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Large-Scale Additive Manufacturing Machine

Dmitri Plotnikov

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This master thesis contains an overview of the additive manufacturing technology and building process of the large-scale Fused Deposition Modelling (FDM) additive manufacturing machine from the old Wafer Handling Diffusion machine. The main part of the thesis is based on practical work and describes the techniques applied during the project. The final product of the thesis is a fully working large-scale AM machine which can print large 3D prototypes from PLA plastic of three different colors and is built with relatively small budget of 10.000 NOK. The university will benefit from such machine by using and applying it for educational purposes.

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Preface

The objective of this master thesis is to develop a design for large-scale additive manufacturing machine able to print multi-color & multi-material parts, as well as build and assemble the machine from the parts existing in the Wafer Handling Diffusion machine. Before the design and building stages, the aim is to conduct a literature review on Additive Manufacturing technology. The purpose of this project is to salvage high-quality parts from the existing equipment and build a machine with a strict budget to fulfill the university's needs. The future machine will be used to complete large prototypes and ready-to-use products from PLA of three different colors for the university's projects.

The university already possesses additive manufacturing machines of different sizes and building techniques, but none of them can produce parts larger than 300×300×300 mm. The machine, built during this master project, has 810×1275×830 mm building volume which makes it the largest FDM AM machine in Norway to the date. The high-performance all-metal Titan Aero extruders with Volcano hot ends and 1.2 mm nozzles can extrude PLA plastic at high rates to support the size of the machine and uncover its full potential and support the enormous building volume. Industrial axes with worm gear mechanisms, high-precision rails, bearing rollers and powerful 3A 3-phase motors with precision up to 0.001 mm per 100 mm are responsible for the machine movement in X, Y and Z directions. Control of mechanical parts of the machine is carried out by TwinCAT software installed on Windows PC, Beckhoff servo amplifiers, and Sercos optical interface. Printer part is managed by the Duet Ethernet motherboard and the Duex2 expansion board. The two control systems are combined to work as one unit with the help of original Beckhoff software, RepRap firmware and specially written for the purpose application.

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List of abbreviations

3D	Three-dimensional
A	Ampere
ABS	Acrylonitrile–butadiene–styrene
AC	Alternating Current
ADS	Automation Device Specification
AJAX	Asynchronous JavaScript
AM	Additive Manufacturing
ASTM	American Society of Testing and Materials
C++	General-purpose programming language
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CMYK+W	Cyan, Magenta, Yellow, Key (Black) and White. Five color printing model
CNC	Computer Numerical Control
DDM	Direct Digital Manufacturing
DSD	Digital Servo Drives
EIA	Electronic Industries Alliance Standards
FDM	Fused Deposition Modeling
G - code	Programming language for Numerical Control
GET	HTTP method to request data from a specified resource
HTML	HyperText Markup Language
HTML-5	Latest version of HTML
HTTP	Hypertext transfer protocol
I/O	Input/Output
ISO	International Organization for Standardization
NC	Numerical Control
PC	Personal computer
PLA	Polylactic Acid
PLC	Programmable Logic Controllers
POST	request method supported by HTTP
R&D	Research and Development
RepRap	Self-replicating manufacturing machine

RP	Rapid Prototyping
RPM	Rotations per minute
SFF	Solid Freeform Fabrication
STL	Standard Tessellation Language
TwinCAT	Windows Control and Automation Technology
V	Volt
WHD	Wafer Handling Difusion

1. Introduction

Additive Manufacturing (AM) is not a new technology on the market. It is also known as Rapid Prototyping (RP), Direct Digital Manufacturing (DDM), Solid Freeform Fabrication (SFF) and 3D printing [1]. AM technology was developed in the 1980s to rapidly create prototypes to represent models of parts before those are built as final products. Today, Additive Manufacturing is used for a wide range of applications: concept, design, custom parts manufacturing, test or short production runs, fitment testing, production molding forms, and ready-to-use products [2].

Modern technologies have advanced significantly both programmatically and technically during the recent years. 3D-printed components are now a common thing. They are now closer to the final product, can be manufactured quickly in large quantities and are much cheaper to produce than before. Advanced machines, raw materials, technologies, modern software are more affordable and easily accessible. The high quality of the final products makes this manufacturing method fast-developing and highly competitive with the conventional production techniques already today.

AM technologies are developing rapidly, and their significance in modern manufacturing is continuously growing. It can even be seen from the purchase history of the machines acquired by different companies in various sectors which bought the machines for manufacturing and educational purposes. The most important benefit is that it gives these companies, even of small size, opportunity to develop, produce and modify parts they require instead of buying them on the side. The part production can now be done quickly and in-house. Researches show that the AM methods are more often used by companies during their manufacturing, research, and development (R&D) processes. It is believed that AM is the future technology, the full potential of which is not yet fully discovered but will be in the nearest future [3].

Fused Deposition Modelling (FDM) or, as it is sometimes referred to, 3D printing, is very popular and one of the most commercially successful Additive Manufacturing techniques. The FDM is an accessible, simple, easy-to-use and reliable technology. It is suitable for office work, user-friendly and is the most used AM technique today. A large variety of materials which are durable, odorless, sturdy, non-toxic, cheap and widely available make the FDM the most suitable technology for the educational purposes. Therefore this manufacturing technique is chosen to fulfill the project goals.

1.1 Background

UiT - The Arctic University of Norway as a technical university shall keep pace with emerging and modern technologies. Industrial Engineering department possesses AM machines that use different AM manufacturing techniques, but they are only able to produce models of small size. Students and university staff must divide models in CAD software into several pieces, manufacture and assemble them manually to complete and produce large prototypes. Building the large AM machine from the WHD machine, which currently is not in use, will benefit both the university and students. The university will improve the educational process by acquiring the relatively cheap-built large additive manufacturing machine, which otherwise is expensive to purchase and start to use the idled before equipment. The students will get the opportunity to build large models using different colors/materials and liberate their engineering creativity by using more practical approach.

This project has been chosen to be executed as the master thesis to help the university to build a large-scale additive manufacturing machine. After a small survey among the university`s technical staff connected to the AM about which manufacturing technique is better to use for printing, it was decided to proceed with the machine using Fused Deposition Modelling (FDM) technique and producing parts of PLA plastic. The university will benefit from the simple and low-cost machine, which can produce parts from cheap and widely available materials. The machine shall be easy-to-use, safe and not require an extensive introduction to its specifics.

1.2 Problem statement, project scope, and limitations

UiT - The Arctic University of Norway has a desire to acquire a large additive manufacturing machine to produce full-size models. By building such machine out of the components available in the old WHD machine, *Figure 1*, the set goals can be achieved and make considerable cost savings.

Figure 1. The WHD machine before the project start

The scope of the project is to design and build a large AM machine that can produce large prototypes. The project's work is divided into three phases which are listed below:

Part I

Part I counts for 1/3 of the total time allocated to the project – 9 weeks. During *part I* the main aim is to give the basic theoretical background of additive manufacturing, definitions, software control, AM machines working principles and available AM techniques.

The study is based on the following scientific concepts and theories which are necessary to gain knowledge to build the machine:

- Additive manufacturing technologies
- Material extrusion process
- Software control and coding
- Fused Deposition Modelling
- CNC hardware and control
- AM firmware

More extended description and overview of different approaches and theories are given further in this chapter.

Part II

Part II is focused on pre-study and planning process of the activities that are necessary to perform during the project.

The pre-study report is delivered as a separate Word document together with the master thesis for the complete overview. Gantt chart is used as a planning tool to manage project activities as well as keep up with the set deadlines for delivery and completion.

Part III

Part III summons the 2/3 of the total time allocated to the project – 18 weeks. During this part the following practical activities are scheduled and planned upon the execution:

1. Investigate the existing WHD machine, examine it`s working principle and working order.
2. Prepare the strategy within the machine building process (needed parts, design, software, management systems)
3. Prepare the Firmware for the machine control
4. Build the machine
5. Model and produce test pieces
6. Prepare a PowerPoint presentation and give an oral presentation of the performed work

The performance and execution of this project may not be as planned and desired due to several limiting factors which influence the building process of the AM machine.
The limitations are listed below:

- Project’s budget is limited to 10.000 NOK – directly influence the quality of the purchased components
- Heavy and highly complex equipment
- Time-frame is set to 5 months for execution of the project’s practical part (design, electrical part, software part, building process, testing, research, parts ordering, thesis writing)
- Long delivery time of the additional components ordered from the foreign supplier – E3D-Online, England
- Extensive size of the project for only one student
- The amount of work and effort needed to get the machine running
- Complicated software – necessary to hire a software engineer
- Fine adjustment of the machine parts to get a good accuracy

2. Additive manufacturing

The name Additive manufacturing (AM) is defined by the American Society of Testing and Materials (ASTM) as a manufacturing technique of building a three-dimensional object by sequential addition of thin layers of material one after another from a 3D data developed in a Computer-Aided Design (CAD) system [4]. Unlike all the conventional techniques, which remove material from the solid block of material, additive manufacturing constructs a solid object by building up the layers from the ground up. This manufacturing approach includes many different production techniques using a broad variety of materials and machines. It allows creating parts with complex geometries quickly, without the need for excessive process planning, with a high level of accuracy and minimum amount of material waste [3, 5].

A 3D model designed with CAD software is directly transformed into an AM machine to produce the finished product without the use of any additional tools. The possibility to create complex geometries allows producing complex parts as one piece, which was not possible or hard to achieve before with the use of conventional material removal techniques [2].

AM is an excellent tool for the modern engineers that allows to explore creativity, prototype rapidly, build and analyze new products. Additive manufacturing techniques have many distinct advantages compared to conventional methods. These give design freedom in creating innovative products and realization of new ideas, allow for re-shaping any product to different applications and optimizing its performance with significantly reduced product development time, cost, human error factors, increased safety. By applying these techniques, it enables the machine to produce almost any complex and impossible component shape.

Although the popularity AM gained in recent years and its apparent advantages, the AM is not the best choice for all the manufacturing tasks and is not a very well-developed technology yet. In some cases, the other conventional techniques might perform better. The current limitations and disadvantages connected to the AM are listed below.

