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Faculty of Electrical Engineering and Informatics

CNC Laser Cutting Machine

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Zásady pro vypracování:

Diplomová práce se bude zabývat vývojem softwaru pro CNC laserový řezací stroj, který je konstruován pro tvorbu výpalků plechů. V práci bude popsána celá SW část aplikace pro ovládání a řízení řezacího stroje. Další část bude věnována řešení CNC části a jejího uvedení do provozu na reálném stroji. Z pohledu HW konstrukce řezací stroj využívá laserovou technologii od firmy Trumpf, dále je stroj osazen průmyslovým počítačem, drivery a motory od firmy B&R.
Teoretická část bude obsahovat přehled technologií CNC řezacích strojů (jak po technické stránce, tak technologické), popis použité laserové technologie a ostatních HW prvků systému. Praktická část DP se bude zabývat vývojem řídícího SW pro výše uvedený stroj a bude zahrnovat ladění motorů, získání jejich limitů (max. rychlosti, zrychlení), řešení synchronizace dvou motorů ovládajících jednu osu, nimimalizace pozičních chyb, propojení stroje s G-kódem, regulace laserové hlavy na Z ose a řízení laserové technologie.

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Seznam odborné literatury:

[1] SUH, Suk-Hwan. Theory and design of CNC systems. London: Springer, c2008. ISBN isbn978-1-84800-335-4.
[2] RAMANATHAN, Ramakrishnan. The IEC 61131-3 programming languages features for industrial control systems. In: 2014 World Automation Congress (WAC) [online]. IEEE, 2014, 2014, s. 598-603 [cit. 2018-10-17]. DOI: 10.1109/WAC.2014.6936062. ISBN 978-1-8893-3549-0. Dostupné z: http://ieeexplore.ieee.org/document/6936062/
[3] B&R Industrial Automation GmbH [online]. 2018 [cit. 2018-10-14]. Dostupné z: https://www.br-automation.com
[4] Trumpf [online]. 2018 [cit. 2018-10-14]. Dostupné z: https://www.trumpf.com

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In Pardubice on 23th May 2019

Jiří Jecha

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ANNOTATION

The goal of this thesis is to develop a complete software solution for a CNC laser cutting machine. Historical development of CNC technology and basic distinction of machining technologies are introduced. Software development starts with an overview of development tools and continues with a description of a created program division and methodology of writing the program. The machine’s primary functions are described with an approach to creating a workable solution to presented problematics. CNC commissioning, with actuators (servomotors) tuning and minimising positional errors, is the major part of this thesis. Created a software solution and its functionalities are described in its visualisation environment. A test workpiece creation procedure is described.

KEYWORDS

CNC, laser, machining, cutting, servomotor, tuning

NÁZEV

CNC laserový řezací stroj

ANOTACE

Cílem této práce je vytvoření kompletního softwarového řešení pro CNC laserový řezací stroj. Historický vývoj CNC technologie a základní rozdělení obráběcích technologií jsou popsány. Tvorba softwaru začíná přehledem vývojových nástrojů a pokračuje s popisem dělení vytvořeného programu a metodologie psaní programu. Základní funkce stroje jsou popsány s přístupem vytvoření funkčního řešení představených problémů. Největší část práce je věnována uvedení do provozu CNC technologie, která zahrnuje ladění motorů a minimalizace pozičních chyb. Vytvořený software a jeho funkce jsou popsány na jeho vizualizačním prostředí. Postup tvorby výsledného výpalku je popsán.

KLÍČOVÁ SLOVA

CNC, laser, obrábění, řezání, servomotor, ladění

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AS	Automation Studio
APT	Automatically Programmed Tool
CHM	Chemical Machining
CNC	Computer Numeric Control
CW	Continuous Wave
EBM	Electron Beam Machining
ECM	Electro Chemical Machining
EDM	Electro Discharge Machining
HMI	Human Machine Interface
LBM	Laser Beam Machining
LD	Ladder
MIT	Massachusetts Institute of Technology
N2	Nitrogen
NC	Numerical Control
O2	Oxygen
PBM	Plasma Beam Machining
PM	Pulse Mode
SLO	Servo Loop Optimizer

INTRODUCTION

The technological need for machining workpieces with complex shapes and high precision (mainly for air and space industry) led to development of CNC technology. This technology enabled high automation of machining processes, which led also to increased productivity. Resulted precision and speed of machined workpieces is also highly dependent on machining technology. Development of laser technology and its integration into machining, mainly steel plates cutting, has opened new options. This technology enables easy control (compared to others), and fast speed of cutting. Thin beams from the laser enable cutting of very complex shapes. It is up to the customer, what kind of material needs to be machined, with what precision, and speed.

The goal of this thesis is to develop a complete software solution of a CNC laser cutting machine. The machine was engineered and built in a company specialising in the automation industry. However, such a machine of laser cutting was the company's first prototype. The task was to gain an understanding the function principles of a CNC machines, laser cutting technology, technological processes of cutting, the actual machine's mechanical and electrical construction and using software development tools.

The thesis is divided into six major sections. The first chapter is devoted to the historical development of CNC. It is described as a historical context which led to the invention of NC and finally let to the development of CNC. A reference to the detailed description is also listed. Basic machining processes are introduced with laser beam technology described.

The second chapter describes used the software development environment with regard to software development, simulation and debugging. Simulation tools for mechanics and visualisation are described.

Project development is contributed to the third chapter. It starts with a detailed description of what were this project's starting conditions, what was the task and what has to be done to fulfil the task. Then the workstation is described. The machine's components are described as mechanical principles and CNC axes. The next is the program development. This section describes a project creation with the whole hardware configuration. Program developing methodology is followed by a description of main machine's functionalities as axes homing, CNC control, laser head control and controlling of the laser cutting. An approach of the mentioned machine's functionalities is described.

The most extensive is chapter four, which describes the CNC axes commissioning. The chapter deals with initial actuators commissioning as servomotor tuning, getting servomotor parameters and servomotor synchronisation on the portal. Then following with positional error measurement, localising the error source and their elimination. The last section describes backlash solving, which includes calculation of its theoretical value, measuring its real value and its solving.

The fifth chapter is program analysis. The developed software solution is described in the created visualisation environment. The functionalities are described.

The last chapter documents a workpiece creation process on this machine.

1 CNC CUTTING MACHINES

CNC cutting machines fall into a wide area called machining. This section introduces the predecessor of CNC machines in the historical part. Machining processes division and technology distinction follow.

1.1 History

When trying to describe the origin and technological development of CNC machines, we have to begin in the late 1940s with a man by the name of John T. Parson, also called the father of NC. [1]

At that time Parson was running a company which was the major producer of helicopter blades. The blades were manufactured on a precision jig mill using an innovative technique developed in 1947. The method was based on using numerical data produced by an IBM computer, which then was used to manually position the milling machine's lead screws by an operator. Calculated data consisted of 200 points on the airfoil curve. The lead screws of the milling machine had to be manually positioned according to the calculated data in two axes. This method was capable of producing airfoil templates with the precision of 0.0015" (0.0381 mm). [1]

When the United States Air Force was about to build new supersonic planes, Parson, seeing the new plane's plans, recognised airfoil shapes which would not be possible to make by conventional machining methods. [1]

Then he began to research, based on the innovative method mentioned above, to devise a methodology to solve this problem. Then he came with an idea of automating this manual process by using a drive mechanism which would be actuated by digital information in the form of punched cards or magnetic tape, and directly would control the lead screws of the milling machine. [1]

In 1948, he introduced this idea to an Air Force team and in 1949 there begun research to bring this idea of a Numerical Controlled (NC) machine to life. This was done with the association of the Servomechanisms Laboratory at MIT. In 1952 MIT presented a functional numerically controlled prototype of a milling machine. [1]

Through this technological advancement, issues like the possibility of machining very complex parts, increased precision, repeatability and shortened time needed for machining were solved.

The time needed to prepare a program on punched cards or magnetic tape was, depending on the complexity of the part, at least 50 times more than that required by machining alone. This impediment was crucial in the practicability of this technology. But the MIT Servo Lab recognised this problem even before the prototype was presented, and they started research on developing a method of automating this process. [1]

In the late 1950s, a young software researcher, Douglas Ross, developed a programming language for automatic programming of NC, which was called an Automatically Programmed Tool (APT) system. His approach was to create a simple language using English in it, and it would be open-ended and easily expandable. This removed the major issue of the programming cost of NC cutting machines. In 1974 the APT became the American standard for programming NC metal cutting tools and in 1978 the international standard. [1]

This connection of PC with NC, in the middle 1970s, was the begging of the term Computer Numerical Control (CNC), or we can say Computerized NC. [2] [3]

For detailed historical development see [1], chapter 5.

1.2 Machining Processes

Machining is a process of removing unwanted material from the workpiece. The final product is then of the desired shape, size and surface quality. [4]

Machining processes are divided into two basic categories; traditional machining and non-traditional. A basic distinction is shown in Figure 1. Traditional machining is then divided into machining by cutting and abrasion. This category requires a tool that is able to penetrate the workpiece and, by relative motion between the tool and workpiece, generate cutting. Into this category belongs machining by Cutting and Abrasion. Non-traditional machining is characterized by the absence of contact with the workpiece or tool hardness. Machining by erosion falls into this category. [4]

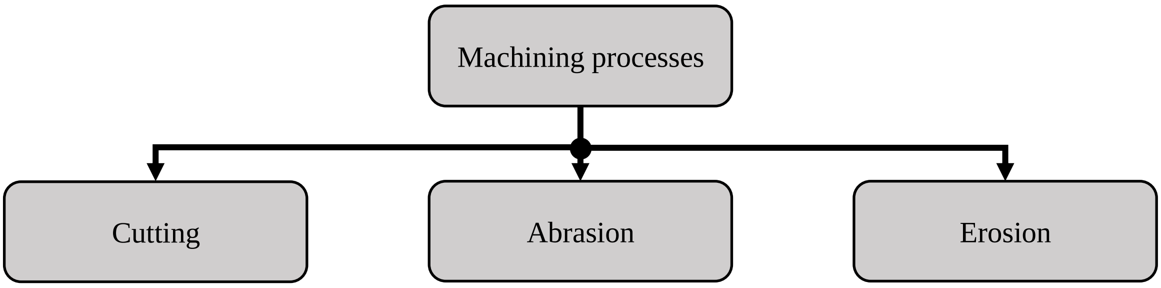


Figure 1: Machining processes (edited from [4])

Machining by erosion is divided into electrochemical erosion and thermal erosion (see Figure 2). Electrochemical erosion contains chemical machining (CHM) and electrochemical machining (ECM). Thermal erosion is based on melting and vaporisation of the workpiece material, and it consists of electric discharge machining (EDM), electron beam machining (EBM), laser beam machining (LBM) and plasma beam machining (PBM).

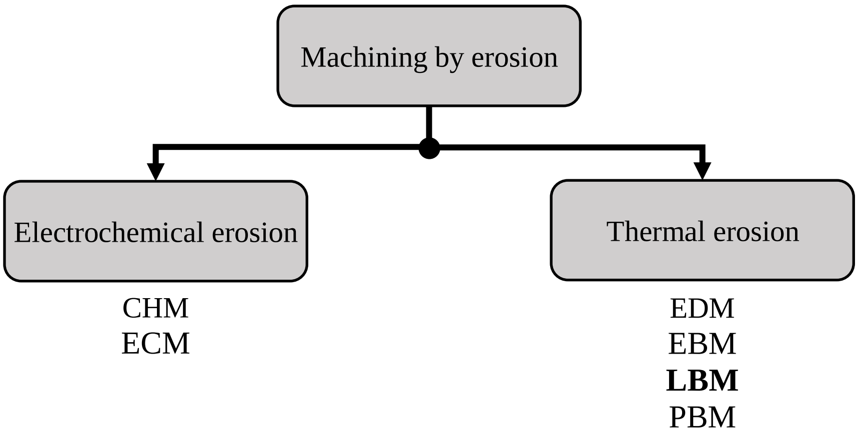


Figure 2: Erosion machining processes (edited from [4])

LBM is introduced in the next part.

1.2.1 Laser Beam Machining (LBM)

Laser beam machining works on emitting a high-power laser beam on the workpiece, which cuts through the material. Cutting is accompanied by emitting working gas (e.g. oxygen or nitrogen) which helps with the removal of melted material and prevents intrusion into the laser head.

A schematic of laser beam generation is shown in Figure 3.

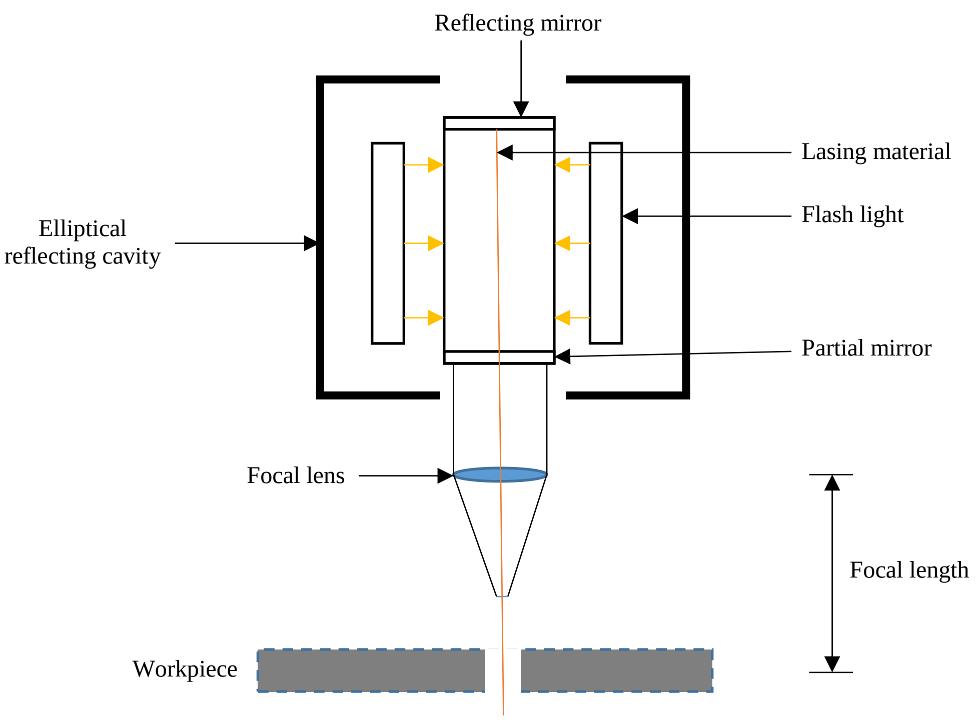


Figure 3: LBM schematic (edited from [4])

Some advantages of this cutting technology are low operating cost, easy process of automation, high-speed machining, and large variety of hard material machining. Disadvantages are high equipment cost, and the maximum material thickness is restricted to 50 mm. [4]

2 SOFTWARE DEVELOPMENT TOOLS

Software development tools necessary for project creation, development and testing are briefly addressed in this section. Figure 4 shows a block diagram of software tools which are described below. Lighter green and yellow boxes mark features, and darker green boxes mark tools for project testing (simulation) or debugging.

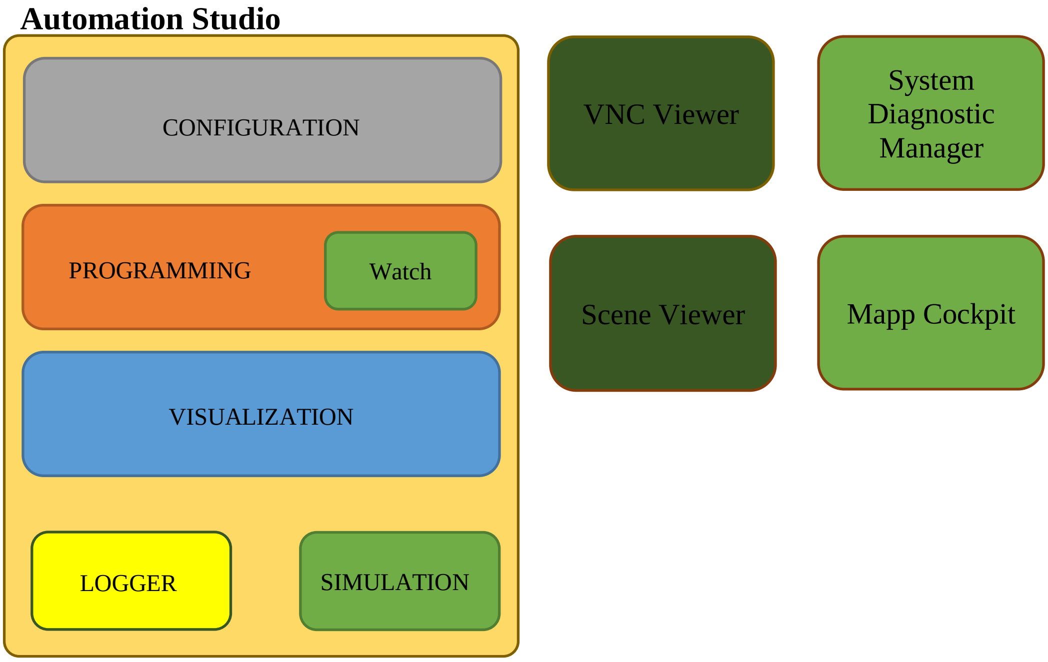


Figure 4: Software development tools

2.1 Automation Studio

Automation Studio (AS) is the main tool for creating an entire project. Project configuration, programming, visualization, and diagnostic tools are integrated into one environment. It is possible to create multiple configurations in one project, depending on hardware. This makes project development and integration easier. [5]

Watch window is used to display all project variables and its values can be manually changed.

Logger window shows activity logs (errors, warnings, etc.). Logger check should be the first step in debugging an error source.

Simulation enables a program test on the PC without the use of real hardware. Tools used within simulation are described below.

AS is available to download from [6].

2.2 VNC Viewer

It is a program used in a simulation for showing a visualisation of a project. First, simulation has to be enabled in the project's CPU configuration (in Physical View under Simulation). There is an IP address via which the VNC Viewer can connect to the project's visualisation.

The VNC Viewer is available to download from [7].

2.3 Scene Viewer

In developing a CNC or a robot application, it is not always an option to develop the software right on the real machine, and hence the Scene Viewer is a useful tool. Figure 5 shows an example of a simulation. In the Scene Viewer's help is a tutorial of how to connect it with AS simulation.

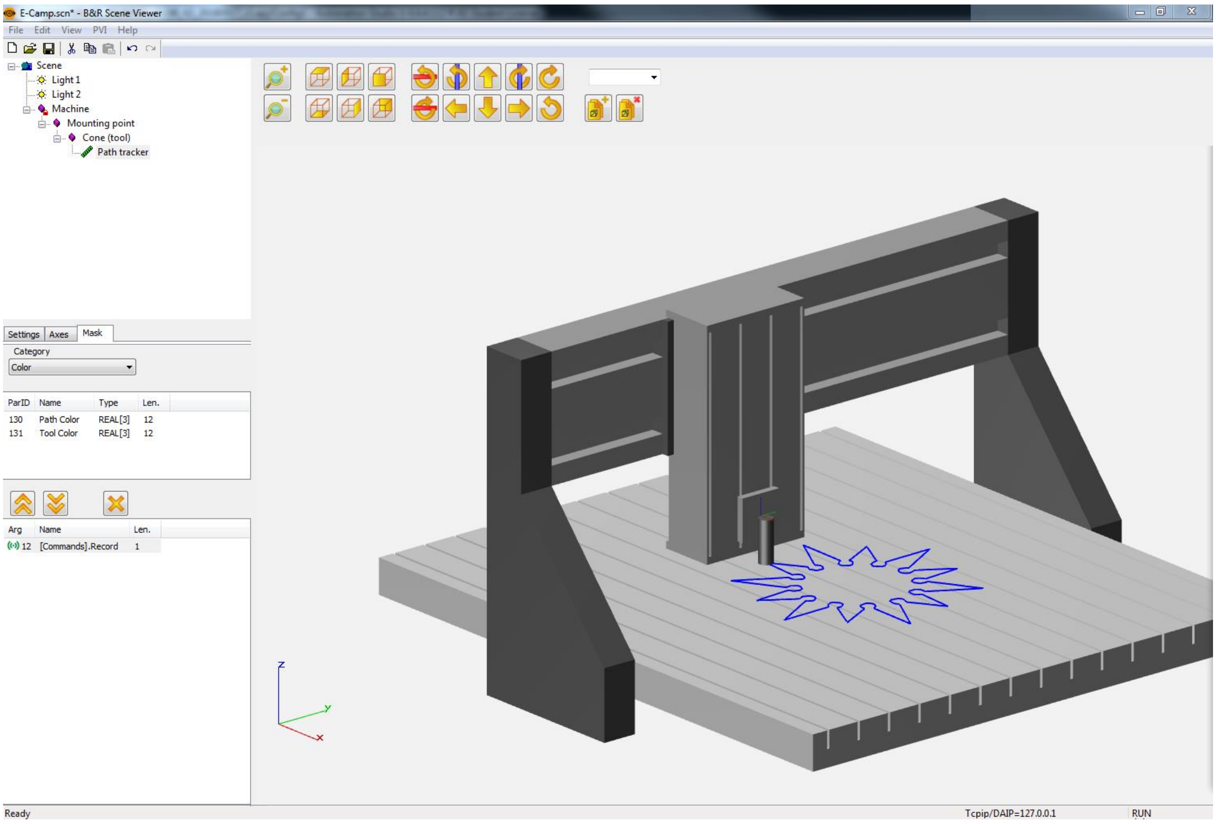


Figure 5: Scene Viewer (image taken from [8])

Scene Viewer available to download from [8].

2.4 System Diagnostic Manager

System Diagnostics Manager (SDM) is a tool accessible via an internet explorer. This enables access to the machine's CPU without direct connection using AS. This tool offers actual CPU usage, software configuration with an error display, logger, memory usage and more. SDM is accessible via a link: *http://IP_Address/sdm/index.html* [9].

2.5 Mapp Cockpit

Mapp Cockpit is a trace tool of variables. Traced variables can be set in the cockpit using the AS mappCockpit feature or directly via a web interface. The following is the link: *http://IP_Address:81/index.html?visuId=mappCockpit* [9]. It allows the plotting of traced variables or the saving of traced data into PC as CSV (see Figure 6).

All data of graphs showed in this thesis are saved using Mapp Cockpit. Matlab is used for graph creation.

Figure 6: Cockpit (image taken from the address described above)

To trace special parameters, the so-called parId can be used. In Table 1 are selected parIds used during project development in the practical part. To find the whole list with a detailed description, see [9] (under Motion control/ACP10/Reference manual/ACP10/NC Trace/ACOPOS Parameter IDs).

Table 1: ParIDs [9]

ParID	Description
91	Encoder1 - actual position
92	CTRL Position controller – actual speed
111	CTRL Position controller - actual position
112	CTRL Position controller - lag error
113	CTRL Position controller - set position
114	CTRL Position controller – set speed
214	CTRL Current controller – actual stator current quadrature component

Format of inserting a parId is: *ACP:SL1:IF1.ST2_Axis1:114* [9].

3 PROJECT DEVELOPMENT

This section contains a description of the starting conditions of this project as well as a description of the assignment. Following from a machine component description and a project basic hardware configuration, software development is addressed.

3.1 Assignment and Starting Conditions

The task is to create a complete software solution for the metal sheet laser machine. This included gaining the necessary background knowledge of this technology (described below). The first step, or subcategory, of the software solution, is axes commissioning, which includes actuator driver tuning, maximal limit searching (max speed, acceleration/deceleration) and mainly positional error eliminating (reduction). The next step is creating a complete software solution of axes control (made up of independent axis control as well as CNC integration), laser head control, laser technology control, suction control, and machine element control (e.g. doors, sliding grid lock). A complete visualisation environment had to be created. A CAD/CAM software generated G-code (CNC program) format had to be specified.

As the starting conditions of this project, a complete mechanical and electrical solution of the laser machine was given. It was necessary to get to know all the machines' mechanical components (movement parts, sensors) and its electrical wiring (mainly to I/O modules of the PLC and motor's drivers). Technical and electrical documentation of the laser machine was used as the main source [10]. An understanding of the CNC laser cutting principle had to be gained. Understanding of the control technologies, such as the laser beam generator (technical documentation [11]), suction (technical documentation [12]) and working gases control, had to be gained.

The machine construction was designed and built by the company K2 Machine [13] This project of building and developing the laser cutting machine is the first of its kind in the company, with no previous experience with laser cutting.

Because the machine is controlled by technology from B&R [14], it was necessary to undergo extensive training at the company, mainly on motion control and CNC technology. Subsequently, remote support with an expert in CNC technology at B&R was established during the project development. A need for special support was because we decided to develop the software on the completely new core of the Automation Studio (Mapp motion instead of ACP10).

Training about controlling the laser technology (laser generator) from the company TRUMPF [15] was undertaken during the laser's commissioning.

3.2 Main Components of the Machine and Basic Description

In this chapter the main components of the laser machine are described, as well as a basic description of some specific parts.

In Figure 7 the placement of the laser machine and its components can be seen. The figure also shows the general dimensions of the workplace. No. 1 is the laser machine. The machine is designed to work with a work plate of size to 3000 × 1500 mm. No. 2 is sliding grate on which the metal plate is put; below is the sliding bin for felt workpieces or waste parts from cutting. In place of no. 3 is the screen for controlling the machine (moving with axes, setting parameters, selecting recipes, loading G-code, etc.). The distributor of the machine is no. 4. No. 5 is a laser beam generator which transmits the high-power laser beam via optic wire to the machine's laser head. No. 6 is a laser generator's (no. 5) cooling unit. The suction unit of fumes from the cutting is no. 7 and its pipeline is no. 8. Nos. 9 and 10 are cutting gasses, nitrogen (N2) and oxygen (O2). Pressured air from the distant compressor is also connected to the machine.

