, that solves these problems in satisfying way.

From Figure 2.5.1.1, Figure 2.5.2.1 and Figure 2.5.2.2 we can see that the model is accurate in low voltage, open loop operation as well as in dynamic operation with full position controller. Results proves that model concept is correct and that parameters identification have been done right. Presented model can be used to simulate many different galvoscanners (moving iron and moving coil), but parameters identification needs to be repeated for every new device. Fortunately presented identification procedure can be applied to different galvoscanner as well.

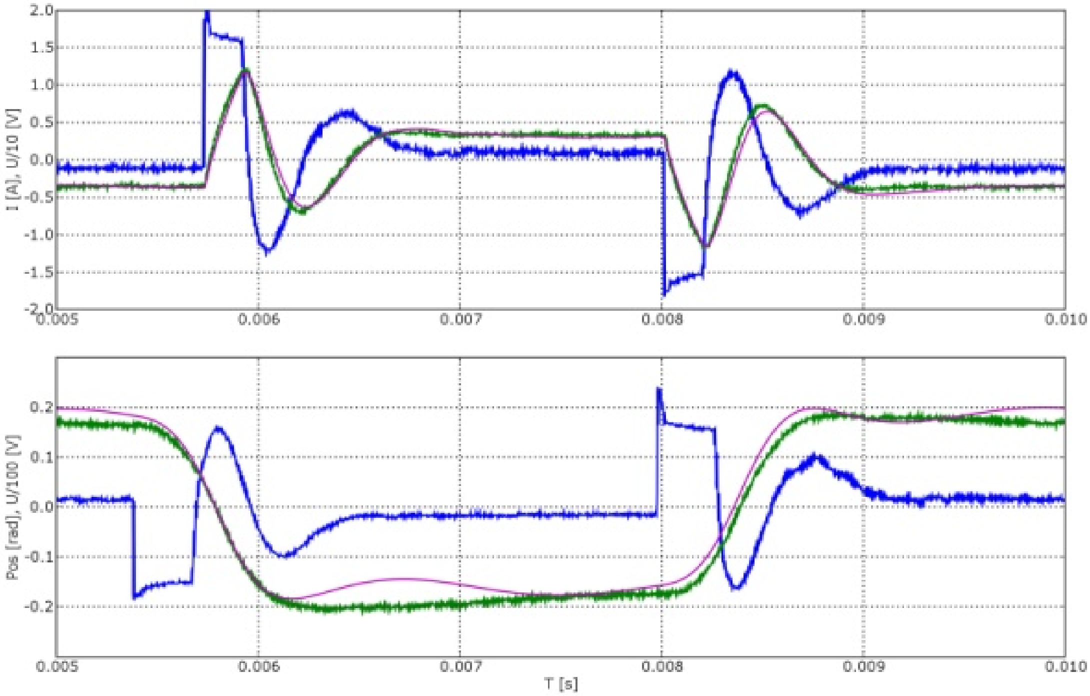

Figure 2.5.2.2: Model tests with large signals (square reference). Top – voltage and current, Bottom – voltage and position. Blue – excitation voltage, magenta – model response, green – galvoscanner response

2.6. Additional models needed for research

The galvoscanner controller used for research uses isp-PAC10 Lattice integrated circuits [13]. These elements (In-System Programmable Analog Circuit) allow very easy reconfiguration of the controller without any hardware changes. In fact reconfiguration can be done by connecting the controller to the PC and uploading new data to the isp-PACs with JTAG interface. The device has four independent programmable "macro-cells" that can be configured as an integrator or filter with defined gain and time constant.

Figure 2.6.1 shows simplified schematic of the isp-PAC10 single macro-cell. Amplifiers IA1 and IA2 have selectable gain (form -10 to 10), switch Sw can be set open or close and Cf are selectable. In reality the device has differential inputs and outputs with additional re-referencing circuit. This circuit assure that common mode output voltage will be always 2.5V (½ of the supply voltage).

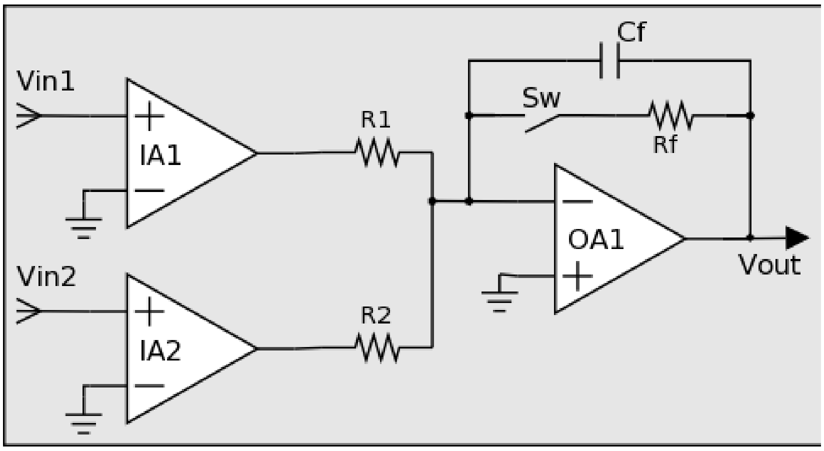

Figure 2.6.1 isp-PAC10 macro-cell block diagram

Lattice gives dedicated tools for programming and even simulation of the standard configuration of the device. However these tools have rather limited use if we need to integrate the device with other circuity or use complicated configurations.

The macro-cell model was created by transforming circuit from Figure 2.6.1 to ngSpice notation, taking into account that inputs and output is differential. Input and output voltage is limited from 0.5 V to 4.5 V maximum to assure that the model will catch over or under voltage conditions. Testing was done by comparing the model and real device response to given input signal in a few different configurations with very good results. This model will be needed for position regulator simulation, especially to check how it will work in “strange” setups.

3. Designed galvoscanner controller used for research

3.1. Hardware configurations of the control system

Typical galvoscanner control system has three layer structure - Figure 3.1.1. The first one is optional. It forms input data signal into position reference being time reference position trajectory- suitable to kind of input data, galvoscanner mode of operation and other requirements. The second layer is position control subsystem (position controller with position sensor) in which position controller generates current reference for subordinate current control subsystem. It consists of current controller, current sensor and power amplifier. Current controller generates reference of galvoscanner voltage, which is amplified in power amplifier and becomes galvoscanner voltage. In some less advanced (simpler) systems, current control subsystem is not used. Then galvoscanner voltage reference is generated directly by position controller. In this case system dynamics is worsened.

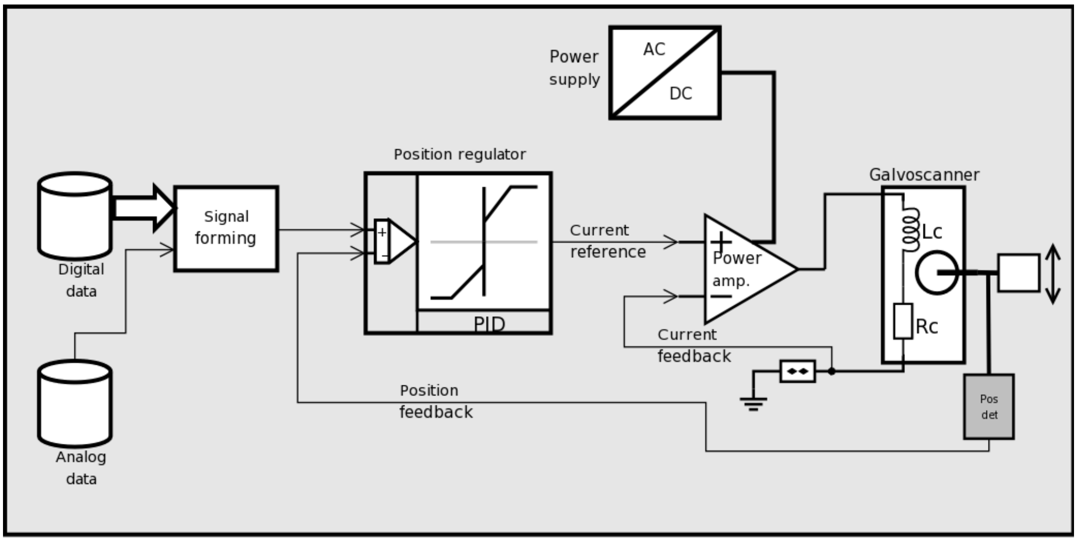

Figure 3.1.1 Galvoscanner's controller block diagram

Data input can be pure digital, pure analog or both – the final application will define the input [7]. Forming of the position reference signal is needed for example when we want to use digital input signal with analog position regulator or have data output device with complicated (hard to interface) outputs. Position regulator is obligatory for all closed loop controllers – it forms voltage or current reference signal for power amplifier that finally drives galvoscanner's coil. Position detector is typically integrated with the galvoscanner in the same case.

Galvoscanner's coil has large inductance and small resistance, so it is necessary supply galvoscanner with high voltage (+/-24 V or more), to achieve desired current dynamics. From another side the steady state voltage value, determined by small galvoscanner resistance, is much lower (usually more than ten times). During work cycle, instant required power varies in wide range. Then average power consumed by the galvoscanner is low (typically not more then 10 W), but this strongly depends on the application and input position data.

Today, with modern ICs and galvoscanners it is possible to implement controller in many ways: pure analog, pure digital or mixed (hybrid). For example we can use digital signal forming block with analog position controller. Quite a lot of different configurations have been used in the industry, but it is not clear which one works best.

3.1.1. “Mostly” digital controller system

By using high speed DSPs and A/D, D/A converters it is possible to create the controller that will have most of its “intelligence” in DSP or other processor. Figure 3.1.1.1 shows example controller of this kind. The controller have A/D converters that convert signals from position detector and optionally analog data source to digital (preferably 16 bit) word. Another D/A converter is used to convert DSP output to analog domain. DSP has to compute current reference signal (for current control subsystem) based on data input and current rotor position.

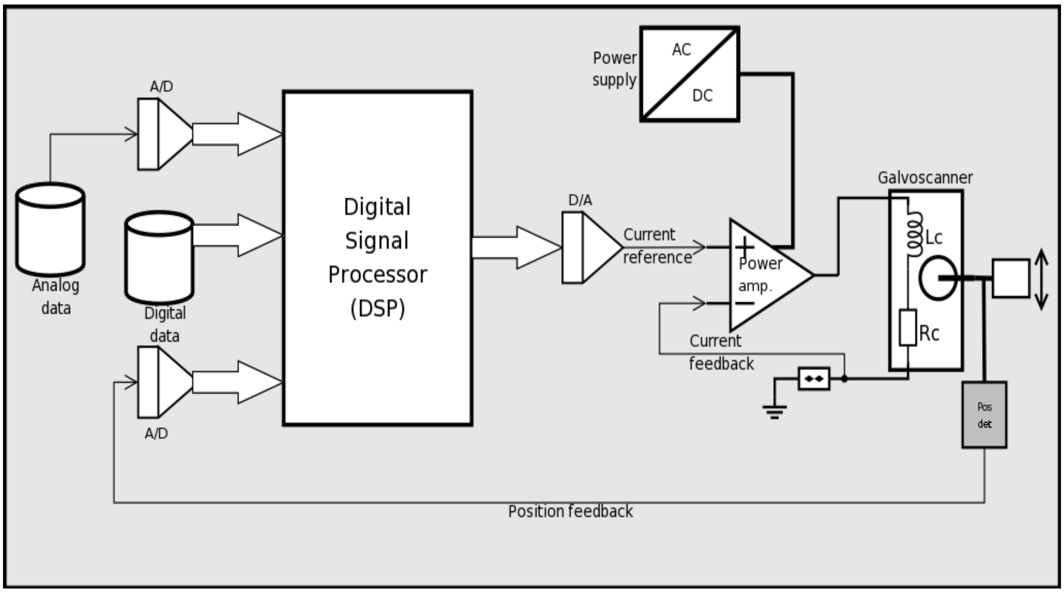

Figure 3.1.1.1 Digital galvoscanner controller

With this structure it is possible to implement many control algorithm like standard PID or others. The system is very flexible and it can characterized by:

- + all control algorithms are implemented in digital domain (in DSP firmware)
- + data input forming is not required when used with digital inputs, but have to be converted when used with analog inputs
- + it is possible to implement almost every algorithm for control or regulation
- + it is easy to tune the controller for different galvoscanners or loads
- + controlled can have some “predefined” parameter sets for different applications changeable by the switch or even automatically
- – it needs very fast and accurate D/A and A/D converters
- – DSP firmware have to work in hard real time mode
- – very fast DSP (preferably floating point) is required
- – small conversion errors or delays can have dramatic impact on the accuracy
- – firmware bugs can cause damage of the galvoscanner
- – very careful PCB (Printed Circuit Board) layout is needed to avoid difference between analog and high frequency digital parts.

3.1.2. “Mostly” analog control system

As the opposite to the previous, analog controller is show on Figure 3.1.2.1. In this controller all regulation and controlling algorithms are realized in analog domain for example by using operation amplifiers. Implementation of such controller is usually complicated, especially if additional functions like current limiter, thermal control or galvoscanner blocking are needed.

Typically simple PD or PID controllers are used. This kind of control system is the most often used in the industry.

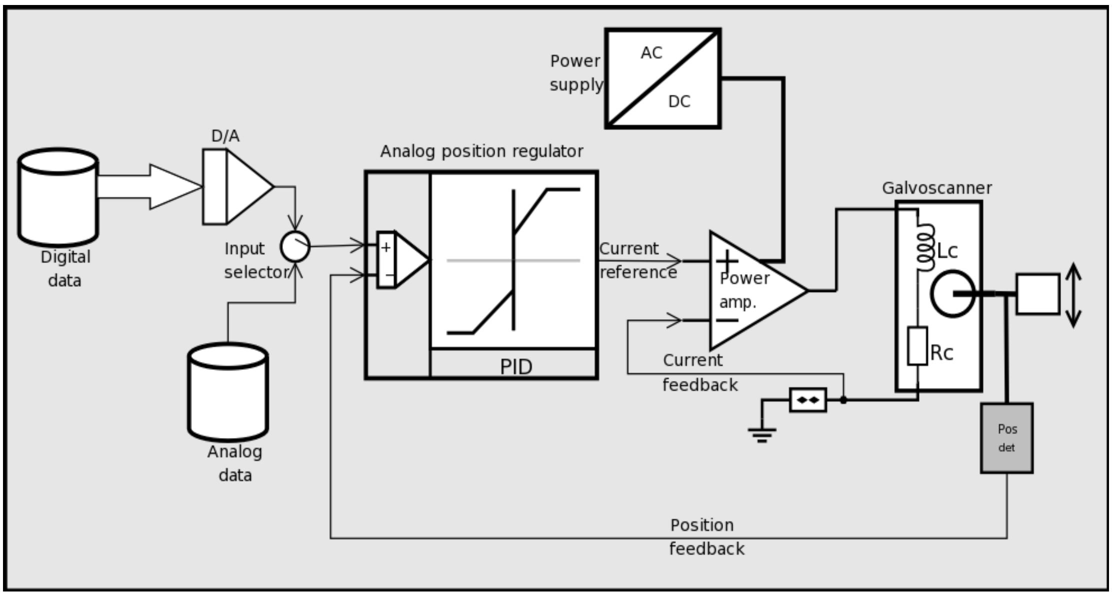

Figure 3.1.2.1 Analog galvoscanner controller

The system shown on Figure 3.1.2.1 has only one D/A converter that is used only for (optional) digital data conversion. The controller can be characterized by:

+ typically use only analog, well know and cheap parts
+ it is robust and even heavy disturbances doesn't cause catastrophic damage to the galvoscanner
+ tuning is done by potentiometers (one needs only a screwdriver to do this)
+ even very high accuracy controllers doesn't need very low noise or uncommon parts
+ it is known for long time in the industry and usually based on PID regulation algorithms
– hardware realization is complicated and need careful engineering
– retuning (for different application) is complicated and sometimes danger for the galvoscanner, because of interactions between controls and lack of visual feedback during setup
– it not possible to precisely change regulation parameters
– the controller works right with only one galvoscanner with one load
– there is a problem with realization of uncommon regulation algorithms (like fuzzy)
– galvoscanner protection circuits have to be implemented.

3.1.3. Other control systems

In the past there were a lot of attempts to improve the galvoscanner's control systems. Manufacturers concentrated on small modification of analog position controllers, trying to introduce something “new” before the others will do it. One company use derivate of the coil current as a “high frequency damping”, another provided adjustments for mysterious “big jump compensation” and so on. Unfortunately, beside these marketing slogans there are not any detailed informations about such attempts available.

In fact none of these modifications are very important and don't improve the system much.

3.2. Research galvoscanner control system

Research systems should allow to perform planned laboratory tests and also should allow some modification of the system itself during research. Planned laboratory research was:

– galvoscanner parameter identification (needed to simulation)
– determine reference quality data o typical galvoscanner system to enable

comparison with modified one
- verify results of simulation investigations
- verify effectiveness of proposed ways of energy efficiency enhancement
- look for other possibilities of improvement of system quality.

Most important is that it should be very universal and easily measurable and reconfigurable. Hardware changes needed for the reconfiguration should be minimal or even eliminated. High accuracy, robust operation is also important. Galvoscanner protection is desirable, because during research there are many things that can go wrong. The best would be, when the protection circuits are completely independent of the control system or power amplifier. Then "experimental" parts can fail but protection will be still active, possibly saving the galvoscanner.

After some initial tests and simulations author decided that reconfigurable analog position controller, power amplifier with current controller and digital signal forming block will the best fit the requirements. Such system will not needed very fast A/D, D/A converters or DSPs (as system with "mostly" digital controller presented in Chapter 3.1.1), but still it will be possible to reconfigure it (lack of reconfiguration possibility is main drawback of "mostly" analog control system from Chapter 3.1.2). Digital forming of the position reference signal causes that many "open loop" algorithms are possible to implement in precise and comfortable way. Figure 3.2.1 shows the block diagram of the designed controller.