AM limitations and disadvantages:

- Range of materials
- Resolution/Layer thickness
- Limited path patterns
- Product size
- Cost
- Manufacturing speed

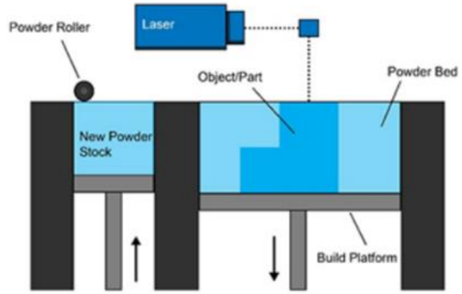
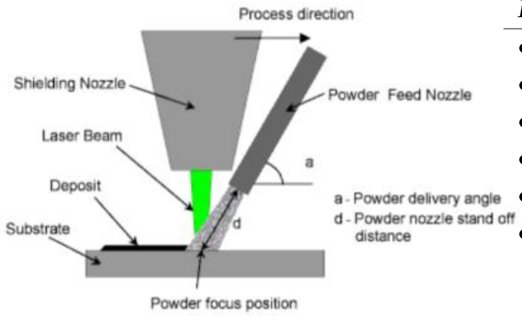
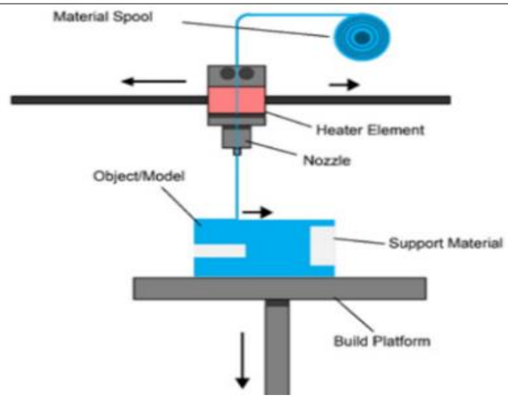
2.1 Additive manufacturing technologies

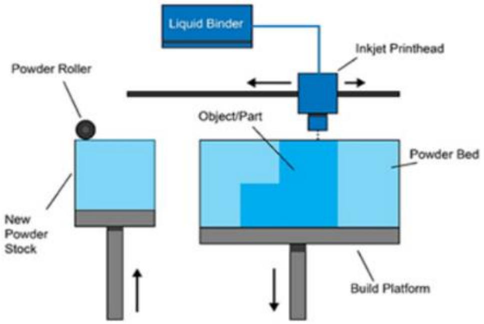
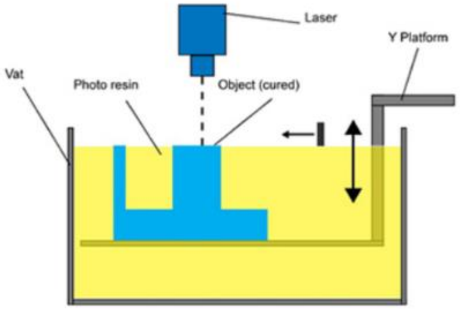
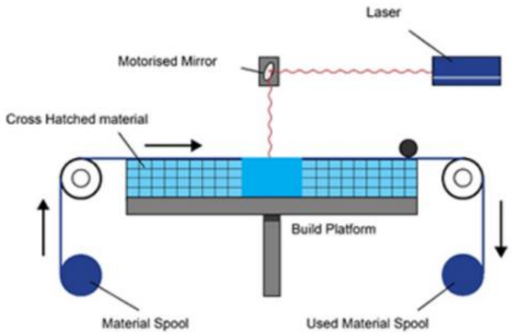
With the rapid development of computer systems and "green manufacturing" trends, AM is becoming more and more popular manufacturing approach in different industries. This approach has many benefits such as the production with nearly zero waste, no requirement for large manufacturing facilities, simpler logistics and more efficient energy consumption compared to the traditional manufacturing methods.

Since the Additive Manufacturing technology has appeared, the vast variety of different AM techniques and materials were developed to serve various applications and needs. Different AM techniques present in the market are listed in *Table 1*. These are divided into three main categories according to what physical processes of material joining are used:

- **Melting or softening material** method produces each layer of slightly melted material which hardens right after it has been applied to the part.
- **Curing liquid/vapor materials** parts are produced from a liquid or vaporized material which sets up after interference with UV-light or heat source.
- **Solid-state joining** is the least favorite technique today due to its complexity and a significant amount of waste. 3D objects are cut out of thin sheets of material foils with lasers and glued together forming a final form.

Table 1. AM techniques sorted according to manufacturing methods [5-33]

Manufacturing methods	Schematic	Techniques	Materials
1. Melting or softening materials			
Laser melting		*Powder bed fusion* • Selective Laser Melting (SLM) [6] • Selective Laser Sintering (SLS) [7] • Direct Metal Laser Sintering (DMLS) [8] • Selective Heat Sintering (SHS) [9] • Electron Beam Manufacturing (EBM) [10]	• Metal • Polymer • Ceramic • Composites
		*Direct energy deposition* • Laser Engineered Net Shaping (LENS) [11] • Direct Metal Deposition (DMD) [12] • Laser Powder Deposition (LPD) [13] • Selective Laser Cladding (SLC) [14] • Laser Consolidation (LC) [15] • Electron Beam Direct Melting (EBDM) [16]	• Metal powder • Metal wire
Extrusion process		• Fused Deposition Modelling (FDM) [17] • Robocasting or Direct Ink Writing (DIW) [18] • Shaped Metal Deposition (SMD) [19] • Extrusion-Based Bioprinting (EBB)	• Polymer • Ceramic • Metal • Graphite • Composites • Bio-ink

<table>
<tr><th>Manufacturing methods</th><th>Schematic</th><th>Techniques</th><th>• Materials</th></tr>
<tr><td>Material and Binder jetting</td><td>
</td><td>• Three-Dimensional Gel Printing (3DGP) [20]
• Inkjet Printing (IJP) [21]
• Multijet Modelling (MJM) [22]
• Ballistic Particle Manufacturing (BPM) [23]
• S-Print [24]
• M-Print
• Polyjet [25]
• Thermojet [26]
• Droplet-Based Metal Manufacturing (DMM)</td><td>• Metal
• Polymer
• Ceramic
• Photopolymer
• Wax
• Composites</td></tr>
<tr><td colspan="4">2. Curing liquid/vapor materials</td></tr>
<tr><td>Laser polymerization</td><td>
</td><td>• STereoLithography (SLA) [27]
• Solid Ground Curing (SGC) [28]
• Liquid Thermal Polymerization (LTP)
• Beam Interference Solidification (BIS)
• Holographic Interference Solidification (HIS)
• Laser Chemical Vapour Deposition (LCVD) [29]</td><td>• Photopolymer
• Ceramic
• Composites</td></tr>
<tr><td colspan="4">3. Solid-state joining</td></tr>
<tr><td>Material adhesion</td><td>
</td><td>• Ultrasonic Additive Manufacturing (UAM) [30]
• Laminated Object Manufacturing (LOM) [31]
• Solid Foil Polymerization (SFP)</td><td>• Metal
• Hybrids
• Metallic
• Ceramic
• Composites</td></tr>
</table>

2.2 Software control

Current control systems for the AM machines consist of two major components: firmware and slicing software. The firmware is integrated into the printer motherboard, understands G-code and sends corresponding commands to the printer components. The slicing software, installed on the desktop computer, generates G-code for the printer firmware [32].

Part manufacturing process using additive manufacturing techniques starts from a 3D CAD model created in a CAD program or by using a reverse engineering technique like 3D scanning. The CAD-file is converted to the format understandable and recognized by the AM machine inside the CAD software, usually to Standard Tessellation Language format (STL-format). The STL-format figure containing information about each layer is sent to a slicing software [33]. Slicing software allows to manage STL model, make slight adjustments to the geometry of the part, fix errors, change parts orientation, set up support structures, assign layer thickness and amount of extruded material, print quality, change machining parameters, simulate the process and generate tool path. All errors and possible bugs are fixed and adjusted during this step. When all manipulations with the STL model are performed, the slicing program generates a G-code. G-code is uploaded directly from the PC using Web Interface, cable, or memory card to the AM machine and built-in software processes the information and manufactures the part [34].

2.2.1 STL file format

The STL-format was introduced by 3D Systems Inc. in the 1987 and got its name after the first and widely used commercial AM process developed by the same company-STereoLithography. Later, with the development of other AM techniques, it was renamed to Standard Tessellation Language [35]. The *.stl* is the most used software file extension for additive manufacturing today. It is generated inside the CAD program or slicing software from a 3D CAD model to be further used in the AM machine [36]. It represents the 3D data output as figure surface boundaries approximated by a mesh of triangular facets. Each of the triangles has three vertices defined by *X, Y, Z*-coordinates and outside normal unit vector pointing outwards from the solid model to the outside part of the triangle. The triangular facets define the outer geometry of the designed solid model. STL-files contain information on each triangular facet, which can be described by the code given in *Figure 2* [37]. STL-files are simple, portable, compact and do not require a lot of memory to be processed, making them suitable for the hardware used in 3D printers. However, they do often contain geometry mistakes, do not specify units, colors and material information and usually need modifications to avoid mistakes during part manufacturing.

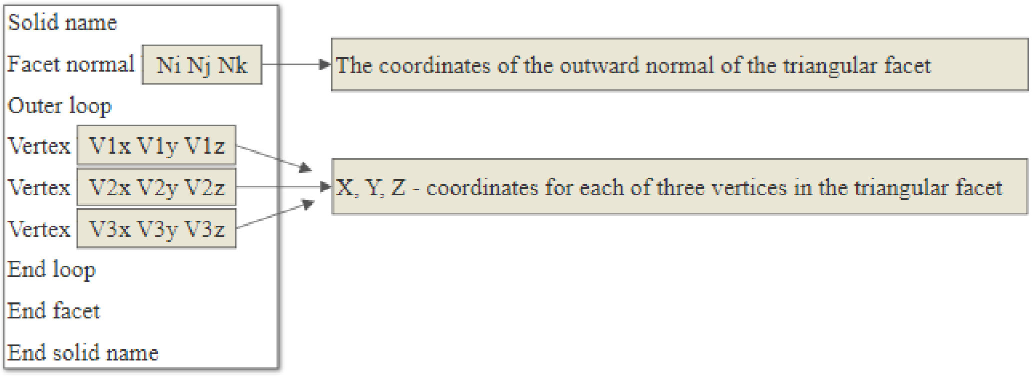


Figure 2. Example of the STL-file data

2.2.2 G-code

G-code, G programming language, Geometric code or NC-code is a most widely used Numerical Controlled (NC) programming language for CNC and AM machines [38]. Although the G-code as a term often describes the whole Numerical Control language, it is the only component of the actual system consisting of different codes such as M-codes, T-codes, F-codes, S-codes, etc. Its last implementation for additive manufacturing was approved in 1982 as *EIA RS-274-D* or *ISO 6983* [39]. G-code for AM incorporates information about each layer of a 3D object and directions for the tool about what path to follow. It is generated by a slicing program from a 3D CAD model to be further sent to AM machine and start the part production. Besides the 3D geometry of the part and the tool movements, G-code also contains the information of material extrusion rates, feed rates, bed and nozzle temperatures, when to switch on/off the cooling fans and other commands for each manufacturing technique that machine must follow during the building process. G-code varies for different machines to cover all the functions, abilities and specifics. It consists of different commands with specific functions written in lines. Each command has its own letter before the numerical value defining machine actions [38].

CNC and AM machines are fundamentally the same, and their control is very similar. That is why it is possible to build a hybrid manufacturing machine that can do both milling and 3D printing. G-code is a universal tool and suits both CNC and AM machines. However, the G-codes in these machines have several differences. The main difference is that CNC removes material to get a final part and parameters for the tool movement are set to be around the part where the material is going to be removed. 3D printers build objects by laying layers according to the modeled shape with fixed layer thickness. The codes for the AM machines are generated with the help of slicing software automatically, unlike in CNC, where each movement have to be specified in a CAM software manually which craves a lot of time and knowledge. The codes for the CNC are different for each tool, material, model size and shape, but for 3D printers these parameters are not relevant, and the codes are the same for any shape.

Some G-code commands with some of their functions used by the RepRap firmware are displayed below. The RepRap is chosen as an example since it is the firmware which runs the motherboard purchased for this project. The commands highlighted with the red color are intrinsic for the AM manufacturing machines only. The rest of the commands are used for both CNC and AM techniques. Even though these G-code commands have the same designations, some of their functions are different and vary with every machine from the different manufacturer due to different equipment specifics and control systems. G-code must be customized for each individual machine to cover its specifics.