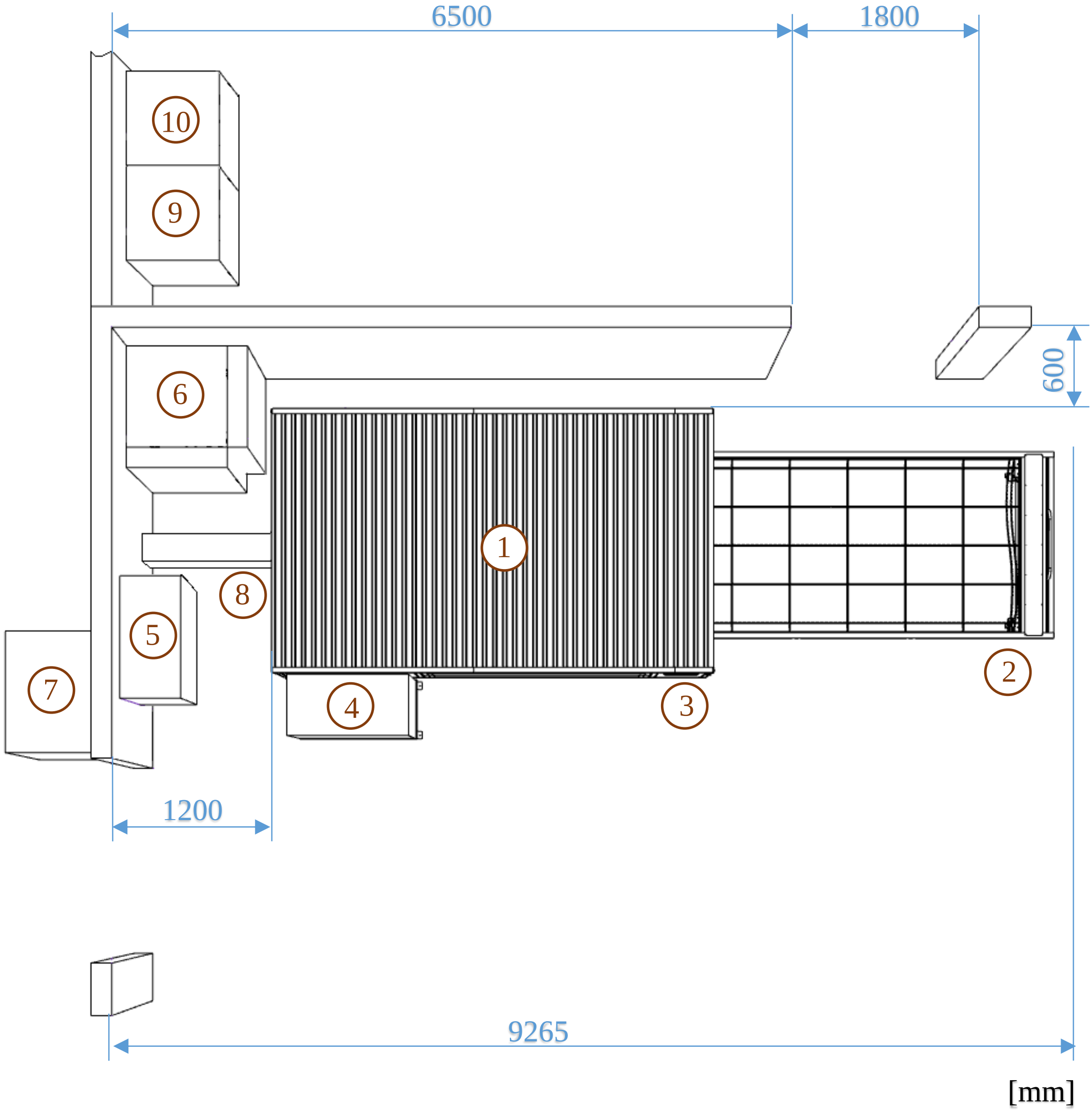


Figure 7: Placement of the laser machine and its component [10]

Figure 8 shows the 3D model of the machine. No. 1 shows four independently controlled doors which enable access to the machine area. No. 2 shows windows enabling visual contact during the machine's operation. A control panel (HMI) is also placed there. No. 3 is the sliding grate and no. 4 is the sliding bin, both controlled manually.

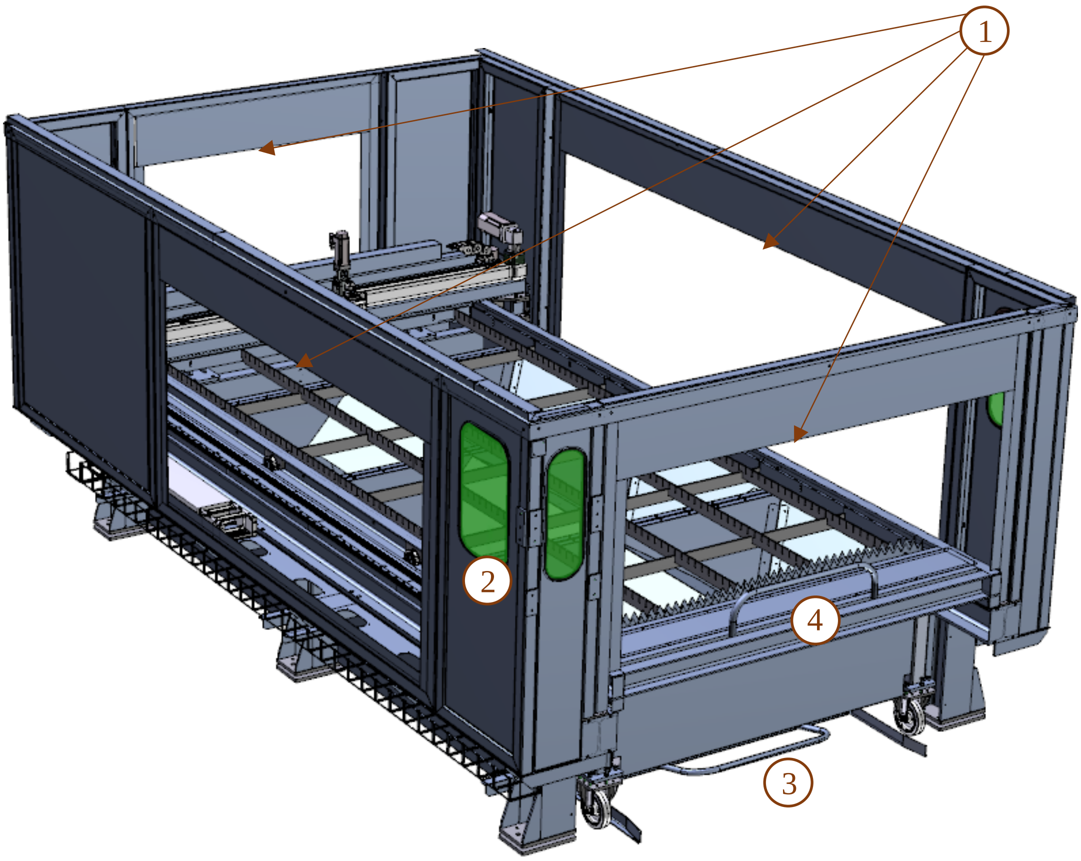


Figure 8: 3D view of the machine [10]

Axis realisation and labelling are shown in Figure 9. No. 1 (yellow) are combs for the X-axis. A portal, no. 2 (blue), carries two actuators for movement in the X-axis direction on the combs. The laser head (green) is placed on a belt drive executing the linear movement in the Y-axis. And no. 3 is the laser head having an actuator for moving in the Z-axis direction.

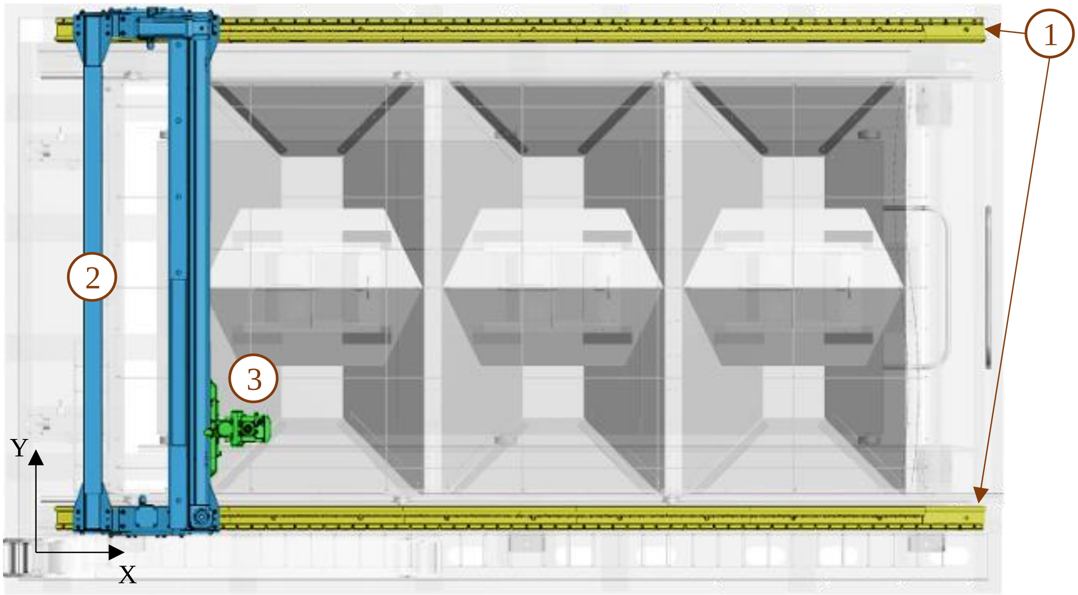


Figure 9: Top view of the machine – axes [10]

Figure 10 shows the suction section of the machine. Nos. 1 – 3 are separate sections controlled by pneumatic cylinders. Opening and closing of each section are dependent on the actual position of cutting.

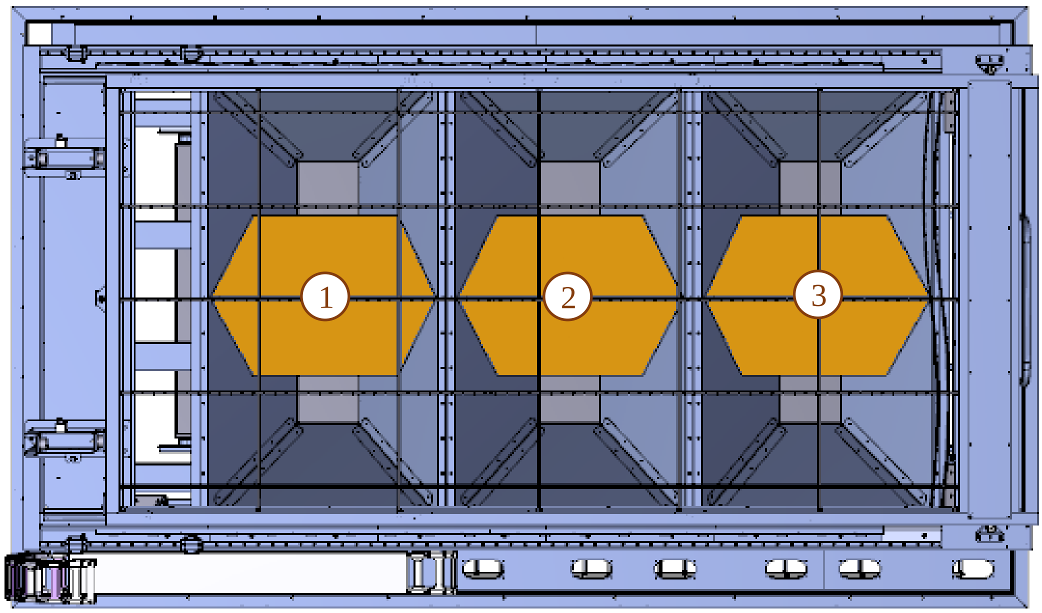


Figure 10: Top view of the machine - suction section [10]

Table 2 contains basic components for the motion control part.

Table 2: List of basic components for motion part (B&R [14] manufacturer)

Name	Note
Panel	
CPU	
Interface card	
3 axis driver	
1 axis driver	
X-axis - motor	
- gear box	1:20
Y-axis - motor	
- gear box	1:25
Z-axis - motor	

Attachment A includes images of the real laser machine.

3.3 Program Development

This section introduces a project creation in AS. A hardware creation is addressed with program structure. A programming style is introduced with a basic description of the program division. The project variables and structure system are introduced. Following, is a description of the main parts of the machine functionalities.

Automation Studio, version 4.5.2, is used in this project. New project creation is described in the software's help [9] under the section **Getting Started**. Under the section **Motion Control** is a tutorial on how to set up axes and CNC.

3.3.1 Creating a Hardware Configuration

After creating a new project, building a hardware configuration is the next step. Figure 11 shows a graphical view of all hardware components. An operational panel, a unit with I/O cards, actuator's drive units, servomotors, and a mobile panel can be seen. Figure 12 shows the hierarchical order of all components.

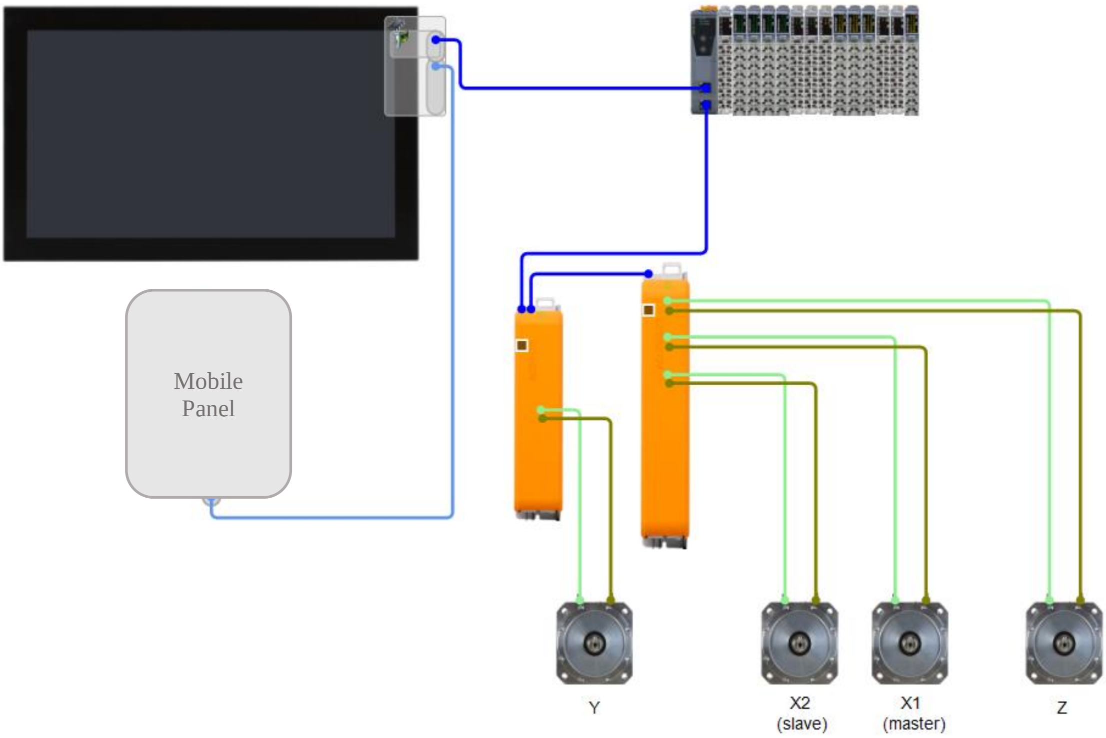


Figure 11: AS - hardware view (image taken from SW [6])

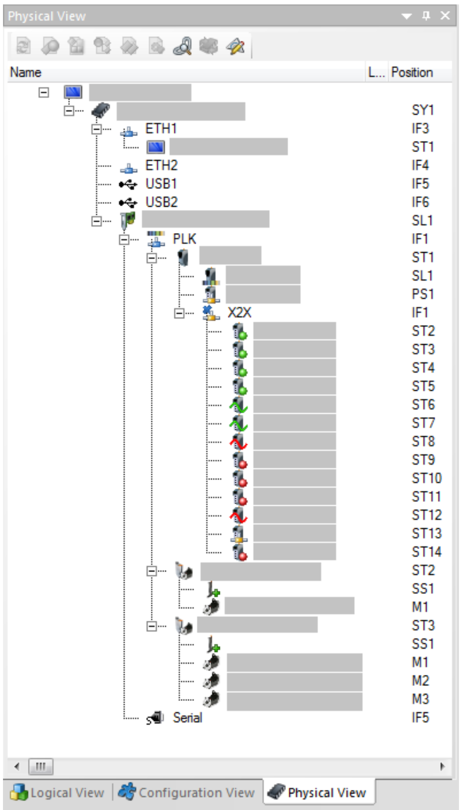


Figure 12: AS - physical view (image taken from SW [6])

3.3.2 Programming

The entire program structure is shown in Figure 13. Folder Libraries contains libraries of all used functions. In the folder, Source, are all files of the program. Division of the program parts is important for clarity and for assigning cyclic timing classes. Some parts of the program are necessary to execute in higher cyclic class and some in lower cyclic class. E.g., the ControlTheHeight section, which is responsible for keeping constant height from the workpiece, is executed every 0.4 ms. The FocalPosition section, which is responsible for setting the head's focal position of the lens, is executed every 100 ms.

Folder Motion contains a program responsible for axes movement setting (speed, limits, etc.), homing procedure, jog control, and CNC control.

Folder Laser contains a program responsible for reading parameters of the head (gas pressure, head temperatures, focal position, etc.), calibration of the head sensor, setting the focal position of the lens, controlling the head's height from the workpiece, and laser control (cutting mode, power, etc.).

Further, there is a file for controlling machine doors (opening, closing). The folder FileMng takes care of file management of recipe files (G-codes) and management of the technological table (creating, editing, etc.). Continuing with the file for alarm control, the folder for visualization (for the main control panel and the mobile panel) and the file controlling pneumatics cylinders.

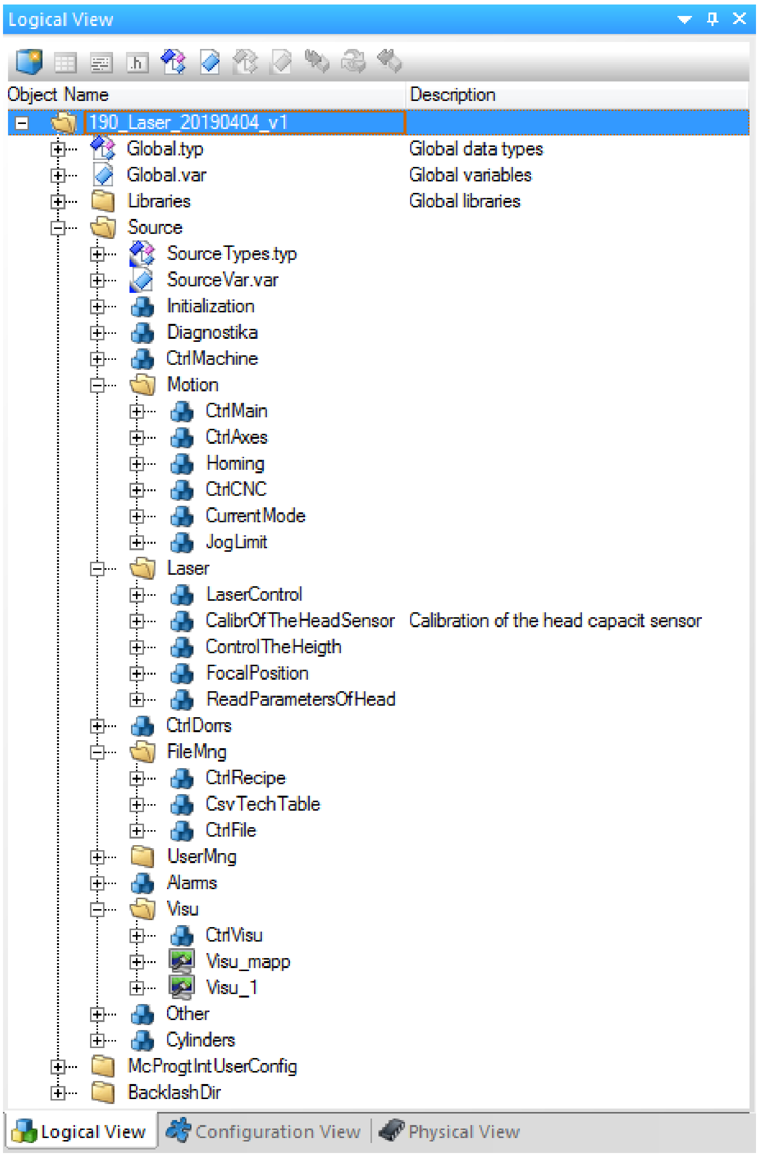


Figure 13: Logical View of the program (image taken from SW [6])

The application was programmed in Ladder (LD) programming language. Figure 14 shows an example of variable structure. On the left is shown the IO structure which contains all input/output ports of the machine. On the right is the main structure containing most of the variables of the machine. Noteworthy is a structure, States, which contains all control variables of state machines in the program.

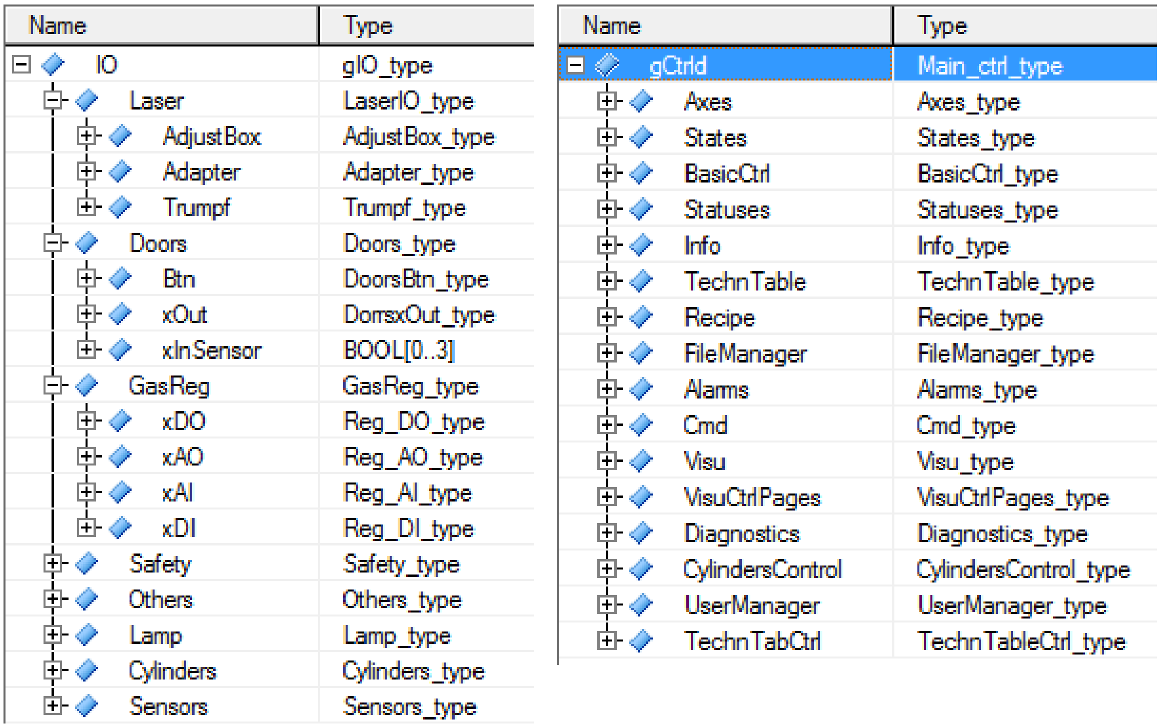


Figure 14: Main variables structure (image taken from SW [6])

Figure 15 shows detail of Axes structure. Here are control structures for all actuators (X1, X2, Y, Z), CNC control, and coupling structures (used for portal coupling and CNC virtual axes coupling).

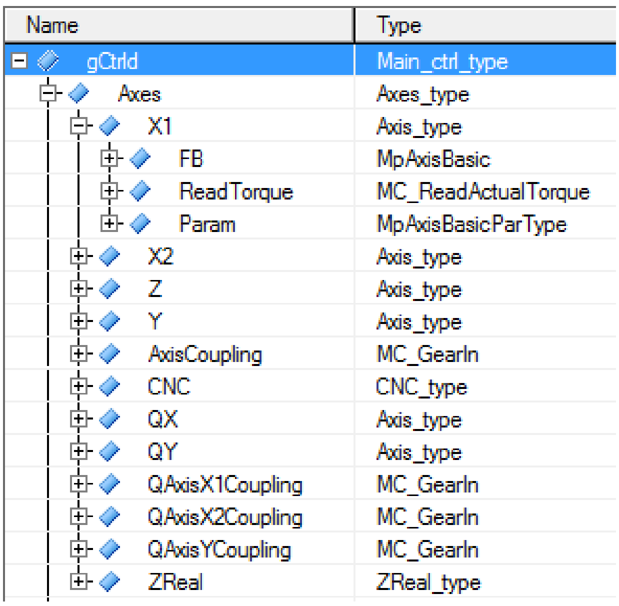


Figure 15: Variable detail to axes structure (image taken from SW [6])

The recipe administration page and technological page, which are working with files are created based on Mapp technology (more information can be found [5] or in AS Help [6]). The description of application screens is devoted to chapter 5.

3.3.3 Axes Homing

After powering on the motors, the first step is always to home the axes. Homing means to get information about the real position of the axes. There are a few options for homing. Direct homing homes the axis on the current position. When homing to an absolute switch, the axis moves in one direction and in a moment of reaching the switch, the axis is homed. Homing using absolute correction of the encoder value starts with subtracting a known offset value from the actual value of the encoder. It results in gaining an actual axis position and the homing is done.

In this project, absolute correction homing mode is used. The advantage of this mode is no need to move axes to their homing (zero) position. It saves time. The disadvantage is in case of replacing a motor, and a new offset value has to be found. Figure 16 shows a step of a state machine which sets homing mode with particular offset values. The distinction of homing modes, between executing simulation or a real machine, can also be seen.

```
//START HOMING
30:
    //FOR SIMULATION
    IF (gCtrld.Info.CPUSerialNumber = 0) THEN
        gCtrld.Axes.X1.Param.Homing.Mode := mcHOMING_DIRECT;
        gCtrld.Axes.X1.Param.Homing.Position := 0;
        gCtrld.Axes.X2.Param.Homing.Mode := mcHOMING_DIRECT;
        gCtrld.Axes.X2.Param.Homing.Position := 0;
        gCtrld.Axes.Y.Param.Homing.Mode := mcHOMING_DIRECT;
        gCtrld.Axes.Y.Param.Homing.Position := 0;
        gCtrld.Axes.Z.Param.Homing.Mode := mcHOMING_DIRECT;
        gCtrld.Axes.Z.Param.Homing.Position := 0;

    //FOR REAL MACHINE
    ELSE
        gCtrld.Axes.Y.Param.Homing.Mode := mcHOMING_ABSOLUTE_CORRECTION;
        gCtrld.Axes.Y.Param.Homing.Position := -21130.442;
        gCtrld.Axes.Z.Param.Homing.Mode := mcHOMING_ABSOLUTE_CORRECTION;
        gCtrld.Axes.Z.Param.Homing.Position := -1498.368;
        gCtrld.Axes.X1.Param.Homing.Mode := mcHOMING_ABSOLUTE_CORRECTION;
        gCtrld.Axes.X1.Param.Homing.Position := -19599.825;
        gCtrld.Axes.X2.Param.Homing.Mode := mcHOMING_ABSOLUTE_CORRECTION;
        gCtrld.Axes.X2.Param.Homing.Position := 7649.474;

    END_IF

    gCtrld.States.MotorsStep := 40;
```

Figure 16: Homing mode

3.3.4 CNC Control

The CNC control is described in Figure 17. When manually positioning axes by jogging, we are operating with real axes coordinates. For example, maximally allowed limits of each axis are applied to these coordinates. Real axes are controlled by the function block *MpAxesBasic* which sends commands directly to the actuator's driver via Powerlink communication.