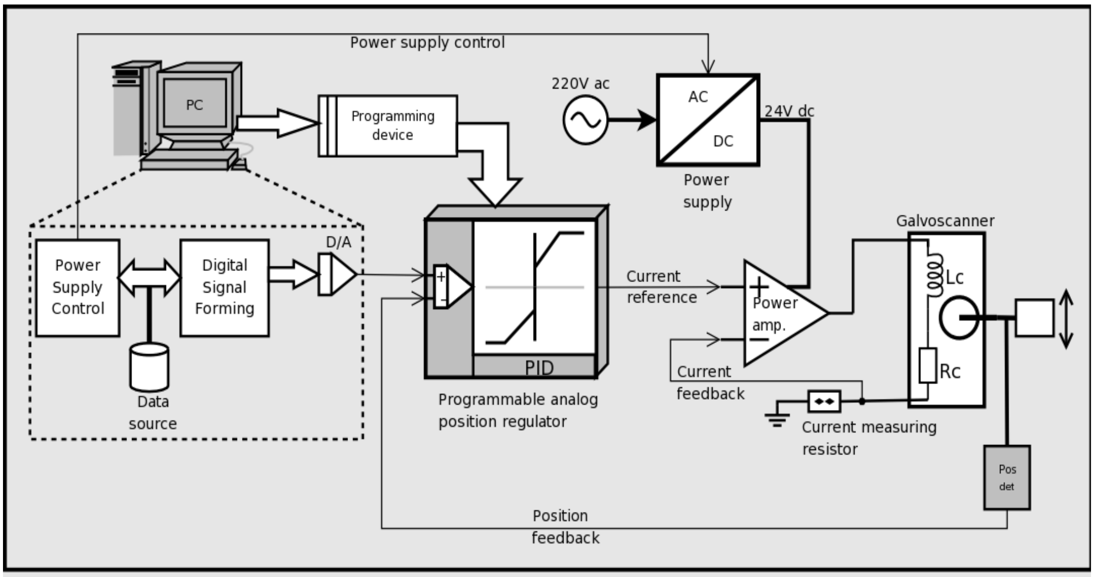

Figure 3.2.1 Designed galvoscanner controller used for research

Following chapters will present the blocks form Figure 3.2.1 in details. To achieve high efficiency and low losses power amplifier is sourced form regulated +/- 24 V DC source. This is relatively low value (as for galvoscanner controllers) but it helps keeping the power components small. Position regulator needs another +5 V and position detector is feed form +/- 12 V source. All needed digital signal processing is done in the PC computer in this system, but in a production version of the controller it should be done in dedicated DPS.

3.2.1. Current control loop

Current controller is realized by power amplifier as shown on Figure 3.2.1. It takes current reference signal form position controller and set the galvoscanner current to follow it. As was mentioned before, galvoscanner parameters (inductance, resistance) and maximal amplifier output voltage limit maximum slew rate of the current. During fast moves current slew rate is usually not high enough. The only way to improve it, is to increase range of the amplifier output voltage changes, what needs respectively higher supply voltage. It makes the controller much more power demanding, less efficient and a bit danger for the galvoscanner.

The amplifier uses modified proportional current regulator tuned to achieve minimum regulation time with no overshoot. Modification concentrates mainly on signal and feedback filtering to minimize risk of output ringing. In fact high frequency noise does not affect operation of the galvoscanner much, but it increases overall losses of the controller. Any ringing in the output signal might also increase high frequency noise generated by the controller. Additionally, even low level changes in the input will cause high output voltage variations because of high gain of the PI controller and inductive load.

The protection of the galvoscanner and amplifier itself is integrated in the used device. Protection circuits consist of over current limiter, short circuit turn off and thermal protection. Additionally amplifier has external “enable” input that can by used to quickly turn off the output in the case of other errors.

3.2.2. Position control loop

During development it was not clear if pure digital, DSP – based position controller will not be the best choice. Author have even created general outlook of such system. However in this case high quality A/D, D/A converters and very fast DSP would be needed. For research system the speed and accuracy is even more important then for typical application, because it is not clear what algorithms will be used or what parameters will be most important.

Another problem is that available audio A/D and D/A converters can not be used without careful study. Such converters very often operates in pipelined mode [14], creating large delays between input and actual sample output. Analog system on the other side lack the ability to reconfigure the controller, what would be very desirable for the research system.

Fortunately at the time of development Lattice introduced theirs isp-PAC programmable analog ICs. These devices are something that looks like PLD (programmable logic IC) but works with analog signals. Used device has four fully programmable differential amplifiers that can be also freely routed one to each other. Overview of the ispPAC-10 is given below on Figure 3.2.2.1 [13]. More details of the macro-cells and theirs simulation model was presented in Chapter 2.

The ability to analog routing and setting the amplifiers by JTAG interface was something that research system needed. By using ispPAC-10 devices it is possible to realize fully analog but freely configurable position regulator. The design was not straight-forward, but finally a good interconnection scheme for the macro-cells was found. The cells are arranged as follows:

Cell 1) Input signal filtering and creating position error signal. It also and outputs proportional regulator term

Cell 2,3) Filtered differential term computation (they realize differentiate operation on the position signal)

Cell 4) Modified integrator. This is the most meaningfully modified part of the controller (and the one that took the most time to design), because ordinary integration (as used in PID controller) does not work right in this controller

The position controller realizes its basic operations of proportional, differential and integral terms computation, complemented by additional auxiliary operations enabling reduction of disadvantage effects. Programmable hardware ensures meaningful flexibility of different control algorithm applications. It also shows new way of controller construction, programmable by cooperating PC and helpful in experimental research work especially.

During development a lot of problems have to be solved, for example programming device for ispPACs [15]. Finally the position regulator was created with single ispPAC-10 device and some additional passive circuits. The block diagram is presented on Figure 3.2.2.2.

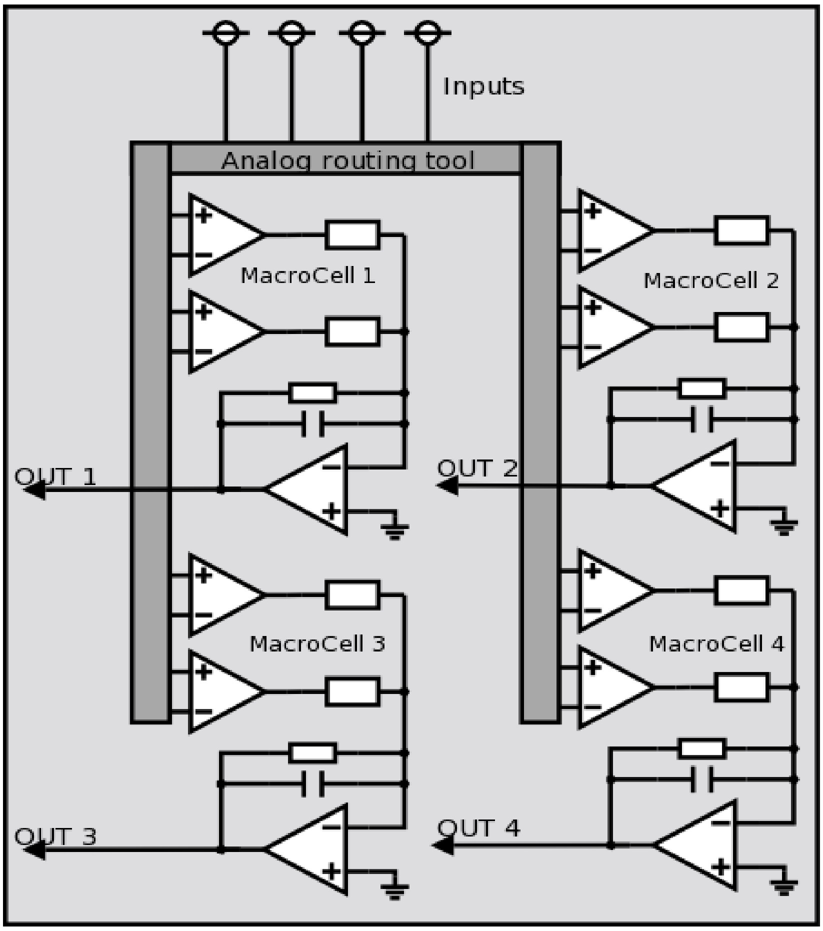

Figure 3.2.2.1 Lattice ispPAC-10 programmable analog device block diagram

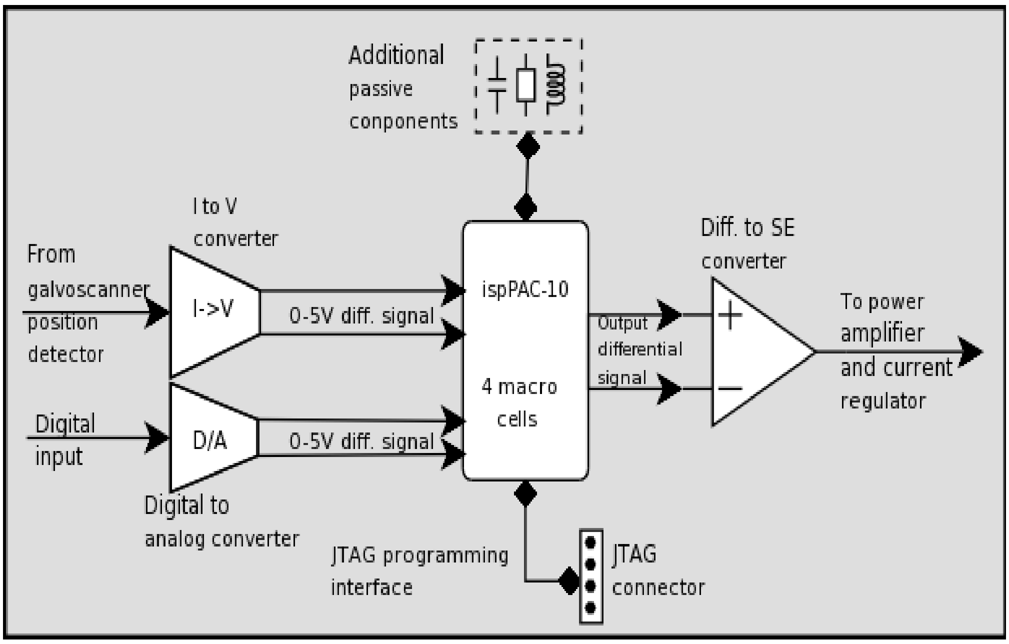

Figure 3.2.2.2 Analog position regulator realized with ispPAC-10 block diagram

Galvoscanner position detector outputs differential current signal that is converted into 0-5 V differential voltage signal. I to V converter also acts as a filter, that cleans up detector switching noise and other disturbances. IspPAC-10 device has some additional passive components connected to further increase gain and time setting range. It is also connected to five pin JTAG header used for programming and testing [16]. The last block (Differential to Single Ended signal converter) is used to prepare the output signal for current control loop and power amplifier that drives galvoscanner's in single ended mode.

Because ispPAC-10 has fully differential macro-cells, overall system is accurate and noise proof. In fact all signals are differential (including internal controller signals) except the “high power end“. The power amplifier needs single ended signal, however the differential – single ended conversion is done just before it. Differential configuration is also very resistant to power spikes or other power disturbances.

Designed controller is well suited for research work because it is safe for galvoscanners (no galvoscanners have been damaged during design) and can be easily reconfigured.

3.2.3. Digital position reference forming block

As was shown on Figure 3.2.1 digital signal forming block is used to actively process digital input data. The idea of performing additional digital signal forming before D/A converter and analog controller (really being position reference) was born, when it was found that small and big position changes (or “jumps”) need different control parameters.

Generally if small jumps were OK then system tends to overshoot at big jumps. On the other side if analog controller was tuned for big jumps, the small ones were realized to slowly. This effect is schematically shown on Figure 3.2.3.1. Even quite complicated regulators (non-PID) were not always acceptable. Such behavior was caused by torsion bar influence and by limited current slope in the galvoscanner. This typically calls for adaptive controllers that are very hard to design and implement, especially in analog domain.

With the selected hardware platform it is not possible to make an adaptive regulator anyway, so a different solution was needed. After analyzing a few concepts, the digital signal forming block before D/A converter was added. The micro processor (or micro controller) fetches digital data points, analyzes them, and compute new points that can be better followed by an analog controller. This task does not require fast processor because very high sampling frequencies are rather not used.

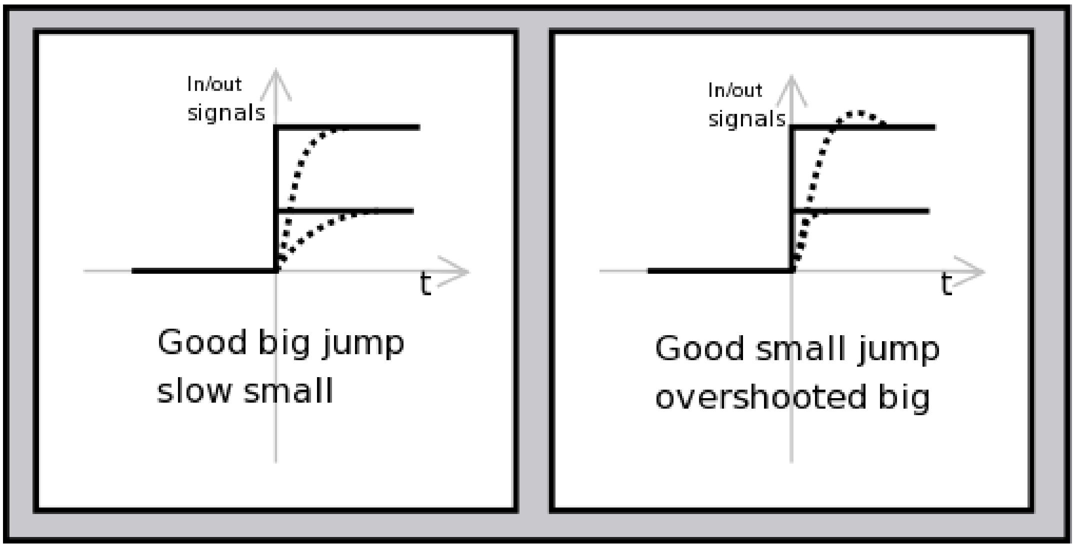

Figure 3.2.3.1 Regulator tuning problems for small and large jumps

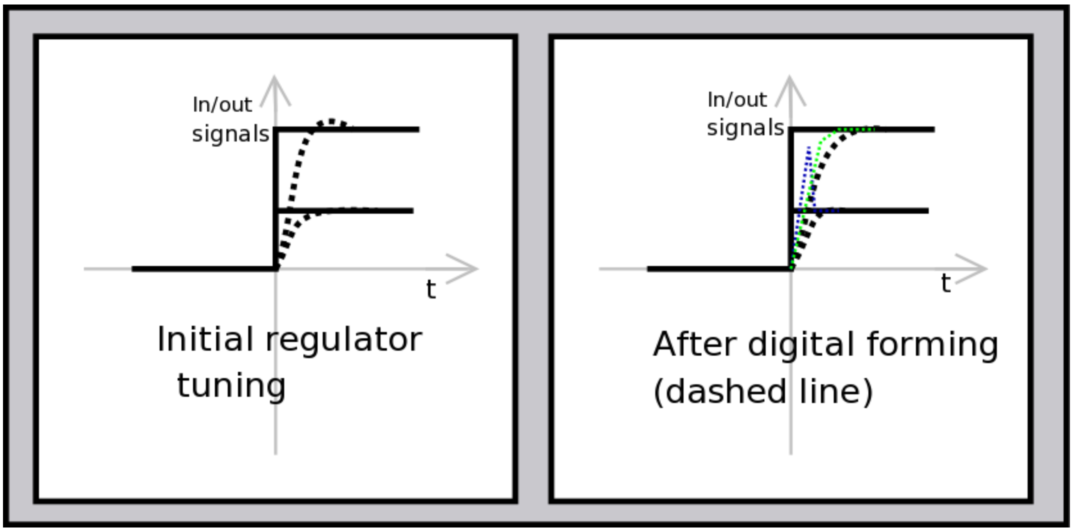

Figure 3.2.3.2 Regulator tuning and operation of the digital signal forming block. Black – reference signal, Dashed blue – signal formed for small jump, Dashed green – signal formed for big jump, Dashed black – galvoscanner position

Additionally algorithm runs in "open loop" further reducing processor load. During testing a normal PC was used, however most new micro-controllers (like PIC18 or better dsPIC for example) would be enough for this task. Large memory is fortunately also not required. The analog controller have to be tuned "to the middle" - small overshoot at big jumps, and not to large delay at small ones – as shown on left half of Figure 3.2.3.2.

Right half of Figure 3.2.3.2 shows how the digital signal forming block is working (dashed lines). For small jumps (blue line) it gives large “impulse” at the beginning of the move (assuring large acceleration of the galvoscanner). In contrast, for large jumps (green line) it reduces the slope of the input signal, finally setting the commanded level.

The way of determining if large or small jump processing should take place have been hard to solve in first implementation of the controller, because hard “mode switching” (small – large jumps) created very unpredictable behavior. When the commanded position was set to square wave signal, with amplitude close to the preset boundary, some jumps were realized differently then others, and response time was not constant.