G – code is a geometric or preparatory code that describes object geometry, tool motion and positioning related to the workpiece

M – code is a machine or miscellaneous code that corresponds to the other machine functions like speed, tool change, machine start/stop, etc

D – defines the diameter parameters

F – feed rate in mm per minute

E – extrusion rate/length of the extruded material

H – heater parameter

R – temperature parameter

N – code line number

T – defines the used tool and assigned number of the tool

S – time parameter, speed, temperature, spindle speed and motor voltage

I – incremental distance from starting point in X-axis direction from the center of the arc

J – incremental distance from starting point in Y-axis direction from the center of the arc

K – incremental distance from starting point in Z-axis direction from the center of the arc

X, Y, Z – position of each axis

G-code generation process consists of several steps [40]:

1. Conceptualization of an idea
2. Creation of 3D model in CAD program
3. Saving CAD model in STL format
4. Creating machining sequence and settings in slicing software
5. Evaluating the ready STL model and settings in slicing program
6. Generating G-code

The graphical representation of G-code generation process is illustrated step-by-step in the flowchart in *Figure 3.*

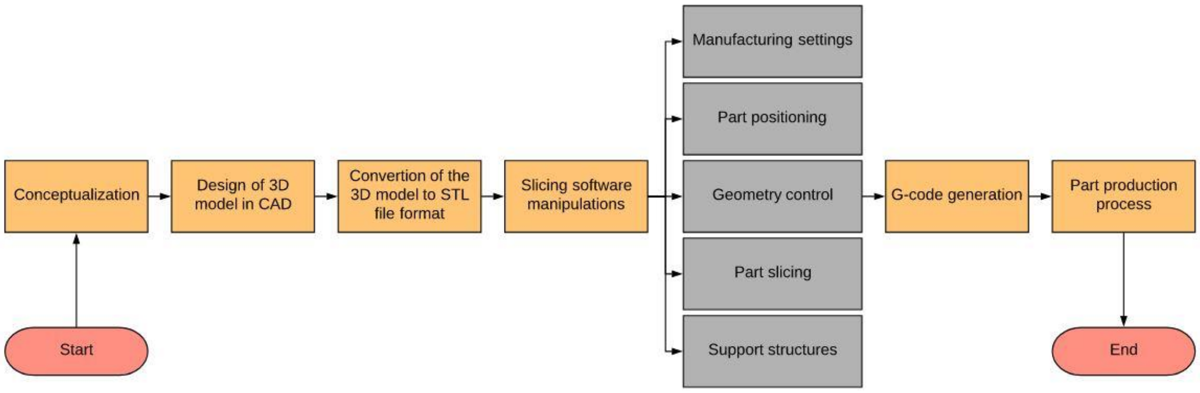


Figure 3. Flowchart of G-code generation process for the AM machine

2.2.3 Single color G-code example

The example of the single color G-code for the FDM 3D printer with one extruder shown in *Figure 5* and *Figure* 6, has been extracted from the *Cura 20.01* slicing software for the LulzBot TAZ 6 3D printer. The figure inside the *Cura* software interface and for which G-code has been generated is presented in *Figure 4.* The G-code contains the machine instructions to build a small gecko. The model is 45.1×44.2×9.2 mm. The layer height 0.25 mm, wall thickness 1.00 mm, 40% infill density, printing speed 100 mm/s, travel speed 120 mm/s, filament diameter 2.89 mm, flow 100%. Optional brim structure was added around the gecko for better connection to the building table.

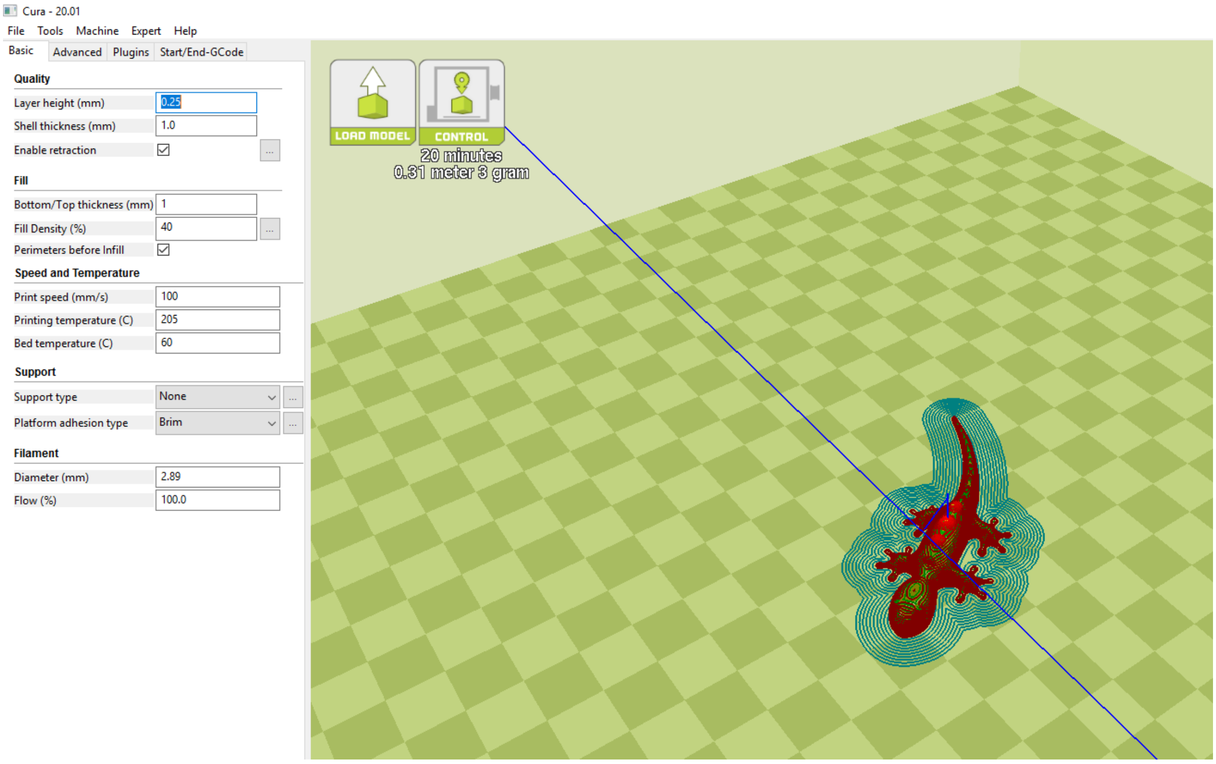


Figure 4. The figure inside the Cura software interface

The G-code is for a complex structure is long and mostly consists of movement coordinates and extrusion rates. All the additional machine commands are specified in the beginning and at the end of the code. *"Start"* and *"End"* parts of the code can be seen in *Figure 5* and *Figure* 6.

gecko_3 - Notisblokk

Fil Rediger Format Vis Hjelp

```
;This profile is designed specifically for LulzBot TAZ 6 3D Printer
;Basic slice data:
;Sliced at: Tue 26-06-2018 11:04:54
;Layer height: 0.25
;Walls: 1
;Fill: 40
;Estimated Print time: 20 minutes
;Filament used: 0.313m 2.0g
;Filament cost: None
G26                             ; clear potential 'probe fail' condition
G21                             ; set units to Millimetres
M107                            ; disable fans
G90                             ; absolute positioning
M82                             ; set extruder to absolute mode
G92 E0                          ; set extruder position to 0
M140 S60; get bed heating up
G28 XY                          ; home X and Y
G1 X-19 Y258 F1000              ; move to safe homing position
M109 R175                       ; soften filament for z homing
G28 Z                           ; home Z
M104 S185                       ; wipe temp
G1 E-30 F100                    ; suck up XXmm of filament
G1 X-15 Y100 F3000              ; move above wiper pad
G1 Z1                           ; push nozzle into wiper
G1 X-17 Y95 F1000               ; slow wipe
G1 X-17 Y90 F1000               ; slow wipe
G1 X-17 Y85 F1000               ; slow wipe
G1 X-15 Y90 F1000               ; slow wipe
G1 X-17 Y80 F1000               ; slow wipe
```

Figure 5. "Start" of the G-code

```
G1 X135.561 Y130.353 E313.86668
G1 X135.556 Y130.418 E313.86792
M107
G1 F600 E312.86792
G1 Z9.275
G0 F10500 X135.556 Y130.418 Z14.206
;
M400                           ; wait for moves to finish
M104 S0                        ; hotend off
M107                           ; fans off
G91                            ; relative positioning
G1 E-1 F300                    ; retract the filament a bit before lifting the nozzle, to release some of the pressure
G1 Z+20 E-5 X-20 Y-20 F3000    ; move Z up a bit and retract filament even more
M117 Cooling please wait       ; progress indicator message
G90                            ; absolute positioning
G1 Y0 F3000                    ; move to cooling position
M190 R50                       ; set bed to cool off
G1 Y280 F3000                  ; present finished print
M84                            ; steppers off
G90                            ; absolute positioning
M117 Print complete            ; progress indicator message
```

Figure 6. "End" of the G-code

2.2.4 Multi-color g-code

The most of the existing on the market slicing software are universal for both single- and multi-color 3D printers and generate G-codes automatically for every printer according to the machine specifics and the used techniques. G-code for multiple color FDM 3D printing would differ from the single color code, even if both codes were created for the same AM machine. The difference between the codes depends on the used techniques and firmware installed on the printer. Different multi-color printing techniques together with their pros and cons are described in section **"1.8.2 Multi-color & Multi-material extrusion"**.

The G-code for multi-color printing using one extruder is the same as G-code for single-color FDM process. The color change is performed manually by pausing the print at the desired layer, changing filament, and continuing. The automatic stop of the print to change the filament is also possible. It can be done in the Notepad by typing M600 into the single-color G-code before the layer where the color has to be changed. The printing process will be stopped automatically, and the machine will give a sound signal when the filament change will be needed. The filament can be changed, and old color remains can be extruded manually to achieve a clean color transition.

The FDM multi-color process for the machines with the several extruders is not very different from the single extruder technique. That is why it is possible to convert almost any FDM machine into a multi-color printer. The LulzBot TAZ 6 3D printer with the double extruder is used as an example to illustrate the code difference between single color G-code and multi-color G-code. The same Cura 20.01 software is used to generate the machining sequence. The

TAZ 6 is adjusted to the same specifications as in the previous example. The CAD model is divided into two separate parts representing different colors. These parts are merged inside the Cura software into one piece to review the object and create the G-code as shown in *Figure 7*.