Until this point, independent axes movement was described, not CNC movement. CNC is controlled by the function block *MpCnc2Axis* which is connected with virtual axes. And virtual axes are coupled to real axes (after CNC block start). This makes the sub-coordinate system, which can be homed independently to the real axis position. After loading the CNC program, its coordinate system is tracked by the virtual axis coordinate system.

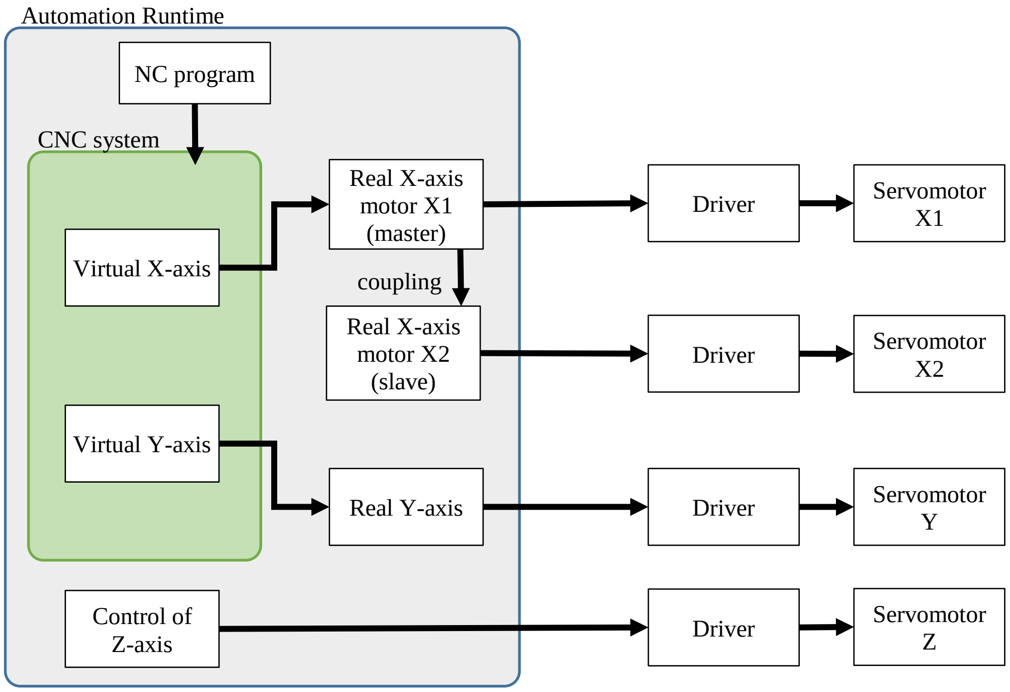


Figure 17: Block diagram of CNC control

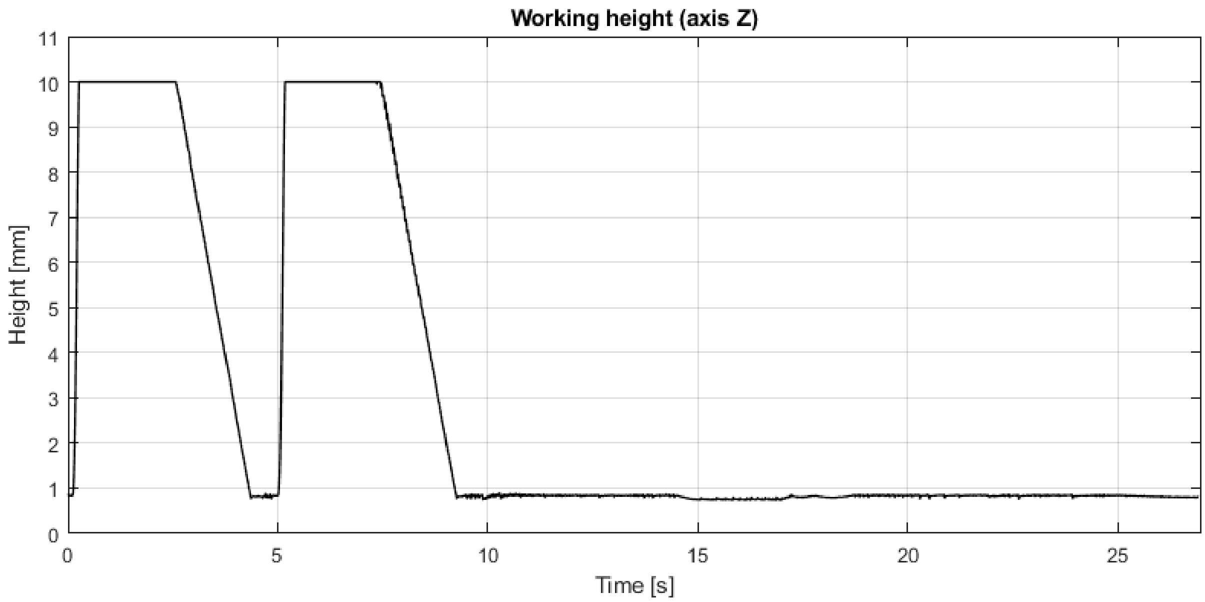
3.3.5 Controlling of the Laser Head

During the cutting, the laser head has to keep a constant distance from the workpiece. On the laser head is an inductive distance sensor which has range from 0.2 mm to 10 mm [11]. This sensor is used for the height sensor of the Z-axis.

After the start of the machine or change of workpiece (material or thickness) the sensor has to be calibrated. The calibration starts by head touching the workpiece, which now refers to the axis encoder zero position. And then using the axis encoder position, the head is gradually positioned to sixteen different positions in the range mentioned above. The calibration is done by its final step, and it moves the head to a position 50 mm above the work plate. The calibration procedure description can be found in [11]

Figure 18 shows the heads distance control in an example. The first plot shows two jumps to the position of 10 mm. This is the “non-cutting position”. The actual head position is 50 mm above the work plate, but the sensors range is only to 10 mm. It is important to decrease any possible contact with the workpiece during the non-cutting (work) movements. There is a risk of fatal damage to the head or interrupting of executing a program. An immediate stop of any movement is programmed in case of material contact with the head nozzle (there is a binary sensor of metal contact).

The second figure shows detail of the same waveform with marked hysteresis of the desired distance. Determined hysteresis of ±5 mm tuned out during the testing as sufficient showing no anomalies on workpieces.



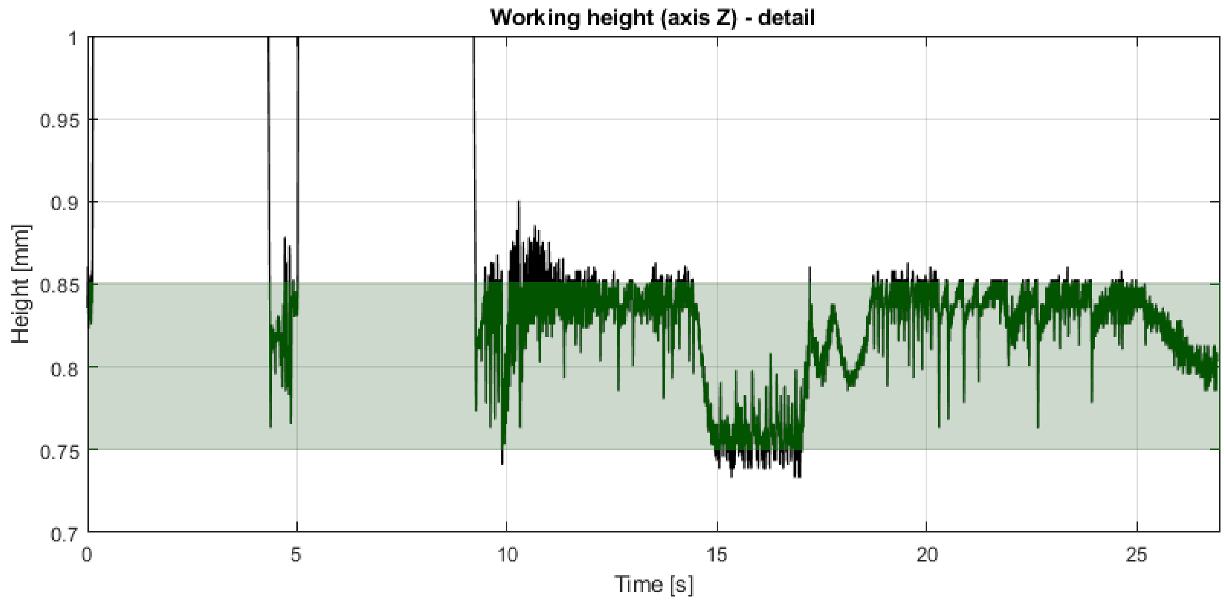


Figure 18: Working distance (Z-axis)

3.3.6 Controlling the Laser and Cutting

The laser has to be started manually on the control unit. Then it needs approximately 20 min for setting itself into a working state. This is signalized on the machine. After the laser is ready, a cutting mode (pulse mode or continuous wave) is selected. Then an analogue value of the power (up to 3 kW) is set. Executing cutting is done by the binary signal which is set after calling an M-function *M100* in G-code, and it is set off by calling an M-function *M10*2.

4 CNC AXIS COMMISIONING

This chapter contains a detailed description of a process of axis set up for CNC application, starting with tuning of actuators and deriving of their limits. Problems with were encountered, as positional error, are described and solved in detail.

4.1 Tuning of Servomotors

Servomotor tuning is crucial for the whole machine functionality and directly influences final actuator performance.

AS Help [16] contains a description of the servomotor tuning procedure including a theoretical explanation with practical examples.

For tuning, an older tool is used, accessible in AS version 4.3 [17], called Servo Loop Optimizer (SLO). Figure 19 shows the Servo Loop Optimizer. No. 1 is the command window for tuning start. No. 2 is parameters window, where the mode of tuning (positional, speed) can be selected. Also here, limit parameters of the motor (e.g. maximum current of the motor in percentage, maximum lag error) can be set. No. 3 is an area of plots (gain and phase). Legend of functions of the plots is on the right side in no. 4. The blue waveform is the measured frequency response, and the red waveform is the calculated frequency response of the closed control loop. [16] Finally, no. 5 shows speed and position controllers, where regulator gain (kV), and an option for applying a certain type of filter (e.g. notch filter) can be seen.

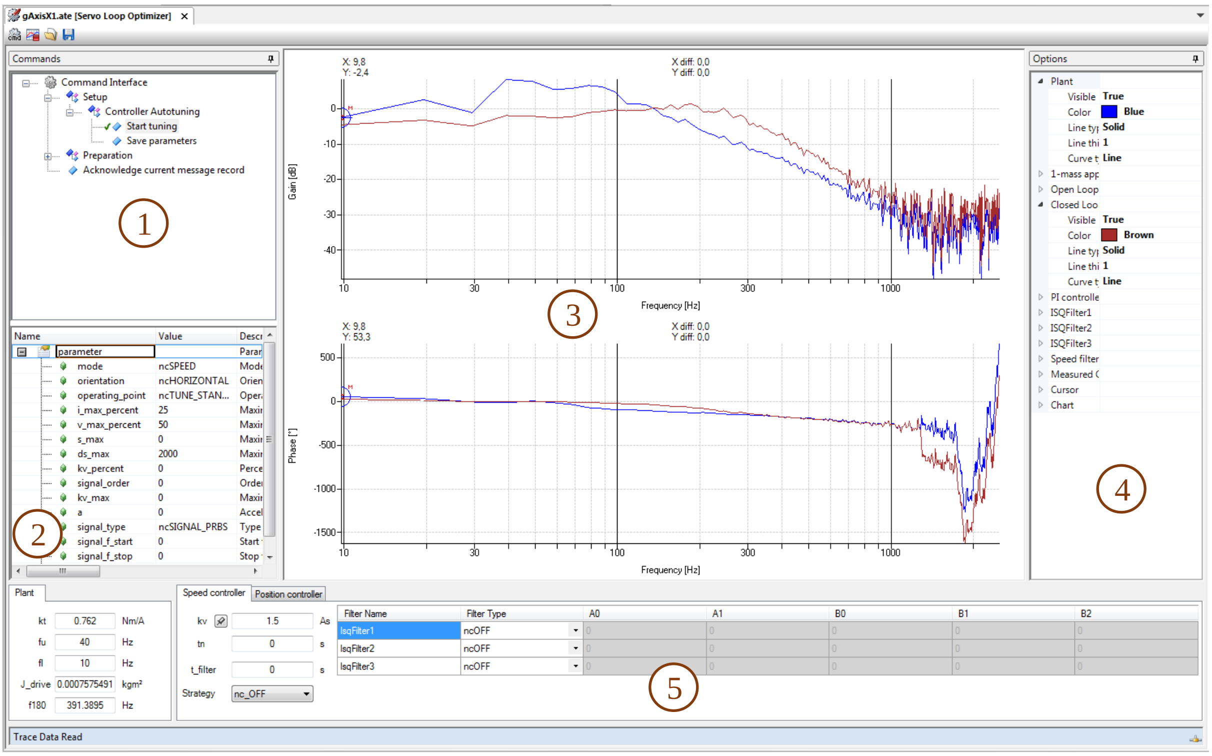


Figure 19: SLO – motor X1- Speed controller (image taken from SW [17])

The goal is to reach a stable regulation system of motor control with a maximum possible gain. A system is stable when, in a closed loop, the characteristics of gain are equal or below 0 dB. [16] We always must start with the tuning of the speed controller. To reach a higher gain of the controller, corresponding filters can be applied.

In this section tuning of the motor X1 is shown. Figure 19 shows the result of the speed controller tuning with value *1.5*. To reach a higher value, some of the available filters can be applied. Figure 20 shows the applied notch filter. The new value of gain is lower than in the previous case. The applied filter didn't improve the gain, so the filter is not used. Moving to the position controller, the result is shown in Figure 21, where the gained value is *464*.

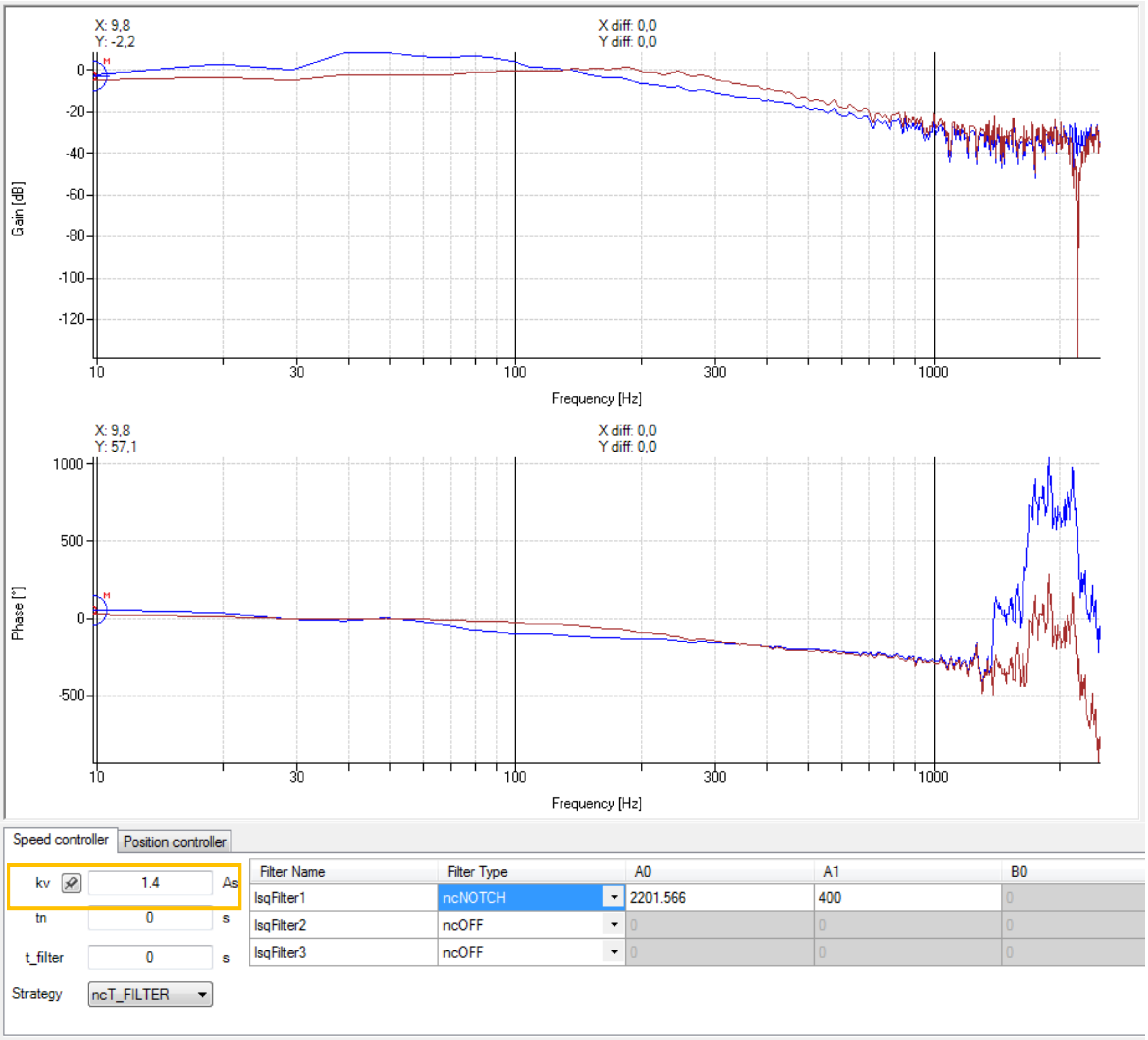


Figure 20: SLO – motor X1 - Speed controller, notch filter (image taken from SW [17])

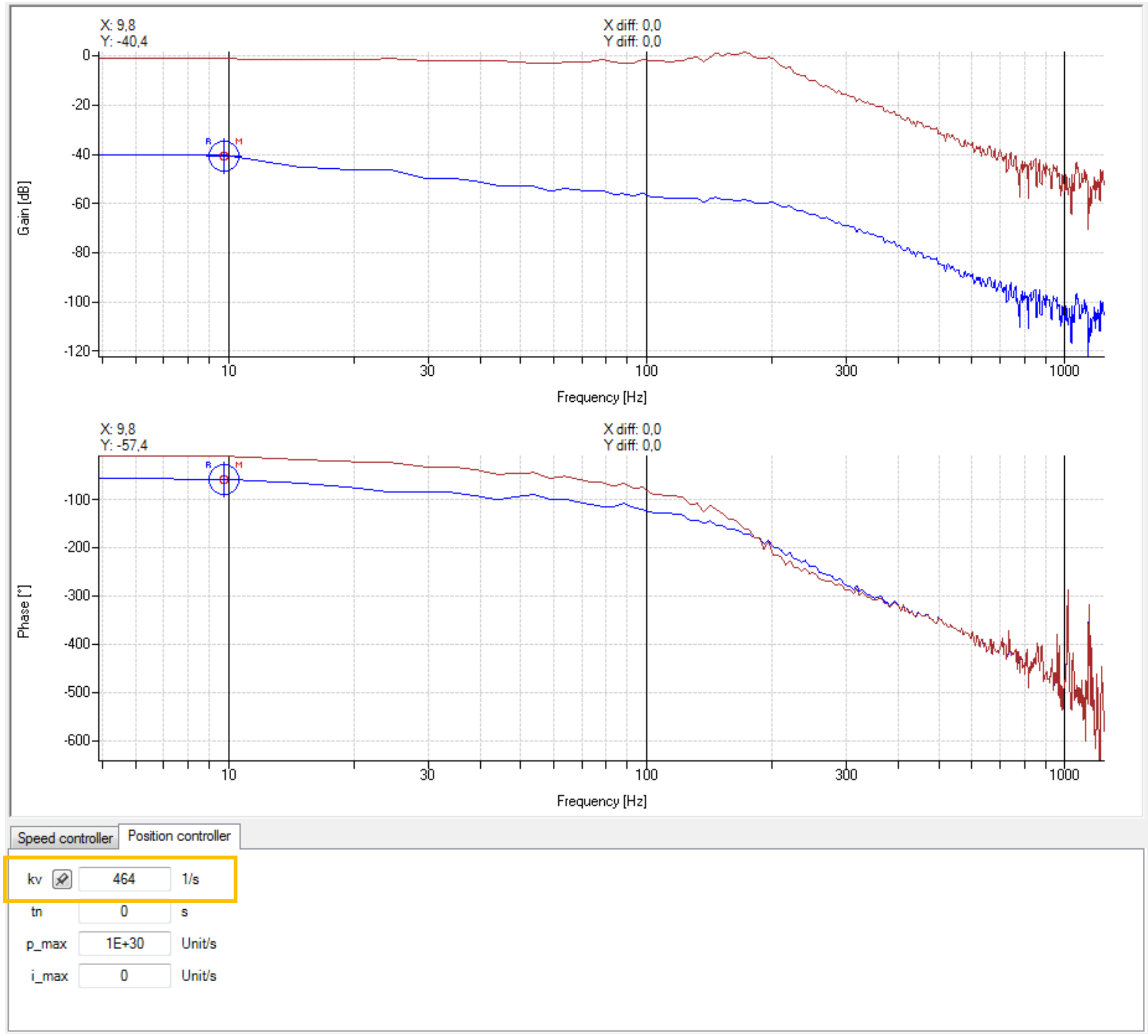


Figure 21: SLO – motor X1 - Position controller (image taken from SW [17])

The tuning had to be repeated multiple times and on different positions of the axes, to minimalize an error of tuning. In this case, five tunings were done for two different positions of axes. Final parameters of regulators are the average of all results.

Table 3 contains results for the speed and position controller for all motors. These parameters are then added into the project (configuration of the corresponding motor), as it is shown in Figure 22 for the motor X1.

Table 3: Values of speed and position regulators

Motor	Speed gain	Position gain
X1	1.5	684
X2	1.6	650
Y	0.25	604
Z	0.35	485

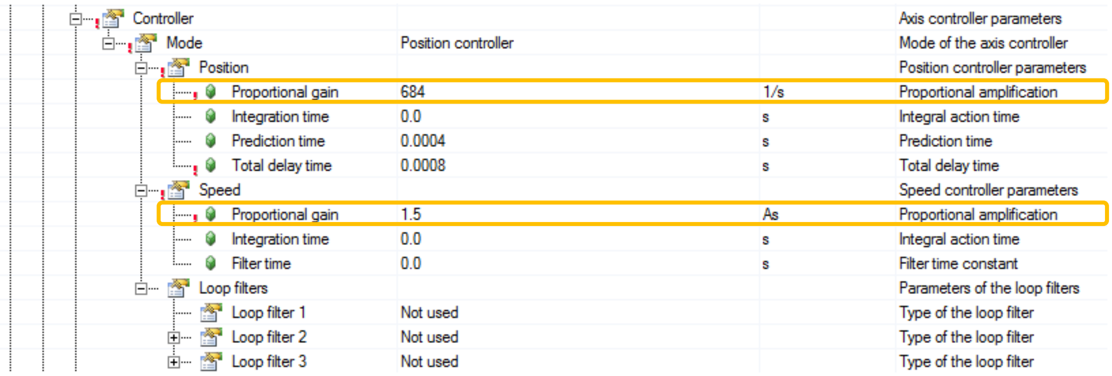


Figure 22: Configuration cut-out for regulators of motor X1 (image taken from SW [6])

4.2 Getting Motors Parameters

Firstly, the actual moved distance of the axis for one whole shaft (or motor in case of Z-axis) revolution needs to be known. This is done by changing a setting in the Configuration View (button to this window can be seen in Figure 12), then selecting appropriate motor, and displaying its configuration. Here, the linear bounded movement needs to be changed to rotary movement, as shown in Figure 23. Moving of the motor is done in degree units. E.g. for the X-axis we have gearbox 1:25, so we rotate the motor about 25*360° and measure the distance. Measured distances for all axes are shown in Table 4.

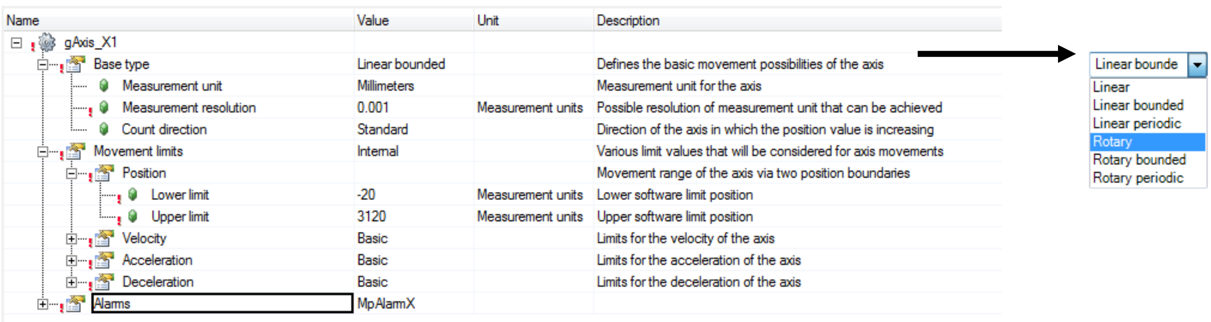


Figure 23: Axis configuration – a type of movement (image taken from SW [6])

Table 4: Distance parameters

Axis	Distance after one shaft revolution [mm]	Gearbox
X	157	1:20
Y	190.210	1:25
Z	5	1:1

These distance values are added to the configuration of each motor (in Gearbox section) and type of movement is switched back to linear bounded movement. From now, the motors are calibrated, and the actual executed distance corresponds to the commanded distance in the program.

The next task is to find maximal motor speed and acceleration/deceleration. We start with calculating theoretical optimal speeds to have start up points for finding real maximal values on the machine. Needed parameters of the motors can be seen in the Physical View (Figure 12), by right clicking on the motor and then selecting *Configuration*. A cut-out of the parameters for the motor of the X-axis can be seen in Figure 24. Another option for finding parameters of the motors is to go to [14] and look up the motor by its name. Needed parameters for all motors are in Table 5.