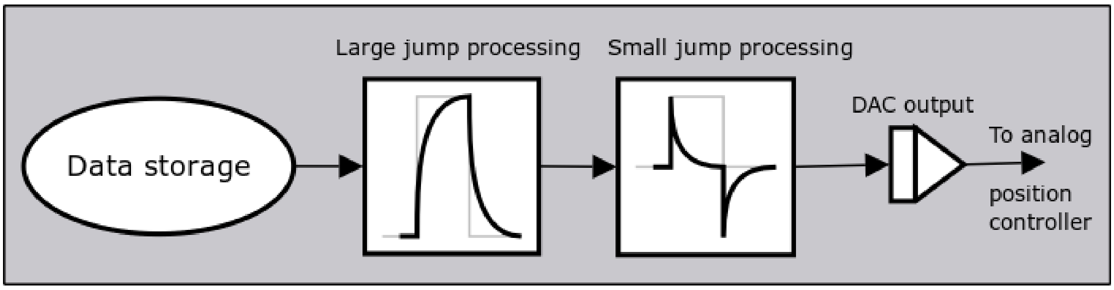

Figure 3.2.3.3. Block diagram of the digital position reference signal forming block.

Final implementation (shown on Figure 3.2.3.3) has both blocks working together. Firstly, large jump processing takes place, reducing signal slopes. Then, small jumps are boosted to achieve better acceleration and breaking. In this way there are no hard “mode switching”, because both block always work together, completing each other. Large and small jump processing blocks are realized as look-up tables in the PC.

The context of these tables have been obtained empirically, by hand adjusting values to get the best response. Finally used algorithm has 2 separate look-up tables (256 values each) – one is responsible for reducing of the slope on big jumps, one for giving impulse on small jumps. To reduce quantization error (table pointers are 8 bit length) special smoothing function is used to extend output to 16 bits.

The point is to reduce the error that is seen by analog controller and to prevent saturation of integration block. This idea works really good and seems to be much more universal and accurate then other methods used by some companies. However we have to remember that analyze is possible only if the points send to the galvoscanners are delayed from original. This might cause problems for certain applications, but it is possible to minimize the delays changing digital forming block parameters.

This method also can not work for application that require real-time data following, like target tracking. Such mode however needs different tuning of regulation parameters, and it will be presented later in chapter 5.

3.2.4. Summary of galvoscanner control system

Presented control system allows author to successfully test and debug many different galvoscanner's control algorithms: PD, PID, modified PID with and without digital signal forming block.

The best results have been achieved by using mixed control system that consist of:

- Digital data source - position vectors stored on hard disk on any other media
- Digital signal forming block – running in the PC or DSP, prefetching data points and changing them to achieve maximum performance from analog position controller and galvoscanners
- Analog position controller – build over ispPAC-10 programmable analog IC, that performs modified PID position control for galvoscanners
- Power amplifier and current controller – amplifies low power differential signals from analog position regulator (to 24 V / 2 A max) for galvoscanner.
- Controlled power supply for power amplifier – by controlling supply voltage for power amplifier it was possible to reduce losses and increase system efficiency. Details about this block will be given in following chapters
- Programming device for ispPAC-10 ICs – please refer to appendix 1 for details.

3.3. Complete controller and efficiency problems

3.3.1. Complete controller used during research

Previous chapters contains description of the main blocks that was used to build complete closed-loop galvoscanner's control system. Physically two channel's analog regulator and power amplifier was build on a single printed circuit board, measuring 12x15 cm with surface mounted components. The board also has a heatsink for power amplifiers.

Two channels was used because it was possible to test much more possibilities and configurations then with single channel. Two channels also allows projection of laser images on the screen, using wildly available and popular in laser shows business “ILDA” files. LSK galvoscanners was mounted on custom X-Y mounting platform with small mirrors on the shafts. The system is presented on Figure 3.3.1.1 and Figure 3.3.1.2 below.

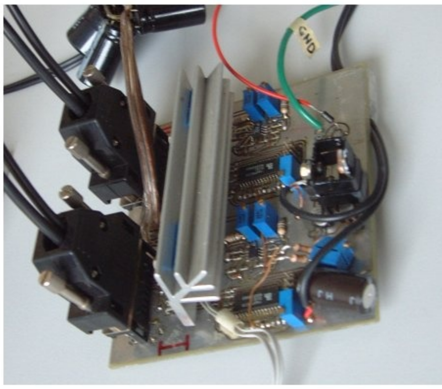

Figure 3.3.1.1 Analog regulator and power amplifier main board

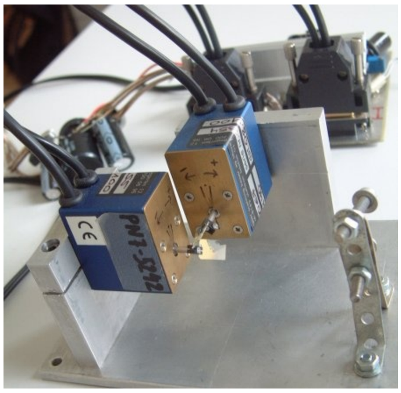

Figure 3.3.1.2 Galvoscanners with mirrors on the XY mounting platform

During tests various lasers were used, X-Y projection results are not described in this paper. Normal PC with DAC's card was used as a data source. The PC also performs digital signal forming needed by the analog regulators. During tests digital oscilloscope was used to record system responses, galvoscanner's voltage, current and other parameters.

This system was initially used to create sample laser images or animations, but in fact visual effect is not very important or meaningful. To get the best looking images a special test pattern and tuning procedures should be used [17]. These procedures are not designed with accuracy in mind and systems that was tuned according to them often shows overshoots and other inaccuracies. However all this flaws are not important in the laser shows and in that are area they perform very well.

Presented system would be best suited to material processing application, but it can work for any application that require precise rotor positioning, without any overshoot or oscillation. Speed is also an concern here, however only if reference position is reached without overshoots.

4. Soft-Switched power supply for galvoscanner control system

4.1. Efficiency problems

During initial tests it became evident that small heatsink used in the system is not enough for the power amplifiers. Firstly it was even not clear why they are running so hot, when the calculated galvoscanner power consumption is rather small (10 W maximum). However everything became clear when we look at the galvoscanner voltage and current way form Figure 4.1.1. Because of the large coil inductance, relatively high voltage (+/-24 V) is needed to achieve required current raise time, but during steady state (when rotor is not in neutral position) only a small portion of this voltage is needed.

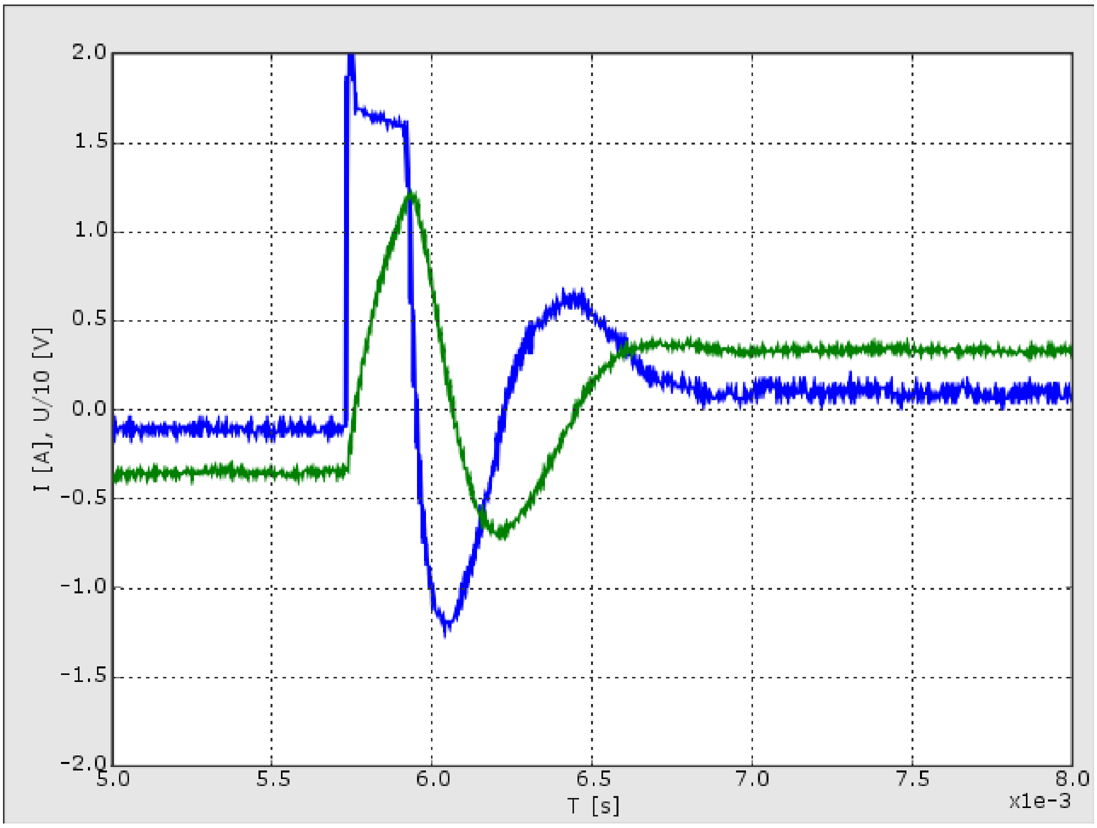

Figure 4.1.1. Galvoscanner voltage (blue) and current (green) during jump and steady state

This effect is explained on Figure 4.1.2 and Figure 4.1.3 below.

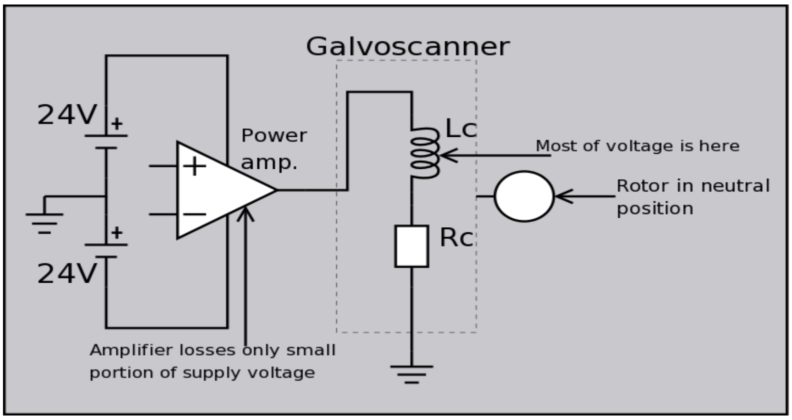

Figure 4.1.2 Equivalent circuit of output power amplifier and galvoscanner during begging of the movement

When the rotor is in neutral position (as on Figure 4.1.2) no current is needed. When the movement begins, we usually need high acceleration in short time, what means very fast current rise. Because of Lc (which is 1.8 mH for LSK galvoscanner) current controller need to apply all available voltage to the galvoscanner. In reality, with small loads, current never reach the limit – the raise time is still to low and we have to begin to break before that time. Because almost all of the supply voltage is on the galvoscanner very little power is dissipated in the power amplifier.

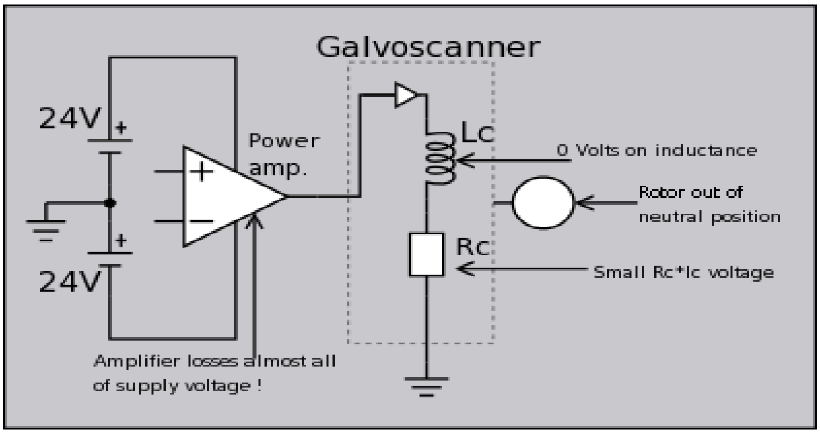

Figure 4.1.3 Equivalent circuit for power amplifier and galvoscanner during steady state with rotor out of neutral position

When the rotor is kept steady near maximum angle, as in Figure 4.1.3, the situation is different. Because of the torsion bar we need to supply constant current to the coil to keep the position. For LSK galvoscanners this current is about 0.5 – 0.7 A. Lc voltage is 0 with DC current, so all voltage is on the Rc, that is only 2.3 ohm in our example with 040EF galvoscanner. Rest of the supply voltage need to be dissipated in the power amplifier. Now we can compute the steady state power losses in the amplifier:

$$Pa = Ua \cdot Ic = [Us - (Ic \cdot Rc)] \cdot Ic = [24\text{V} - (0.5 \cdot 2.3)] \cdot 0.5 = 11.425\text{W}$$

where:

$Pa[W]$ -	Power amplifier power losses
$Ua[V] = Us - (Ic \cdot Rc)$ -	Power amplifier voltage
$Ic[A]$ -	Galvoscanner coil current
$Us[V]$ -	Power supply voltage

More then 11 W of losses is needed just to keep the rotor steady! Average power consumption during normal operation is less, but during testing such situation is quite typical – for example we use low frequency square wave max to max when testing or tuning the regulators.

To overcome this problem a special soft-switched power supply was used. This supply control the voltage that is actually needed by the galvoscanner and adjust it to limit the losses.

4.1.1. Power supply requirements

To increase efficiency of the system we need to provide a special controlled power supply. Output voltage of such supply should be similar to the voltage needed by the galvoscanner itself – in this way power lost on linear power amplifier would be minimal.

Ideally the power supply should keep only small voltage loss on the amplifier, but realistically only reduction of the voltage during steady state is possible. The required voltage (during high speed operation) is changing to fast to be followed by any power supply. Fortunately losses during normal operation are not very high.

Because galvoscanners (especially position detectors) and analog regulators are very sensitive to electrical noise very "quiet" power supply is required. EMI (Electro-Magnetic Interference) and other disturbances as well as noise in the supply voltage should be minimized. Output voltage also should be very well filtered. To achieve high efficiency with large variation of the voltage a high frequency switching supply is preferable. Switching power supplies are however known source of EMI what can disturb system operation [18], [19].

To sum up power supply should meet particular requirements:

+ Output voltage must be as high as needed by the galvoscanner in dynamic state (+/- 24 V), while output current must be at least maximum peak current allowed by the galvoscanner (3-5 A)

+ Output voltage need wide control range, form 0 to maximum value
+ Output voltage regulation time should be low (below 10 ms)
+ EMI generated by the supply should be minimal
+ Power efficiency of the power supply should be high (over 90% is desirable).

4.1.2. Power supply control problems

Even the best regulated power supply will not work fast and accurate enough to constantly keep the voltage across power amplifier Ua low. If maximum possible efficiency is needed class "T" amplifiers [20] might be an answer and are subject for future tests.

The considerations above let to formulate an idea of application of additional special low bandwidth voltage control loop that would control only the power supply. Such loop should reduce the losses during steady state (that are dominant) not disturbing amplifier and controller operation during transients. Power supply controller have to estimate time curve of needed voltage and set the reference to the power supply according to the estimated curve. Typical (not forward) control would produce errors like these graphically shown on Figure 4.1.2.1.

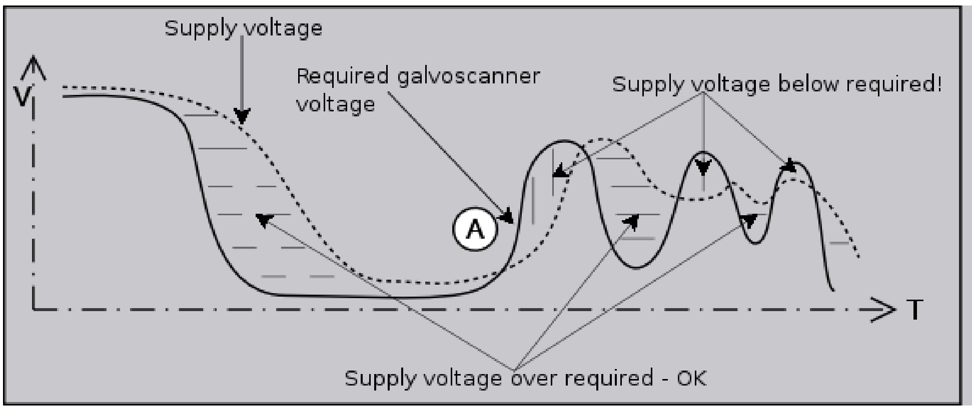

Figure 4.1.2.1 Example output from power supply without voltage prediction algorithm (solid line – minimum supply voltage, dashed line – power supply output voltage)

During control process controller have to compute galvoscanner voltage $u_g(t)$ that is also amplifier output voltage. This signal defines minimum supply voltage $u_{smin}(t)=u_g(t)$. In reality supply voltage have to be higher to insure correct work of the amplifier itself, so we control power supply by using reference voltage:

$u_{sref}(t)=u_{smin}(t)+u_0$ where u_0 - constant parameter.

Minimum supply voltage $u_{smin}(t)$ and power supply reference voltage $u_{sref}(t)$ is predicted in real – time, basing on galvoscanner position reference signal. Prediction algorithm have to include power supply dynamics (voltage rise/fall time) to achieve desired results. This algorithm can be realized in many ways, some of them will give better efficiency then others. In this research author wants to test the concept only, so simple prediction algorithm have been used.

If the power supply is controlled from a microprocessor that also controls position data (for galvoscanners), we can analyze the data before it will be send to the galvoscanners and calculate the reference voltage. In this way the power supply doesn't need to be very fast – required voltage will always be reached on time if the digital system knows the delays. Such controller can also be integrated with digital signal forming block, presented before.

4.1.3. Voltage reference prediction algorithm

Presented power supply and it's control system was designed using standard PC computer running on QNX real-time operation system (today RTAI Linux is a good free alternative [21]). The computer outputs voltage reference to the power supply that controls it in analog mode. All other needed computations are done by the PC.

Using previous example with the minimum supply voltage (from Figure 4.1.2.1) the presented power supply with prediction algorithm is working like on Figure 4.1.3.1.