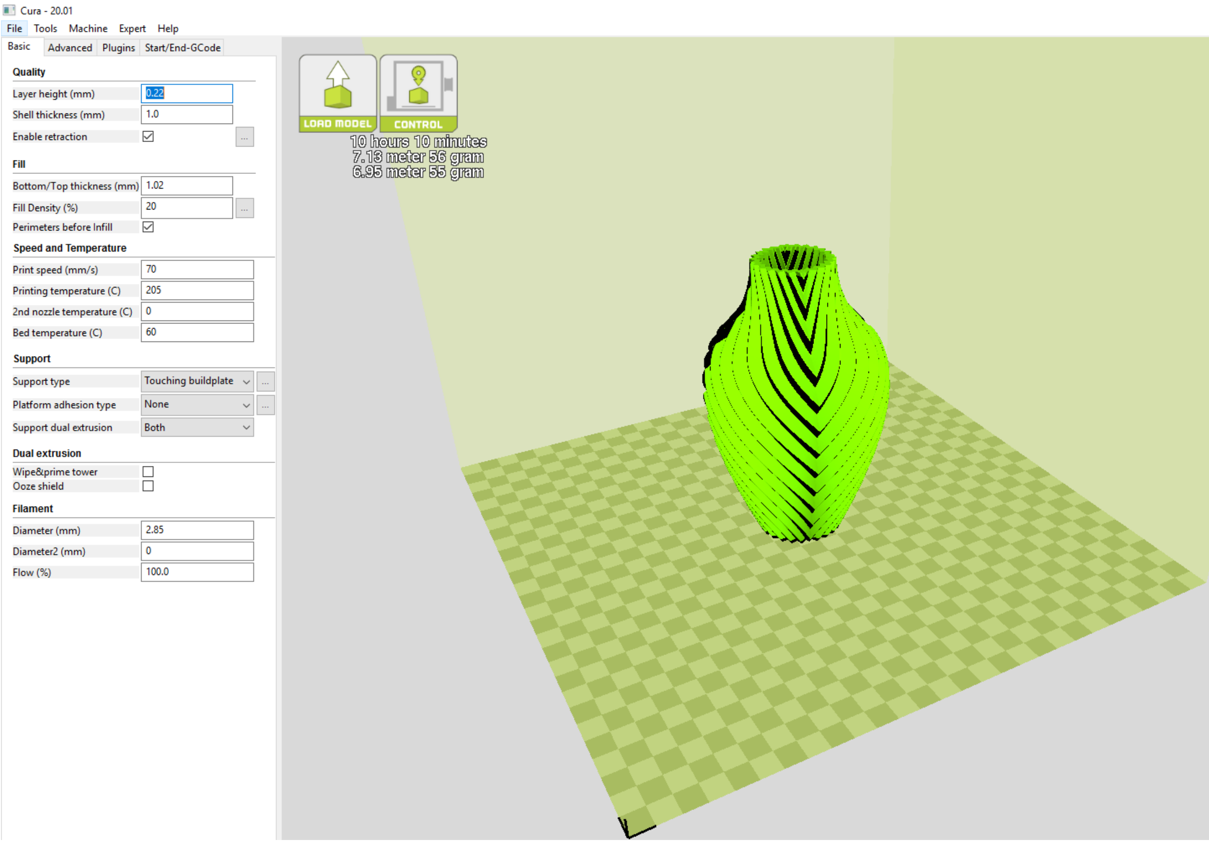


Figure 7. Multi-color printing in Cura

In case of several extruders, the G-code contains tool change commands (T0 and T1), extruder rate for each extruder (F), and tool offset (E). These values can be seen in Figure 8 at the *"Start"* part of the G-code. The rest of the code is identical to the single color process.

chromatic-a-2 - Notisblokk

Fil Rediger Format Vis Hjelp

```
M190 S60.000000
M104 T1 S205.000000
M109 T0 S205.000000
M109 T1 S205.000000
T0
;Sliced at: Tue 26-06-2018 10:57:30
;Basic settings: Layer height: 0.22 Walls: 1 Fill: 20
;Print time: 10 hours 10 minutes
;Filament used: 7.13m 56.0g
;Filament cost: None
;M190 R60 ;Uncomment to add your own bed temperature line
;M104 S205 ;Uncomment to add your own temperature line
;M109 T1 S0 ;Uncomment to add your own temperature line
;M109 T0 S205 ;Uncomment to add your own temperature line
G21         ;metric values
G90         ;absolute positioning
M107        ;start with the fan off
G28 X0 Y0   ;move X/Y to min endstops
G28 Z0      ;move Z to min endstops
G1 Z15.0 F10500 ;move the platform down 15mm
T1                      ;Switch to the 2nd extruder
G92 E0                  ;zero the extruded length
G1 F200 E10             ;extrude 10mm of feed stock
G92 E0                  ;zero the extruded length again
G1 F200 E-16.5
T0                      ;Switch to the first extruder
G92 E0                  ;zero the extruded length
G1 F200 E10             ;extrude 10mm of feed stock
G92 E0                  ;zero the extruded length again
G1 F10500
;Put printing message on LCD screen
M117 Printing...

;Layer count: 634
;LAYER:0
M107
G0 F10500 X123.087 Y121.250 Z0.425
G0 X123.087 Y122.558
;TYPE:SKIRT
G1 F900 X123.087 Y121.250 E0.05446
```

Figure 8. "Start" of the multi-color G-code

The tool is automatically changed several times during the print. One of the tool change procedures is illustrated in Figure 9.

```
G1 X122.141 Y112.643 E26.01632
G0 F10500 X121.805 Y112.550
G0 X121.491 Y115.389
;TYPE:FILL
G1 F2400 X121.118 Y115.762 E26.02542
G92 E0
G1 F600 E-16.50000
G1 Z103.045
;Switch between the current extruder and the next extruder, when printing with multiple extruders.
;This code is added before the T(n)

T1
;Switch between the current extruder and the next extruder, when printing with multiple extruders.
;This code is added after the T(n)

G0 F10500 X120.700 Y166.830
G0 X120.377 Y166.854
;TYPE:WALL-INNER
G1 Z102.945
G1 F600 E0.00000
G1 F2100 X120.405 Y166.850 E0.00049
```

Figure 9. Tool change in G-code

The *"End"* of the code is almost identical to the single color code. The only difference is the additional lines for each extruder at the process termination stage, *Figure 10.*

```
G1 F1800 X157.332 Y190.143 E112.87505
G0 F10500 X158.299 Y189.884
G1 F1800 X158.585 Y189.598 E112.88203
M107
G1 F600 E111.88203
G1 Z139.785
G0 F10500 X158.585 Y189.598 Z144.575
;End GCode
M104 T0 S0                    ;extruder heater off
M104 T1 S0                    ;extruder heater off
M140 S0                    ;heated bed heater off (if you have it)
G91                                ;relative positioning
G1 E-1 F300                        ;retract the filament a bit before lifting the nozzle, to release some of the pressure
G1 Z+0.5 E-5 X-20 Y-20 F10500 ;move Z up a bit and retract filament even more
G28 X0 Y0                          ;move X/Y to min endstops, so the head is out of the way
M84                        ;steppers off
G90                        ;absolute positioning
```

Figure 10. "End" of the multi-color G-code

2.3 Software for slicing

Slicing software or “slicer” is a connecting link between CAD program and an AM machine. These user-friendly slicing programmes, with different levels of difficulty to suit both beginner and an advanced user, are very important for AM process and contain many essential options for creating geometry instructions and setting up the printing parameters [41]. This software converts the digital 3D model into printing commands. AM machines are unable to handle large 3D CAD-files that are necessary to separate into 2D layers or contours using “slicing algorithm” in slicing software before these are sent to the 3D printer. The model is divided into layers along the vertical axis Z with imaginary horizontal planes. The layers have a calculated thickness, and their position is fixed inside the program along the vertical lines. Setting up the right layer thickness is important as it will influence the final product finish and production time. The thickness is set up according to the desired printing resolution, capabilities of the printer, material specifications and printing speed. Thick layers or low resolution will result in poor quality, rough surface, but the manufacturing time will be significantly reduced since fewer layers are needed to complete the part. Such fast manufacturing process would be suitable for quick prototypes and parts which do not require to have high quality. The final products should be made using the smallest layer thickness possible to achieve the best quality. All overhang structures of the model need to be reinforced by the support structures to hold them in place. After all the parameters are composed, and the machine is set up, the program generates the G-code for each layer of the model which is exported to AM machine to start the manufacturing process [42].

Key features of the slicing software:

- Preparation of a 3D model for AM process
- Printer settings (bed and nozzle temperature, moving speed and movement directions)
- Addition of support structures
- Division of CAD file into 2D layers (contours) and setting up the layer thickness
- The orientation of the part (or placing several on building platform if needed)
- STL-file geometry management (mesh repair, filling empty spots and layers, filling and printing directions, etc.)
- G-code generation
- Setting up building parameters (feed/extrusion rate, tolerances)
- Integration into machine control
- Review of printing files (the whole model or individual layers)
- Adjustment of material data
- Simulation of G-code inside to confirm its integrity before manufacturing of the part
- Approximate estimation of production time and material usage

2.4 Firmware

The software is a significant part of the machine which manages all the systems. Without the proper software, an AM machine, even with the most advanced hardware, will not produce a single part. It sets up and regulates operational parameters to get desired results in 3D product manufacturing corresponding to the task posed by the operator, defines the quality of the finished products, follows and controls the manufacturing process in real-time.

There is a considerable amount of software available on the additive manufacturing market for managing different machines for every possible application. AM machines are controlled by firmware integrated into a microcontroller. The microcontroller is the brain of the machine, controlling all its actions by sending signals to the hardware components according to the G-code generated by slicing software on the computer [43]. It senses input parameters and identifies the machine actions according to the programmed logic written in the source code. It connects all the hardware components and provides communication between all the parts. Firmware reads and processes the G-code, then it sends the movement information to the drivers which control the stepper motors, controls the temperatures, speed, extrusion rates, material flow, etc. All control software share similarities and have a common objective – to control the AM machine movements during the manufacturing process. The main difference lies in a reaction to the commands which is defined by algorithms and logic hidden inside the program to cover different functions of the machine and support different hardware. Therefore, even though the programs may be similar, they will function differently [42]. Machine controlling unit currently available on the market have some reliability issues. Most of the cheaper machines are built around simple microcontrollers which process a large number of simultaneous operations leading to system crashes, incorrect performance, and a significant reduction in speed and quality issues. Expensive machines have more powerful management systems, and their performance is more robust [43]. Industrial machines are more complicated than public-oriented machines and perform more steps during the manufacturing process. Therefore, such machines are usually managed by several microcontrollers forming the microcontroller systems - Programmable Logic Controllers (PLC) [35].

Additive manufacturing machine software is similar to CNC machine control software and uses the same programming language based on C / C ++. These programs provide and simplify communication between the user and a 3D printing machine, reduce the complexity of printing process, cover the machine specifics and allow to use better technology solutions. Each AM machine model has its own printing management software covering all the possible functions, and therefore the original equipment manufacturer (OEM) provides the software specially made and integrated for each printer model because all machines are different [39]. Most of the firmware simple solutions for the FDM printers are available for free in open sources.

2.5 Material Extrusion

Fused deposition modeling (FDM)

Fused Deposition Modelling (FDM), or as it is sometimes referred to, 3D printing, is a very popular and one of the most commercially successful additive manufacturing techniques. This material extrusion process was developed in 1989 by Scott Crump who later co-founded the US company *Stratasys Inc.* [40]. The first FDM AM machine was introduced by *Stratasys Inc*. in 1991 with the name “3D-Modeller” [44].

The FDM machine has a head, which moves along the path set by the G-code and builds up layers of semisolid molten thermoplastic material of different layer-thickness through a nozzle in a controlled manner onto a building platform. The building material is fed through the extruder to the nozzle where it is heated up above its melting point so it can flow through. The extruded material hardens right after ejection and bonds to the previous layer forming a three-dimensional object. There is a great variation of the FDM machines available on the market to satisfy every customer's need. Simple machines usually have a small building space, have a printing head with one extruder either with the direct drive or remote drive (Bowden type) for both primary and support structures, lack precision and stability. More sophisticated and expensive printers are larger in size with bigger building space, more precise, stable during long builds and can have several extruders for different colors or materials [3].

The FDM process is simple and can be divided into six main categories listed below. The flowchart diagram illustrated in *Figure 11* was created to cover in details all the processes performed during the FDM manufacturing.