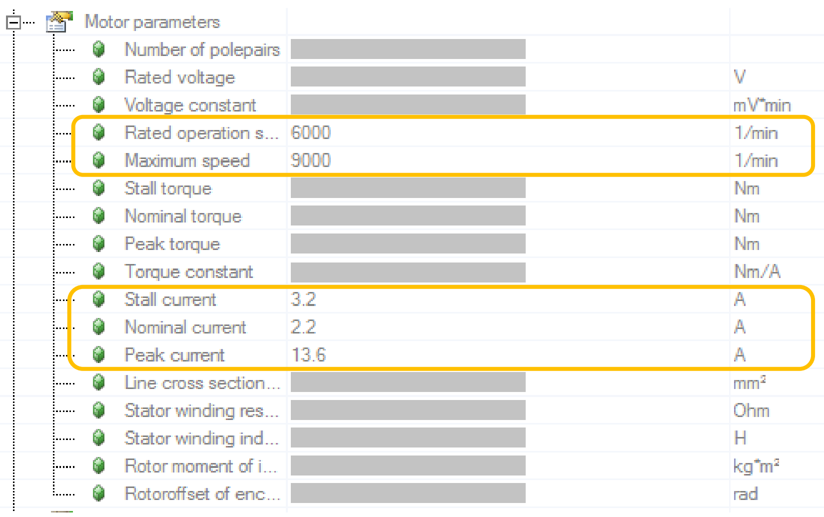


Figure 24: Configuration cut-out of the motor (X-axis) (image taken from SW [6])

Data in Table 5 are collected as described in the last paragraph and shown in Figure 24.

Table 5: Motor parameters

Axis	Operation speed [1/min]	Max. speed [1/min]	Nominal current [A]	Stall current [A]	Peak current [A]
X	6000	9000	2.2	3.2	13.6
Y	6000	9000	0.71	0.82	3.7
Z	6000	9000	0.71	0.82	3.7

The calculation for the speed will be shown for the Y-axis. We start by getting the travelled distance per one revolution of the motor using data from Table 4, see (1).

$$D_{1rev} = \frac{190.21}{25} = 7.6084\ mm \tag{1}$$

Then we multiply this value by revolutions per minute from Table 5. For operational speed, see (2).

$$v_{op} = 6000\ \cdot\ 7.6084 = 45{,}650.4\ mm/min \approx 46\ m/min \approx \mathbf{0.76\ m/s}. \tag{2}$$

And for maximal speed, see (3).

$$v_{max} = 9000\ \cdot\ 7.6084 = 68{,}475.6\ mm/min \approx 68\ m/min \approx \mathbf{1.14\ m/s}. \tag{3}$$

The final speed of the motor should be in the interval between 0.76 m/s and 1.14 m/s. It is important to mention that by increasing the speed, torque decreases, and it can make a problem depending on the load of the axis. Meaning, we can go higher than this maximum calculated speed. Calculated speed intervals for all axes are shown in Table 6.

Table 6: Calculated interval of motors speed

Axis	Operation speed [m/s]	Max. speed [m/s]
X	0.78	1.18
Y	0.76	1.14
Z	0.5	0.75

Figure 25 shows linear movement (distance: 140 mm) of the Y-axis with an applied maximum speed of 10 m/s and an acceleration/deceleration also of 10 m/s^2. Going from the top, the first graph shows the required speed; for this movement, its peak is 7 m/s. The second graph shows the actual speed. Here can be seen a high oscillation, which is causing high vibrations of the machine. The third graph is a lag error, where we can see a peak value exceeding 4 mm. The last graph is the motor's current. In comparison with the maximum motor current in Table 5, in this case we can see that the current is reaching the motor's maximum value. This example clearly shows the wrong parameters of the limits.

Figure 26 shows results of the same linear movement as above, but now the maximum speed is set to 1 m/s and acceleration/deceleration to 1 m/s^2. The lag error's peak value is now on 4 μm which is 100x less than the previous example. Also, the current is below the motor's nominal value. This setting shows the correct limit values.

Table 7 contains the found limit parameters for maximum speed and maximum acceleration/deceleration of all axes. Because of machine vibrations, which were caused by high-speed movement of axes during the machine work, acceleration/deceleration values for axes X and Y have been decreased to 2 m/s^2.

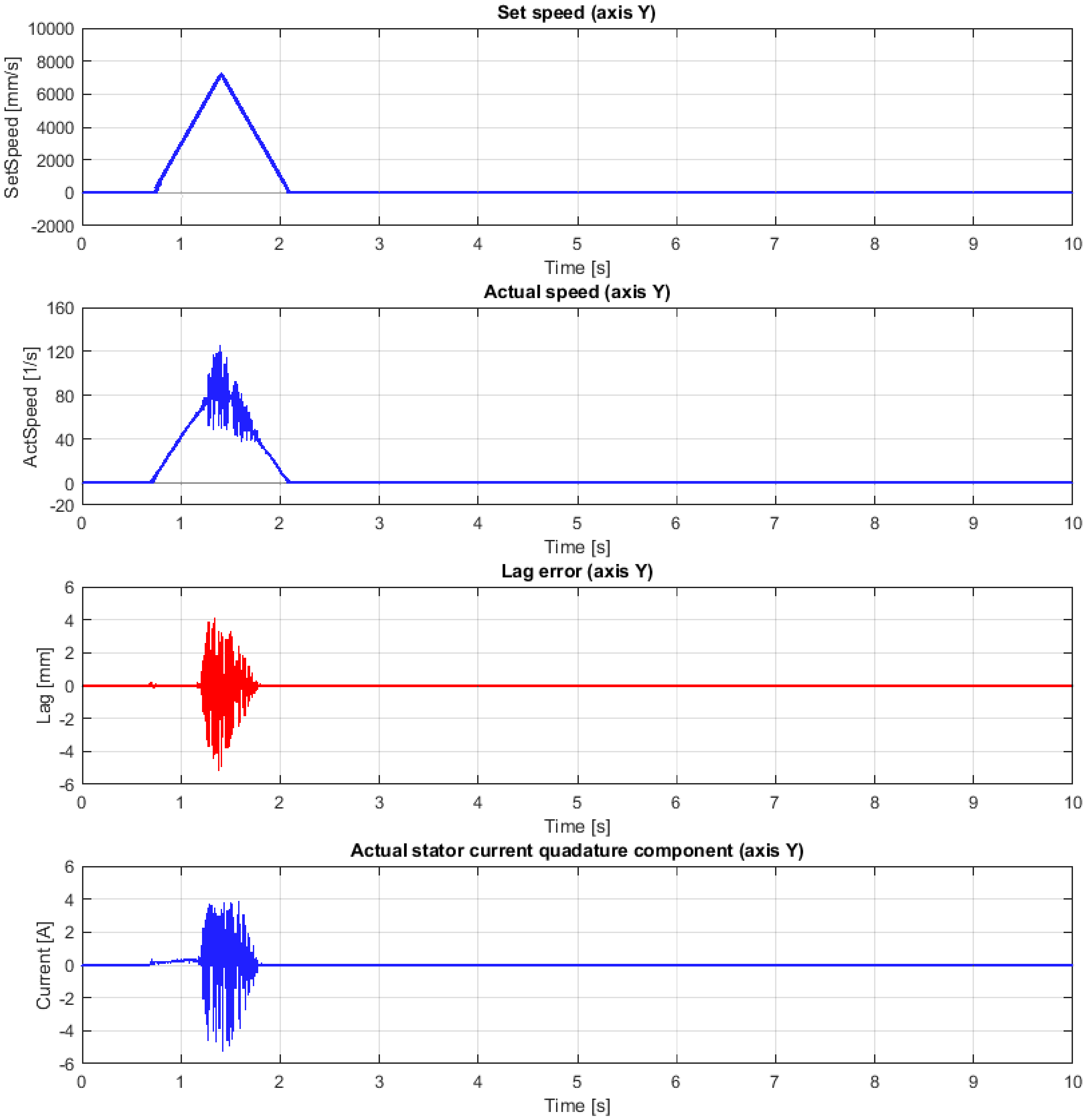


Figure 25: Y-axis - speed 10 m/s - acceleration/deceleration 10 m/s

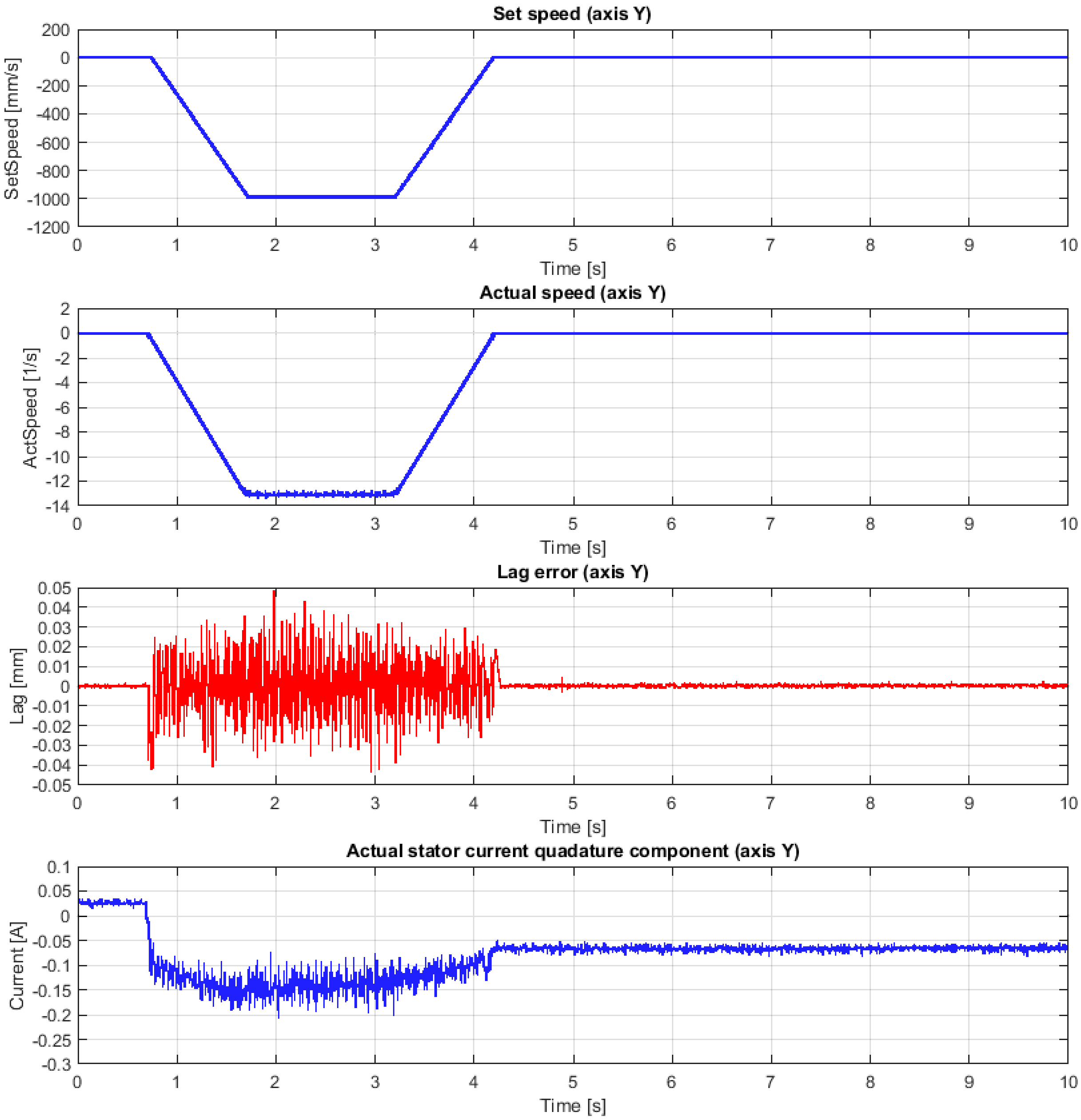


Figure 26: Y-axis - speed 1 m/s - acceleration/deceleration 1 m/s

Table 7: Found speed and acceleration/deceleration limits

Axis	Speed [m/s]	Acceleration/deceleration [m/s^2]
X	1	4
Y	1	10
Z	1	4

4.3 Synchronization of Motors on the Portal

The motor X2 is coupled with the motor X1 via the function **MC_GearIn** after powering on both motors. It means, the X-axis is controlled by motor X1 (which is a master), and motor X2 (which is a slave) traces the master motor in real time. Figure 27 shows motor labelling.

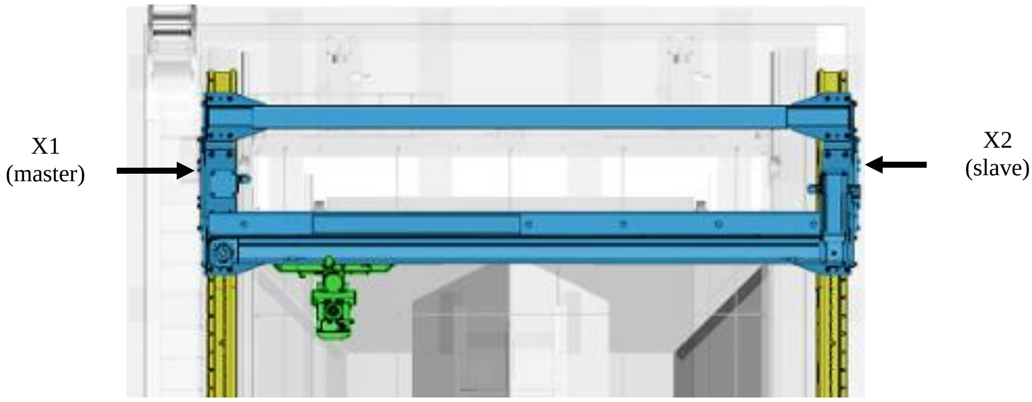


Figure 27: Portal [10]

A proper synchronisation was tested on the linear movement of the motors. Figure 28 shows the linear movement of the X-axis (first graph) and torque of the motors (second is motor X1 and third motor X2). For properly synchronised motors the torque of the motors should have a very similar shape. This graph shows non-trivial differences, so further examination was necessary. Instead of torque, current characteristics were done, which is shown in Figure 29. The current characteristics are measured on the same axis movement as in Figure 28. The first graph shows linear movement. The second and the third graphs show the current characteristics of the motors, and the fourth graph is the difference between the current characteristics. As the characteristics of the current show, one is inverted. It is due to one motor being reversed, and it is rotating in the opposite direction than the other. The fourth graph shows no significant differences in the current of the motors until approximately half of the distance. Then the difference starts rising.

A suspicion was made that the motors are not properly synchronised. Due to a delay in command receiving in one motor, tension is caused, resulting in different motor torque or current consumption.

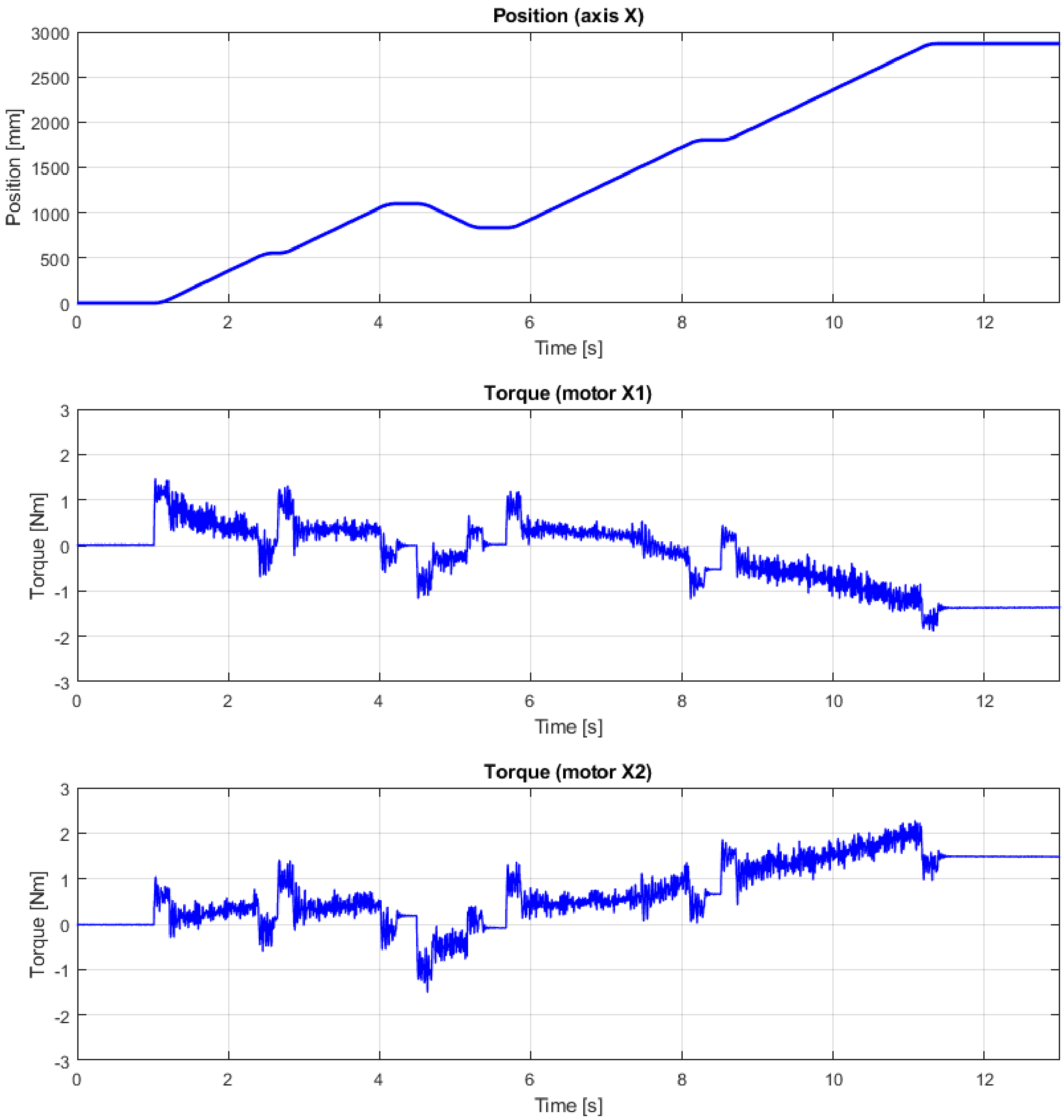


Figure 28: Portal - torque characteristics

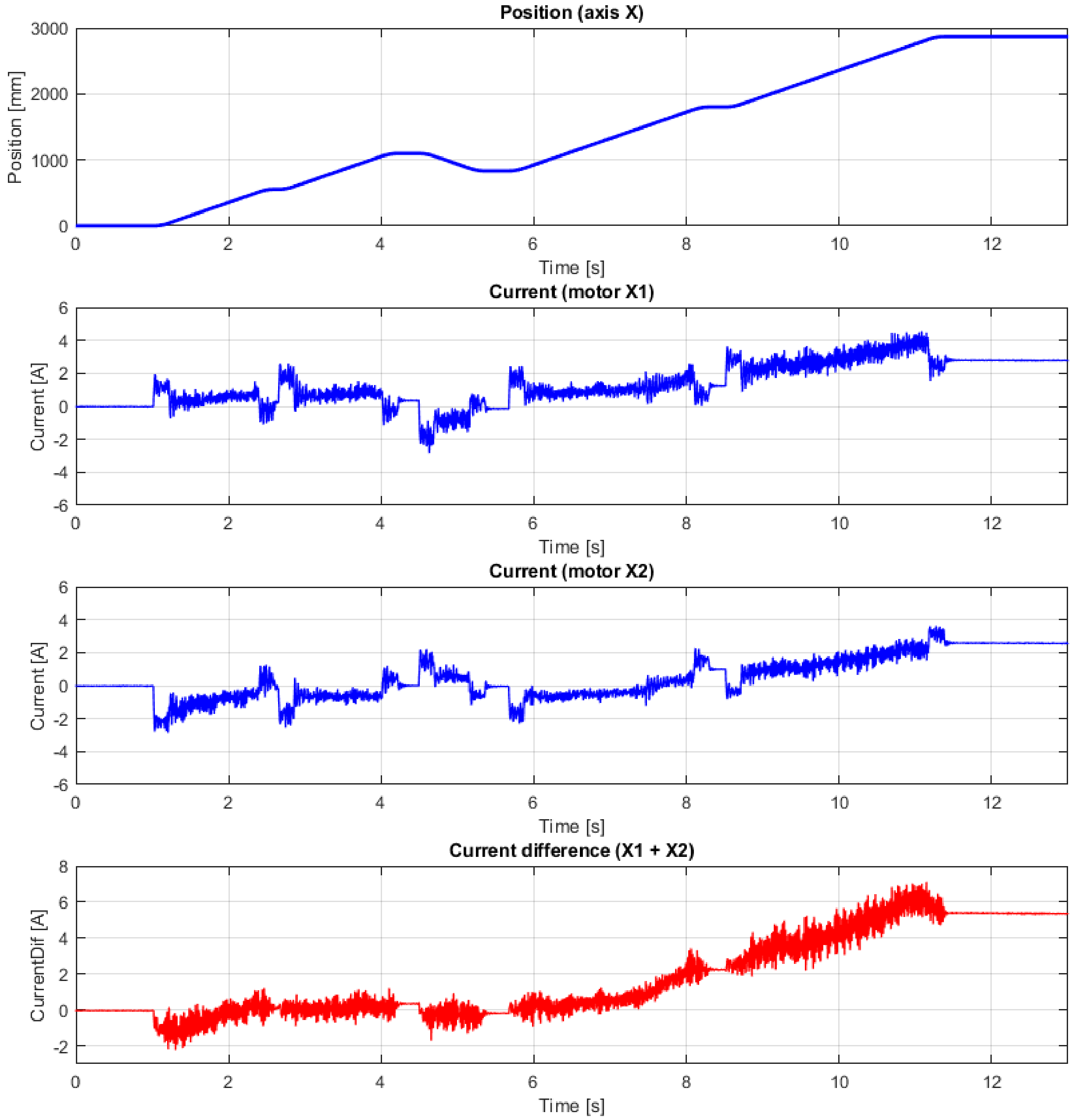


Figure 29: Portal - current characteristics

According to [18], *set speed* parameters were traced for both motors (see Figure 30). The first two graphs are parameters of *set speed*, and the third is their subtraction. The graph shows a constant delay between the two motors.

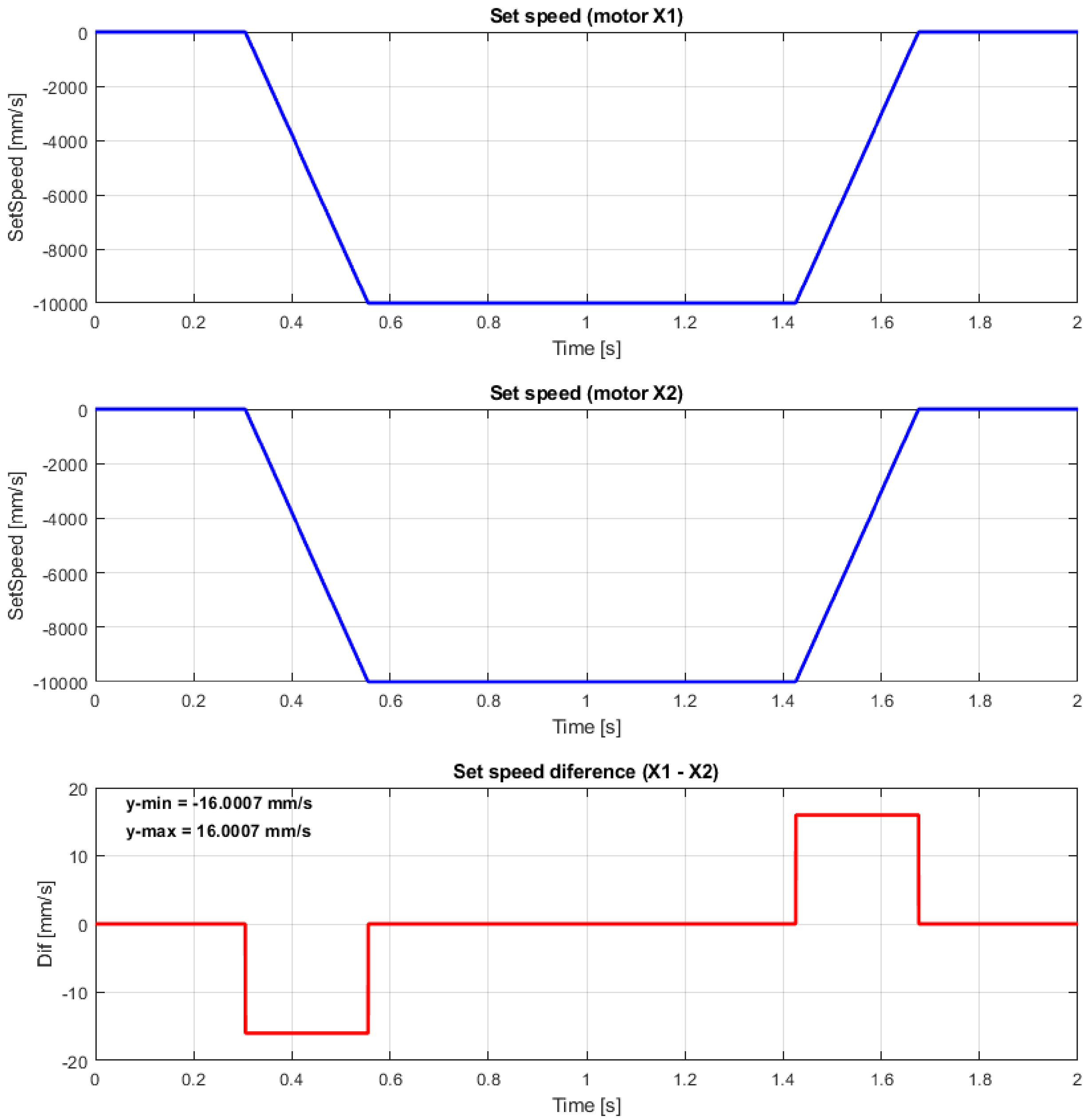


Figure 30: Portal - measuring synchronisation

A source [18] states that in case of a deviation (which is this case), the parameter *Total Delay Time* in axis configuration has to be changed. The value was changed from its default value (from *0.0004* to *0.0008 s*) in motor X1 configuration (see Figure 22). Figures 31 and 32 show differences after the changed configuration. The delay was eliminated.