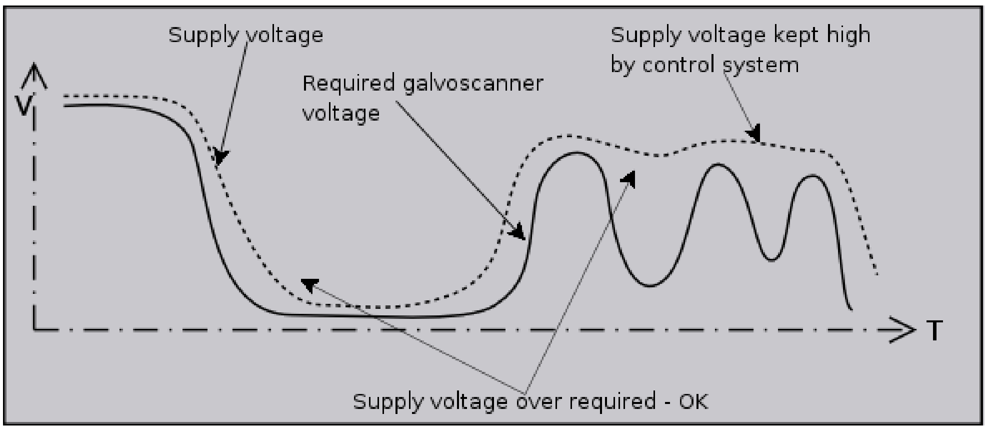

Figure 4.1.3.1. Example output from microprocessor controlled power supply with prediction algorithm (solid line – minimum supply voltage, dashed line – power supply output voltage)

When required voltage changes quickly supply voltage is kept high, over the maximum required values. This might decrease efficiency and increase losses in power amplifiers but unfortunately there is no other (except class T amplifiers) way to keep maximum speed and accuracy. When galvoscanner is kept in one position for a long time supply voltage is reduced, but it is raised before fast moves begins. The situation becomes more complicated when we have two channels powered from single power supply. However microprocessor just do the same prediction of the reference voltage for two channels and chooses higher value.

Of course it is possible that losses in one channel will be very high while it is stopped because the other one might need full voltage at the same time. Fortunately practice shows that such situation is very rare and the system works correctly. The losses in the power amplifiers are low and quite small heat sinks used are enough to keep acceptable temperature.

Of course not all applications can use such implementation – for example target tracker don't know how the target will move, so a priori prediction of the needed voltage is totally impossible.

4.1.4. Hardware configuration of the power supply controller

For the presented research system a special innovative ZVS-CV (Zero Voltage Switching – Clamped Voltage) with modified power circuit was used. This power supply is greatly overpowered for the galvoscanners, but it was build with other uses in mind. It is also an experimental system itself.

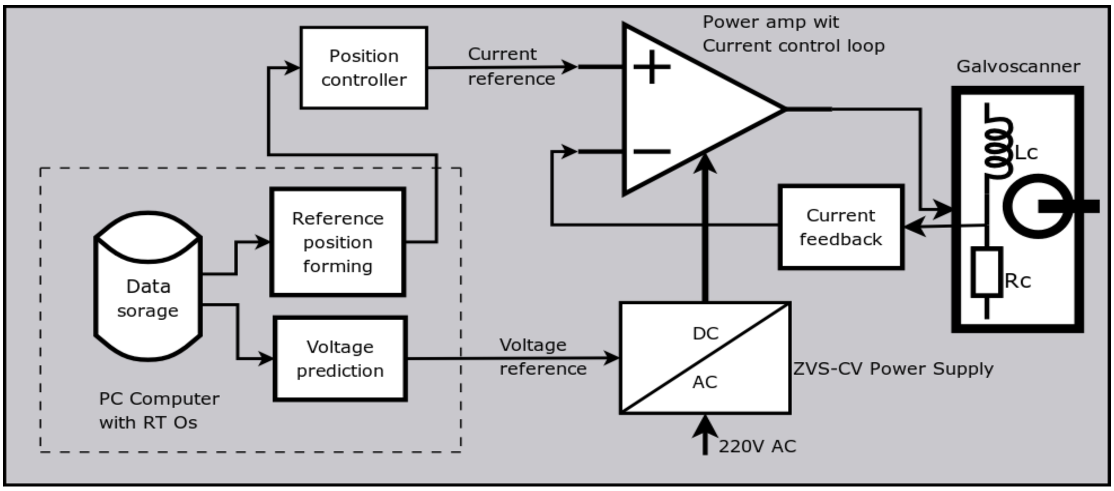

Figure 4.1.4.1 Block diagram of the voltage control system

Figure 4.1.4.1 presents block diagram of the used configuration. Power supply is controlled from the same PC that also performs “digital signal forming” functions for the analog regulator. The PC is also a source of data points that are read from memory during scanning or generated on the fly (for example square or sinusoidal waveform) during testing or tuning.

4.2. Special, low noise ZVS-CV power supply

4.2.1. Drawbacks of the typical ZVS-CV power supply

As was stated before a very “quiet” power supply with low EMI is preferable especially for research purposes. It should be noted that most commercial ZVS power supplies are not well suited for this particular application because they are designed to work with mostly constant load that is in 80%-100% of nominal. Also fast voltage changes on the output are not allowed.

Typical ZVS-CV power supply presented on Figure 4.2.1.1 operates at fixed frequency with variable phase shift between primary bridge branches [22]. This permit identical operation of the bridge branches independent of the output duty cycle. Each branch operates with 50% duty, what is needed for soft switching, while the output voltage can change. When M1 and M4 or M2 and M3 are on, transformer primary is supplied from input DC source. If the phase shift between 2 branches is less then 180° transformer primary is periodically short circuited by M1 and M3 or M2 and M4. In this state no power is transferred to load. If the MOSFETs in the same branch would be driven without any delays simultaneous conduction could occur, causing a short circuit of the DC source. Knowing very fast switching times of the MOSFETs and theirs low resistance an catastrophic failure would occur. Dead-time between commutation of MOSFETs in the same branch should be added prevent this. However this dead-time not only reduce the risk of the short circuit but also can achieve a ZVS operation.

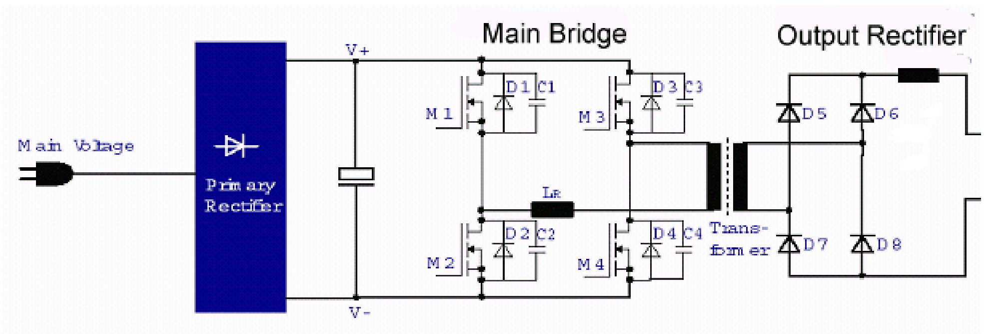

Figure 4.2.1.1. Normal ZVS-CV power supply

To understand this operation, let's assume that M1 and M4 are conducting (transferring power to load) and then, in the end of this period switch M1 is turned OFF. When both devices in the same branch are off, energy stored in transformer's leakage inductance LR will keep current flow in the same direction as before. This current can not now flow throw M1 or M2 so it would flow throw the capacitors C1 and C4, discharging capacitance C2 and charging C1. The diodes prevent negative voltage on C2 and over DC supply voltage on C1. Finally when voltage across M2 is reduced to 0 the switch can by turn ON without lossless. The dead-time should be adjusted to match transition time that varies due to transformer primary current changes.

During next transition (from M2, M4 to M2, M3) operation is similar, but the primary current is lower or even zero. We should keep in mind that with short circuited primary, the current flow is kept only by energy stored in LR. During next transition, when M4 turns OFF, LR energy might not suffices to charge C4 and discharge C3. The voltage across M4 will not goes to zero and lossy switching will occur. The primary current (LR current) is defined by the power supply load. When the load gets smaller current is reduced and lossy switching begins. M1 and M2 will be switched at zero voltage longer then M3 and M4, because LR current is always greater during M1, M2 transition. At no-load or very low-load the energy stored in LR is almost zero, so it is not possible to achieve zero voltage switching for any branch.

Such ZVS-CV supplies have some problems with EMI and losses when output current drops below some critical value that is needed to keep zero voltage switching [23]. Then switches become hard switched thus EMI and losses increase. This is especially true for high power supplies that operate from high voltage DC sources.

They use big power MOSFETs (IGBTs are usually to slow) that have large parasitic capacitance Cs. The MOSFETs cannot be mounted very close together because of the required heat sink. Fast switching of power devices causes very high pulse currents during commutation. When any MOSFET in the bridge is closing it shorts out it's own Cs (discharging it from full DC source voltage) and other MOSFET's Cs in the same branch is charged at the same time. The currents involved can easily reach 100 A or more in the pulses. These pulses are repeated two times each operating period of the supply.

All energy stored in parasitic capacitances is lost in the MOSFETs during switching. This causes a lot of EMI in the rest of the circuit, especially if the input bridge is large, and losses are high. This generally does not cause problems with cooling (because heat sinks have to be designed for such power), but efficiency of entire system will be significantly reduced. Normal ZVS-CV supplies should not be used in this mode, or should be completely turn off if no load is connected. To improve the low-load operation a saturable inductor is sometimes added in series with primary winding of the transformer. This technique does not work right when both phase shift and load are changing, and cannot help if load current is zero.

4.2.2. Modification and design of the low EMI ZVS-CV converter with resonant inductors

To solve the problems with EMI and low load operation a special ZVS-CV power supply have been designed with the objective to maximally reduce EMI and increase efficiency in all modes of operation [24]. Circuit shown on Figure 4.2.2.1 consist of transformer (TR) fed from full bridge MOSFET converter (M1-M4). Parasitic capacitances (C1-C4) are also shown. The transformer does not have to have controlled leakage inductance, because two additional resonance inductors (LR1, LR2) are added. The transformer and output inductor (LF) are planar, because of very high losses caused by skin effect that could occur at this current level and frequency.

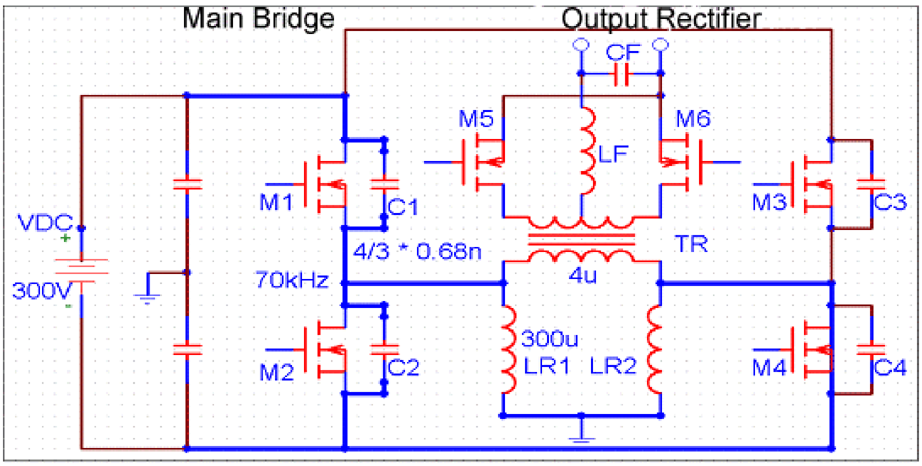

Figure 4.2.2.1. Modified ZVS-CV converter with resonant inductors

Resonance inductors LR1 and LR2 have to be carefully chosen to achieve ZVS mode and have no impact on normal operation of the supply (details will be given later). Also power MOSFETs have to be controlled from special “intelligent” driver that constantly sets dead-time (delay between switching of MOSFETs in the same converter branch).

Output voltage (or current) is controlled by phase-shift like in normal ZVS-CV supply. If properly chosen, inductors LR1 and LR2 will cause ZVS independent of output current and phase shift in all switches. It is also possible to reduce LRt (leakage of the transformer), which reduces ringing at the output rectifier. The prototype has active output rectifier made of low voltage MOSFETs that have less voltage drop then Schottky diodes. Rectifier MOSFETs are also much faster then diodes so ringing is lower. In fact even the fastest diodes turn on or off as a result of voltage level on anode and cathode, so they are always "late".

Active rectifier can be driven in the manner that all switches will be in proper state exactly when needed. Output filter inductor was chosen quite large not only to reduce current pulsation. It also reduces short circuit current and stress on power devices when such situation occurs.

Above about 40-50% of nominal load presented power supply operates like normal ZVS-CV converter. Transformer current is much larger then LR1 or LR2 current, so these inductors don't play any significant role is this mode. Large output filter inductor and active rectifier helps to keep the primary current high even during free wheeling period (when primary is shorted by MOSFETs). This current lead to identical operation (with ZVS mode) of both branches, independently of output voltage.

Converter controller have to set the dead-time as short as possible according to load current and phase shift. Long dead-time reduces maximum duty-cycle and output voltage. Without load or with low load only inductors LR1 and LR2 can achieve ZVS, because transformer primary current is almost 0.

4.2.3. Analysis of the modified ZVS-CV power supply

To make theoretical analysis and find out the proper values of LR1 and LR2 a simplified schematic of single MOSFETs branch can be drawn. As shown on Figure 4.2.3.1, only MOSFET's parasitic capacitances and inductor LR1 are taken into consideration. However to use this schematic it is necessary to know other power supply parameters before. Output voltage, current and input voltage are usually determined by the application.

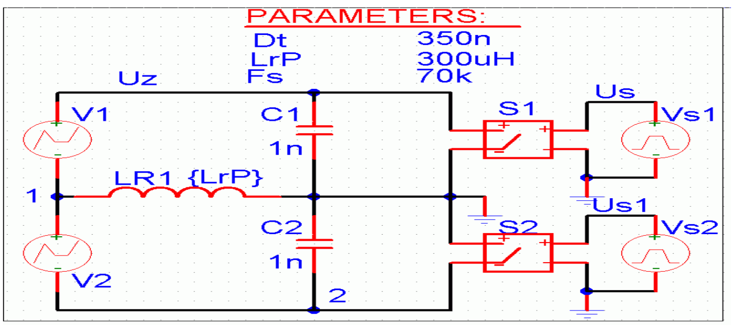

Figure 4.2.3.1. Simplified schematic of the single converter branch

One of the most important parameter that is set by designer is the operating frequency. It is determined by allowed weight and size of the converter, magnetic materials used for cores and semiconductor devices. For this supply Fs = 70 kHz (period Ts = 14.286 μs) was chosen, because of magnetic cores and skin effect that might be problematic in high current windings of the transformer. Large output MOSFETs with big capacitances also work better at lower frequencies.

The dead-time (Dt) between switching of MOSFETs in single branch was determined by the controller used and by the transition time at full load. At full load transformer current is large, so transition time is very short. Controller however, does not set the dead time properly when difference between full-load and low load dead-time is to big, so maximum Dt have to be limited. For this supply Dt = 350 ns at no-load was chosen as the most optimal value.

Parasitic MOSFET's capacitances C1 and C2 can be obtained from data sheets, but because of Muller's effect the capacitance should be increased by 4/3 for analysis. For devices used in the prototype correct value is 0.7 nF. Transformer capacitance can be spread symmetrical between C1, C2 and added to them. Measurements show that used transformer has 0.6 nF parasitic capacitance. Adding these values gives $0.7+\frac{0.6}{2}=1\,nF$ for C1 and C2. This power supply was connected to 220 V AC outlet that gives 300 V DC after input rectifier and filter.

In Figure 4.2.3.1 we can see that there are four possible states of the circuit, but only three of them are valid from technical point of view. State with both switches closed will create short circuit with V1, V2, S2 and S1. The valid states are:

– Switch S1 is ON and S2 is OFF - Inductor LR1 is supplied by single DC input source V1.
– Switch S1 and S2 OFF – Inductor LR1 recharges C1 and C2
– Switch S1 is OFF and S2 is ON – Symmetrical to 1, but the polarity across LR1 is reversed

State 1 and 3 persist for $T13=\frac{Ts}{2}-Dt=\frac{14.286\,\mu s}{2}-350\,ns=6.793\,\mu s$ while state 2 lasts for Dt = 350 ns. In state 1 and 3 voltage on LR1 is constant, while state 2 is short enough to assume that current in LR1 does not change. According to these statements every state can be described by an equation.

State 1 and 3:

$$U_{LR1}=L_{R1}\cdot\frac{di_{LR1}}{dt} \tag{1}$$

LR1 voltage is constant while its current linearly increase. Maximum occurs at the end of state 1. In steady state LR1 current is symmetrical, so:

$$I_{LR1max}=\frac{1}{2}\cdot\Delta i_{LR1} \tag{2}$$

State 2:

$$I_{C1}=C1\cdot\frac{du_{C1}}{dt} \tag{3}$$

During state 2 we can assume that C1 current is constant because LR1 is relatively large and Dt is short. C1 voltage increase form 0 to (V1+V2), while C2 voltage decrease from (V1+V2) to 0. To achieve ZVS voltage across C1 or C2 must change by full DC input voltage or 300 V in dead-time period Dt. Currents in C1 and C2 have the same value but opposite sign, while LR1 current is the sum of them.

$$I_{LR1}=2\cdot I_{C1} \tag{4}$$

From (1), (2), (3) and (4) maximum LR1 inductance and maximum current can be computed. The computed LR1 value can be seen as "the largest that achieve ZVS with given C1, C2 and Dt".

$$LR1=\frac{Ts-2\cdot Dt}{16\cdot C1}\cdot Dt \qquad I_{LR1_{max}}=\frac{0.5\cdot Ts-Dt}{2\cdot LR1}\cdot Uz \tag{5), (6}$$

The RMS current in LR1 can be easily computed, because it is symmetrical triangle-wave, and we know its maximum.

$$I_{LR1rms}=\sqrt{\frac{1}{Ts}\cdot\int_0^{Ts} i_{LR1}^2(t)}=\sqrt{3}\cdot I_{LR1\,max} \tag{7}$$

Knowing that Ts = 14.28 µs, Dt = 350 ns and Uz = 150 V we get LR1 = 297.3 µH, $I_{LR1_{max}}=1.71A$ and $I_{LR1\,rms}=1A$. Computed value is the maximum value for LR1 that will achieve ZVS. Smaller inductors could be used, but in this case current would be higher and in fact we would end up with a bigger inductor and bigger losses.