FDM process consists of [40]:

- Material loading/feeding
- Material melting
- Pressing the material through the nozzle
- Material extrusion/retraction according to the constructed path
- Material bonding to the previous layer to form a solid structure
- Addition of the support structures to allow overhangs and complex part geometries

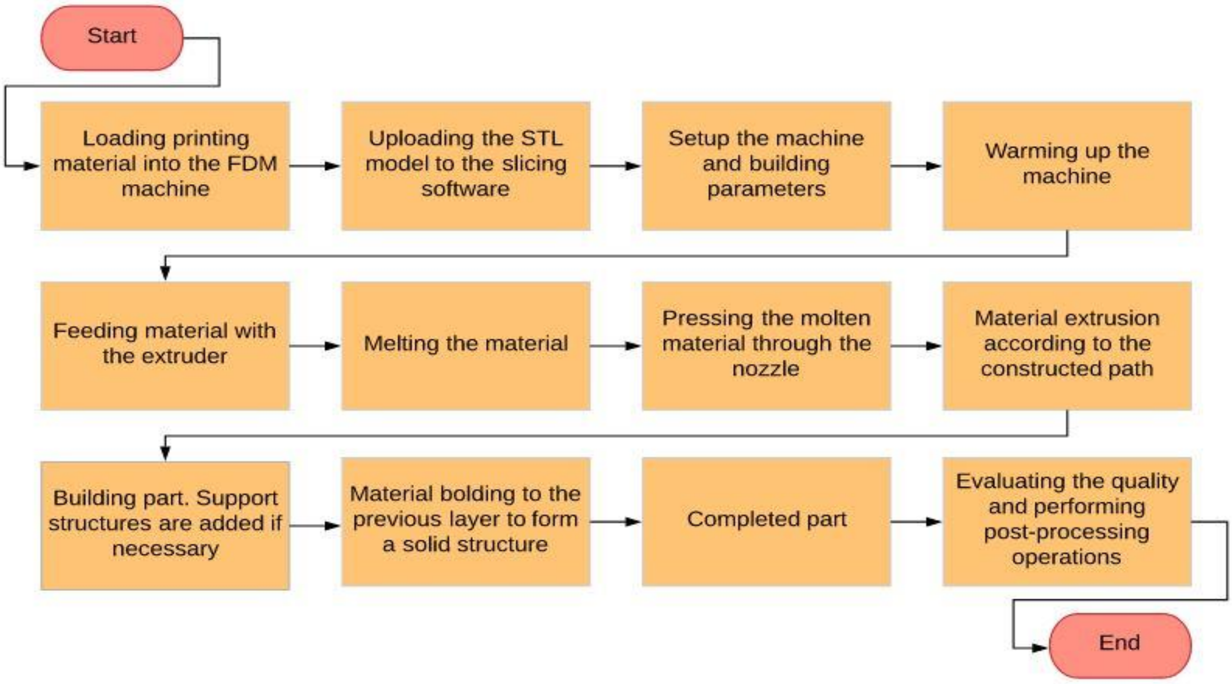


Figure 11. FDM additive manufacturing process

The FDM is a well-known, simple, easy-to-use and reliable technology. It is suitable for office work, is user-friendly and the most used AM technique today. A large variety of materials which are durable, odorless, sturdy, non-toxic, cheap and widely available make the FDM the most suitable technology for the educational purposes for which the machine will be used. Despite all the advantages mentioned above for the FDM technology, the speed, accuracy and surface finish of the manufactured parts are quite low yet compared to the other available today AM technologies. However, there are some FDM machines on the market with the hybrid technology which combine AM and CNC machine into one unit and may solve the quality problems [45].

Advantages of the FDM process:

- Less expensive machines than other techniques
- Considerable variation of different materials of different properties and colors which are cheap and widely available
- Non-toxic materials
- No specialized knowledge needed to manufacture parts
- Information is available online
- No chemical post-processing operations
- Suitable for office use

- Cheap to produce parts
- Open-source systems (OSS)

Disadvantages of the FDM process:

- Products are not very strong and have low mechanical properties
- Poor surface finish (low resolution in Z-direction)
- The relatively slow manufacturing process
- A lot of material waste when producing with several materials or colors
- Material lift-off, while printing long parts, is common
- Some materials need a powerful heat source inside the machine

The FDM 3D printers are simple devices. They usually consist of four stepper motors. Three of them provide movement of the printing head in *X*, *Y* and *Z* coordinates and one-fourth motor is responsible for filament extrusion through a nozzle. The FDM machines also consist of the motherboard, end stops for each of the axes, heater elements, thermistors, frame, worm gears or rails with belt systems, build a table, screen, and some other minor components.

During the printing process, the software of the 3D printer translates commands from G-code to movement signals which are then sent to drivers (actuators) which supply the required output currents to motors and control micro step operations. The management system of an AM machine is illustrated in *Figure 12*. The G-code contains information about movement direction and speed; distance traveled in each direction, positions where the filament material shall be extruded and retracted.

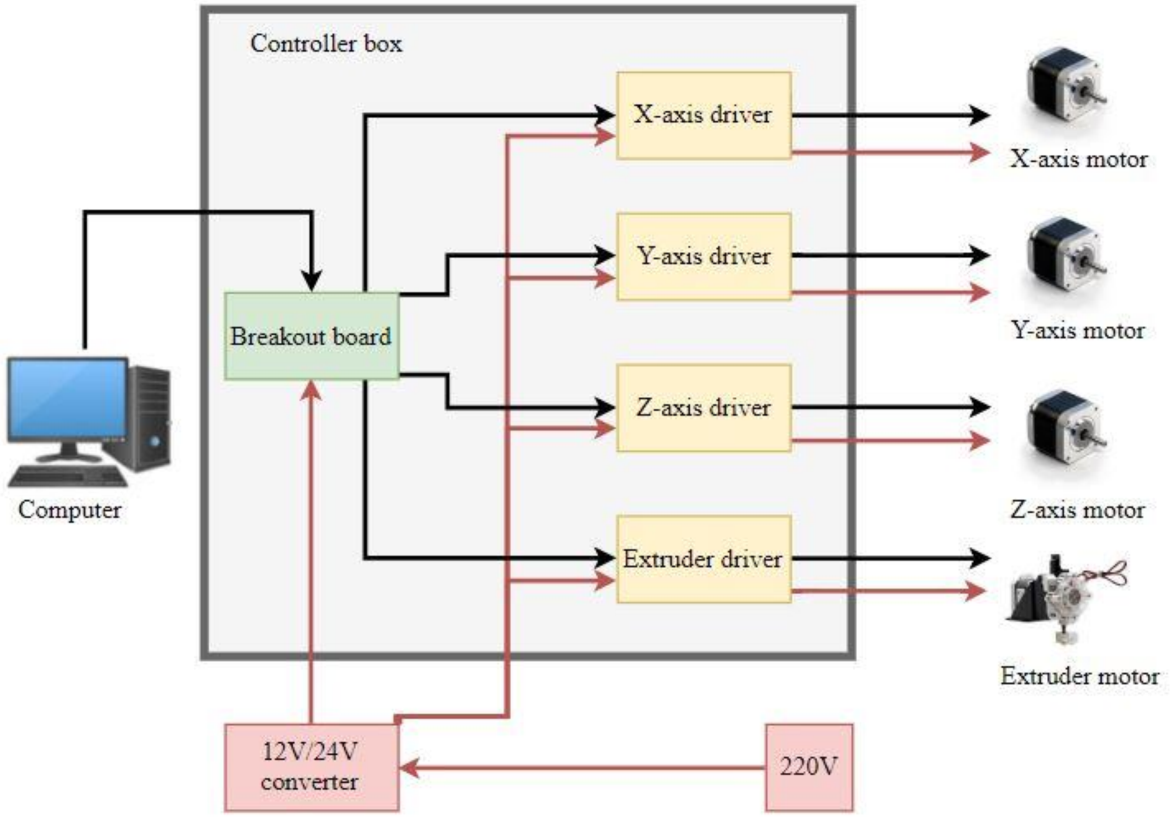


Figure 12. Schematic of the AM machine management system [46]

1.8.1 Filament

Filaments for the FDM printers are available in broad variety of materials, sizes, and colors. PLA plastic, which suits well for large-scale builds, is a material of choice for this project. This material type is easy to print with, cheap, stable, robust, durable, odorless, non-toxic, widely available and unlike, for example, ABS plastic, it does not tend to warp during printing due to absence of inside tension, does not require the use of heated table and enclosed space around the printing area [46].

The filament diameter is also an important and crucial parameter. The most common filament diameter sizes for FDM 3D printers today are 1.75 mm and 3.00 mm. The filament diameter of choice depends on several factors:

- Desired material extrusion rate/flow
- Printing speed
- Hot end`s temperature and size
- Extruder type
- Layer height
- Environment (enclosed/not enclosed)
- Machine size
- Nozzle size

Polymers have a bad heat conductivity, and this leads to complications with the filament core melting. The thicker the filament is, the harder it is to melt the core. The 1.75 filament suits better for high quality builds using a small diameter nozzle due to a smaller amount of pressure required from the extruder to push the material through. However, 3.00 mm filament is a better choice for the large builds with the larger nozzle where resolution is not the highest priority [44]. Titan Aero extruders, purchased for the project, can support both 1.75 mm and 3.00 mm filaments. It is decided to use 3.00 mm filament due to large nozzles, 24V printer part system, amount of extruded material during the large print jobs and availability of the material at the university. Most important advantages and disadvantages of the 1.75 mm and 3.00 mm filaments are listed in *Table 2* below.

Table 2. Comparison of the 1.75 mm and 3.00 mm filaments [44]

1.75 mm	**3.00 mm**
Thin and breaks easier	Stiff and hard to move around
Does not require much force to be pushed through the nozzle	Requires significant force to be pushed through the nozzle
Heats up quickly and has better heat transfer efficiency	Needs a longer and larger hot end to melt the material to its core
Suits small diameter nozzle	Suits large diameter nozzle and supports printing with thicker layers
Faster extrusion speed possible which allows printing faster	Performs well in an enclosed environment with high temperatures and remains in its original state longer under heat
Specialized filaments are available such as carbon, glass fiber, etc.	Allows to use flexible materials
Harder to manufacture to get the diameter within the tolerance. The diameter of the filament can vary and affect the printing quality	Has better roundness and diameter size tolerance according to the filament manufacturers
Suits better 12V system	Suits better 24V system

The FDM technology is the most widely used additive manufacturing technology among both the industrial manufacturers and hobbyists today. There is a large variety of materials available for FDM printers of different physical properties and colors:

Thermoplastic polymers - acrylonitrile–butadiene–styrene (ABS), polyactic acid (PLA), polycaprolactone (PCL), polycarbonate (PC), high impact polystyrene (HIPS), polyamide (PA), polyvinylidene Fluoride (PVDF), polyetheretherketone (PEEK), polyetherimide (PEI).

Engineering polymers - polyphenylsulfone (PPSU), polyetherimide (ULTEM), polyaryletherketone (PAEK), polyetheretherketone (PEEK), polyacrylamide (PARA), tribofilament – IglidurTM [44].

1.8.2 Multi-color & Multi-material extrusion

The FDM technology advances rapidly with every year. Multi-color, full-color, and multi-material parts' manufacturing, which are recently developed, become cheaper, more accessible, and reliable. Newer technology development made the FDM more effective form of manufacturing and allowed to widen its usability, quality, value and promote the final models from prototypes to the ready-to-use products [47].

Most of FDM 3D printers were used to produce parts with a single extruder and were limited to print with only one color until the new multi-color printing technologies made it through to the FDM market. Many companies have their own solution on how to implement multi-color printing. Some suggest new technical solutions while some develop add-ons for the already developed hardware. There are several different ways to implement a multi-color & multi-material parts manufacturing in the FDM process today: by printing with one extruder and changing the filament manually during printing, having several extruders, applying CMYK+W color mixing and colorizing.

A short overview of the existing multi-color & multi-material technologies in FDM are described below, as well as their advantages and disadvantages:

1) **One extruder**

The first attempts to create the multi-color prints were made with the use of a single extruder. The printing job had to be stopped manually at the desired point of time for the manual filament change and then continued with the new color. Modern solutions are automated and stop the printing process according to the developed printing strategy. However, the change of filament is still performed manually [48].

Pros	Cons
- No need to upgrade existing equipment	- Not able to mix several colors
- Simple technology	- Limited color scheme
- A small amount of material waste	- Low speed
- Can print with different materials	- Need a constant overview of the process

2) Several extruders with individual hot ends and nozzles

This is the most expensive approach of all due to the requirement of more hardware. Several extruders and more advanced motherboard are necessary to support the additional equipment. Using several extruders allows to extrude the large quantity of material, reduce the material waste and speed up the printing process due to continuous operation without the need to change filament during printing. This approach also allows printing with materials of different properties and melting temperatures that can be predetermined for each extruder [49].