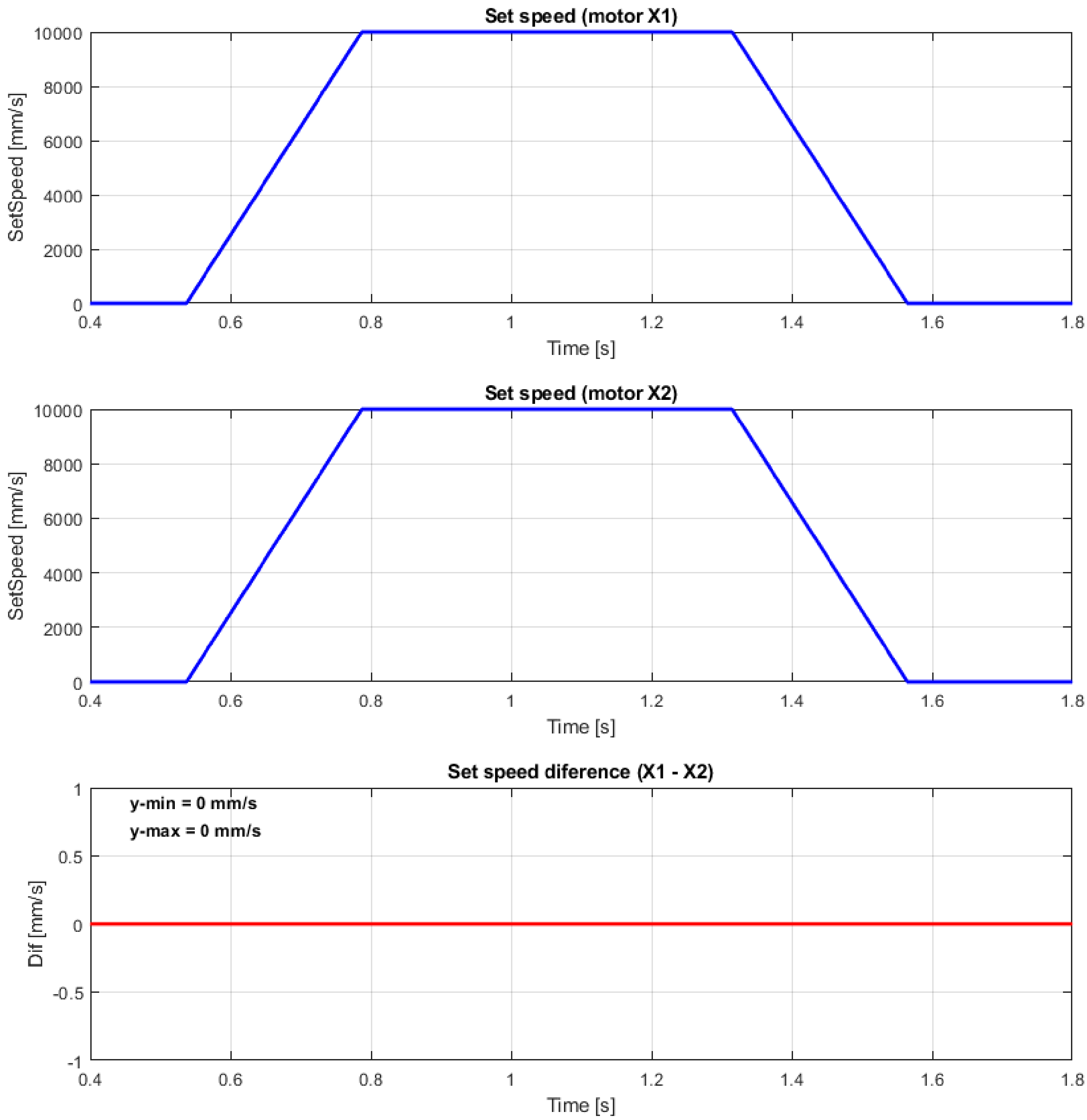


Figure 31: Portal - synchronized motors - test 1

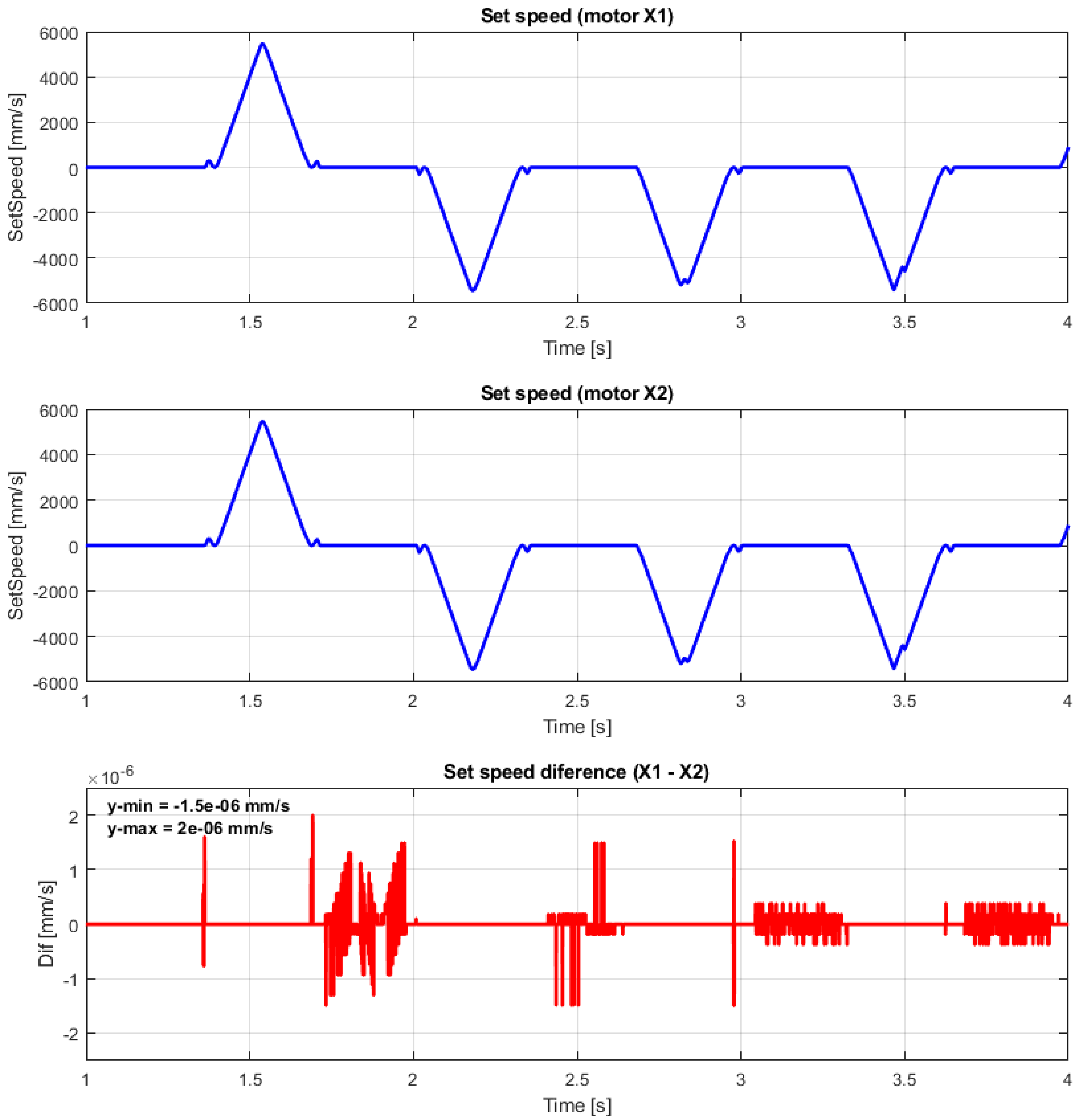
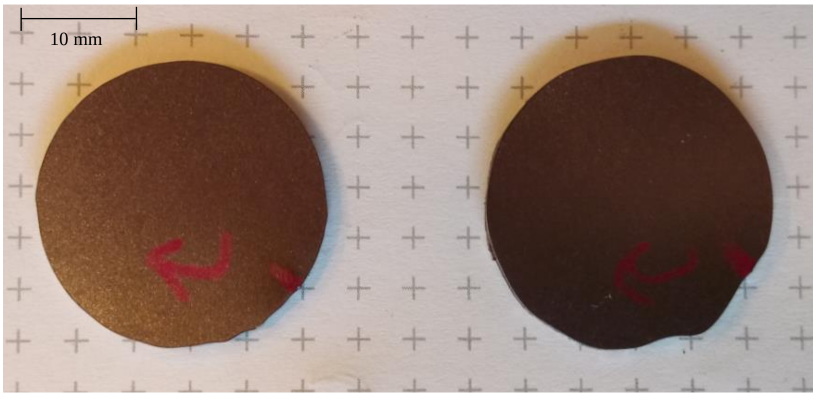


Figure 32: Portal – synchronised motors - test 2

Torque and current measurements have been done after the configuration change. Resulted characteristics were similar as in Figures 28 and 29. After a deeper examination of characteristics, a mechanical cause was confirmed. The portal rails were not precisely straight all over their operation distance. The mechanical problem was not possible to eliminate. This problem brings no limitation to the machine functionality, but it affects motors stress and consumption.

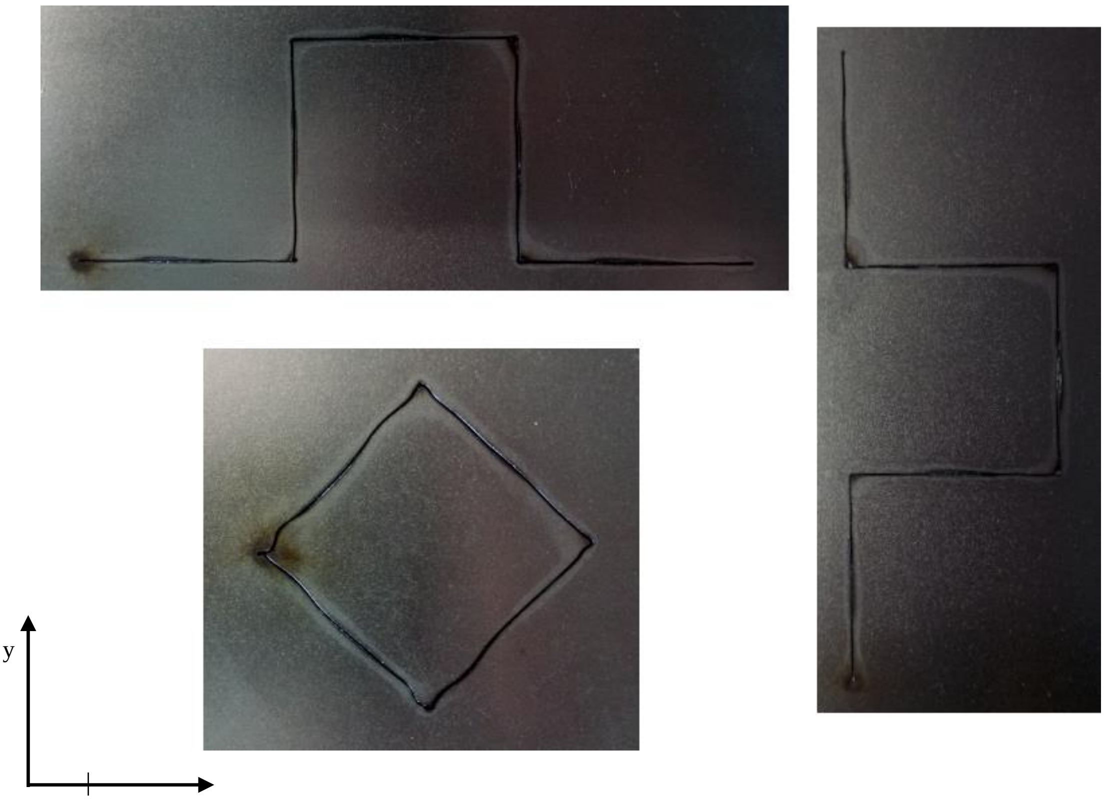
4.4 Positional Errors

To identify a positional error of the axes, it had to be measured on real workpieces. Figure 33 shows two machined circles which were made with different maximum cutting speeds. Significant differences can be seen in circle shapes. To identify a source of an error, further test cuttings were necessary. Figure 34 shows special test cuttings for identifying a source of the positional error. A positional error is present on both axes.



Max. cutting speed: **1000 mm/min** **60000 mm/min**

Figure 33: Test circles



max. cutting speed: **60000 mm/min**

Figure 34: Test cuttings

In the next part is measured the size of the lag error of the axes, as a potential source of this inaccuracy.

4.4.1 Lag Error Measurement

Lag error is the difference between the set position and the actual position of an axis. A lag error is measured on the circle shape shown in Figure 35, with radius 25 mm and max. speed of 60000 mm/min.

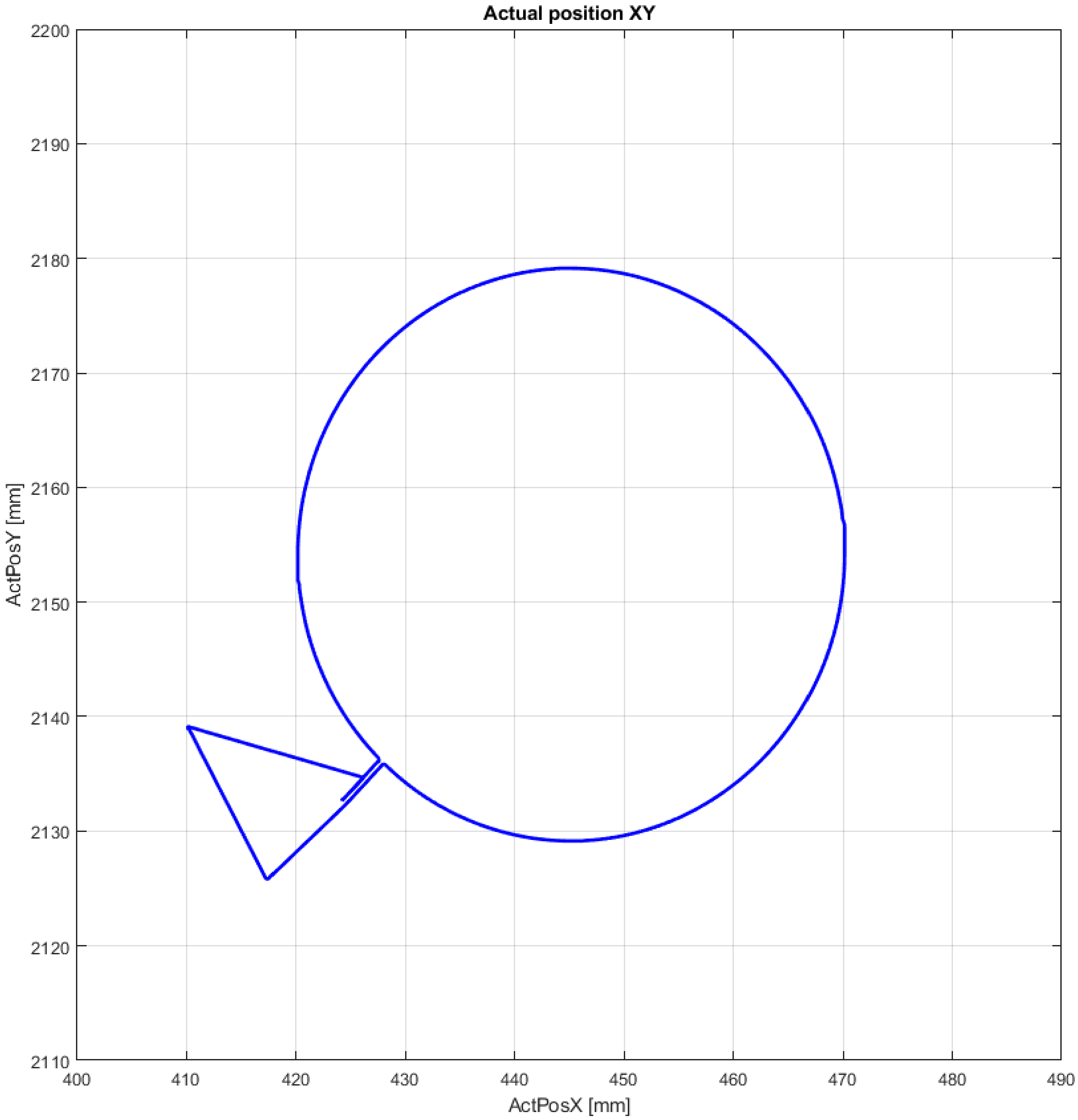


Figure 35: Circle test move for positional error

The actual position, set position and their difference (lag error) is shown for the X-axis (Figure 36) and the Y-axis (Figure 37). The peak-peak value for the X-axis is 60 µm and for the Y-axis is 251 µm. It is a significant difference in axis positional error, and it is necessary to be decreased.

In the next part, feedforward controller to the Y-axis and measured lag error for the same test shape is added.

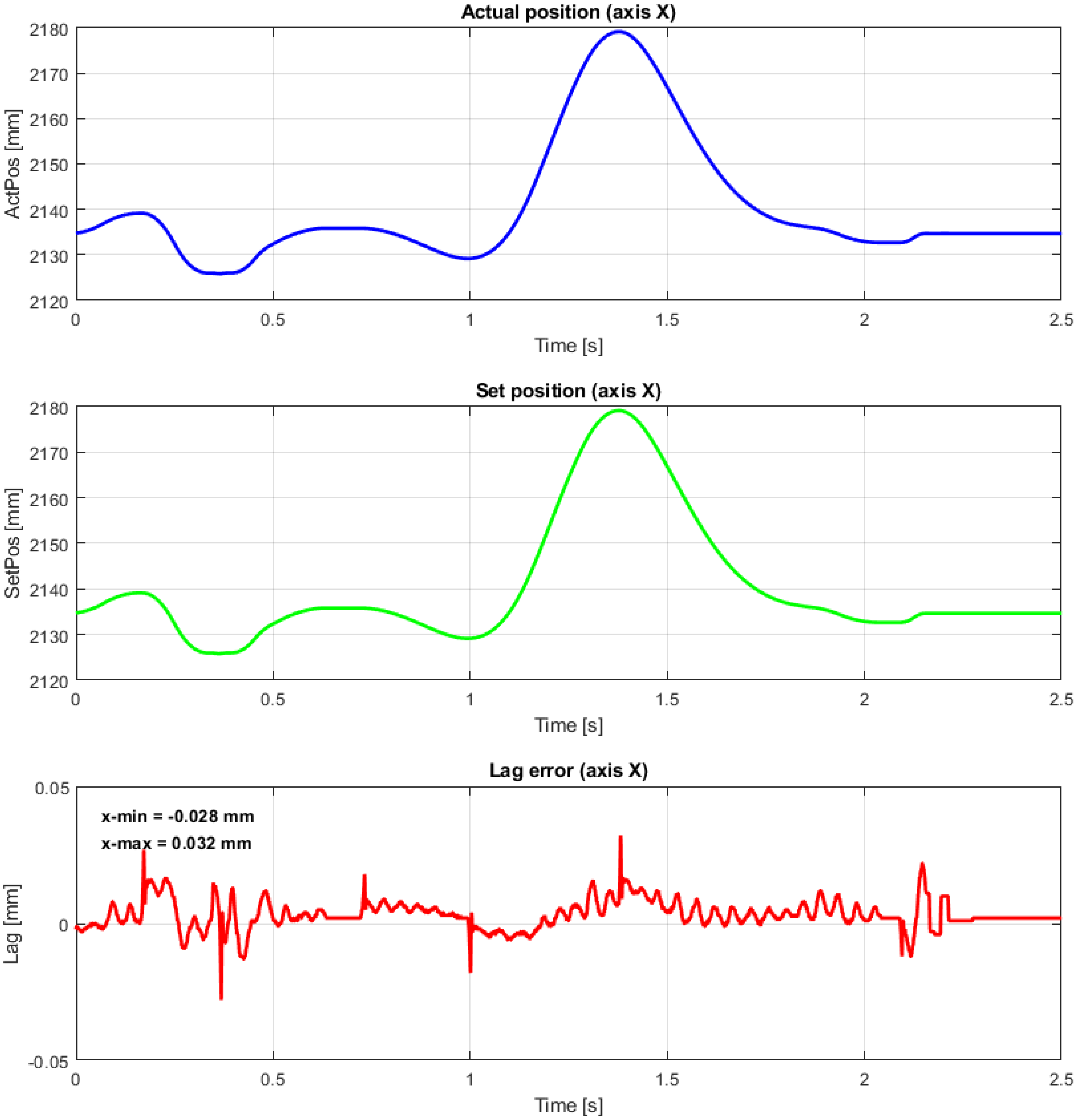


Figure 36: Circle – X-axis examination

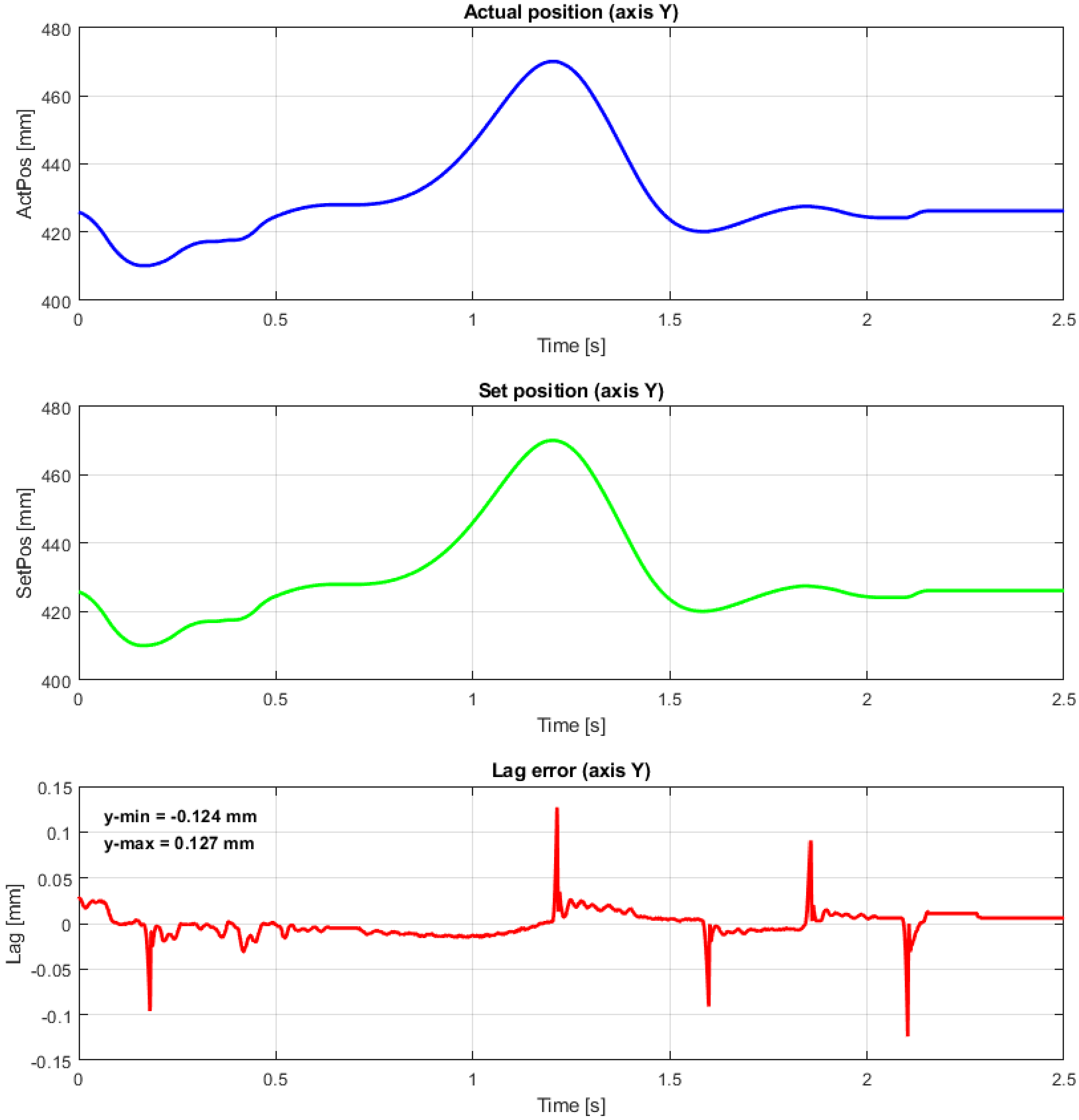


Figure 37: Circle – Y-axis examination

4.4.2 Adding Feedforward Controller

Because of the Y-axis construction layout – mainly its load (the Z-axis mechanics), it is appropriate to use a feedforward controller. Configuration of the feedforward controller is shown in Figure 38. Measured values of lag error for the X-axis (Figure 39) and the Y-axis (Figure 40) show decreased positional error. Peak-peak values of the positional error are 33 µm for the X-axis and 34 µm for the Y-axis. The results show, applying the feedforward controller has been successful in lowering the positional error.