Theoretically average voltage across LR1 in steady state must be zero. M1-M2 branch in the converter works with 50% duty-cycle all the time, but M3-M4 branch can has some disturbances, when the phase shift is changing. However the duty-cycle differs very little form 50% and difference time is so small that it never causes any problems.

4.2.4. Control system of the power supply

Presented ZVS-CV converter is controlled by integrated circuit (UCC3895) specially designed for such application. It consist of phase controlled PWM module, two independent dead-time modules and analog amplifier. This amplifier can be used as an output voltage or current regulator. Because of the large time constant of the output LC filter (compared to the switching frequency) and to improve regulation accuracy two loop system was used. Inner current loop consist of PI regulator, while the voltage is controlled by PID regulator.

Real device can easily change it's output voltage in about 1ms without any ringing and it is quiet enough (low EMI) to not disturb precision analog circuits.

It is evident that presented system is rather complicated and it might be difficult to set up and tune out of the laboratory. However it proves that the idea is correct and it is worth to implement. Of course for miniature or low-cost system it is possible to scale it down, removing some blocks, or using simplified versions.

4.2.5. Tests performed on the real device

After successful commissioning of the presented power supply a lot of tests have been made. Designed prototype is over sized for the galvoscanner control system, but it have been build to also suit other applications. Performed tests include:

+ EMI and other disturbances emission
+ Efficiency for various output currents and voltages
+ Output voltage and current ripple
+ Response time for current or voltage reference signal
+ ZVS for various loads

All of the tests have been passed by the prototype.

5. Experimental results and regulator tuning methods

5.1. Control system tuning requirements

In previous chapters it was stated that almost every application needs different tuning of analog and digital controllers. For example image projector for laser shows will concentrate on overall look of the image, while accuracy and overshoots are not very important. On the other hand system used in material processing machine have to control position as accurately as possible, while speed control is secondary concern.

We can also divide the applications between the ones where the data (position reference) is known a priori, and the ones where the position reference is difficult or even impossible to predict. This division very important for the system presented in this paper, because were the data is not predictable it is not possible to use digital signal forming block. Where the data is known we can even pass it throw digital forming, and store processed data before performing actual functions.

The requirement to know the data a priori might seem to be a very serious limiting factor for the presented system. Fortunately most of the galvoscanner's applications have all data available before actual run. These applications are:

- Material processing machines
- Laser shows, image projection
- Semiconductor processing
- Most of medical applications

Only a few others need to relay on unpredictable inputs. The most important is target tracking in military systems. In such systems target is “marked” by a laser beam that is placed on and follows it. The position accuracy is very important for target tracking applications, but in fact they do not produce very difficult signals for galvoscanner's position controller. For example Figure 5.1.1 presents example – often meet in reality 2D trajectory of the target. Such trajectory consists of some sharp turns, and long straight runs.

Next Figure 5.1.2 shows the required galvoscanner's position and speed to follow target form Figure 5.1.1. Solid line is X position and speed, while dashed line Y.

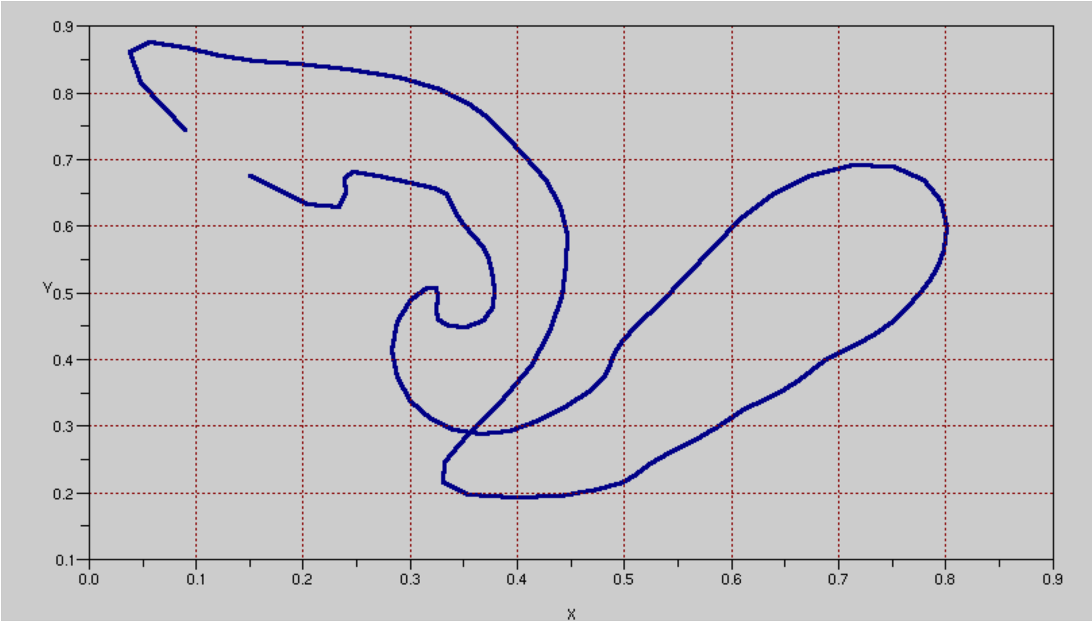

Figure 5.1.1. Example, arbitrary X-Y trajectory of the target

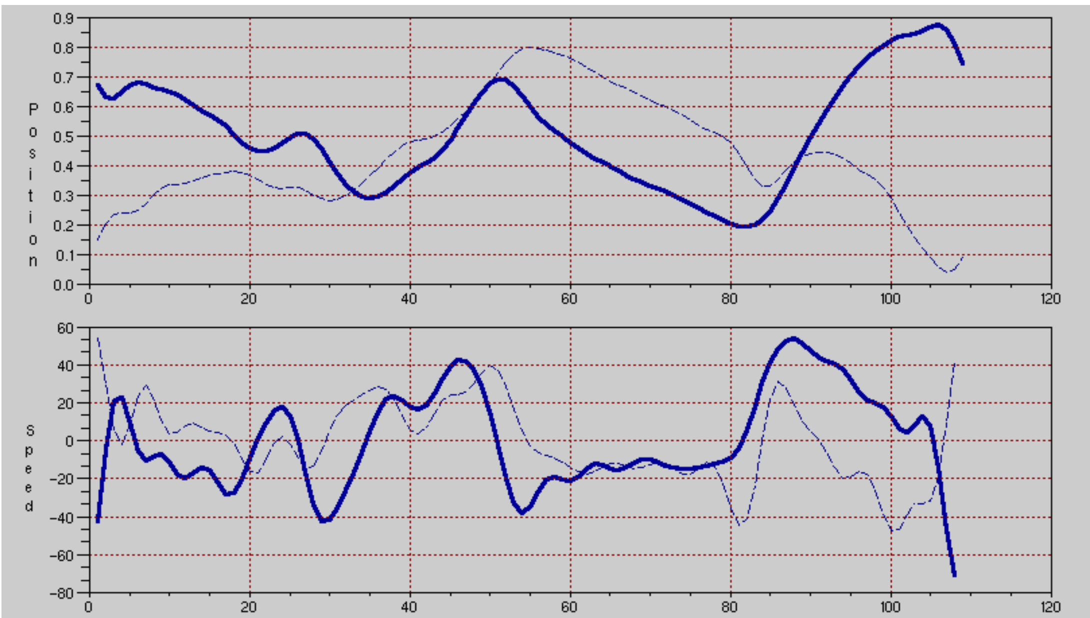

Figure 5.1.2. Required X (solid line) and Y (dashed line) galvoscanner's position and speed to track the target from previous figure

As we can see from Figure 5.1.2 even quite complicated trajectory requires only slowly changing, continuous position signals. These signals are easy to follow for the position controller because they have no discontinuities or fast slopes in relation to galvoscanners possibilities. Galvoscanner controller should be tuned to achieve minimum response time and maximal position control accuracy, without worrying about overshoots that could occur after the step input signal.

Position controllers should always have error integration part. This is necessary, because it is impossible to set proportional error amplifiers for enough high gain, to achieve desired accuracy.

High gain setting can very easy produce oscillations, quite often non damped, and in extreme cases oscillation with constantly increasing amplitude. Second case will almost surly destroy the galvoscanner.

5.2. Position controller performance

5.2.1. Methods for measuring position controller performance

Companies that produce galvoscanners or drivers for them, gives some performance data, however it is not clear how it was really measured. On many data sheets we can see “step response time” or “small signal step response time”, but we can not be sure if the values given by different manufacturers means the same.

When comparing performance achieved by different driver and galvoscanners common quality criterion is needed. However there is no defining the response times or position controller performance. Figure 5.2.1.1 shows different possibilities for response time determination. For standard rise-time “t1” can be used measured from 10% to 90% of the full signal. However for material processing application step response rise-time “t”, measured form reference signal step to the point where 99% or even 99.5% of reference position is reached, would be much more valuable.

For others applications (target tracking for example) step response time is not so important, anyway. Step signals usually do not exist there, however time delay from reference position waveform to actual position is critical. This concept can be seen on Figure 5.2.2.2, when we consider time delay between magenta (reference position) and green (actual position) waveform.

When it comes to control system performance, situation is more complicated. As it was stated earlier controllers can be (and should be) tuned in different ways, dependent on the final application. For laser shows overshots, as shown on Figure 5.2.1.2 are no problem, while for material processing they would be not acceptable. This means that regulation time can also be determined in different ways.

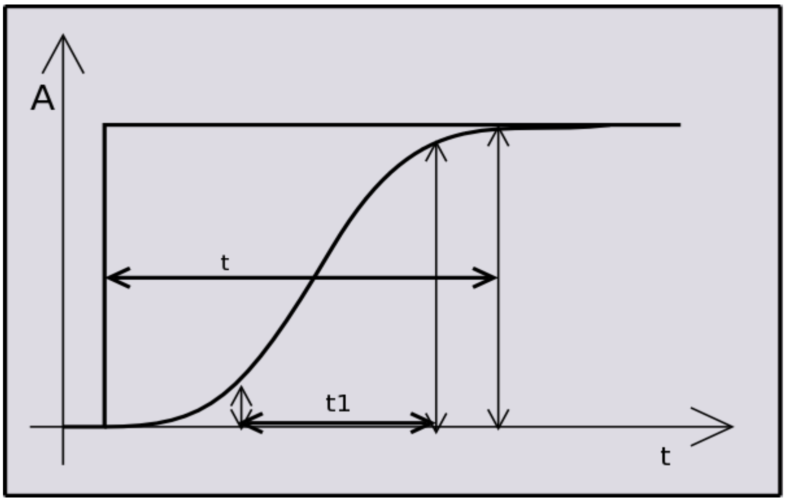

Figure 5.2.1.1. Different methods step response rise-time determination.

Comparing galvoscanner control systems is very hard and in fact can not be generally done for all systems. For this research author decided to tune his systems to get the shortest possible step response rise-time, without overshoots or oscillations. This method corresponds to “t” case in Figure 5.2.1.1 or “t3” case in Figure 5.2.1.2.

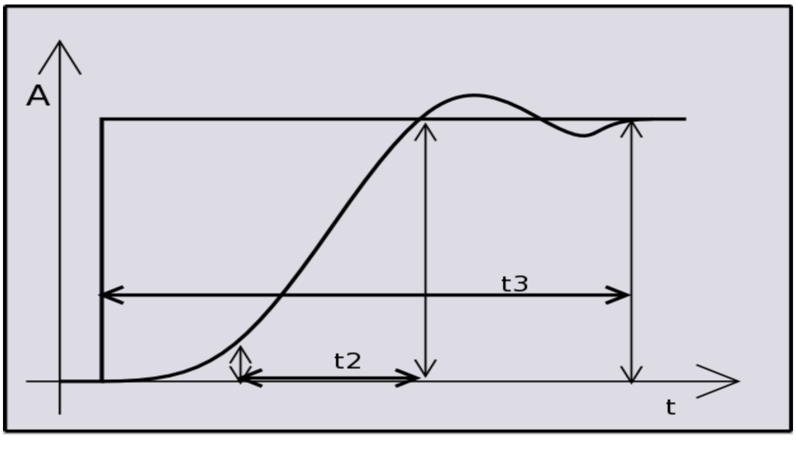

Figure 5.2.1.2. Two main ways of step response rise-time determination when (in overshoot case) overshoot occurs

This method was used because it is the hardest to achieve in real world. Of course it is impossible to define where the galvoscanner's position reach reference value, because of limited accuracy of measurement. However measuring when the position pass 99% of reference position is relatively easy and accurate enough and this value will be used.

5.2.2. Position controller without digital position reference forming.

Analog position controller used in research system was tuned to for the best performance, when working with digital signal forming block. Sinusoidal, triangle and square position reference signal were used in experimental tests, because they are most common for measuring performance of galvoscanner control systems used in material processing applications. An example waveforms are presented below on Figure 5.2.2.1, Figure 5.2.2.2 and Figure 5.2.2.3. Tests have been made for large and small rotor angles, while all data was recorded on digital oscilloscope. Blue waveform is the galvoscanner voltage, green is the actual position, while magenta is the position reference signal.

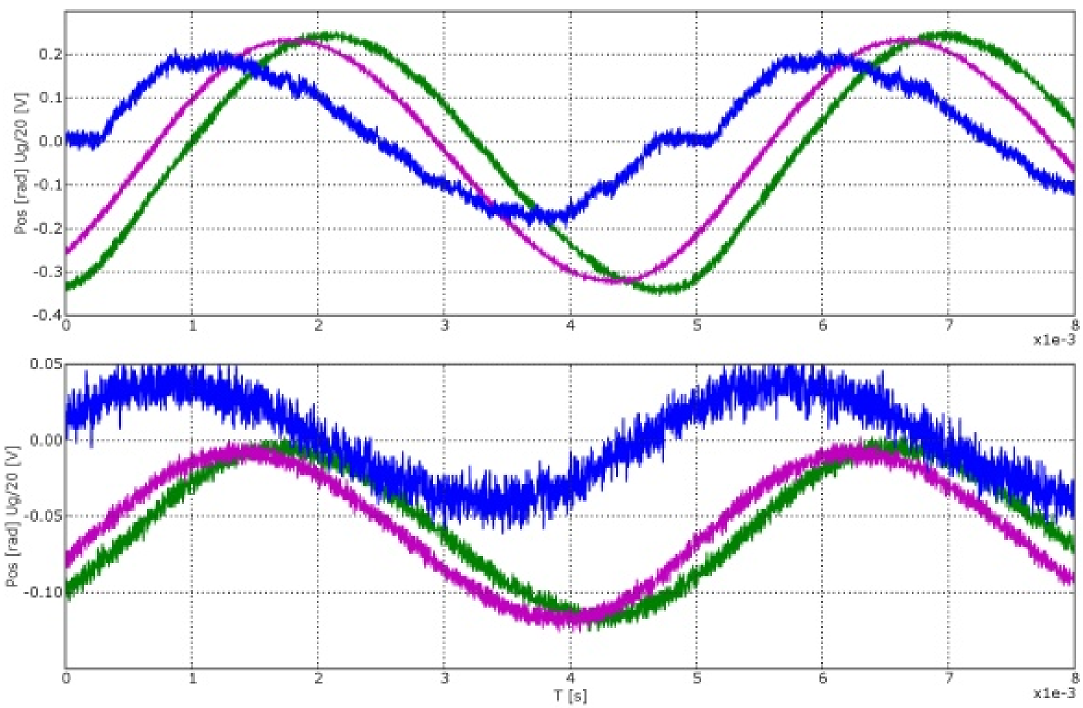

Figure 5.2.2.1. Transient waveforms in sinusoidal reference case (magenta – ref. Signal, green – galvoscanner position, blue – galvoscanner coil voltage).

During large angle moves galvoscanner voltage seems to be wrong at 0 and 5-th ms. The problems however are not caused by analog position regulator, but by nonlinear behavior of the galvoscanner itself. The amplitude have been set large enough to pass the maximum angle of the rotor, and “touch” the nonlinear region. The same signal during small angle is clear and does not have any nonlinearities.