Pros	Cons
- Continuous operation	- Expensive technology
- Can print with different materials	- Hard to position nozzles on the same height to avoid contact between not used extruders and the part
- A small amount of material waste	- Unused nozzles have to be on standby temperature settings to avoid material oozing out and ruining the print quality
- Fully automated material change	- Waiting time for the standby nozzle to heat up
- Each extruder can be set up differently	- Limited color scheme

3) Color mixing with one nozzle and several extruders or CMYK+W

3D printers with CMYK+W technology are ones of the most advanced multi-color FDM machines. They can mix separate cyan, magenta, yellow, key (black) and white filaments to get the desired color scheme just like a plain desktop printer. Five extruders feed five filaments on a controlled matter into a large hot end where the materials are melted, mixed according to the generated code and extruded as one strand through a single nozzle [50].

Pros	Cons
- Not limited color scheme - Enough to buy only five colors - Possible to use fewer filaments if desired	- Only a few slicers can implement this technology - Five extruders - Need to extrude material (waste) before printing with the new color wasting material and time - The color of the model can be slightly different from what was designed

4) Colorizing

Colorizing is the newest step towards the multi-color FDM 3D printing. This approach combines two separate printing technologies: Inkjet and FDM. Such printers project ink droplets on the special color-absorbing white PLA filament in between each layer creating a colorful model [51, 52].

Pros	Cons
- The color spectrum is not limited - Only one filament is needed - Zero material waste	- The most expensive existing technology on the market - Not the well-developed technology yet - None of the open source software can support this printer type

The large-scale additive manufacturing machine, built during this project, is using three individual extruders with the direct drive to implement multi-color & multi-material extrusion. The large Volcano hot ends and corresponding nozzles of different diameters, purchased for this project, have one of the largest extrusion rates on the market today among the budget-friendly and high-quality products. These parts will allow to take advantage of the broad printing space of the machine and produce large prototypes with the high speed. Other techniques will not be suitable due to a smaller amount of extruded material, low printing speed, and reliability issues.

3. Method: Design and Integration

Chapter 2 describes the practical approaches used to build a large-scale AM machine during the project. It includes and describes in detail the components testing procedure, mechanical part design, mechanical part building, design and production of the needed parts, software development, machine adjustment and setup, testing of the completed machine as well as provides the list of ordered parts.

3.1 Hardware assembly

The project is based on Wafer-Handling-Diffusion Machine (WHD)

Year of construction: 04/2004

Serial number: 14030 33/1

Manufacturer: Jonas & Redmann Automationstechnik Gmbh, Germany

The partly disassembled WHD machine, which has not been in use for several years, serves as a starting base for the transformation and building process for the large-scale additive manufacturing machine in this project. The WHD machine was purchased as used by a local company and has never been run at the university. Therefore, the working order of the components was unknown, and some individual key elements of the machine had to be tested. These elements were determined to be used further in the project to prove their working order. The elements testing had to be performed before the development of strategy and building process itself to save time ahead and decide regarding the project’s budget allocation.

Due to the machine’s complexity, it was necessary to run tests on electrical components. The motors, digital servo drives, cables and other electrical components, were extracted and removed from the machine. These components could be tested “on the table” in lab conditions. According to the *Beckhoff manual on Digital Servo Amplifiers of model series AX 2000* [53], the motor drive testing procedure could be done by wiring the components of the system together with the few wires. The schematic wiring diagram for the testing procedure is represented in *Figure 13*.

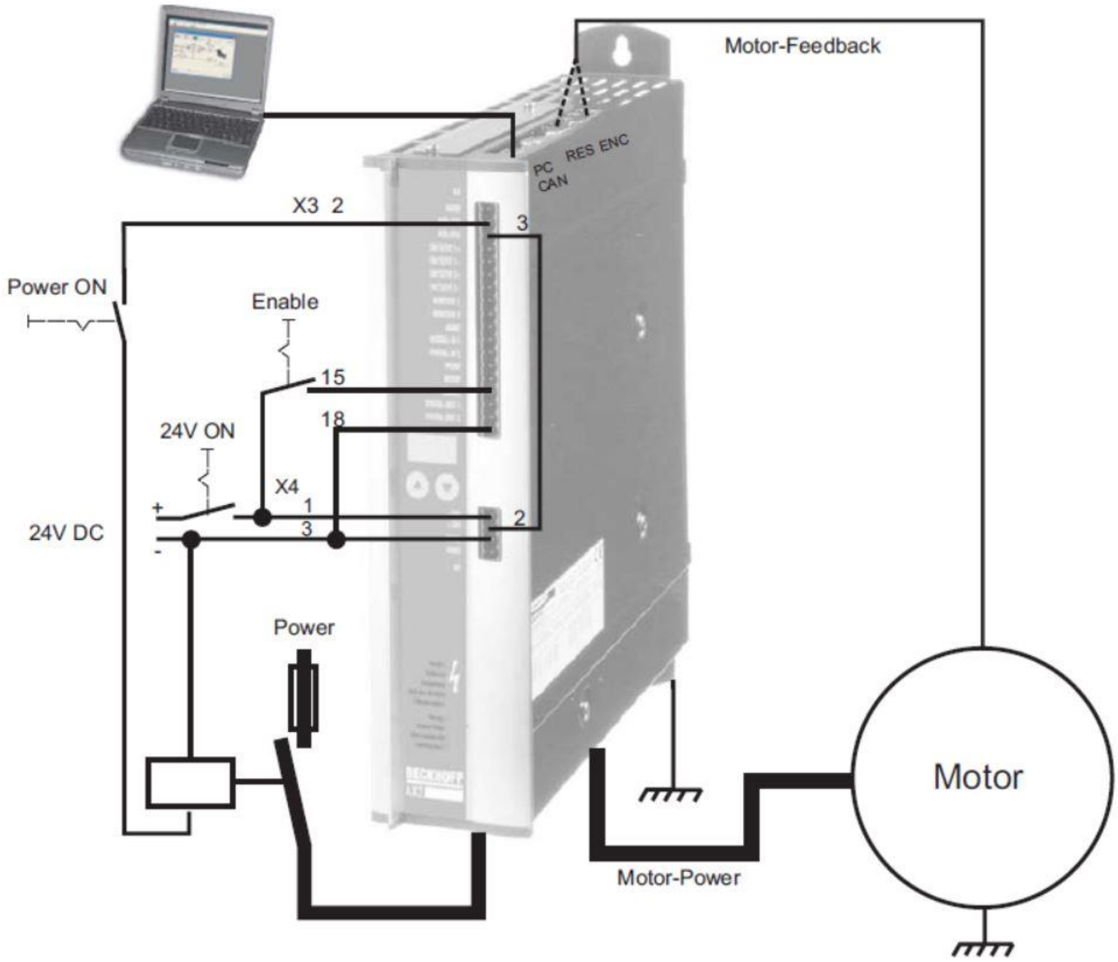


Figure 13. Motor drive test wiring, schematic from Beckhoff manual [53]

3.1.1 Testing procedure

The following components have been removed from WHD machine for testing:

- 1 x AC electrical motor – Beckhoff AM237M-0020 (without a brake)
- 2 x AC electrical motors – Beckhoff AM237M-0021 (with a brake)
- 3 x Digital Servo Drives – Beckhoff AX2003AS (corresponding to the 3 x AC motors)
- Windows PC (installed S-drive program) with the RS232 serial interface to connect a null-modem cable
- Motor power and motor feedback cables
- The digital servo drive (servo amplifier) connectors were also signed and removed from the machine to simplify wiring process of the tested system, see *Figure 13*.

Some additional equipment to run the test:

- ABB 24V supply
- 6 Ø2.5 mm cables
- S-Drive software
- Safety switch
- Cable for the 380V power supply

Motors and DSD were tested one by one with the help of the S-drive program installed on Windows PC with the RS232 communication interface. The system would only function when all necessarily connected links are wired and connected correctly. The layout of the lab testing procedure can be seen in *Figure 14*. S-drive program used for testing was set up according to the Beckhoff manual. This program allows establishing online communication between Windows PC, digital servo amplifier, and servo motor through RS232 serial cable. The servo amplifiers must be adapted individually for each motor according to the requirements of installation on the machine. Important actual values of the motor performance can be read out from the amplifier and displayed on the PC monitor in oscilloscope function. During the setup, interface modules built into the amplifier are recognized, and additional parameters required for motor position control will be available. At the beginning of basic functions' test, original data from the servo drive can be loaded and saved on the external storage and loaded again when needed. For test purposes, the amplifier must be reset, and default motor-specific data uploaded from data library available from the factory with pre-set settings for the common combinations of servo drive and motor.

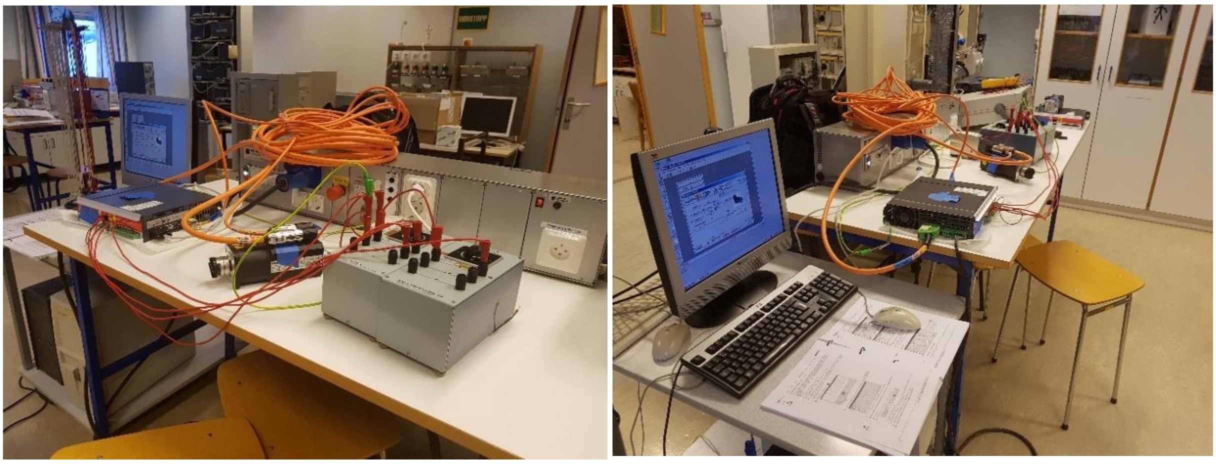


Figure 14. Motor drive test in the electro lab

After the setup of servo amplifier and the motor is completed, the motor jogging test (speed test) is performed. The parameters of speed in RPM, torque in A and direction of the motor are applied. The motor moved according to the set parameters and responded to the commands adequately. The actual warning and errors which could occur would have been listed on the 'Status' screen. During the drive test, no errors were discovered, and it was concluded that all components are in perfect working condition and the further work on the project may continue using existing parts.

The testing setup allows to connect up to six servo amplifiers inline using Sercos interface to synchronize them to each other and steer the system with the TwinCAT program on the PC. This configuration with three connected servo amplifiers was later used for the software development and machine movement.

3.2 Prototype CAD design in SolidWorks

The main goal of the practical part of this project was to propose a design for the large additive manufacturing machine based on the existing equipment in the donor WHD machine. The future machine should have strong and stiff mechanical part, three-dimensional movement with the largest possible useful building space and ability to produce large multi-color & multi-material prototypes. Prior the start of the building process, two-thirds of the WHD machine equipment is removed from the aluminium profile frame, list with specifications on the needed parts is made, mechanical components are tested, and all the required measurements for the CAD design model are performed.