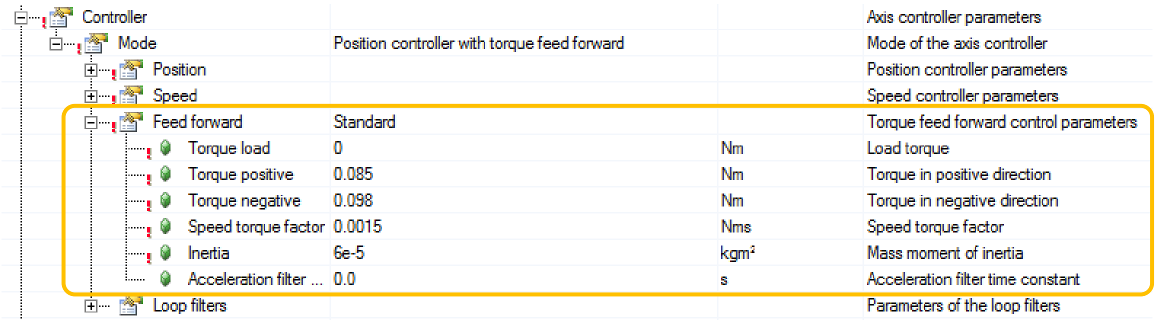


Figure 38: Axis Y - feedforward controller (image taken from SW [6])

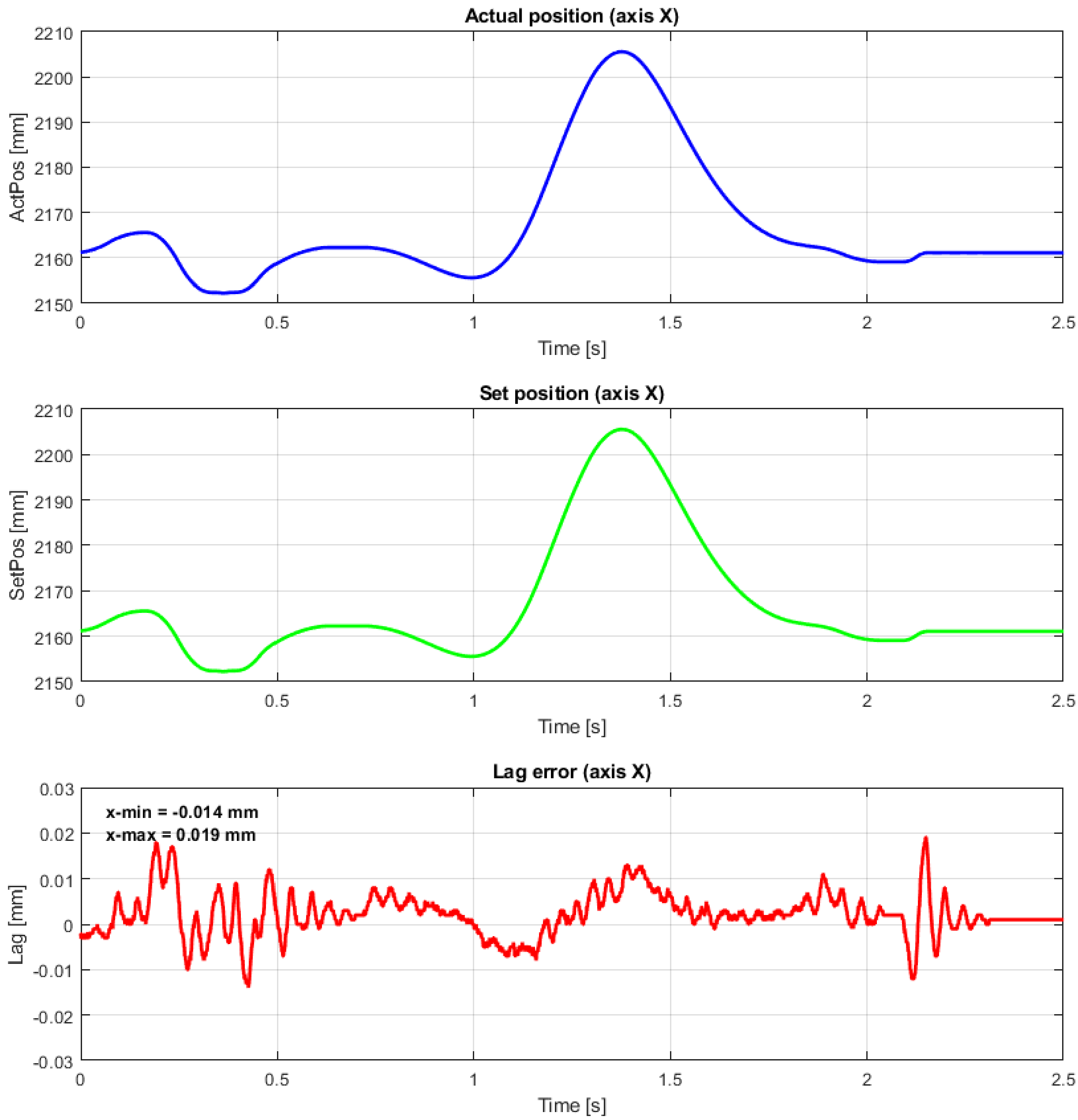


Figure 39: Circle - X-axis examination (with feed forward on Y-axis)

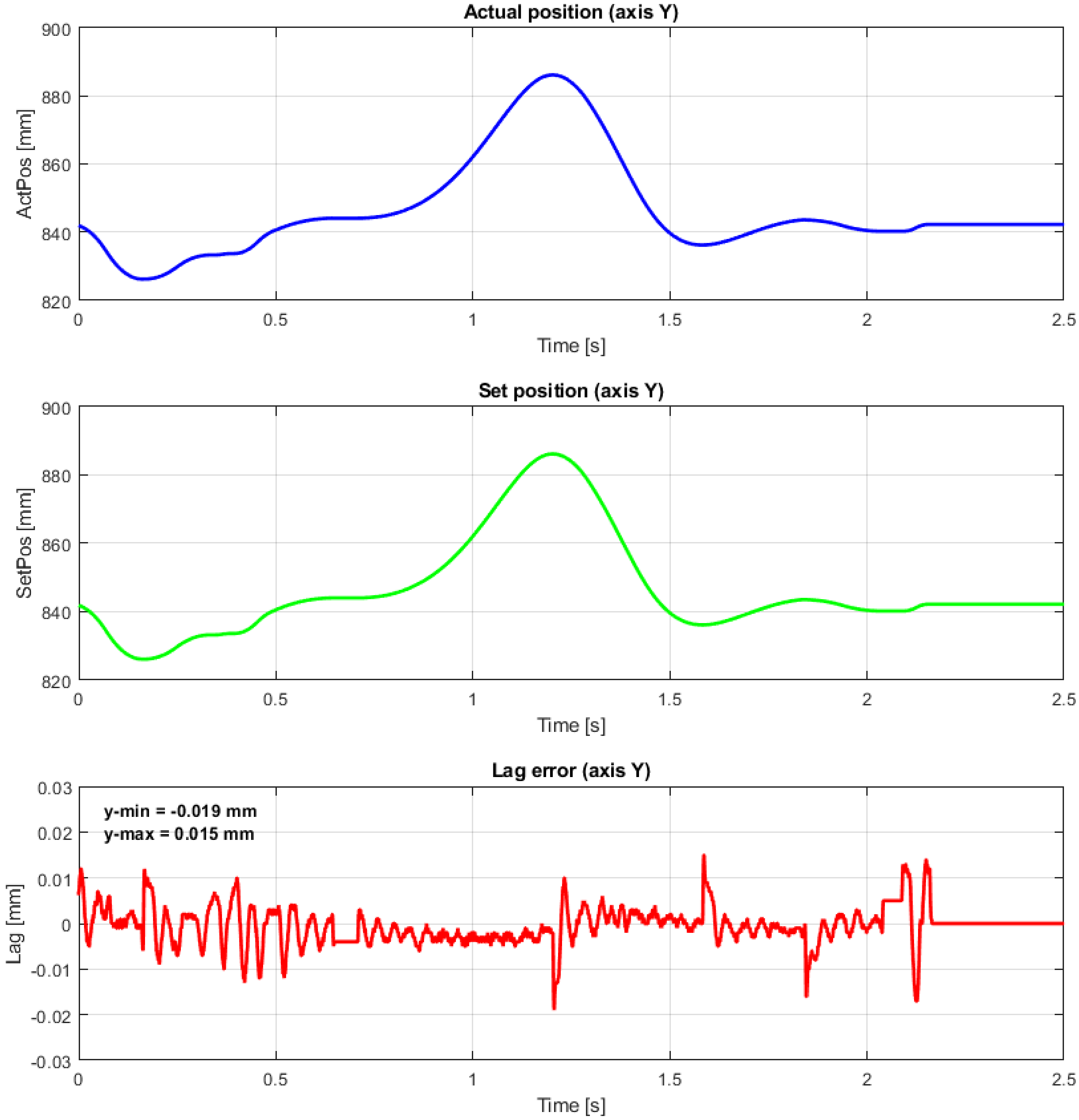


Figure 40: Circle - Y-axis examination (with feed forward on Y-axis)

However, the scale of the positional error was too low to cause such deviations as shown in Figure 33 and Figure 34. A mechanical cause was identified as the result of this examination.

4.4.3 Improving Mechanic of the Z-axis

As concluded in the previous part, the source of the variable positional error is a mechanic of the Z-axis. The above addressed positional error source was caused by the Y-axis load (the Z-axis with the laser head), which with increased speed (acceleration or deceleration) caused the load to shake. A solution was provided by improving mechanics (adding a lead to the

Y-axis). Figure 41 shows the original mechanics of the Y-axis and Figure 42 shows enhanced mechanics. The variable positional error was eliminated by this enhancement.

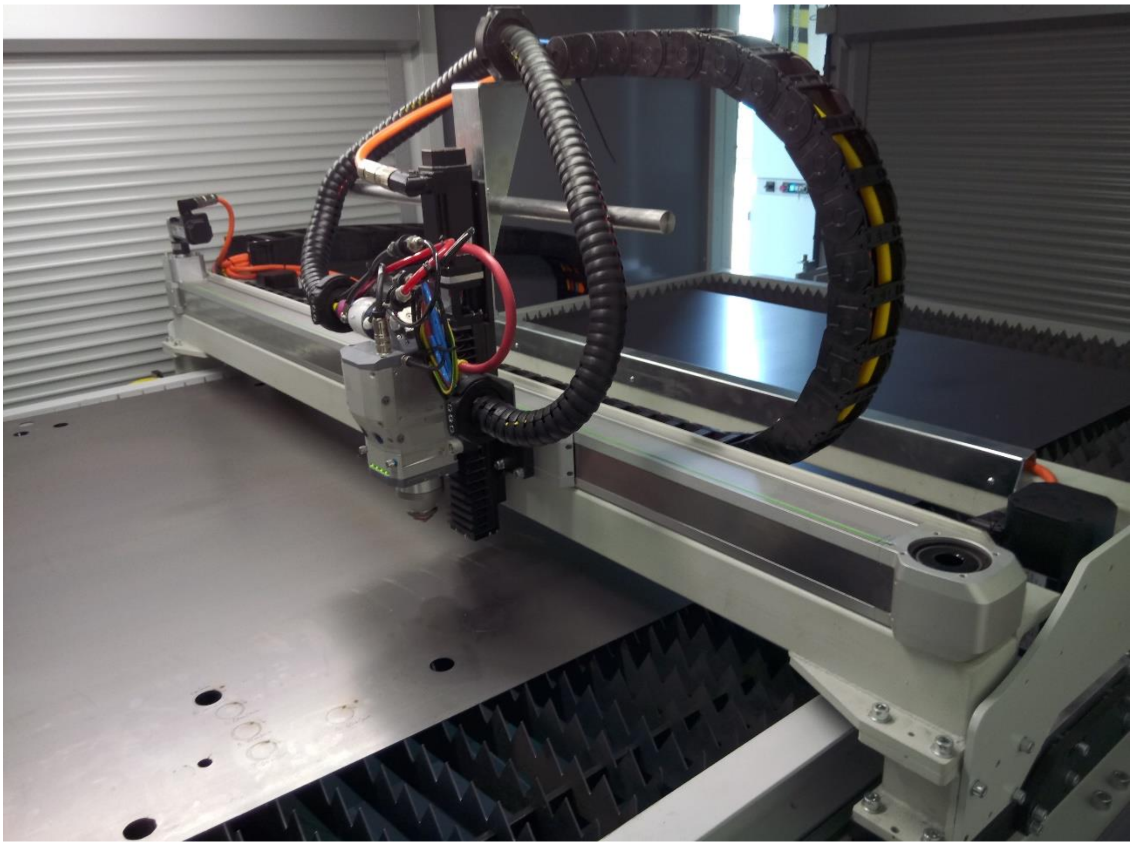


Figure 41: Portal - original mechanic

Figure 42: Portal - enhanced mechanic

4.5 Backlash

Laser cutting, where the minimum beam diameter can possibly be 100 µm [11], is prone to mechanical backlash. In the previous section, the lag error was reduced to its maximum peak-peak value of 34 µm, and the variable positional error, dependent on the speed of the head, was eliminated. After further test cuttings, a constant positional error (non-dependent on speed) in the Y-axis was identified. This was caused by mechanical backlash on the gearbox. The following sections are devoted to identifying and eliminating the error value.

4.5.1 Calculating Theoretical Backlash

The variables shown in

Table 8 are needed for calculating maximal the theoretical backlash of the axis. The first two parameters (gear ratio and max. backlash) are gained from the gearbox datasheet available from [14] and the last parameter (actual linear distance after twenty-five revolutions of the motor) had to be measured on the machine.

Table 8: Needed variables for calculating backlash - Y-axis

Name	Value	Unit
Gear ratio **i**	25	[-]
Max. backlash $\mathbf{J_t}$	25	[arcmin]
Linear distance for 25 revolutions of the motor $\mathbf{D_M}$	190.21	[mm]

The approach to the calculation of the backlash is described with the use of Figure 43. The gearbox is working as a divider of resulted movement. One revolution of the motor's shaft (no. 1) results in $\frac{1}{25}$ revolution on the end shaft (no. 2). Thus, for one revolution in 360° of the end shaft, 25 revolutions of the motor is needed.

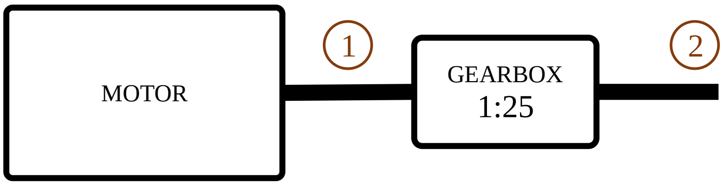


Figure 43: Diagram of motor-gearbox link of Y-axis

Firstly, it is necessary to calculate the maximal possible backlash in degrees

$$Deg = \frac{J_t}{60} = \frac{25}{60} = 0.4167°, \quad (4)$$

where

Deg is degrees [°],

J_t is maximal backlash of the gearbox [arcmin].

Equation (5) calculates the resulted linear value of the backlash. Calculated the theoretical maximal value of the backlash for the Y-axis is 0.220 mm.

$$E_D = \frac{D_M \cdot Deg}{360} = \frac{190.21 \cdot 0.4167}{360} = 0.220\ mm \quad (5)$$

where

D_M is a linear distance for one revolution of end shaft [mm].

The same approach is applied to the X-axis. Table 9 contains all the important data (gear ratio and max. backlash are taken from the gearbox datasheet available from [14]).

Table 9: Needed variables for calculating backlash - X-axis

Name	Value	Unit
Gear ratio **i**	20	[-]
Max. backlash $\mathbf{J_t}$	19	[arcmin]
Linear distance for 20 revolutions of the motor $\mathbf{D_M}$	157	[mm]

Results, applying (4) and (5):

$$Deg = 0.334°,$$

$$E_D = 0.146\ mm.$$

4.5.2 Real Backlash on the Axes

The Digital Dial Gauge for measuring the precise value of backlash was set to the axes. Then movement in the positive direction of 10 mm was executed, followed by movement in the negative direction of the same distance. The resulted difference from the starting position was recorded. To decrease the measurement error, measurements for the X-axis and the Y-axis were repeated eight times. Measured real backlash is shown in Table 10 for the X-axis, and Table 11for the Y-axis.

Table 10: Measuring real backlash - X-axis

Trials:	1	2	3	4	5	6	7	8	Average:
Value [μm]:	40	46	42	37	35	40	38	40	40

Table 11: Measuring real backlash - Y-axis

Trials:	1	2	3	4	5	6	7	8	Average:
Value [μm]:	366	386	372	378	388	380	374	380	378

Measured real values of backlash can be a maximum of double of the calculated maximum theoretical value. It is due to the measurement method, where executing positive and negative movements; the backlash takes effect two times.

Considering the laser beam diameter backlash of the X-axis, it is too small to be playing any significant role in the workpiece precision. Its real value is seven times lower than its calculated theoretical value. However, the backlash of the Y-axis is significantly high.

There are two options for eliminating backlash of the Y-axis. The first is to replace the gearbox with one having a lower value of maximum backlash. The second option is compensation of backlash using software function. The second option is discussed in the following part.

4.5.3 Solving Backlash

By the B&R [5], a complete software function for resolving backlash was delivered. And with a B&R’s specialist, the software solution was implemented and set in the program. A positional error on the Y-axis was reduced to the peak-peak value of 20 µm.

Figure 44 and Figure 45 show the backlash compensation in two directions (clockwise and counter-clockwise). The red curvature is the required shape, and the blue curvature is the actual encoder position (axis position).

In Attachment B, additional figures of positional characteristics of these two presented shapes are included. Lag error graphs show peaks exceeding the above stated maximal deviation of the error. Those peaks are of short duration and are caused by rapid axis movement change. These error peaks have a low influence on the final workpiece’s dimensions. A note to this is addressed in chapter Future Work.

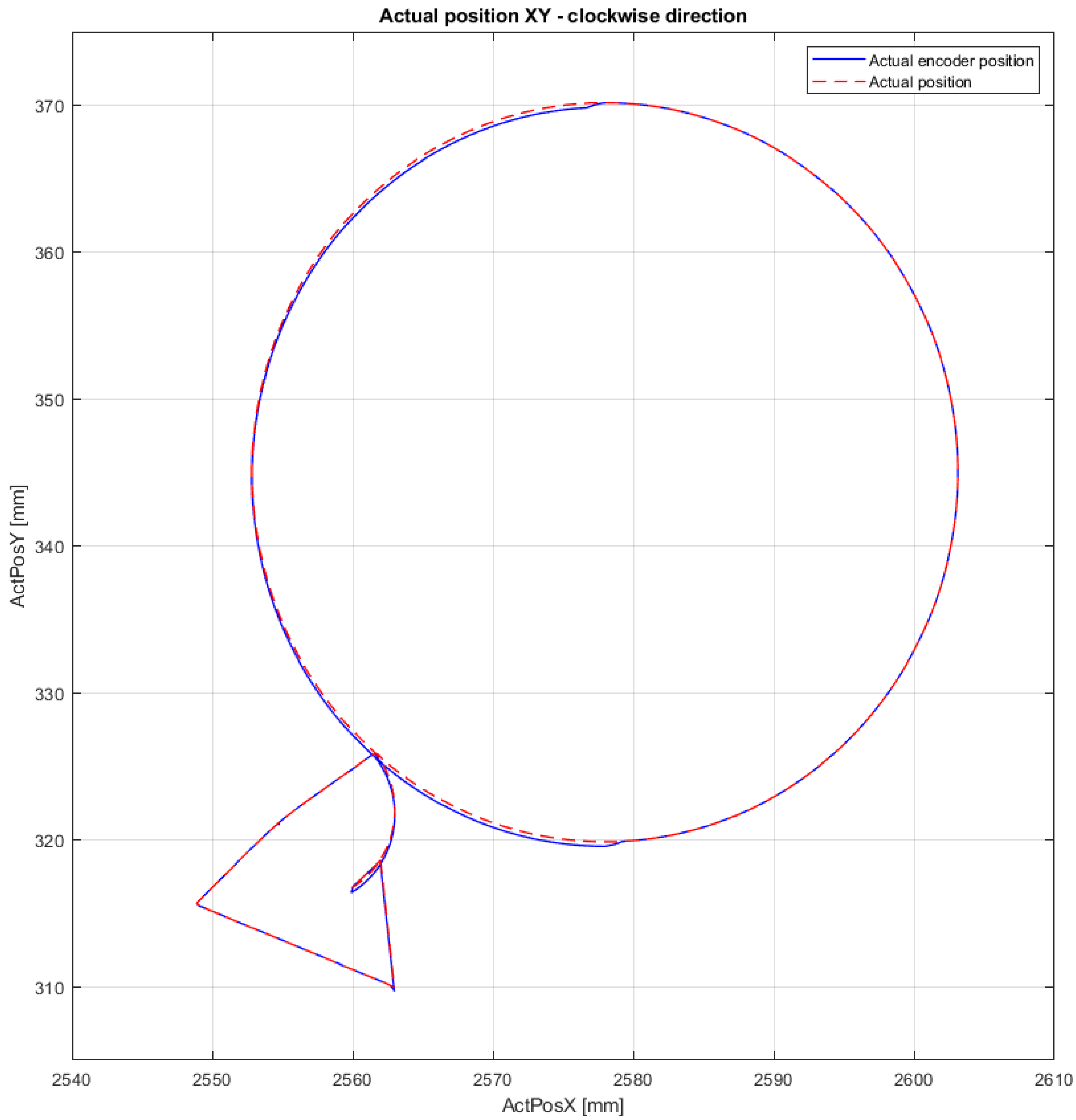


Figure 44: Backlash - clockwise direction

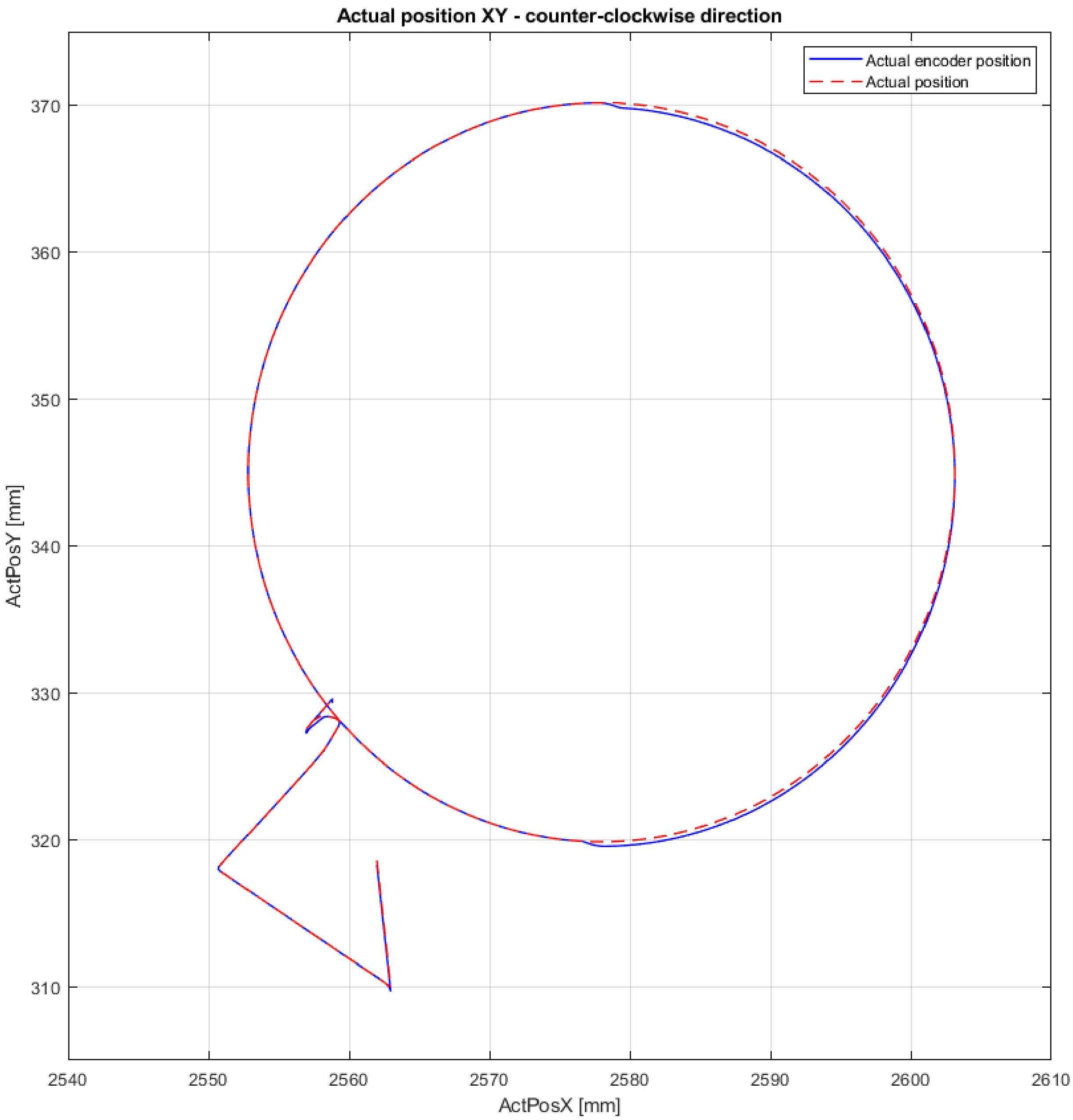


Figure 45: Backlash - counter-clockwise direction

5 PROGRAM ANALYSIS

This chapter addresses the description of application pages which were created. This chapter interconnects with section 3.3., where the program development is described. In Attachment C, images of the screens of the created visualisation are included. Each section of this chapter starts with reference to a corresponding image.

5.1 Main Page

See Attachment C, Figure 1.

The main page is displayed after the machine starts. On the top, the information bar containing the main machine states, e.g. Laser Safety Active, Machine Initialised, can be seen. Laser Safety Active indicates the actual machine mode state (automatic or service). The bottom bar contains the main icons, such as Starting Page, Axes Jog, CNC and Recipe. These icons are for the machine operation. Top and bottom bars are always displayed and, depending on the displayed page, they do not change. In the middle are all icons.

5.2 Starting Page

See Attachment C, Figure 2.

The Starting Page contains initialization control block, motors control, CNC control and laser control.

The initialisation block controls the lock of the sliding grate. Power on and off, error reset, and automatic homing procedure (axes goes to predefined zero position), are controlled by the motor control panel. The CNC panel can be operated after the motor power on in the motor panel. Virtual axes are coupled with the real axes and only CNC movement can be executed (G-code execution). In this panel is the error reset button, which resets an error which occurred in the CNC mode. The homing button sets virtual axes' coordinates to the zero. The last panel is the laser panel. Via this panel, the external control of the laser is set, and it can be, then, controlled from the program application.

5.3 Jogging

See Attachment C, Figure 3.

Manual independent control of the axes is a basic feature of the machine. Depending on the position and shape of the workpiece, it is necessary to move the laser head to the desired position. On the left are actual positions of the axes (to get the actual position of an axis, the example for the Y-axis code is: ***gCtrld.Axes.Y.FB.Position***). In the middle, there is the window with two speed settings which can be freely edited as needed (speed parameter setting for the Y-axis in code is: ***gCtrld.Axes.Y.Param.Velocity***). And on the right, buttons for controlling each axis movement (only one axis movement at the time is enabled) are located.

5.4 CNC Control

See Attachment C, Figure 4.

The CNC Control page is the page which is displayed during the operation state of the machine (during the cutting). On the top left, the page contains virtual axis coordinates, and actual axes speed information.

In the top middle, the simulation button is located which is used for executing a test. Axes movements are executed in the same way as in the process of actual cutting. This means that the Z-axis stays still, and the laser head emits the visible red light, which simulates the cutting beam. Next to it, M-function states and laser states are displayed.

The right top block contains information about the actual loaded technological table. The actual plate material and thickness information are shown in the actual loaded technological table window. Setting of the head's focal position and inductive sensor calibration are also placed here.

The CNC program start and stop buttons are enabled after successful loading of the technological table, focal position set, and calibration of the head sensor.

5.5 Technological Tables

See Attachment C, Figure 5.

The concept of the technological tables was created as a folder system in the private part of the memory. The first level of folders refer to the type of material (steel, copper, etc.). The second level refers to the material thickness (1 mm, 5 mm, etc.). In the second level folders are CSV files with cutting parameters such as cutting power, cutting height, etc. It is possible to create, rename, and delete any folder or CSV file. After loading a specific technological table, its editing is possible.

5.6 CNC Program Management

See Attachment C, Figure 6.

It is possible to load, delete, and rename recipe, in this page. How a CNC program is loaded into the machine is described in chapter 6.

5.7 Suction Control

See Attachment C, Figure 7.

To prevent contact with the operator, gases from the steel cutting must be sucked from the machine. On the image in the attachment, the manual control page of suction is shown. There are three suction sections, where each can be individually controlled. Also, the manual suction start button is present.

The workplace of the sliding grid is then divided into three parts. A relevant suction section depending on the actual position of the laser head is open. Only one section (causing the highest thrust) at a time is open. After finishing the cutting, the suction remains on.

5.8 Door Control

See Attachment C, Figure 8.

Through this service page, all four doors of the machine can be controlled. Doors can also be controlled by physical buttons on the operational panel (see Attachment A).