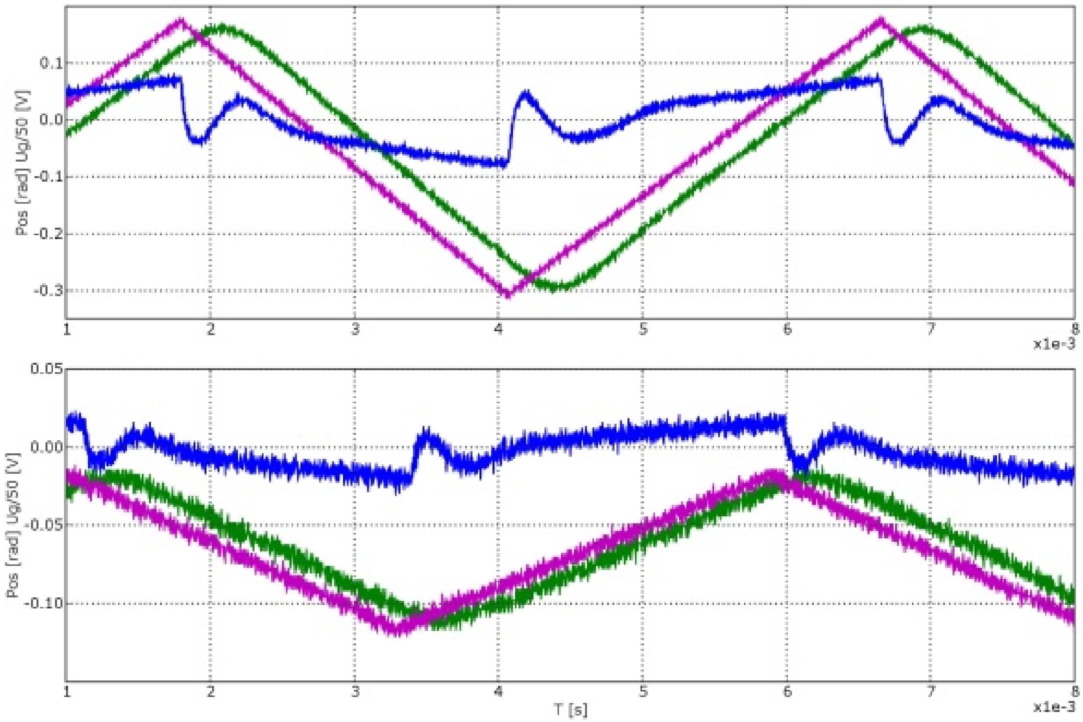

Figure 5.2.2.2. Transient waveforms in triangle reference case (magenta – ref. Signal, green – galvoscanner position, blue – galvoscanner coil voltage).

Triangle signal looks as excepted – real rotor position is delayed from the reference, while the shape is closely followed. Only when the direction is changing position is not as sharp as the reference signal. All these tests were made with large mirrors mounted on the rotor, so the inertia was larger then in typical application.

Case when square reference position signal was used needs some more comments. Small jumps looks normally (no overshoots) but large jumps are not followed in the best way. Galvoscanner position overshoots the reference about 5% and setting to the desired level takes 1.8 ms. This time is very long, especially if we take into account that reaching of the desired value takes only 0.6 ms. This behavior is caused mostly by integration block of this "modified PID" controller. Integral reaches higher level then needed to hold the rotor in final position, before this position is achieved. Then it takes a lot of time to reduce it to the desired value because error is small. This might seem that the integration coefficient should be reduced, but please keep in mind that this regulator should be used with digital signal forming applied to the reference signal. In that case the slopes would be reduced, effectively preventing all these problems.

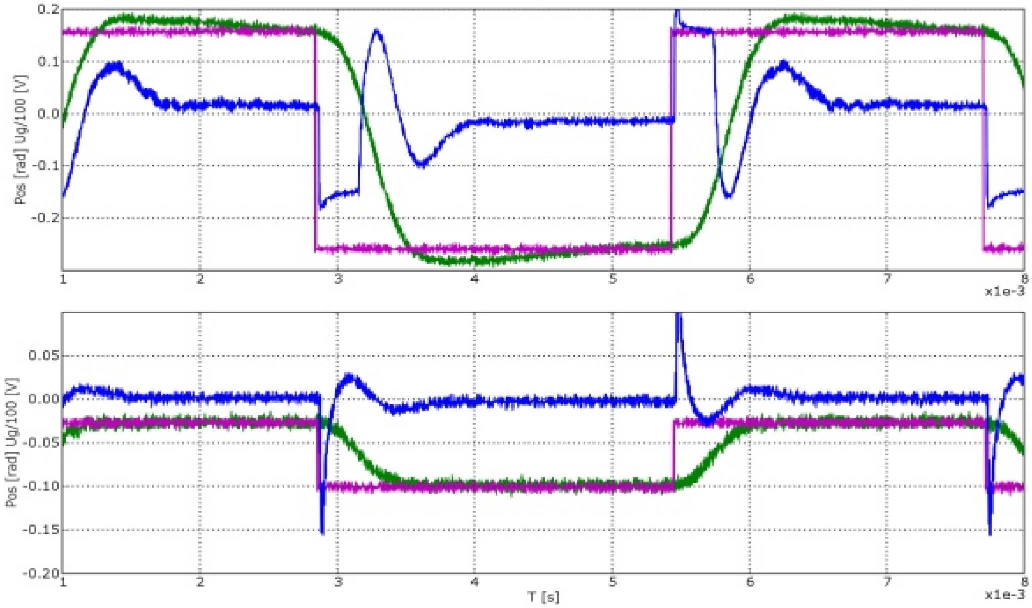

Figure 5.2.2.3. Transient waveforms in square reference case (magenta – ref. Signal, green – galvoscanner position, blue – galvoscanner coil voltage).

It should be noted that current control is usually not able to follow current reference signal in transients, because of large galvoscanner inductance. To improve current rise and fall times much larger voltage have to be used what makes the system very inefficient.

5.3. Performance of the new advanced control system

5.3.1. Position controller with digital position reference forming block.

As have been stated earlier digital position reference forming block performs two major functions: it reduces the slopes of the step input signals to the level reachable by the galvoscanner, and it gives a "boost" to the small steps, to achieve larger acceleration of the rotor.

For large jumps, such behavior reduces the time when actual position is much different then reference position, effectively reducing overshoots caused by out of range work of position controller integrating part. For small jumps it achieves faster response times, increasing maximum galvoscanner speed. Separation between small, and large jumps is quite floating – it is difficult to define a precise boundary. The boundaries are also depended on galvoscanners or loads with different moment of inertia.

5.3.2. Small jump (step) processing and achieved performance

Figure 5.3.2.1 Shows how the digital signal forming changes input position signal to improve small jumps performance. Unfortunately fast, low-voltage signals of the research system are hard to measure accurately. There the noise presented on both waveforms is mostly created by the digital oscilloscope and is not presented in real circuit. Oscillations on reference position signals are unfortunately not only the measuring errors.

It took some time to figure out where they are created. Finally author found out that digital to analog converters used during research where responsible for such behavior. Final application should use high quality, minimum 12-bit DACs (Digital to Analog Converters), with low noise output amplifiers.

Analog position regulator prefer being supplied by differential input signals, because of differential nature of input amplifiers. Used DACs unfortunately could not produce such signals. When working in noisy environment with long signal cables, using of differential DACs is strongly recommended.

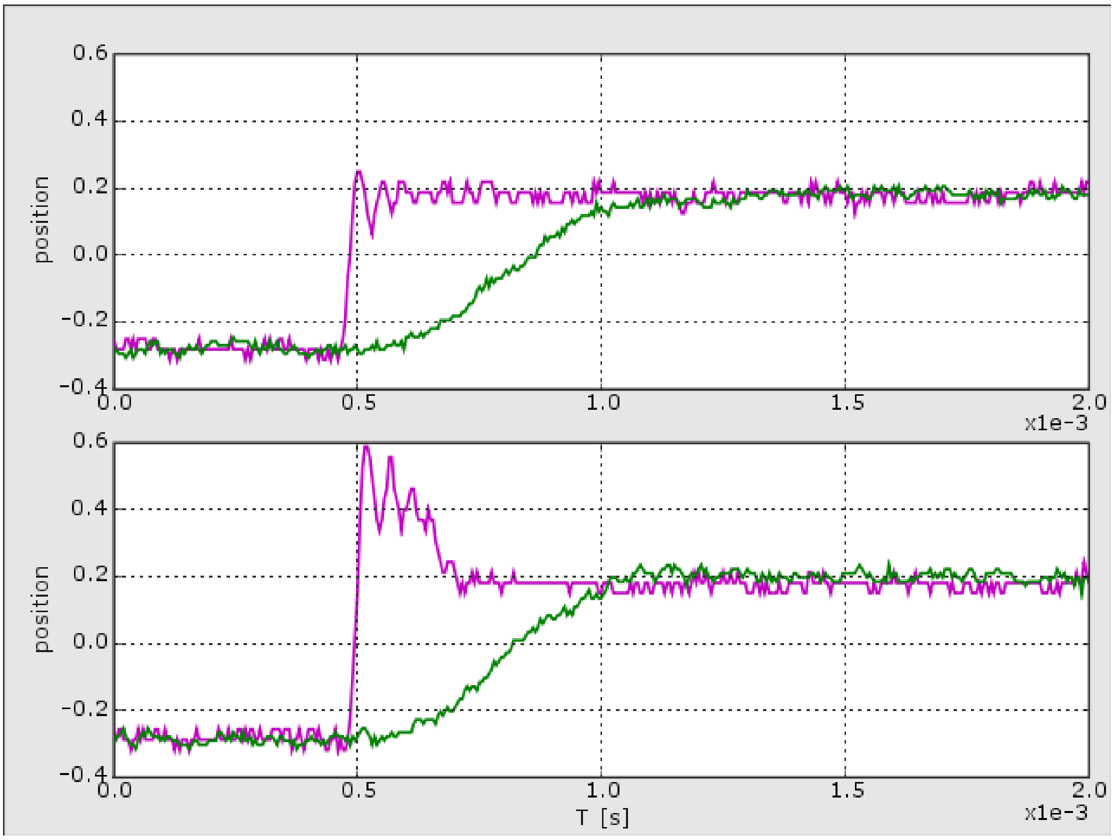

Figure 5.3.2.1. Digital signal forming during small jump (magenta – ref. Signal, green – galvoscanner position).

Upper part of Figure 5.3.2.1 presents original input position signal (magenta) with galvoscanner step response (green) without digital position reference forming. Measured response time (input position step to the point when galvoscanner position reached 99% of final value) is about 0.74 ms. Take into account the long time, that is needed to reach last 10% of the final value.

Lower part of this figure shows the same waveforms but with digital position reference signal forming applied. Response time is 0.55 ms now, and reaching critical last 10% is much faster. Below (on Figure 5.3.2.2) is shown how galvoscanner coil voltage has changed after application of digital position reference signal forming.

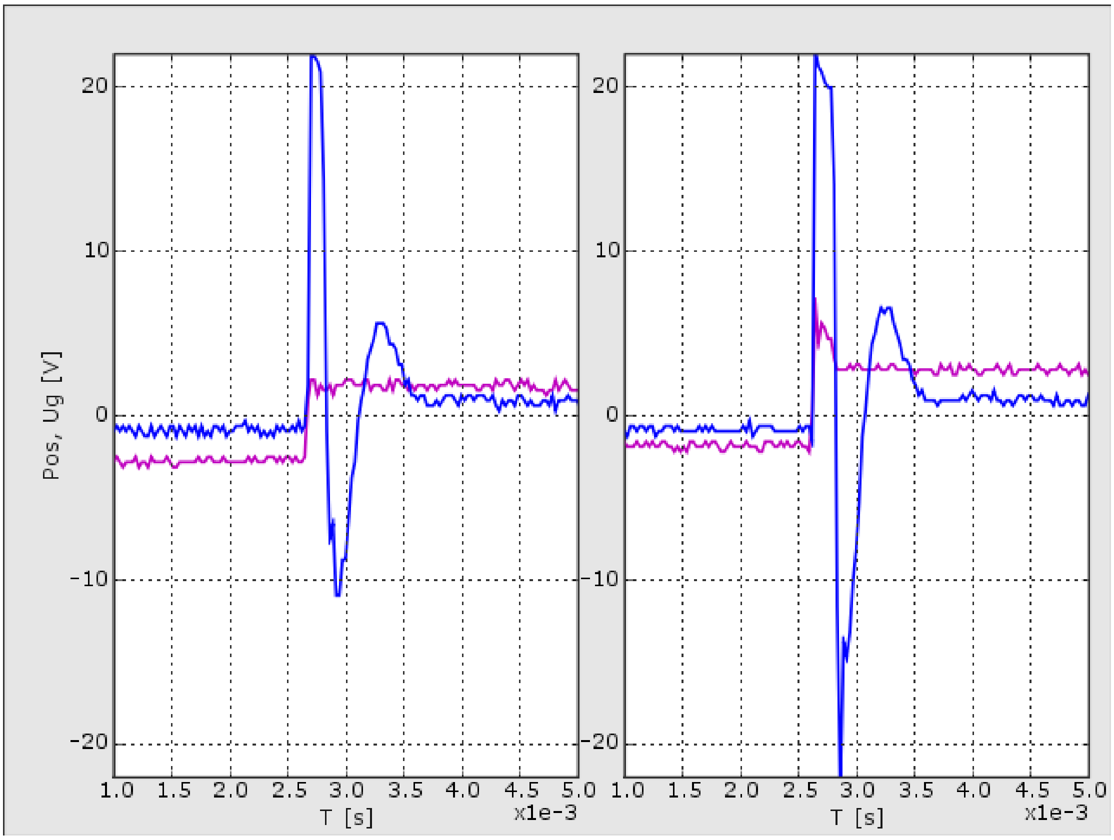

Figure 5.3.2.2. Reference position signal and galvoscanner coil voltage with and without digital signal forming (magenta – ref. Signal, blue – galvoscanner coil voltage).

For normal, not processed signal (left part) breaking is not done with full voltage, and acceleration last not as long as with processed signal (right part). Response time have been reduced form 0.74 ms to 0.55 ms (34%), that is a very short value for moving-iron galvoscanners. As was stated earlier, large mirrors have been used to expose all differences between systems and all parts of the move.

5.3.3. Large jump processing and achieved performance

For large jumps digital signal forming works in different way. Instead of giving initial "boost" (which is not needed now anyway), it reduces the slope of the reference signal to the value that is reachable by the galvoscanner. Because of this there is no situation, when commanded position differs largely from actual position. Now integral part of the analog regulator does not have time to reach to high value, as it was common before.

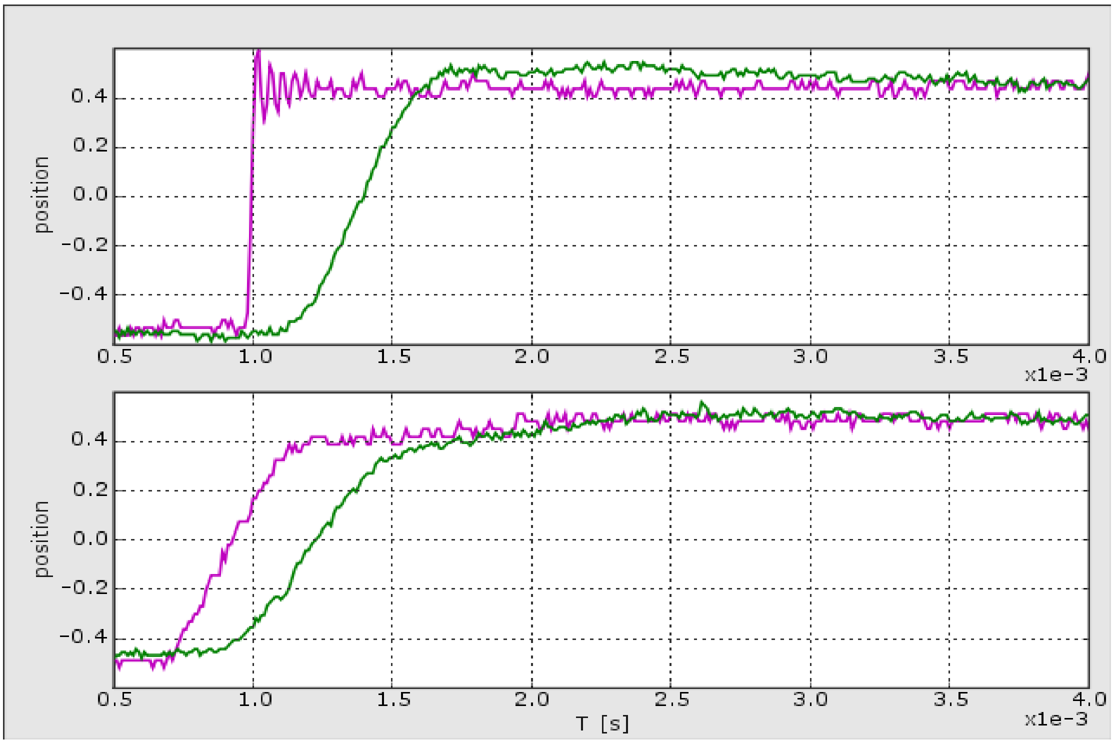

Figure 5.3.3.1. Reference position signal and actual position with and without digital signal forming block (magenta – ref. Signal, green – galvoscanner position).

Figure 5.3.3.1 Shows large signal step response of the galvoscanner with and without digital signal forming applied. Upper part shows not processed, "normal" signals. Reference position (green) has typical step shape. Actual position reaches desired value after 0.6ms, but it overshoots about 6%. Getting back to the final value takes another 1.5 ms which gives 2.1ms total response time.

Long time needed to get back after overshoot is caused mostly by integral therm of modified "PID" analog regulator. Integral reaches to high value when actual position differs largely form commanded position, and then it takes a lot of time to reduce it's value. After overshoot error is small, so all changes of the integral therm are slow.

Application of the digital signal forming reduces difference between commanded and actual position in the beginning of the move, and integral therm does not have time to “over integrate” now. All move now takes only 1.1 ms which is nearly 50% improvement.

Unfortunately we also can see inaccuracy of the used DACs. In the upper part of Figure 5.3.3.1 there are oscillations, while on the lower part the signal is distorted at about 1.5 ms. It is not clear why the final value changing so long time after the actual move, while it should be rock solid at 1.5 ms. Galvoscanner position follows this false value, creating a feeling the actual move is very long.

Next Figure 5.3.3.2 presents another view of the comparison. Digital signal forming have been applied to the falling slope, while raising have been left unchanged.