During the design stage of the project, several different possible designs were drawn and evaluated in CAD program - SolidWorks. All the physical dimensions of the available equipment were measured. All the parts needed for visualization of the future machine were separately drawn in SolidWorks and assembled into one large assembly. Designs of X, Y, Z-axis and work table assemblies are presented and described in details further in this part. Appearances of the parts were kept as close to the originals as possible to get the most accurate and detailed model. After a careful evaluation of different possible designs, the final design of the model was developed in SolidWorks and approved by the supervisor. All details on the machine design are explained further in this section. All models and designs drawn during the prototype stage are available in the separate .cad files delivered along with this thesis as attachments.

3.2.1 X-axis

The X-axis assembly remains in its original state as it has been removed from the machine with 906 mm movement length. This axis appears to be the weakest of the three available in the donor machine due to the small diameter of the worm gear, weaker case design, and belt mechanism. It is decided to place the axis in such place and position where it will be submitted to the smallest amount of load and stress possible. Such placement will allow to maintain the precision of the original equipment, provide reliability, and avoid possible vibrations and deformations. The X-axis is attached to the Z-axis and is holding three light independent extruders. *Figure 15* represents the X-axis assembly design drawn in SolidWorks. The axis has spacers on each side to clear the belt mechanism on one side and fix two rollers on each side, which slide on the rails along the Z-axis. So is made to cancel out side-to-side movements during extrusion head movements.

Figure 15. X-axis SolidWorks assembly

3.2.2 Y-axis and work table

The Y-axis assembly is designed to hold the building table and slide it in Y-direction. It is placed on two 80×80 mm profiles under the X- and Z-axes. The travel of X-and Y-axes defines maximum dimensions of the building plate. The width of the table is limited by the head movement in the X direction. The useful movement between the limit switches on X-axis is

1000 mm. The useful movement, however, can be a little bit shorter on the real model. It can be evaluated later and will depend on the printing head specifications.

The Y-axis is the largest and the most robust axis of the future machine. The original distance between the limit stop bumps is 1750 mm. It defines the absolute maximum movement of the table on the worm gear. Y-axis has two limit switches placed on either end of the worm gear, and their position can be adjusted according to the purpose. Four rollers are used for table support to make the work table stiff and stable. The original Y-axis assembly needs a slight modification. The design of the assembly allows to spread the rails, fix them to the frame of the machine to widen the track for better support on the sides. The structure of the axis consists of two (W×D×L) 40×120×2003 mm, one 40×103×2003 mm profile and two connecting walls 15×183×200 mm. The designed width of the new track is 703 mm. The connecting walls are significantly higher than the rollers on the rails, meaning that it is not possible to fix the work table directly to the rollers. The 50 mm spacers are needed to move the table higher to clear the walls and avoid collisions during table movement.

After a careful evaluation of the available hardware, the table length is calculated and defined to:

$$1700/2 + 1700 * 0.25 = 1275 \text{ mm}$$

where 1700 mm is the distance between the limit stop bumps plus 25 mm, small safety margin, added intentionally from each side. The overhang of the table is defined not to exceed 25% of the total table length which corresponds to 317.5 mm from the rollers on each side to make the table stable and avoid the possible deformation. The table is resting on four 110 mm long rollers, two rollers on each rail. The distance between the rollers is set to be:

$$640 - 100 * 2 = 440 \text{ mm}$$

The table assembly consists of a wooden plate with the dimensions of 1300×1090×15 mm, and a glass plate with the dimensions of 1275×1070×4 mm. The glass plate is fixed and attached to the wooden plate with Plexiglas stoppers on the sides. The table leveling is performed along the supporting profiles placed on the side of each rail and adjustment fixtures on the worm gear. The SolidWorks model of the Y-axis assembly is presented in *Figure 16*.

Figure 16. Y-axis and work table SolidWorks assembly

3.2.3 Z-axis

The Z-axis, see *Figure 17*, is the shortest axis in the whole printer assembly. It has a useful movement of 830 mm between the limit switches. The axis is placed approximately 740 mm above the work table and fixed with four 80×80 mm profiles to the frame of the WHD machine. 1600 mm long rails are removed from the assembly, moved to the sides and fixed to the frame. The rails are replaced with cut-to-fit 80×80 mm rails to make the axis shorter. Existing aluminium plate on the assembly are supporting the weight of the X-axis assembly and moves the axis up and down in Z-direction.

Figure 17. Z-axis SolidWorks assembly

3.2.4 Complete assembly

The illustration of the final assembly for mechanical part of the additive manufacturing machine is provided in *Figure 18*. The mechanical part is constructed from and combines parts' designs modelled in SolidWorks. The model contains simplified frame with the right dimensions for illustration purposes. Calculated building space of the designed machine is (X, Y, Z) 810×1275×830 mm for the three printing extruders and 906×1275×830 mm for the central extruder.

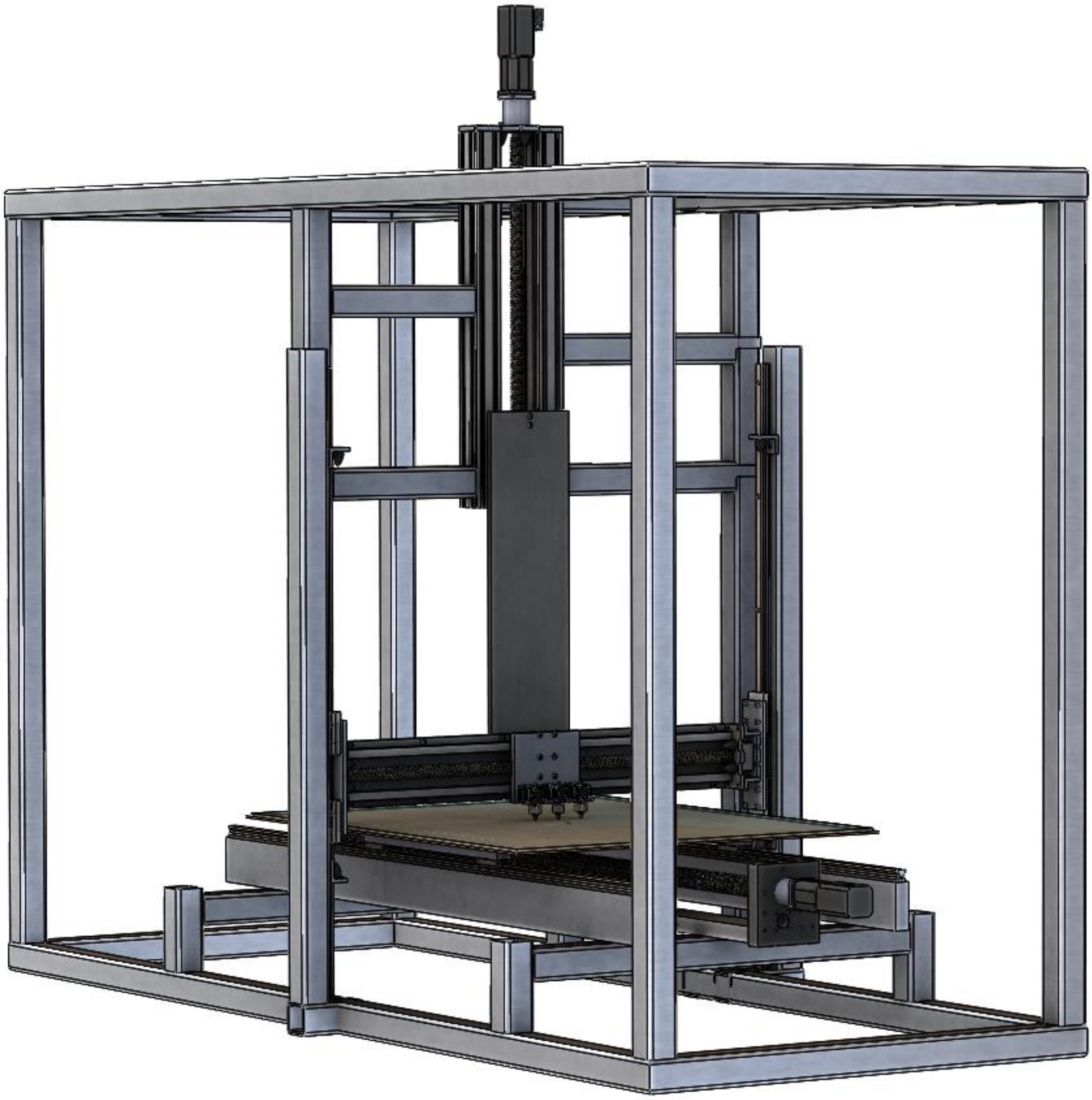


Figure 18. Printer assembly in SolidWorks

3.2.4 Limitations of the design

The complete SolidWorks assembly has not been evaluated for loads, weight and deformations. The integrity of the frame remained intact after the previous machine was removed. This machine and its frame have been designed for the industrial use and are very robust and will fully support the new purpose. The components of the machine will be used for moving lightweight extruders and control cards with the combined weight not exceeding 1.5 kg. Since the original design of the moving components and frame that were initially designed for industrial use has not been subjected to the extreme modifications, they still meet the factory standards of strength and reliability. The load simulations on the machine components have not been performed in SolidWorks to verify their integrity because it is believed that they are much stronger than needed and appear to be over-engineered for the purpose.

3.3 Additional hardware components

After conducting the design and prototyping part for the machine, the list of required additional parts was put together as quickly as possible to receive the required parts in time to complete the project and also allow some time for final testing and minor adjustments. The budget assigned for this project was limited to 10.000 NOK = approx. 1.000 EUR. Most of the parts for mechanical structure of the printer were already present in the WHD machine and needed to be removed, modified and installed to the reassigned places. Some minor pieces necessary for fitting the mechanical components were manufactured at the university on 5-axis CNC machine. All the other necessary printer part components purchased for the project were ordered from the same supplier, E3D-Online.com, to ensure compatibility of components. The choice was based on the budget, machine specifics, and products' quality. The plywood and glass plate were purchased from local suppliers. The complete part list with prices is provided in *Attachment 4, Part list.*

Some of the purchased key components with their short description are listed below:

- **3 × Titan Aero extruders for 3 mm filament with direct drive and active cooling**

Titan Aero extruders are of high-quality, lightweight and compact. Each extruder package includes heater cartridge, temperature sensor, heatsink, standard V6 heater block, 0.4 mm nozzle, 40×40×10 mm fan and all the necessary hardware for installation.

- **3 × All metal volcano hot end (0.6, 0.8, 1.0 and 1.2 mm nozzles) + silicon socks**

These hot ends have larger diameter nozzles and an increased size compared to the V6 hot ends. They can extrude a vast amount of material to support the available building capacity of the machine. Silicon covers or socks for the volcano hot ends are purchased to protect the building area from heat generated by the large hot ends and meant to improve the printing stability and quality.

- **Duet control system**

Duet Ethernet Electronics controller card is a modern, high-quality and high-speed motherboard running RepRap firmware. It can support two extruders and up to seven in total with the use of Duex5 expansion board. It is decided to use only three individual extruders in the machine. Therefore the Duex2 expansion board supporting two additional extruders is chosen. PanelDue Display 4.2-inch touchscreen display with the real-time control functions and overview of the running system is the third component of the control system. It provides better control over printer functions during the G-code execution and allows to make minor adjustments without changing the code.

- **Plywood**

Plywood plate is cheaper and lighter alternative to aluminium. Such plate is chosen for the project due to budget limitations. The surface of the plate is not flat, but the soft layer of polyurethane foam laid down between the glass plate and wood compensates for the surface imperfections.