6 CREATING A WORKPIECE

The procedure of creating a final workpiece from a technical drawing is described in this section.

CAD/CAM software Wrykrys [19] was used for this project. The software creates a G-code file from a DXF file. It is also possible to create drawings or edit loaded drawings. Special a postprocessor was ordered to suit the desired code format.

The process starts with the operator of the laser machine downloading required technical drawings in the DXF format. Figure 46 shows the operator's workstation. Then this software, for the generation of a CNC program (G-code), creates a set of drawings for cutting. New positions for starting and ending the cut, are added. Figure 47 shows a work program for this example. Further, a G-code is generated and sent via an FTP client to the laser machine.

The G-code is loaded in the laser machine. The operator moves the axes to a required position and homes the virtual axes (in the Starting Page). According to the used work plate type and thickness, the operator selects the right technological table and loads it. The set of tasks (setting of the focal position of the laser head and calibrating of the head inductive sensor execution), are all done in the CNC page.

After the laser head calibration is done, the cutting can be executed. Figure 48 shows the final workpieces of the executed program (see Figure 49 for another view of the final workpieces).

Figure 50 shows the cut quality for 3 mm metal sheet thickness.

In Attachment D, the video of the actual cutting of this work program is attached.

Figure 46: Workstation view

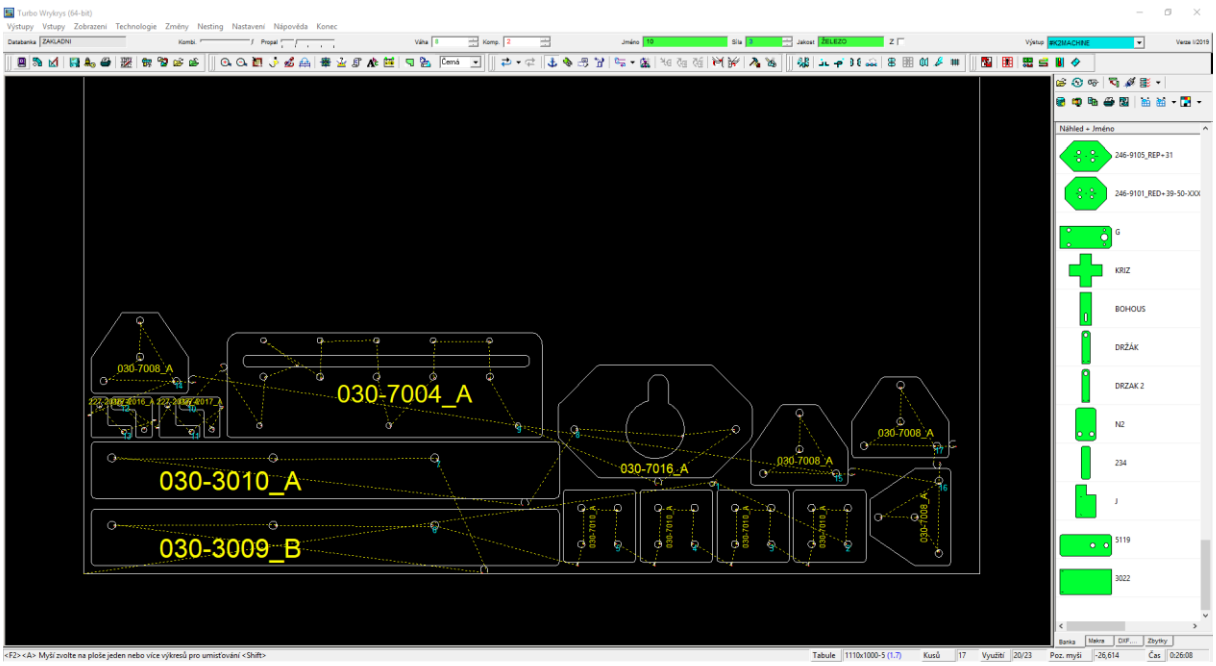


Figure 47: Wrykrys work-plate view (image taken from SW [19])

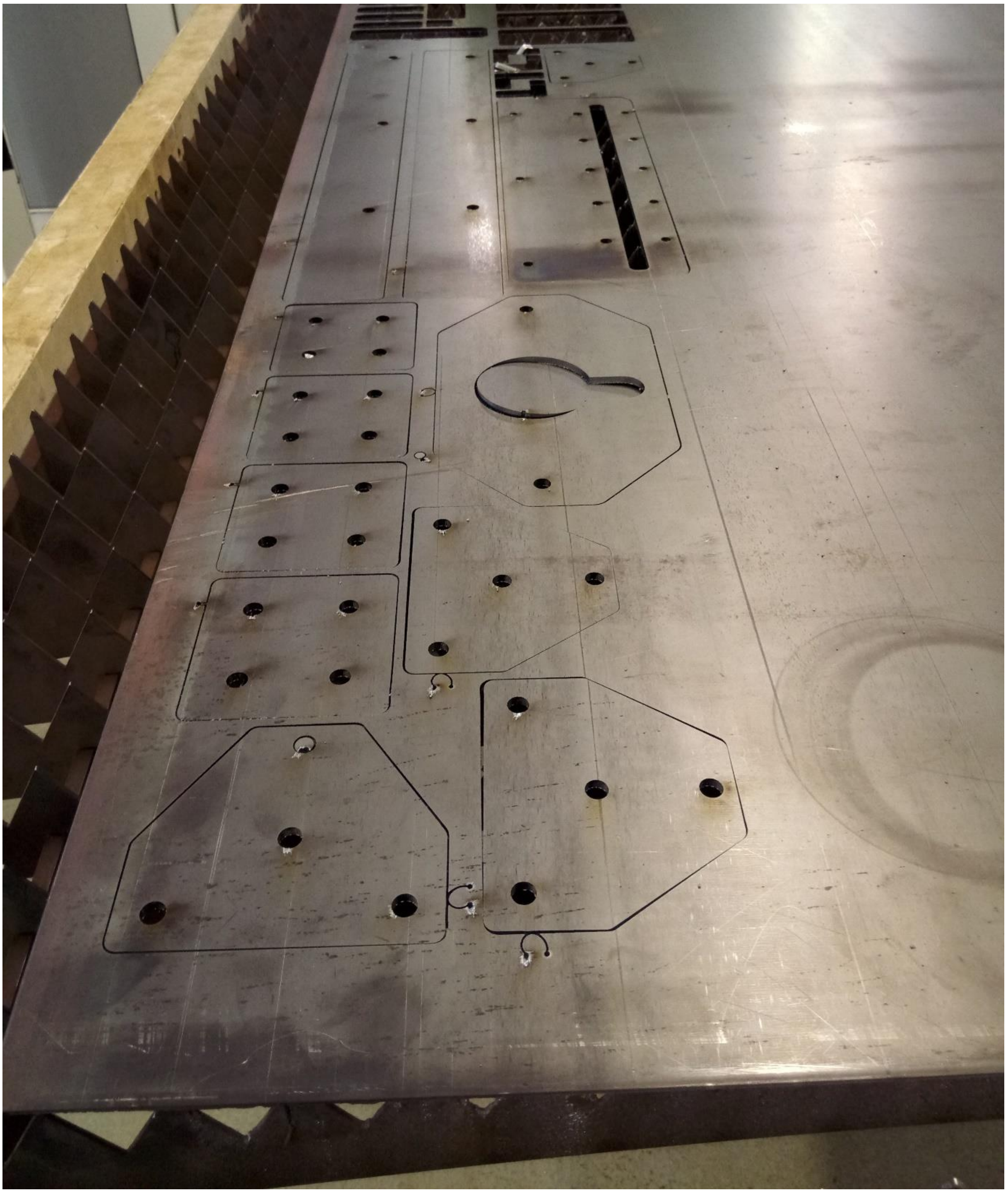


Figure 48: Work-plate with cut workpieces

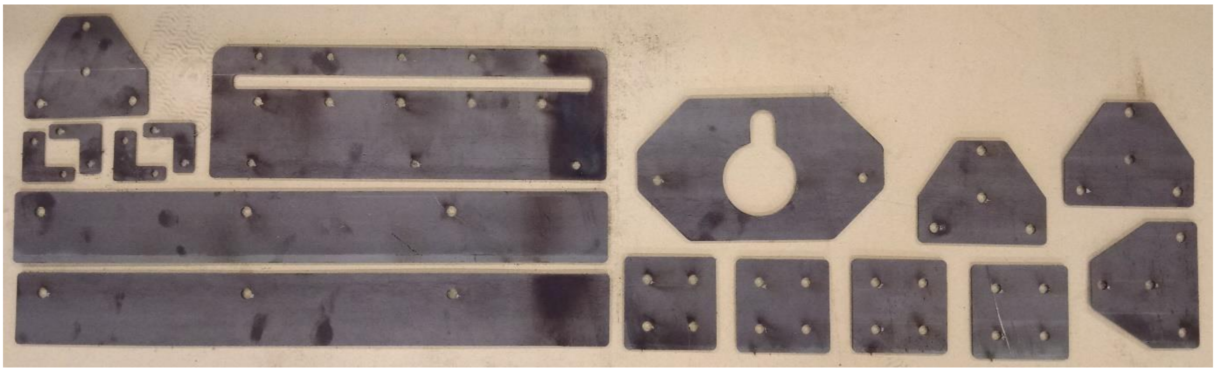


Figure 49: Workpieces

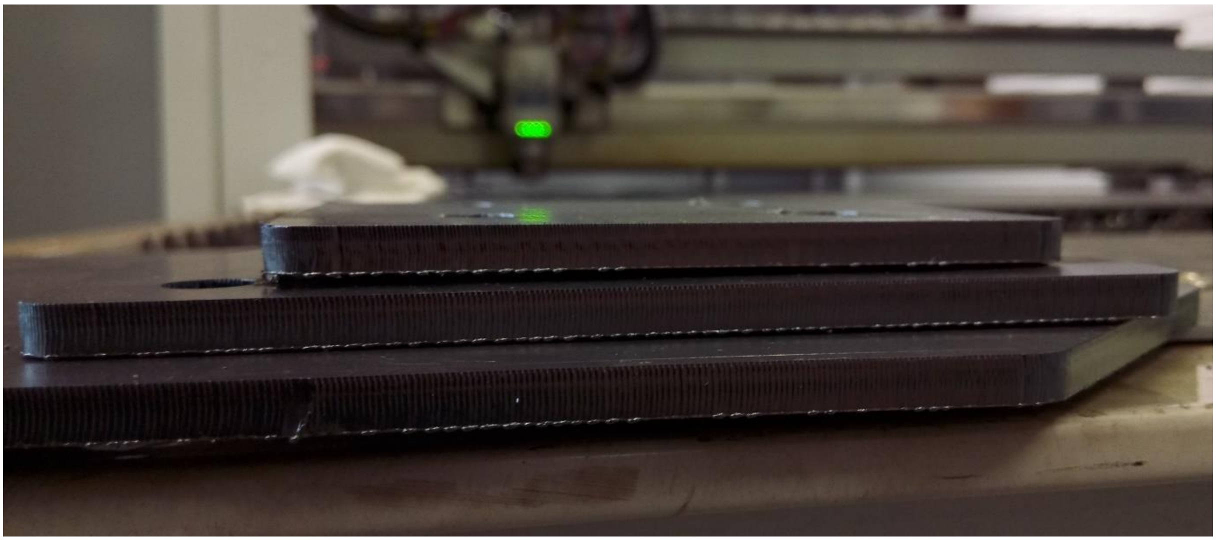


Figure 50: Quality of the cut (3 mm plate thickness)

CONCLUSION

The goal of this thesis was to develop a complete software solution for the CNC laser cutting machine. Before the start of the software development, it was necessary to gain knowledge from multiple areas. This included gaining the understanding of CNC machine function principle, laser cutting technology, technological processes of cutting, actual machine mechanical and electrical construction, and using software development tools. This is documented through the whole work content.

The beginning of the thesis was devoted to the general content of CNC and machining technologies. It included historical development and introduction of machining processes.

Software creation was introduced and described. It was followed by the project development description. Firstly, the project starting conditions, what was the task, and what had to be done to fulfil the task were described. The machine's components were described. The program development, from the start, was discussed. The main machine's functionalities description and solution were addressed.

To the biggest challenge of the project development was contributed chapter four. It is the most extensive part of this thesis. It was described the CNC commissioning from the beginning (servomotors tuning) to the end (eliminating positional errors). After servomotor tuning, the servomotor parameters were found (maximal speed, acceleration, deceleration). Subsequent discussion involved synchronisation of two servomotors on the portal. In that state, the machine was able to execute independent (jogging) and CNC moves.

Further, problems that occurred during the development, and which made the task challenging were described.

The first problem was discovered on the X-axis servomotors (servomotors of the portal) which, after executing some movement, led to the high value of the torque as well as the high conception of current. The portal servomotor synchronisation testing and improvement were done. However, this did not solve the problem. After a deeper examination, the source of the problem was discovered. The X-axis rails weren't absolutely balanced, which led to the high value of torque on the portal's servomotors. Magnitude of this problem is addressed.

The second problem occurred while executing a test circle movement. The workpiece contained significant error in the shape. Positional error examination was done. The significantly higher value of lag error on the Y-axis compared to the X-axis was measured. The feedforward controller was applied, and the error was decreased. But the prime value of the error would not cause such an error in workpiece shapes. Further testing was done, and it was discovered that the error on the workpiece was changing with the axes speed. A mechanical source was identified and solved.

In further testing, the manufactured workpieces still contained a significant shape error. More test cuts were done. The source of the error, which was present only on the Y-axis, was identified. This led to suspicion that backlash was the source of the error. Calculation and measurement of backlash were done. The backlash on the Y-axis gear was confirmed. The solution was addressed.

Chapter five was devoted to program analysis. The developed application was described in its visualisation environment. Also, functionalities were described.

In the last chapter, the workpiece creation process on the machine was documented.

To conclude, in the thesis all points of the assignment were addressed. The application software development was described, and its function presented in the thesis itself. In chapter Future Work, the future development of the created software solution is addressed.

FUTURE WORK

The software described in this thesis contains basic functions of CNC machines. The machine contains all functions necessary for its working, but existing CNC cutting machines correspond with a wider range of functions and properties. This is the question for further development. Following is the list of enhancements for the next version of the software:

- adding a graphical view of G-code on the main panel with tracing of cutting state,
- option for rotation of the coordinate system,
- creating a user interface,
- user edit option for setting offset of the motor's encoder after its change or removal,
- statistics,
- backlash compensation improvement (elimination of the lag error peaks, see chapter 4.5).

REFERENCES

[1] MERCHANT, M. AN INTERPRETIVE REVIEW OF 20TH CENTURY US MACHINING AND GRINDING RESEARCH [online]. Cincinnati, Ohio, USA: TechSolve, Inc, 2003 [viewed 2019-03-30]. Available from: http://abrasiveengineering.com/merchantbook.pdf. E-Monograph.

[2] SUH, Suk-Hwan. Theory and design of CNC systems. 2008. London: Springer, 2008. ISBN 978-1-84800-335-4.

[3] SMITH, Graham T. CNC machining technology. 1. New York: Springer-Verlag, 1993. ISBN 978-3-540-19586-3.

[4] EL-HOFY, Hassan. Fundamentals of machining processes: conventional and nonconventional processes. 2nd ed. Boca Raton: CRC Press, 2014. ISBN 978-1-4665-7702-2.

[5] Automation Studio. B&R [software]. Eggelsberg: B&R Industrial Automation, 2019 [viewed 2019-03-08]. Available from: https://www.br-automation.com/en/products/software/automation-studio/

[6] Automation Studio V4.5 [software]. V4.5. Eggelsberg: B&R Industrial Automation, 2019 [viewed 2019-05-05]. Available from: https://www.br-automation.com/en/downloads/software/automation-studio/automation-studio-45/automation-studio-v45/

[7] VNC Viewev [software]. Eggelsberg: B&R Industrial Automation, 2019 [viewed 2019-05-05]. Available from: https://www.br-automation.com/en/downloads/software/hmi-software/vnc-viewer/vnc-viewer-winxp-win7-win81-win10/

[8] B&R Scene Viewer [software]. Eggelsberg: B&R Industrial Automation, 2019 [c viewed 2019-05-05]. Available from: https://www.br-automation.com/en/downloads/software/simulation/br-scene-viewer/?noredirect=1

[9] Automation studio Help Explorer [software]. V4.5.2.10. Eggelsberg: B&R Industrial Automation, 2019 [viewed 2019-05-05]. Available from: https://www.br-automation.com/en/downloads/software/automation-studio/automation-studio-45/automation-studio-v45/

[10] 190 – CNC laser. K2 Machine, 2018. Technical documentation

[11] TruDisk. Trumpf Laser, 2018. Technical documentation

[12] Návod k obsluze. KEMPER, 2018. Technical documentation

[13] K2 Machine [online]. Pardubice - Staré Hradiště: K2 Machine, 2018 [viewed: 2019-02-05]. Available from: https://www.k2machine.cz/

[14] B&R Industrial Automation [online]. Eggelsberg: B&R Industrial Automation, 2019 [viewed 2019-02-01]. Available from: https://www.br-automation.com/

[15] TRUMPF [online]. Ditzingen: TRUMPF, 2019 [viewed 2019-02-05]. Available from: https://www.trumpf.com/

[16] Automation studio Help Explorer [software]. V4.3.5.24. Eggelsberg: B&R Industrial Automation, 2019 [viewed 2019-05-06]. Available from: https://www.br-automation.com/en/downloads/software/automation-studio/automation-studio-43/automation-studio-v43/

[17] Automation Studio V4.3 [software]. V4.3. Eggelsberg: B&R Industrial Automation, 2018 [viewed 2019-05-06]. Available from: https://www.br-automation.com/en/downloads/software/automation-studio/automation-studio-43/automation-studio-v43/

[18] TM441 - Motion Control. B&R Industrial Automation, 2018. Training module

[19] WRYKRYS [software]. V4/2018. Plzeň: Wrykrys, 2018 [viewed 2019-02-21]. Available from: http://www.wrykrys.cz/cz/download

LIST OF ATTACHMENTS

ATTACHMENT A - LASER MACHINE PHOTOS

This attachment contains images of the laser machine.

Figure 1 is the view of the laser machine with workstation for creating a CNC program. Figure 2 shows the front view of the laser machine with the opened front door. The sliding bin is shown in Figure 3 and sliding grate is shown in Figure 4.

Figure 1: Workstation view

Figure 2: Front view on the machine

Figure 3: Sliding bin

Figure 4: Sliding grate

ATTACHMENT B - BACKLASH POSITION GRAPHS

This attachment contains additional figures for a description of backlash compensation.

Figure 1 shows diagrams of the clockwise movement of the circle with 50 mm diameter. The first graph is the actual encoder position. The second is the actual position. The difference between the previous two position characteristics is in the third graph. The non-zero difference is a result of backlash compensation. The fourth graph is the lag error.

Figure 2 contains the same graphs as described above. It is the same shape but executed in a counter-clockwise direction.