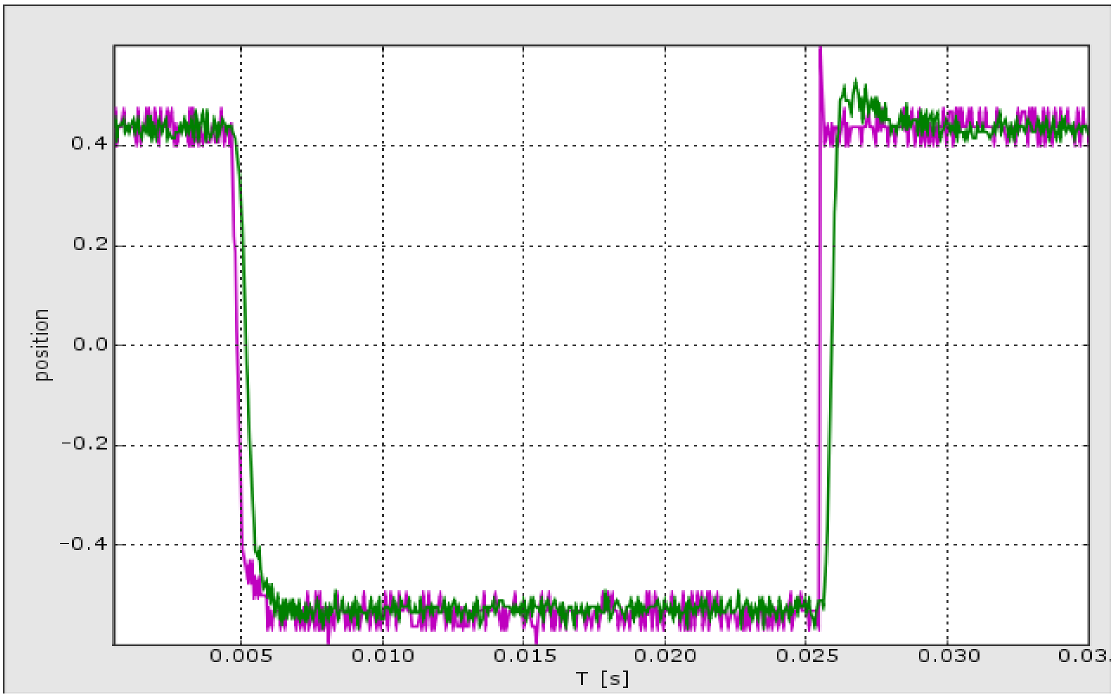

Figure 5.3.3.2. Reference position signal and actual position for processed and unprocessed signal (magenta – ref. Signal, green – galvoscanner position).

It can be clearly seen that on falling edge both waveforms, commanded (green) and actual (magenta) are going very close together. On rising edge actual position can not follow the step signal. Galvoscanner reaches very high top speed but it can not break on time (because of integral regulator therm, as was explained earlier) and overshoots.

5.3.4. Performance improvements summary

Response times for system with and without digital position reference signal forming have been summarized in Table 5 below.

Table 5. Performance improvement over typical control system.

Jump value	***Response without digital position reference signal forming***	***Response time with digital position reference signal forming***
Small jumps (below 20% of full range)	0.74 ms	0.55 ms (improvement 34%)
Large jumps (over 80% of full range)	2.1 ms	1.1 ms (improvement 48%)
Middle jumps (about 50% of full range)	1.4 ms	0.82 ms (improvement 41%)

Power efficiency improvement is very difficult to measure accurately. Power consumption is depended on input signal waveform, what makes comparison valuable only for one defined situation. The improvement is almost 0 if we use very signals with out many fast large jumps (galvoscanner is not stopped in one position), but it can be as large as 50% if we use signals when most of the time galvoscanner is kept in one position. Last situation was in fact frequent during laboratory research – we use low frequency square wave position reference, while observing results on the oscilloscope. In that case work without controlled power supply was impossible because of overheating output amplifiers – system consumed about 24 W of input power. With controlled power supply power consumption drops to 5-7 W. Table 6 shows achieved results for particular position reference signal.

Table 6. Power consumption improvement over typical control system.

Position reference signal	***Power consumption without voltage control***	***Power consumption with voltage control***
Square wave full scale, 10 Hz	24 W	7 W (improvement 32%)

5.3.5. Applications requirements summary

Typical applications of galvoscanners can be dived to three major types, each of them needs different tunning and has to meet different requirements [6]:

1) Laser shows, image projection – Position accuracy and response time are not very important if the overall look of the image is good. The main problems comes from very high laser powers that are needed, and because of this large mirrors. Data points are known a priori and it is possible to very easily implement digital signal forming before DACs and position regulators.
2) Material processing – Accuracy is major concern here, while speed is not very important. As in point (1) all data is known before it is send to galvoscanner, so digital signal forming is also possible. With material processing machines accuracy is more often limited by the position sensors (integrated with galvoscanners) rather then used electronics.
3) Target tracking/marking – Such applications needs both accuracy and speed, but in majority of all cases they produce "easy to follow" signals. Real targets can not change speed or turn instantly, so position signals are never discontinues or step. Of course no data is known a priori so digital position reference signal forming is difficult or impossible to realize. Fortunately with such signals properly designed and tuned analog controllers will give acceptable results.

Control system presented in this research work can be used to almost all applications, without any, or with very little hardware modification. Programmable analog devices (ispPAC-10) allows changing every parameter of analog regulator, so achieving best performance image projecting as well as material processing is possible. We can also use digital signal forming block to further improve the system, but this time we will be limited to applications that know all data points before actual run.

6. Summary

6.1. Summary of achieved results

Galvoscanner control systems with position controllers are today not widely known by developers. Marketing consideration force manufacturers to creation of systems that are not suitable for research, and can be normally used only with one application.

This paper presents fully programmable and configurable advanced galvoscanner control system, that can be used for many different applications without any hardware modifications. Regulation time have been reduced in comparison to other control systems, by using digital signal forming block and programmable analog regulator.

Electrical efficiency of the system have been improved by using controlled, high-quality power supply with output voltage dependence of position reference, that reduce looses in the final power amplifier. All blocks of the system are controlled form PC, however it is possible to build a self contained system using modern signal processors or DSPs.

6.2. Future research subjects

6.2.1. Galvoscanner's operation with non-constant load

Experiments showed, that when the load of the galvoscanner is changing (even only a little) retuning of the regulator is usually necessary. It is rather not possible to find an optimum for different loads, because it would slow down the response or even worse it could bring oscillations and overshoots in some cases. Oscillations are particularly danger for the galvoscanner.

When the system is designed to work only in precisely known, unchanging conditions it is possible to fix all settings. However with time, even if load is constant, galvoscanner parameters might drift, as well as analog components used in the regulator. Thermal drift might also cause problems. Because of it some high precision galvoscanners have integrated heater and temperature sensor, to stabilize operation temperature of the unit [25].

When the conditions are unknown, or when we know that the load will change other (adaptive) solutions are needed. There is nothing special in tuning digital regulators, but analog present much bigger challenge. Analog regulators are normally fitted with mechanical potentiometers, that have to be set up by the user. If the application is supposed to work without any user intervention, or there are no persons qualified to set it up, we have to use components that will allow remote tunning, preferable from the micro-controller.

Today there are digital potentiometers that could be used instead of mechanical ones, but analog programmable devices like ispPAC-10 seems to be much better solution. These elements allow not only to tune regulator parameters, but even allow to change the regulator configuration. With simple potentiometers we would need about 5-6 separate units, and we still would be limited to the one configuration. With ispPAC-10 almost every think can be changed and we have only one IC on the board.

Unfortunately fully configurable analog regulator alone is not enough to create a complete automatically tuned system. Above it, we need to know how to set it and we need some hardware that physically perform this task.

6.2.2. Finding the optimum regulator parameters

When galvoscanner load is changing, or even if the system changes it's scanning mode (for example from raster to vector) regulator parameters should change if the performance is critical. The problem is simple if the working conditions are changing in the previously known way. We can create a few sets of parameters and load appropriate set when it is needed. If the conditions are not known self tuning or self learning system can be applied.

Such task is rather complicated (and it could be the subject of another research), but we have penalty of time to do it. After the conditions change, the controller sends a step or other command to the regulators, records the response, check if it is correct and if not slightly changes the parameters. Then it makes another try. To do such work there is no need to use very fast DSP because the computations are not done in real time. Only the sampling rate of the feedback is important to acquire enough points for the accurate computations. Block diagram of the system is shown below on Figure 6.2.2.1.

During research only the first method (without feedback) was tried. Implementation of the active parameter tuning with the A/D converter feedback will be hopefully done during future test.

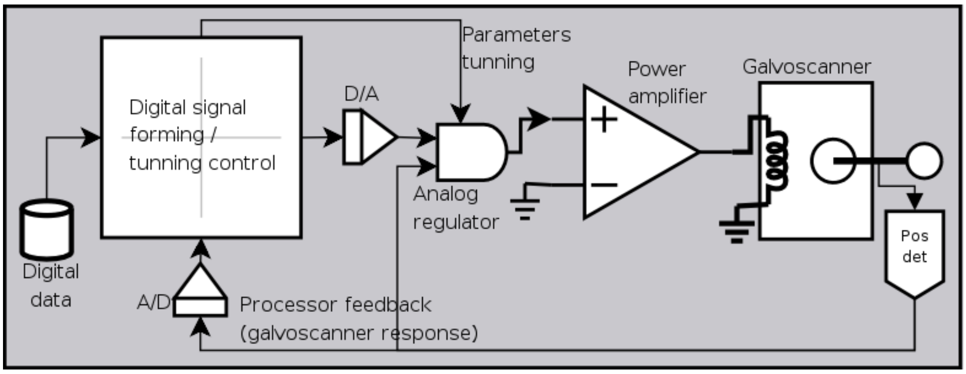

Figure 6.2.2.1. Automatic regulator tunning

6.2.3. Class "T" power amplifiers

Every galvoscanner control system needs power amplifier and very often current regulator in it's final stage. Linear power amplifiers are very accurate and can achieve very low noise and fast current regulation, but they are also very inefficient. Efficiency can be greatly improved by using actively regulated power supply, but there is also other alternative.

Today switched power amplifier are constantly gaining popularity, because of high efficiency, but typical method (PWM with constant frequency) is not well suited for precise, high speed control as needed by galvoscanner control system. To achieve needed accuracy very high switching frequency would be needed, that can produce radio interference and EMI.

Recently Tripath introduced class "T" switching power amplifiers (generally for audio applications), that can also be used for other tasks. These amplifiers uses very complicated circuits and algorithms, along with non constant switching frequency. Declared efficiency is about 70-80% with high quality MOSFETs used as power switches. These devices could possibly be used also for galvoscanner's controls systems with some modifications to the input stage and output filters. This ideal is generally worth to try, however there is some research work needed to incorporate Tripath ICs to the galvoscanner control system.

7. <u>Appendix:</u> ICSP programming device for ispPAC-10 analog ICs.

7.1. Genesis of the designed programmer

Most of the new programmable integrated circuits have some form of In-Circuit Serial Programming (ICSP) interface. It enables to quickly program and test new firmware in different applications without any hardware changes. To program and test micro-controllers and other programmable devices (like ispPAC-10) a special service connector is provided on the board.

There is no single standard for ICSP interface. Almost every manufacturer has it's own specification for ICSP capable devices and provides dedicated programming hardware. Often, even the same manufacturer has a few different programmers for different chip families. This can be accepted in mass production, but is rather problematic for designing and prototyping. The main problem is that such dedicated programmers are suitable only for single task – programming or testing. It means that designer have to have a lot of different programmers that often can not be connected to the PC at the same time. Sometimes software drivers for them uses incompatible input files format that creates further complication.

To overcome this problems and to provide a single small and efficient programming device for many chips the new universal ICSP programmer was designed and build. In the begging, idea was to build single device that can program many different micro-controllers (MicroChip's PIC and ispPACs mostly) and eventually other programmable ICs (GAL22V10).

However, during designing of software driver it was clear that it can be made to support many different communication standards like: SPI, I2C, JTAG or RS232. It was also possible to create a simple digital recorder with moderate sampling rate. The programmer can be used as an application debugger or tester, making it a very universal and handy device. Author uses it for about 4 years with good results for programming, testing and debugging his designs like: temperature controller for intelligent buildings, CD Player and of course this research work.

7.2. Typical ICSP requirements

ICSP usually does not need very high transmission rates however, time relation or signal sequences are often very strictly defined. Typically the start-up sequence or programming pulses times and delays are specified within 10-50µs. Following this is guidelines is very important because it is quite easy to destroy programmed device in milliseconds. This is especially true for EEPROM or EPROM ICs because they are sensitive to programming pulses. FLASH ICs are much more robust. This means that every universal programming device should be able to give microseconds accuracy and should be very reliable. As was mentioned earlier, data transmission is not critical but it is also desirable to reduce programming time.

If the programmer is also supposed to service as application debugger or digital recorder then the time resolution should be 2-5µs and clock frequency above 100 kHz. It might seem not very hard to reach, but we have take into account that different and sometimes not standard protocols have to be realized. It is impossible to use typical dedicated ICs to do the task, because of these reasons. There should be also possibility to configure lines as inputs or outputs on the fly, and to provide high power / high voltage outputs. Very desirable is also adjustable power supply and possibly a simple hardware. Finally (after a few tries) all this goals were met.

7.3. Hardware of the programmer

To cut costs and design time very simple hardware platform was chosen. The block diagram of the programmer is shown on Figure 7.3.1.

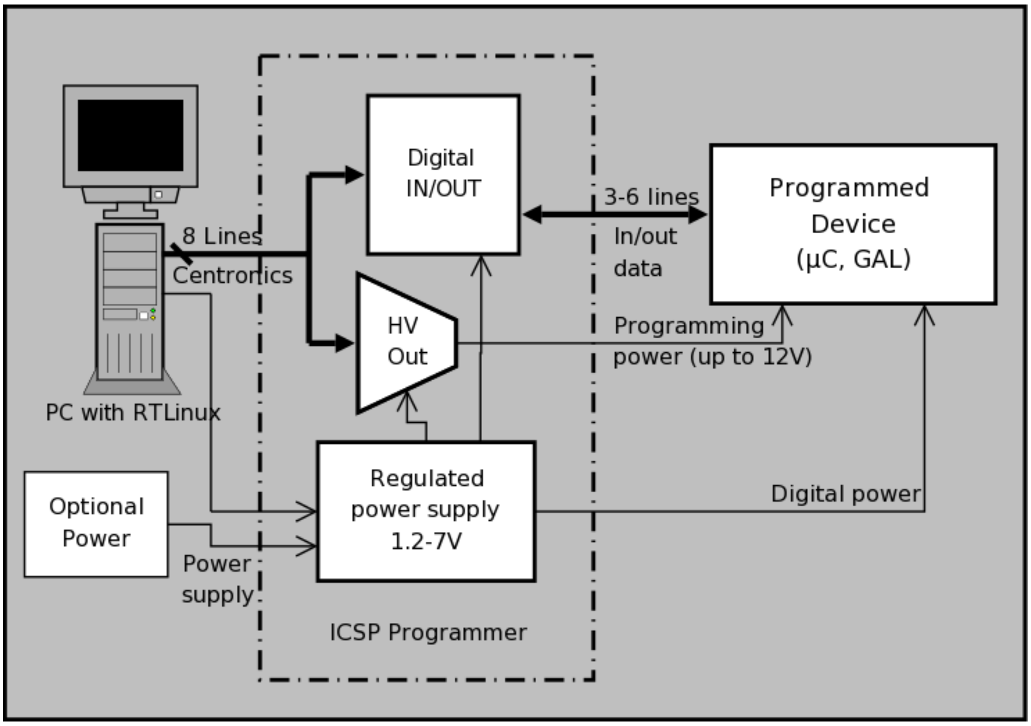

Figure 7.3.1 Block diagram of the designed programming device

This cause very high load on control PC's processor especially during high frequency transmitting or receiving.

The programmer has 3 configurable input or output lines with TTL signal levels, 3 output / high impedance TTL lines, 2 high voltage outputs (regulated 1.2 - 15 V, 200 mA) and regulated 1.2 – 7 V power supply. Voltage regulator is short-circuit protected and has 1 A current capability. The programmer consists of digital Input/Output block, high voltage lines amplifier and regulated power supply.

Input/Output block is build over single programmable IC – Lattice GAL22V10. This device is fast, has high power TTL outputs, and is easily configurable for given tasks. As high power output block an ICL7667 dual amplifier was used to convert TTL signals from PC to 15 V / 200 mA outputs. An application power supply consists of an integrated voltage regulator with short circuit and over temperature protection block.

All of the blocks are connected to PC standard parallel port (Centronics). This port was chosen because:

1. Most PCs and Laptops have it
2. It is very easy to configure and program it
3. It does not need any special hardware to work
4. It is robust
5. Cables or other hardware is not critical for proper operation.

The programmer has 20 pins connector and dedicated cable as a target application connection. Programmer needs its own power supply (8 – 15 V, 1.5 A maximum) for operation. It was build to enable powering it directly from control PC (12 V power line). However, if accurate high voltages are needed it is necessary to use dedicated stabilized power supply, that also have been build.

7.4. Safety and isolation

It is a good practice to implement some kind of isolation between PC (with its noisy power supply and main board) and programmed device or IC. Such isolation is usually achieved by using optical isolators and dedicated power supply with good line isolation, Figure 7.4.1.

Presented programmer however does not have any galvanic isolation from PC. This means that PC, programmer and programmed device have to share the same ground and are all subjected to voltage surges if they occurs in any of the components. The isolation have not been implement because of quite complicated, bidirectional interface between PC and programmer. To achieve isolation it would be necessary to add some logic to both sides of the isolators and also to provide power supply for that would share ground with PC.

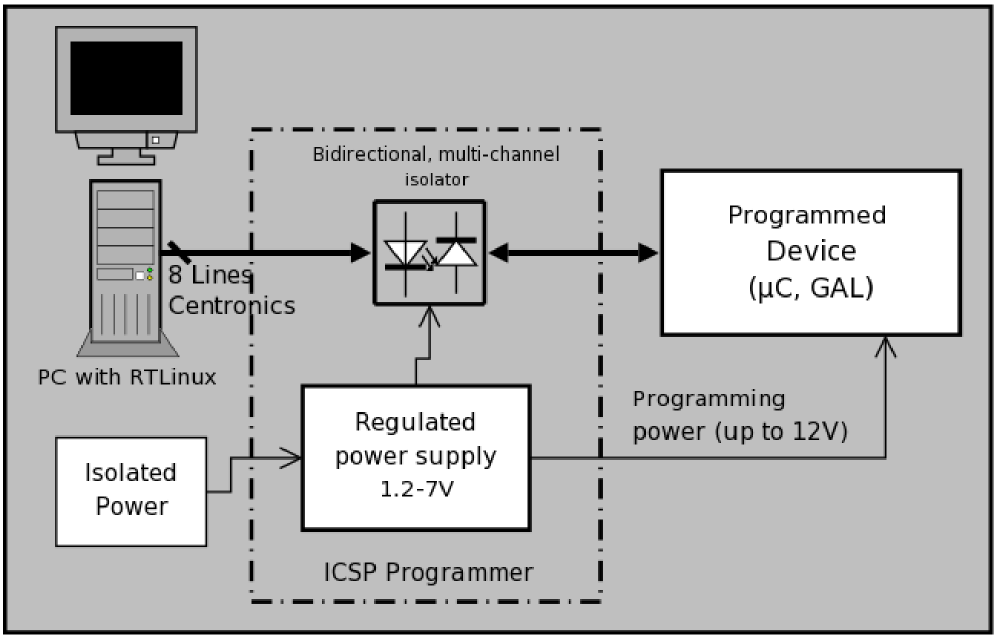

Figure 7.4.1. ICSP Programmer with optical isolation

After some tests, it was decided that there will be no galvanic isolation from PC. Required complication of the hardware is not worth the increased protection. PC used for programming can be connected to power line (230 V, 50 Hz) with surge filters or even with isolation transformer, effectively reducing probability of component damage. Author using this programmer for about 4 years without any problems so far, so it can be assumed, that line filters with additional GAL IC between PC and programmed device is enough protection.

7.5. Software drivers

Programmer places all control tasks on PC. Such implementation is very universal and almost all interface standards can be realized with appropriate driver software. To meet needed performance a high quality real-time operation system and driver is essential. It is important that soft real-time is not enough because deadlines and jitter have to be kept below certain values all the time. Software failure can lead to destruction of the programmed device or meaningless received data.

To meet these goals QNX was chosen as the real-time operating system. It is very fast, reliable, easy to configure and it was well know by the author. It is not recommended to write real-time control programs under Windows, even if it is well know for most users and very popular, because of hard real time demands during programming procedure realization. Not many computer have QNX installed, so using the programmer out of the laboratory or without dedicated notebook is problematic. Concurrently work is in progress to port all the software to RTAI Linux, that will achieve similar performance but the driver is not ready yet.

Control software was written in C – very popular and widely known language. The driver is implemented as a library of functions rather then stand alone program. Such configuration was chosen because it gives the best control of the programmer's hardware. It is very universal and easy to add new protocols or functions without any changes to the existing programs. Functions was grouped in the modules by category.

Whole library consist of 17 modules 16 header files and over 60 functions, plus some “inline” functions, that are not accessible for the user. Many common communication standards and file formats are implement already (JTAG, SPI, I2C and so on). Functions also can be used to directly control programmer's lines. All of the functions can be used directly in any QNX program. It can be seen that by using the library it is very easy to load files in different formats and then send or receive application data. All parameters like speed, polarity, protocol or format can be changed on the fly in very short time – very useful for debugging.

As was stated before time resolution and accuracy of micro seconds is needed to meet the ICSP programming specifications of some chips. Such short response time and low jitter is quite difficult to achieve even for hard real-time operation systems. QNX (and RTAI Linux) running on modern PCs however can meet such requirements. For QNX the easiest way was to disable all interrupts during critical time.

To accurately measure time TSC (Time Stamp Counter) – 64 bits counter presented on every new PC processor was used. This counter is incremented at every clock cycle, so it is enough to know the frequency of the processor to measure the time. For testing 1.7 GHz Pentium 4 was used, however Pentium running on Intel main-board is not the best choice for real-time use.

Most of this boards have SMI (System Management Interrupt) “feature” - an interrupt that is called by system controller every few seconds. This is completely invisible for the software and OS, so it is impossible to block it in typical way. This can cause occasional jitter of several hundreds of micro seconds. It is sometimes possible to disable SMI by writing to main-board registers, but it is system depended and usually not documented anywhere. Unfortunately only that PC was available at that time.

With 1.7 GHz clock it is theoretically possible to measure about 7 nsec, but realistically this value is much longer i.e. about 0.7 μsec. This is cause mostly by long time needed to access I/O ports. The other problem is how long time can be measured in that way. TCS is 64 bits in nature, but to speed up operations typically only 32 bits are used, however functions for full 64 bits access are also provided. To give a good overview of possible measurement range for 32 and 64 bits counter the maximum available time is computed:

For 32 bits

$$T_{max} = \frac{1}{1.7\,GHz} \cdot 2^{32} = \frac{4294967296}{1700000000} \approx 2.5\,seconds$$

And for 64 bits

$$T_{max} = \frac{1}{1.7\,GHz} \cdot 2^{64} \approx 1.08 \cdot 10^{10}\,seconds \approx 125590.58\,days \approx 344\,years$$

It is clear that even 32 bits counter should be sufficient for most of the time, but if one use 64 bits counter the measurement range is many times longer then the lifetime of typical PC.

Using this programmer and drivers makes possible to very quickly reprogram ispPAC-10 chips in the analog regulator or to read the current configuration. Standard file format (JEDEC) is used for easy interface with other design tools provided by Lattice for the used chips.

8. Used symbols

8.1. Galvoscanner parameters

$CR[\Omega], CL[H]$ -	Galvoscanner DC resistance and inductance
$BEM[\frac{V \cdot s}{rad}]$ -	Back Electromotive force
$TRC[\frac{N \cdot m}{A}]$ -	Torque constant
$KTR[\frac{N \cdot m}{rad}]$ -	Torsion bar constant
$FR[\frac{N \cdot m \cdot s}{rad}]$ -	Mechanical friction constant
$RIN[kg \cdot m^2]$ -	Rotor inertia
$MAN[rad]$ -	Maximum rotor angle

8.2. Galvoscanner models state variables

$T_E[N \cdot m]$ -	Electrical torque (created by coils)
$T_{TB}[N \cdot m]$ -	Torsion bar torque
$T_{FR}[N \cdot m]$ -	Mechanical friction torque
$I_C[A]$ -	Galvoscanner current
$Uc[V]$ -	Galvoscanner voltage
$\omega[\frac{rad}{s}]$ -	Rotor angular velocity
$Pos[rad]$ -	Rotor position
$Icom[A]$ -	Position detector common mode current
$Idif[\frac{A}{rad}]$ -	Position detector differential current per radian

8.3. Power supply and voltage prediction algorithm

$u_g(t)[V]$ - Galvoscanner voltage

$u_{smin}(t)[V]$ - Minimum power supply voltage

$u_{sref}(t)[V]$ - Power supply reference voltage

$LR1, LR2[H]$ - Resonant inductors 1 and 2

$C1, C2[F]$ - Power switches capacitance

$Uz[V]$ - ½ of DC primary supply voltage

$Dt[s]$ - Delay time (between turn OFF on one switch and turn ON of the other in the same branch)

$Ts[s]$ - Switching period

Authors Publications

1. Michal Widlok: *Design of high efficiency, low noise ZVS-CV power supply for laser diode*. EPE-PEMC, Riga, 2004
2. Michal Widlok: *High efficiency, low voltage ZVS-CV DC-DC converter*. Zeszyty Elektrotechniki AGH, Kraków, 2004
3. Michal Widlok: *Using Linux for real-time control of ICSP interface for programmable device*. SENE, Łódź, 2005
4. Michal Widlok: *ICSP programmer controlled with RT operation system from PC parallel port*. Zeszyty Elektrotechniki AGH, Kraków, 2005
5. Herbert Widlok, Michal Widlok: *Computer aided teaching of power electronics*. EPE-PEMC, Portoroz, 2006
6. Henryk Chodkiewicz, Ryszard Cichocki, Tomasz Stefanski, Michal Widlok: *Magnetometric method of sea mines detection*. UDT Europe, Hamburg 2006
7. Henryk Chodkiewicz, Wacław Kosalka, Michal Widlok: *Construction and testing of hydrodynamic trasducters for sea mines*. UDT Europe, Naples, 2007

Patent in preparation:

Hydrodynamic sensor for non impact sea mines with differential transducers and electronically compensated static field, R&D Marine Technology Center, Gdynia 2007

List of Figures

Bibliography

[1]. Laser F/X: *Galvanometrer theory of operation.* www.laserfx.com

[2]. Robert K. Mueller, Newton, Mass: *Dynamo Transformer*. Patent Nov. 22, 1949, 2,488,734, US Patent

[3]. Laser show technology: *Inside the Optical scanner*. Laser show technology, laser.shows.org/scanners.htm

[4]. Laser show technology: *Interscan*. Laser show technology, laser.show.org/interscan.htm

[5]. Goldwaser S.: *Sam's Laser FAQ*. Samuel M. Goldwaser, repairfaq.ece.drexel.edu/laserfaq.htm

[6]. Cambridge Technology: *Galvoscanners datasheets*. Cambridge Technology, Inc., www.cambridgetechnology.com

[7]. Laser F/X: *How laser shows work - Laser Projector.* www.laserfx.com/Works/Works3.html

[8]. Laser F/X: *How laser show work - Scanning system.* www.laserfx.com/Works/Works35.html

[9]. Scilab Group: *Scilab documentation.* www.scilab.org

[10]. Zalewski A., Cegieła R.: *Matlab - obliczenia numeryczne i ich zastosowanie.* PWN, Warszawa 1997

[11]. ngSpice group: *ngSpice docummentation.* ngspice.sourceforge.net

[12]. LSK: *Galvoscanner 040EF datasheet*. Laser Scannig Keiser, www.laserscanning.com

[13]. Lattice: *ispPAC10 Datasheet.* www.latticesemi.com

[14]. Analog Devices: *Analog Devices book.* www.analog.com

[15]. Michał Widlok: *ICSP programmer controlled with RT operation system from PC parallel port*. Zeszyty Elektrotechniki AGH, Krakow 2005

[16]. Michal Widlok: *Using Linux for real-time control of ICSP interface for programmable device*. SENE, Łódź, 2005

[17]. ILDA group: *ILDA articles*. www.ilda.org

[18]. Dieberger K., Ainger H., Grafman D.: *Improving the full bridge, phase shift ZVT converter for failure free op.*. IAS, 1998

[19]. Moham N., Tore M., Undeland W., Robbins P.: *Power electronics*. John

Wiley & Sons, New Yourk 1999
[20]. Tripath: *Class "T" amplifiers*. Tripath Technology, Inc., www.tripath.com
[21]. RTAI project: *RTAI documentation*. www.rtai.org
[22]. Dieberger K.: *A new generation of power MOSFETs offers improved performance*. Advanced Power Technology, 1998
[23]. Michał Widlok: *Design of high efficiency, low noise ZVS-CV power supply for laser diode*. EPE-PEMC, Riga 2004
[24]. Michał Widlok: *High efficiency, low voltage ZVS-CV DC-DC converter*. Zeszyty Elektrotechniki AGH, Kraków 2004
[25]. LSK: *Technical papers*. Laser Scanning Keiser, www.laserscanning.com
[26]. Zdzisław Grunwald, praca zbiorowa: *Napęd elektryczny*. Wydawnictwo naukowo-techniczne, Warszawa, 1987
[27]. Sikorski W.: *Słownik terminów i komunikatów komputerowych*. Mikom, Warszawa, 1993
[28]. Henryk Tunia, Marian Kazmierkowski: *Automatyka napędu przekształtnikowego*. PWM, Warszawa, 1987
[29]. Redaktor Andrzej Horodecki: *Sterowanie w napędzie elektrycznym i energoelektronice*. Wydawnictwo Politechniki Lubelskiej, Lublin, 1999
[30]. Kazmierkowski M. P.,Tunia H: *Automitic Control of Converte - Fed Drives*. PWN, Warszawa, 1994
[31]. Citko T., Tunia H., Winiarski B: *Układy rezonansowe w energoelektronice*. Wydawnictwo Politechniki Białostoskiej, Białystok, 2001
[32]. De Doncker W., Lyons J.: *The auxiliary resonant pole commutate converter*. IEEE, Industry Applications Society Annual Meeting, 1986
[33]. Hua G., Young E., Winiarski B: *Novel zero-current transition PWM*. IEEE Trans., November 1994
[34]. Jabrzykowski S., Citko T.: *Bridge configuration of class E converters*. Archive if El. Engineering, 2003
[35]. Praca zbiorowa: *Projektowanie przekształtnikow tyrystorowych*. WNT, Warszawa, 1974
[36]. Tunia H., Smirnow A., Nowak M., Barlik R.: *Układy energoelektroniczne - obliczanie modelowanie, projektowanie*. WNT, Warszawa, 1982

[37]. Laningham I.: *Poznaj Python w 24 godziny*. Infoland, Warszawa, 2001

[38]. Papamichalis P.: *Digital signal processing theory, algorithms and implementations*. TII, Texas, 1994

[39]. Sacha K.: *Mikroprocesor w pytaniach i odpowiedziach*. WNT, Warszawa, 1985

[40]. Palassche R.: *Scalone przetworniki A-C i C-A*. Wyd. Komunikacji i Łączności, Warszawa, 1997

[41]. Glinka T.: *Maszyny elektryczne wzbudzane magnesami trwałymi*. Wydawnictwo Politechniki Śląskiej, Gliwice, 2002

[42]. Latek W.: *Teoria maszyn elektrycznych*. WNT, Warszawa, 1988

[43]. Lukaniszyn M, Wrobel R., Jagieła M.: *Komputerowe modelowanie bezszczotkowych silników tarczowych*. Oficyna wyd. Politechniki Opolskiej, Opole, 2002

[44]. Sochodzki R.: *Mikromaszyny elektryczne*. Wydawnictwo Politechniki Warszawszkiej, Warszawa, 1996

[45]. Turowski J.: *Obliczenia elektromagnetyczne maszyn i urządzeń elektrycznych*. WNT, Warszawa, 1982

[46]. Pelczewski P.: *Sterowanie optymalne układu napędowego nadążającego za modelem*. Politechnika Warszwska, Warszawa, 1987

[47]. Turnau A.: *Sterowanie docelowe układami nieliniowymi w czasie rzeczywistym*. Uczelniane wyd. Naukowo-dydaktyczne AGH, Kraków, 2002

[48]. Senderski A.: *Sterowanie pozycyjne napędem elektrycznym z ograniczonym zrywem*. Uczelniane wyd. Naukowo-techniczne AGH, Kraków, 1998

[49]. Branch M. A., Grace A.: *Matlab Optymization Toolbox user's guide*. Math Works, Inc., Natick, 1996

[50]. Turnau A., Grega W., Kolek K.: *Sterowanie w zintegrowanym środowisku czasu rzeczywistego*. CATIE, Kraków, 1997

[51]. Martelli A.: *Python cookbook*. O'Reilly, USA, 2002

[52]. Hollabaugh C.: *Embedded Linux*. Addison-Wesley, USA, 2002

[53]. Praca zbiorowa: *Debugging with GDB, GNU source level debugger*. Wind river systems, Alameda, 1994

[54]. Embree P. M.: *Digital signal processing C algorithms for real-time*. Prentice

Hall PTR, 1995

[55]. Brodziewicz W., Jaszczak K.: *Cyfrowe przetwarzanie sygnałów*. WNT, Warszawa, 1987

[56]. RTO-MP-MSG-035: *The effectiveness of modeling and simulation*. R&T Organisation, 2005

[57]. Lakomy M., Zabrodzki J.: *Cyfrowe układy scalone*. PWN, Warszawa, 1986

[58]. Banachowski L., Kreczmar A.: *Analiza algorytmów i struktur danych*. WNT, Warszawa, 1989

[59]. CHUA LEON O.: *Komputerowa analiza układów elektronicznych algorytmy i metody obliczeniowe*. WNT, Warszawa, 1981

[60]. Kirch O., Dawson T.: *LINUX - podręcznik administratora sieci*. Wyd. RM, Warszawa, 2000

[61]. Schwartz A.L.: *Matlab Toolbox for solving optimal control problems*. MathWorks Inc., Natick, 1995

[62]. Turnau A.: *Przykład projektowania z wykorzystaniem pakietu Simulink*. WNT, Warszawa, 1993

[63]. Senderski A.: *Digital control of position electrical drive systems based on 3d reference*. IFAC Symposium, Zurich, 1991

[64]. Tadeusiewicz R.: *Sieci neurowowe*. Akademicka oficyna wyd., Warszawa, 1993

[65]. Varga Sz., Farkas S.: *Realization of position controller by fuzzy logic*. PEMC, Budapest, 1996

[66]. Yager R., Filev D.P.: *Podstawy modelowania i sterowania rozmytego*. WNT, Warszawa, 1995

[67]. Strzelecki R., Kasperek R., Fedyczak Z., Kobylecki G.: *Sterowanie impulsowymi sterownikami mocy prądu przem. o poprawionych właściwościach*. SENSE, Łódź, 1997

[68]. ElennF.: *UNIX. Administracja systemu*. Oficyna wyd. READ ME, Warszawa, 1997

[69]. Herbert Widlok, Michal Widlok: *Computer aided teaching of power electronics*. EPE-PEMC, Portoroz, 2005

[70]. Henryk Chodkiewicz, Ryszard Cichocki, Tomasz Stefanski, Michał Widlok:

Magnetometric method of sea mines detection. UDT Europe, Hamburg 2006

[71]. Henryk Chodkiewicz, Waclaw Kosalka, Michal Widlok: *Construction and testing of hydrodynamic trasducters for sea mines*. UDT Europe, Naples 2007

This book has been created using only open-source software.