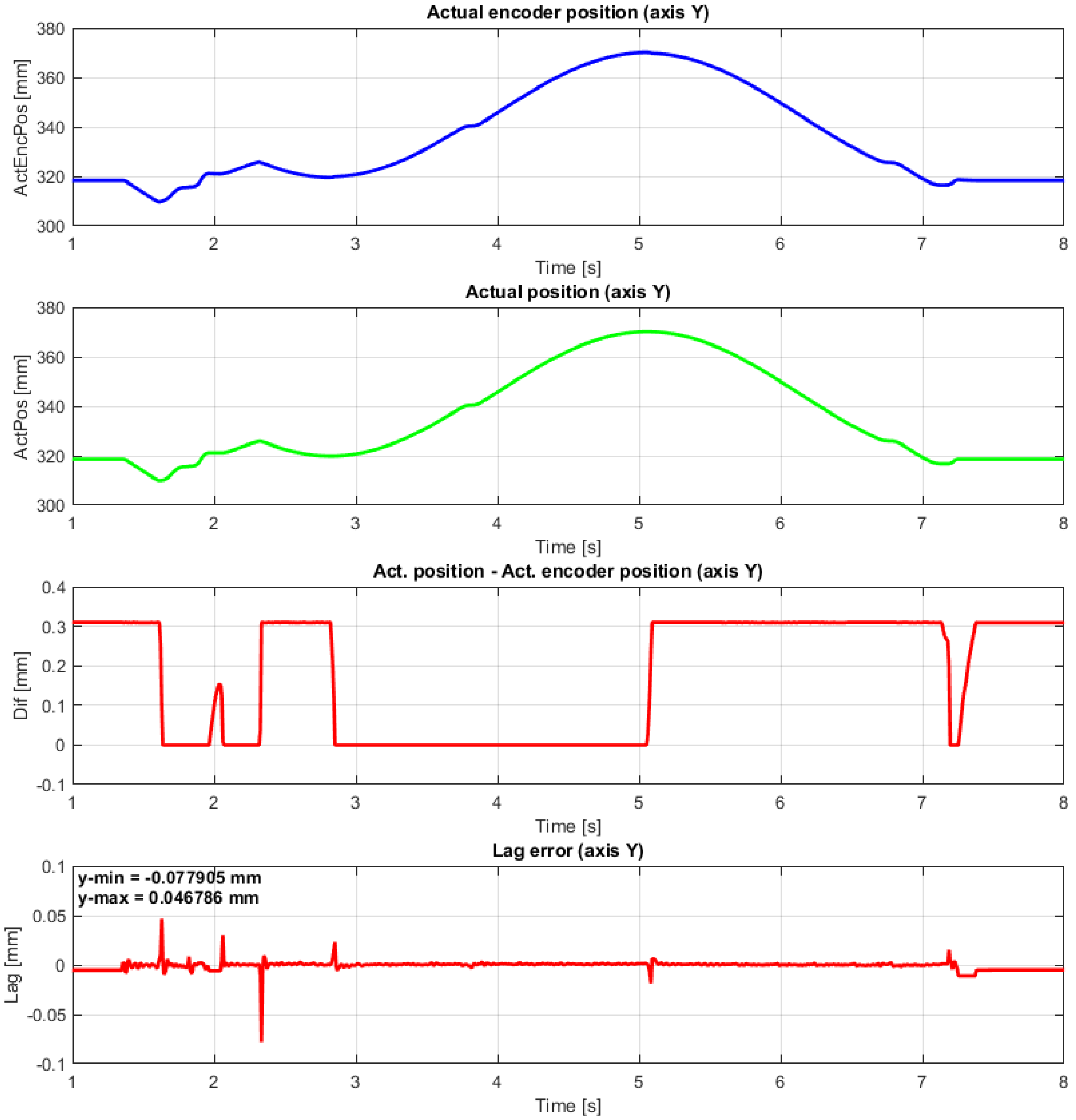


Figure 1: Backlash position plots (axis Y) -clockwise direction

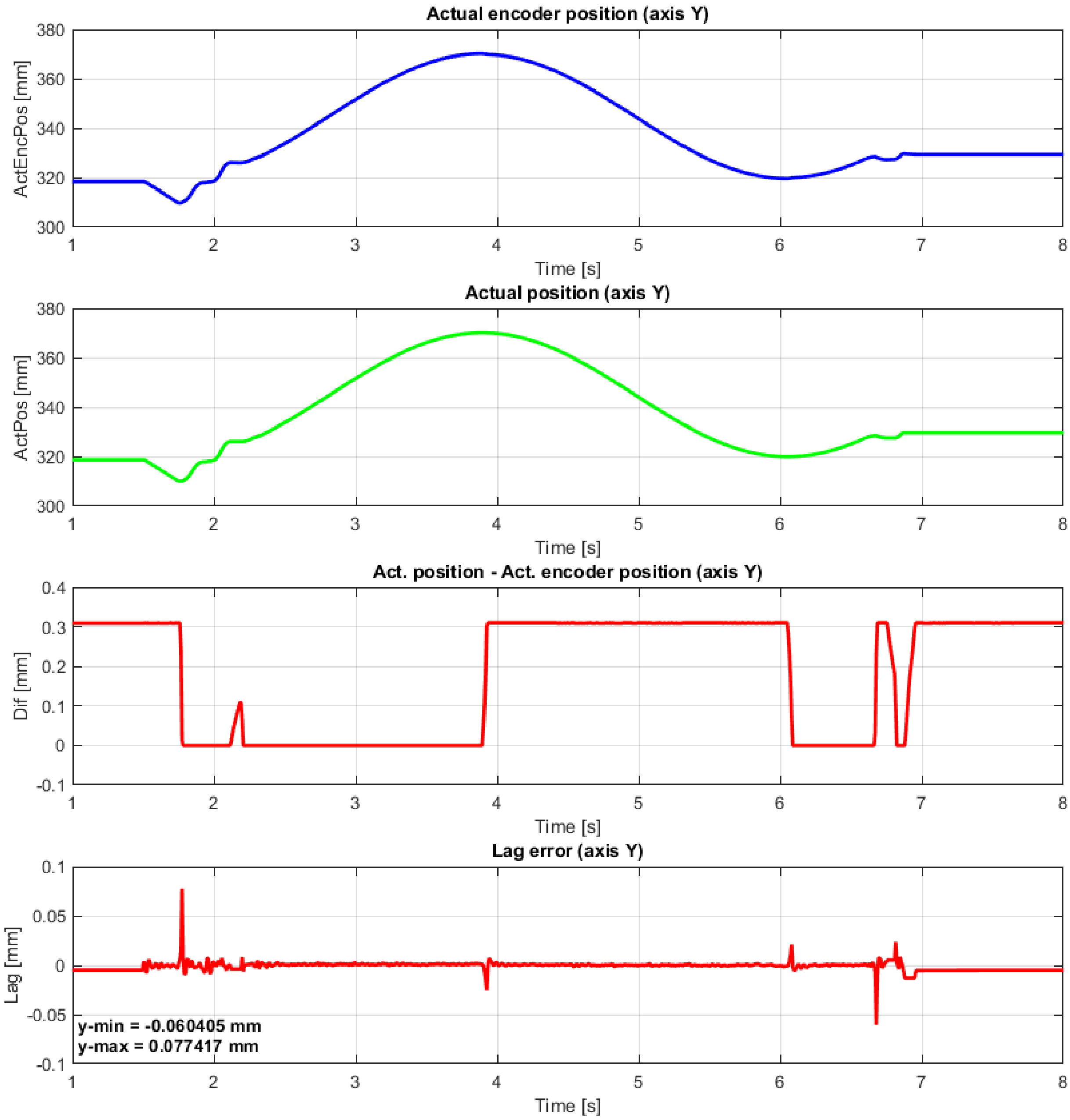


Figure 2: Backlash position plots (axis Y) -counter-clockwise direction

ATTACHMENT C - APPLICATION VISUALIZATION

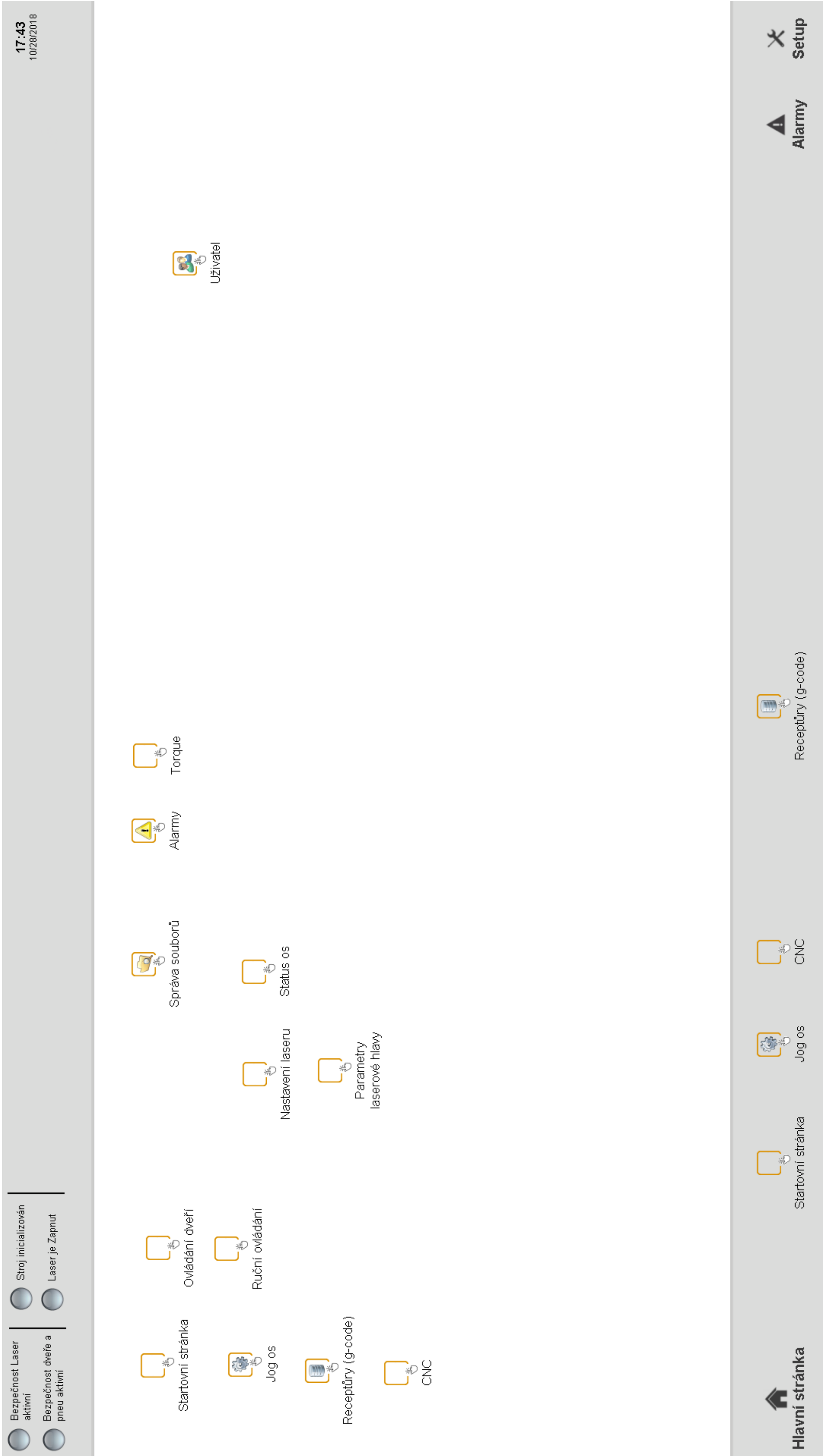


Figure 1: Main page

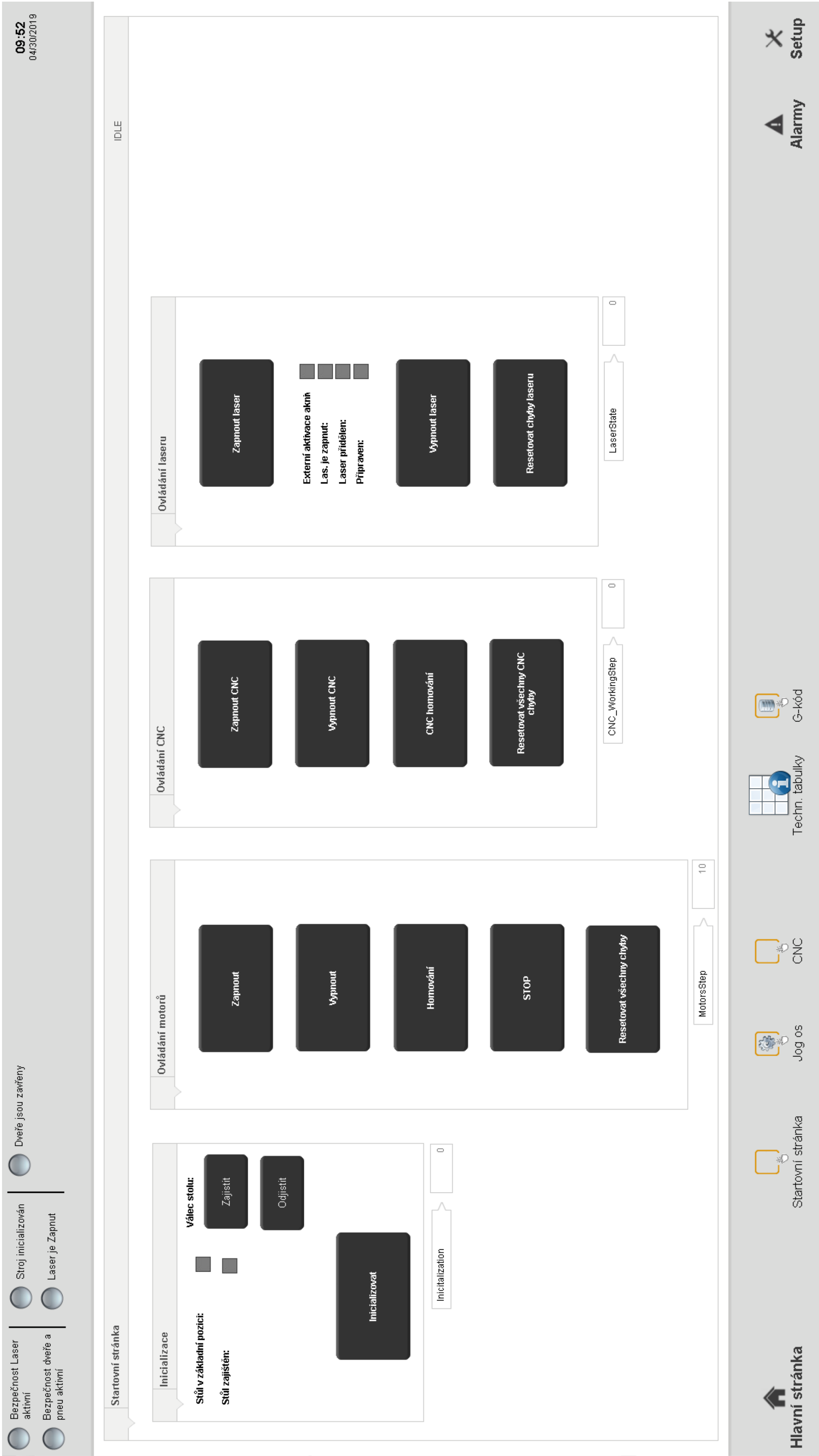


Figure 2: Start page

Figure 3: Jogging page

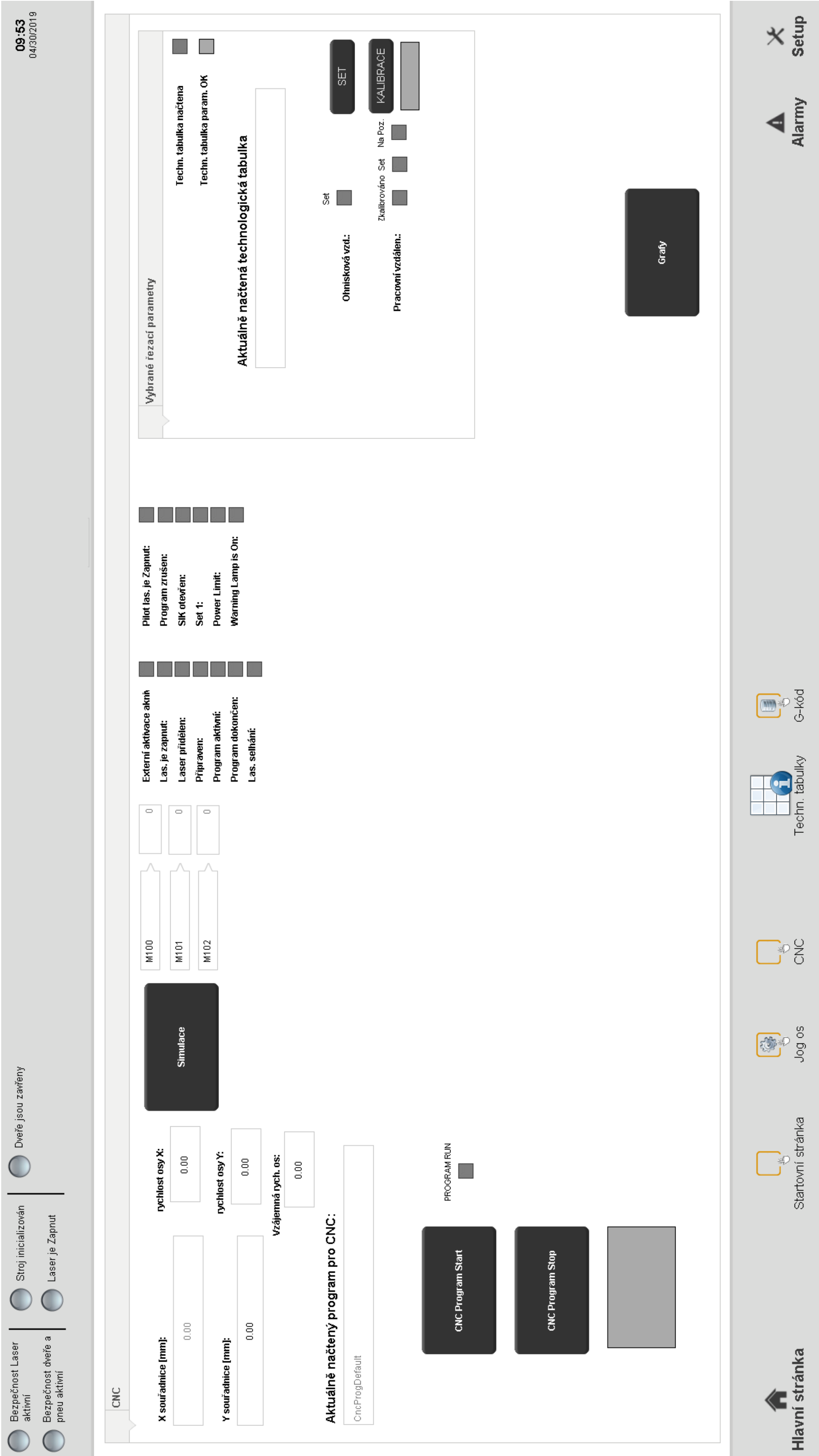


Figure 4: CNC page

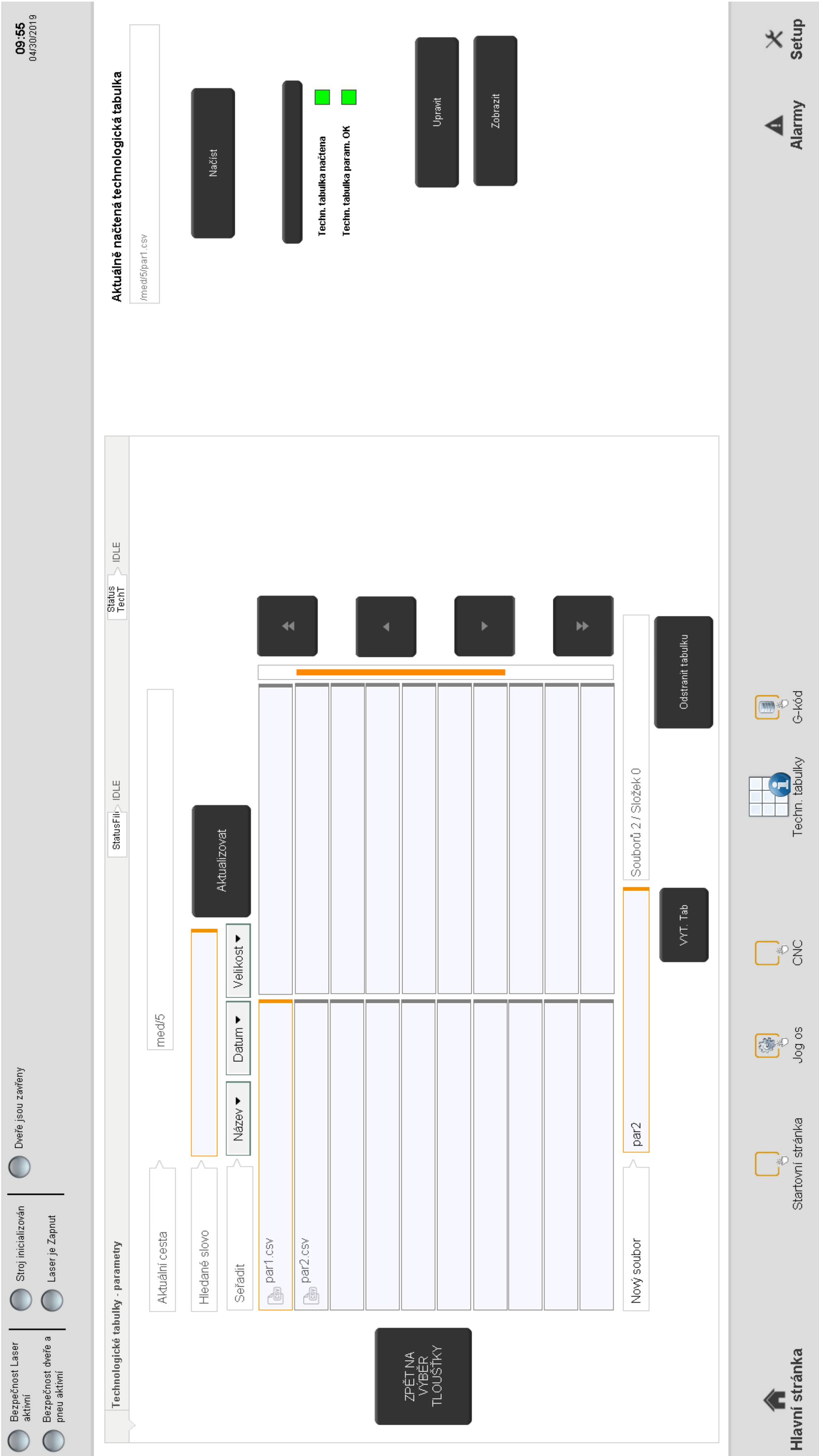


Figure 5: Technological table page

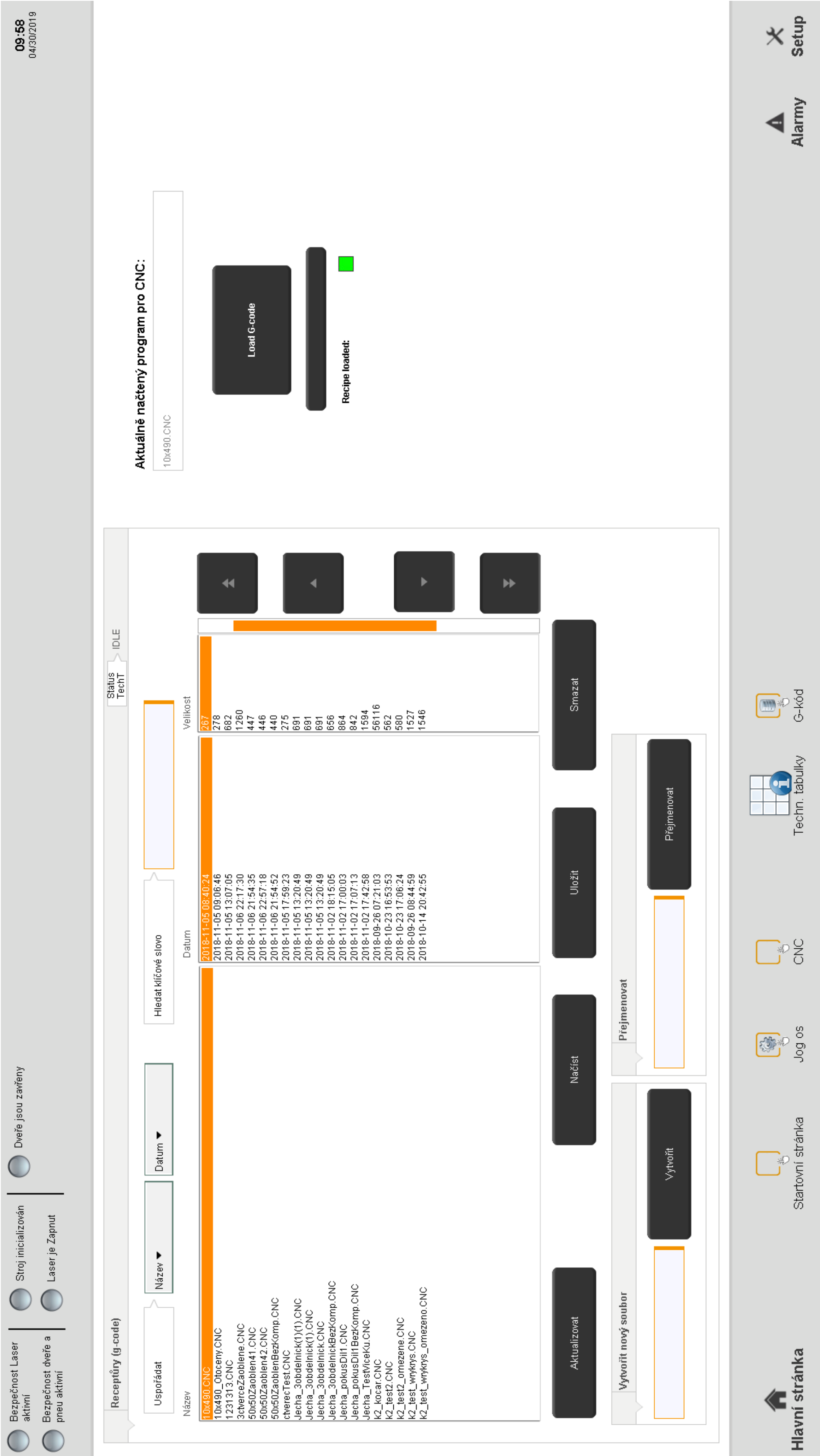


Figure 6: Recipe page (G-code)

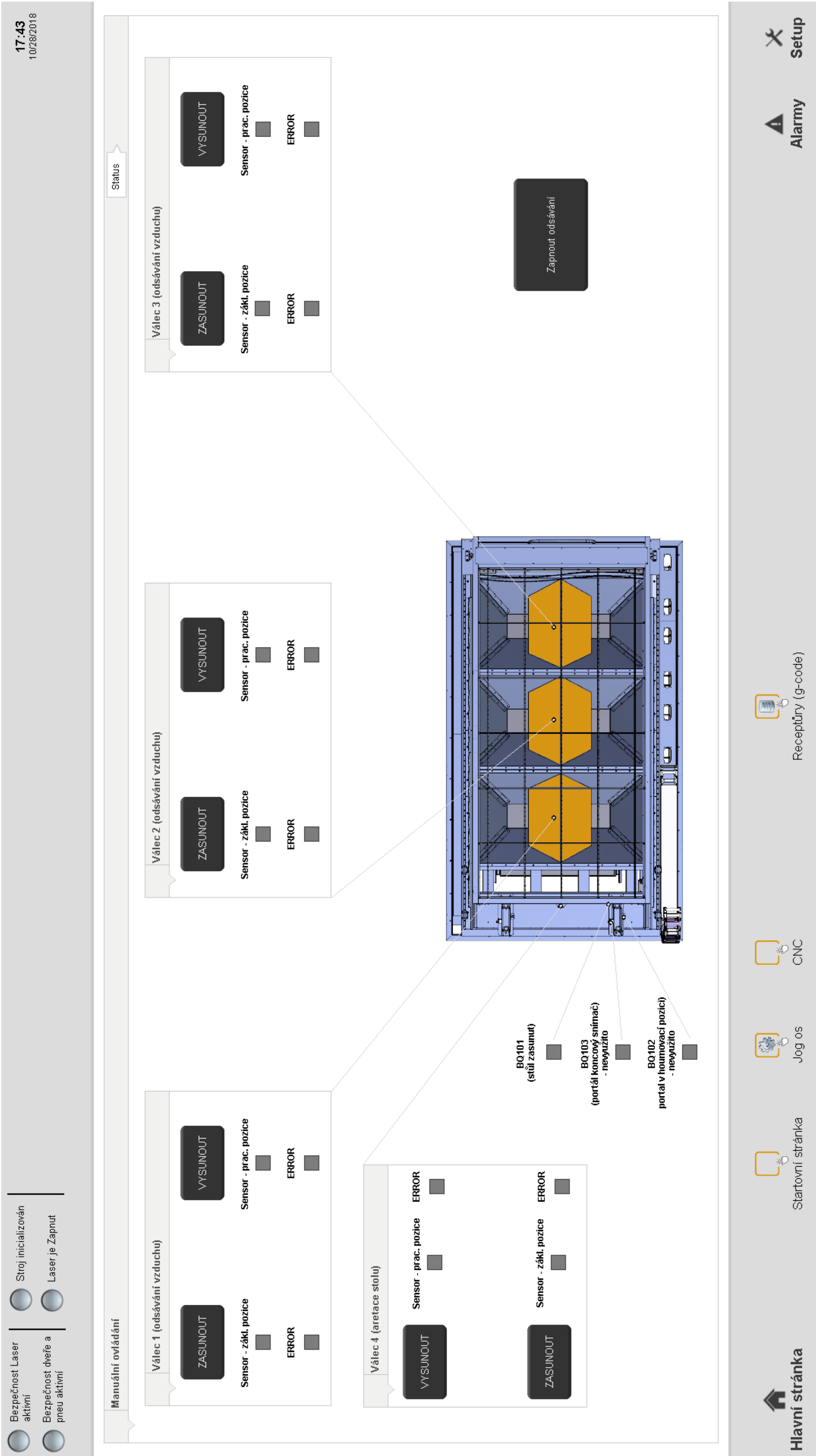


Figure 7: Suction page

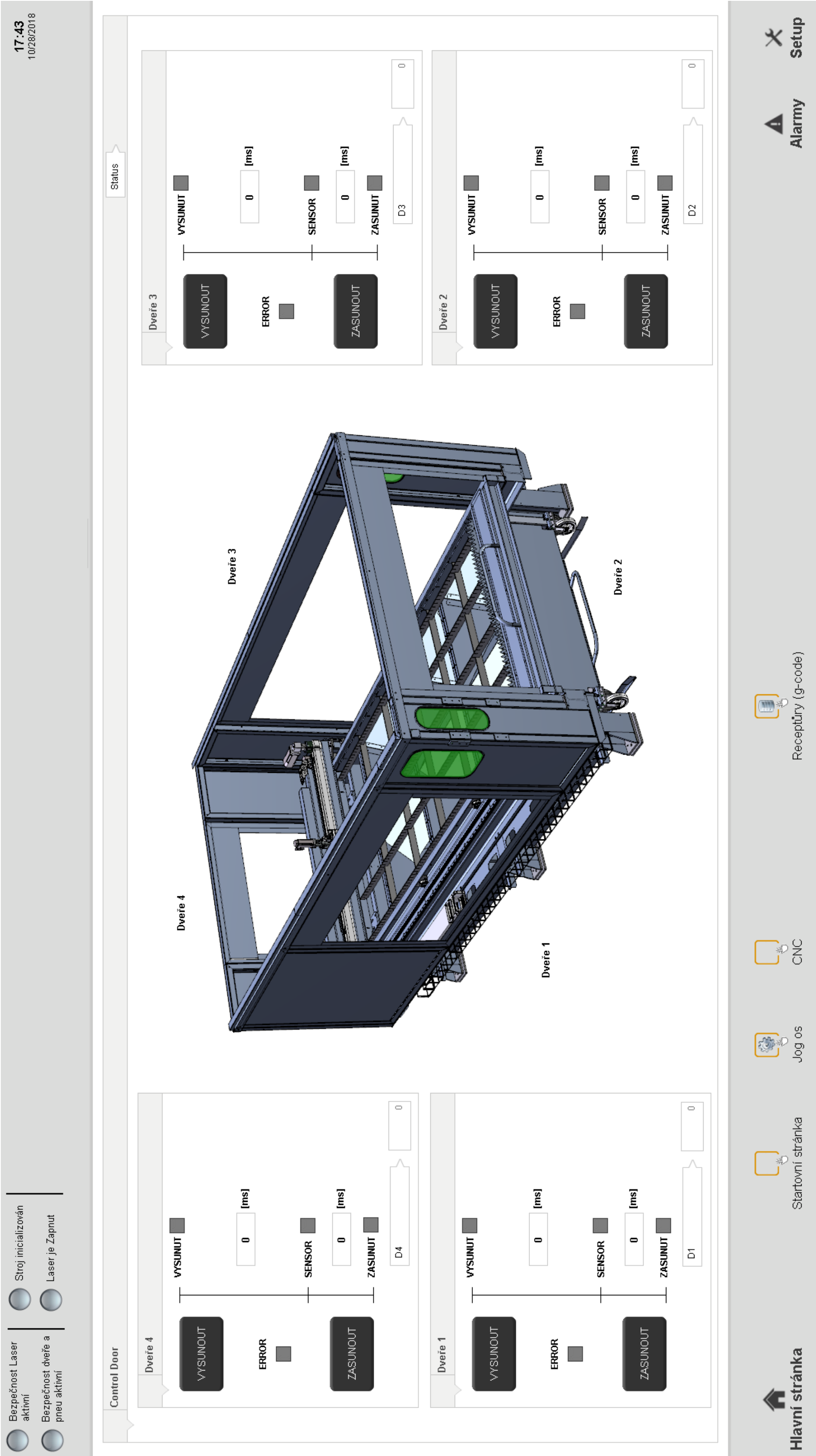


Figure 8: Door control page

ATTACHMENT D - CD

CD content:

JechaJ_CuttingMachine_JP_2019.pdf - own thesis text

CuttingMachineVideo.mp4