- **Glass plate**

It is a common practice to use glass as the top layer on the building table in additive manufacturing machines. The glass has a smooth surface which allows good accuracy and simplifies the part removal process.

3.4 The mechanical part of the AM machine

The future additive manufacturing machine had to be built inside existing frame to WHD machine. Since the WHD machine was provided as a complete assembly at the beginning of the project, everything inside the frame needed to be removed to empty the space for the future work and new assembly. The WHD machine was a very complex unit, built for industrial use and purposes. It contained parts moved by electrical AC motors and pneumatic motors. The disassembly job took longer time than firstly anticipated; overall it took about three weeks due to machine’s complexity and the amount of the existing components inside. The goal was to save and keep the current expensive and high-quality equipment undamaged, which can be used and applied in this project as well as in other future projects at the university. According to the original plan, only one-third of the machine should have been removed, and new machine should be built in only one end of the frame. Due to some complications discovered during the beginning of the building process, the original design needed to be modified and changed during practical work. Several additional parts were designed and produced to improve the quality of the build. One of the modifications made was an adjustment of placement for machine body to fit axis inside the frame. The part of the frame for the new machine assembly is 1126 mm wide while the X-axis which goes inside the frame is 1350 mm wide. To fit the axis inside the frame, the body of the additive manufacturing machine was moved deeper inside to the wider section on the frame. In the end, two-thirds of the WHD machine was removed to empty the needed space.

The existing equipment previously removed from the WHD machine was used in the assembly for mechanical part of the new machine. According to the already established 3D SolidWorks model all worm gear mechanisms needed to be slightly modified to fit the new purpose. All the modifications were carefully evaluated before the changes were done to maintain the strength, integrity, and precision of the original equipment. The building process, as well as the modifications, are described in the following chapter. Pictures taken during the project execution as well as SolidWorks models and technical drawings of the 3D printed and CNC produced parts are presented in *Attachment 5. Process*, *Attachment 6. Produced parts, and Attachment 9. 3D printed parts* to show the progress and amount of work performed.

3.4.1 X-axis

The X-axis remained in its original state. Two specially designed spacers were 3D printed to verify the fitment and machined on the CNC machine. The spacers were placed on each end of the axis and attached to the two rollers to slide along the 1600 mm high precision rails. Both spacers were designed in SolidWorks, and the machining sequence for the CNC machine was prepared with the help of the CAM program EdgeCam and later sliced from steel on the 5-axis CNC machine. The spacers connect to the axis with four M8 screws and attach to each roller with four M8 screws, see *Figure 19*.

Figure 19. 19a. Left side spacer 19b. Motor side spacer

Later testing showed the imperfection of the chosen strategy. One side of the X-axis on the motor side was significantly heavier than the other end due to motor placement and massive billet aluminium motor case. The motor end tilted down considerably, and the axis was moving at the slight angle. Such behavior of the axis would cause problems at a later point in time if left in such state at this stage without making adjustments. The concept needed to be revised and reconsidered, and further modifications had to be done. The spacer on *Figure 19a* was removed, and two new additional spacers have been machined and installed on the X-axis. The new concept has two rollers attached to the new spacer 115 mm from each other on either side of the axis, *Figure 20*. This modification increased the contact area and helped to stabilize the axis from any unwanted movements. The assembly after modification is then hung in the middle and balanced, see *Figure 20*. The lighter side of the axis got the 8.75 kg counterweight to move the center of gravity to the middle of the axis.

Figure 20. X-axis assembly

3.4.2 Y-axis

Initially, the Y-axis in *Figure 21* was 183 mm in width. It consisted of two 80×120×2003 mm profiles with high precision rails, one 80×103×2003 mm profile and two connecting walls 15×183×200 mm which held the worm gear in place. The axis was disassembled, and rails were moved 350 mm to each side apart from the worm gear. This modification helped to widen the track and gain table support on each side. The original construction of the axis did not allow any movement above the connecting walls. Four 80×80×120 mm profiles were used as spacers to lift the tracks above the worm gear and let the table clearance on each end of the axis. The axis itself was placed on two 80×80 profiles 220 mm above the frame bottom. The middle section was attached to the original aluminium fixtures with adjustments possibilities.

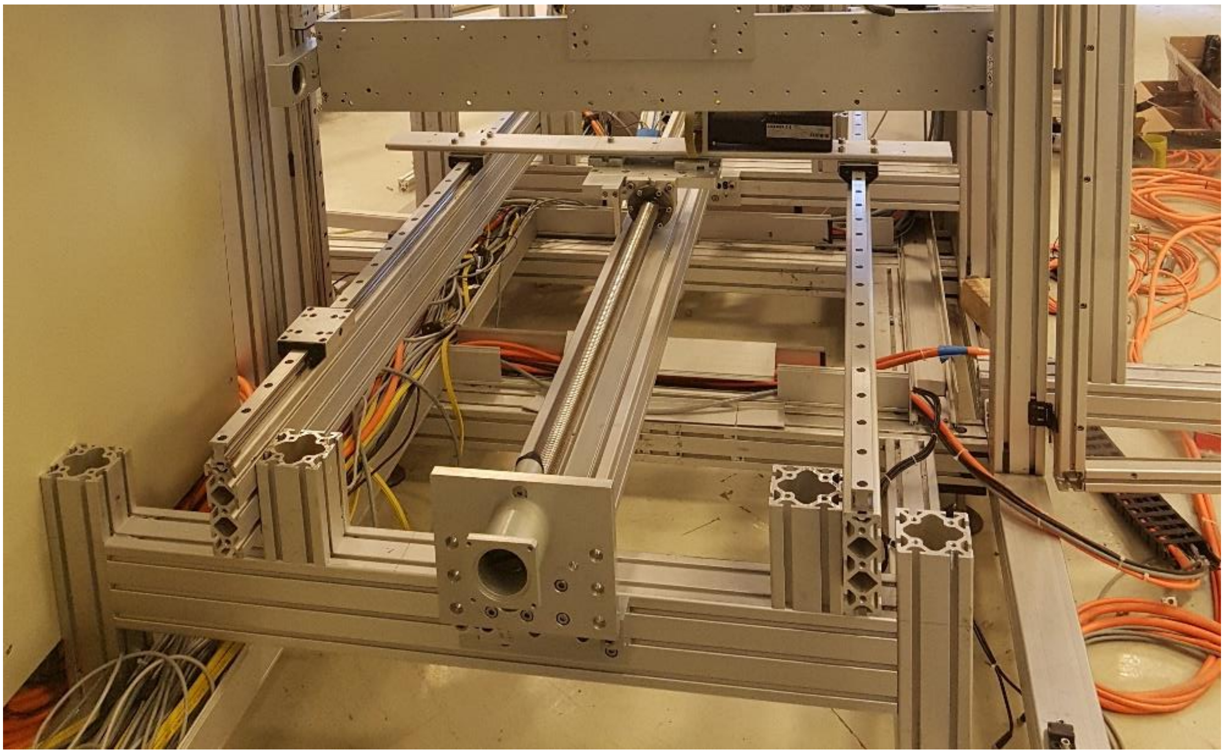


Figure 21. Y-axis assembly

3.4.3 Z-axis

The Z-axis in *Figure 22* was significantly modified according to the original idea described in design part. The rails were removed from the axis and replaced with the 890 mm 80×80 profiles on each side. The axis is attached to the frame with four equal lengths 80×80 profiles above the center of the X-axis. During the assembly of the X-axis, it is discovered that the motor of the X-axis is hitting the frame. Therefore, one 80×80×2000 mm profile was removed from the frame and moved 300 mm to the side and attached to four horizontally placed 40×40×450 mm profiles. Such placement widened the structure and allowed the motor clearance. The Z-axis is reattached with the four new profiles to be exactly above the middle of the X-axis and the building table.

Figure 22. Z-axis assembly

3.4.4 Frame

The frame of the WHD had to be slightly modified to meet the new purpose. All the profiles unnecessary for the project were removed to be reused and to simplify access to machine parts as well as for better visual purposes. The pneumatic control box was reduced in height for the rail clearance. Touch screen panel and other unnecessary equipment had been removed and replaced with Plexiglas windows. One door was cut-to-fit around the widened track of the X-axis. After all the modifications, the frame was leveled horizontally in all corners to improve machine adjustment inside.

3.4.5 Building table

Measurements for the printing table were taken as soon as most of the machine's mechanics was assembled. Such approach provides the most accurate result and depicts the largest possible size for building space. The final size of the plywood plate was decided to be 25 mm longer than calculated to provide space for ten evenly distributed 10×12×30 mm Plexiglas glass fixtures. The final size of the plywood plate is 1300×1090×15 mm. The glass plate is manufactured according to the calculated values and is 1275×1090×4 mm. The glass is resting on the 3 mm thick polyurethane foam, usually used as a house floor isolation, to compensate for wood surface imperfection and to improve the table levelling. The fixtures do not press the glass down to the plywood and only limit its movement in Y-direction. The fixtures were placed only on two edges to limit the glass movements considering that the table moves only along Y-axis. The final table assembly installed in the machine is shown in *Figure 23*.

The final table specifications are following:

- Glass weight = 13.9 kg
- Plywood weight = 7 kg
- Table weight = 20.9 kg

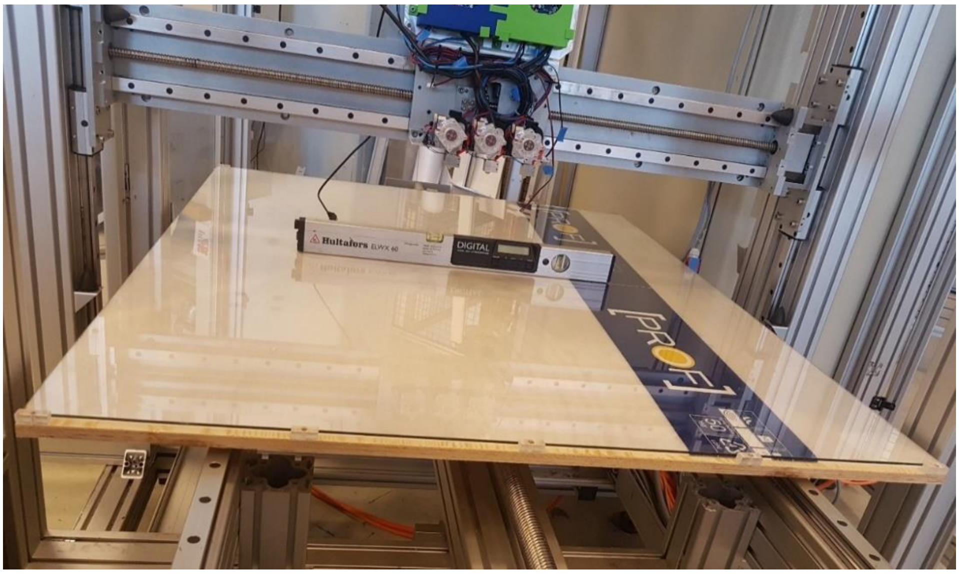


Figure 23. Final table assembly

3.5 Printer part assembly and testing

The additive manufacturing part of the machine was assembled on a specially made small table, see *Figure 24*. This was done for testing purposes before the components were attached to the rest of the machine. The printer system consists of the Duet Ethernet motherboard, Duex2 expansion board, PanelDue Display touchscreen, three stepper motors, three limit switches, and three extruders. Duet Ethernet motherboard came with the preinstalled RepRap firmware 1.19.2. Before the test, the firmware was upgraded to the latest version 1.21-RC4, which has improved performance features and system stability according to the manufacturer.

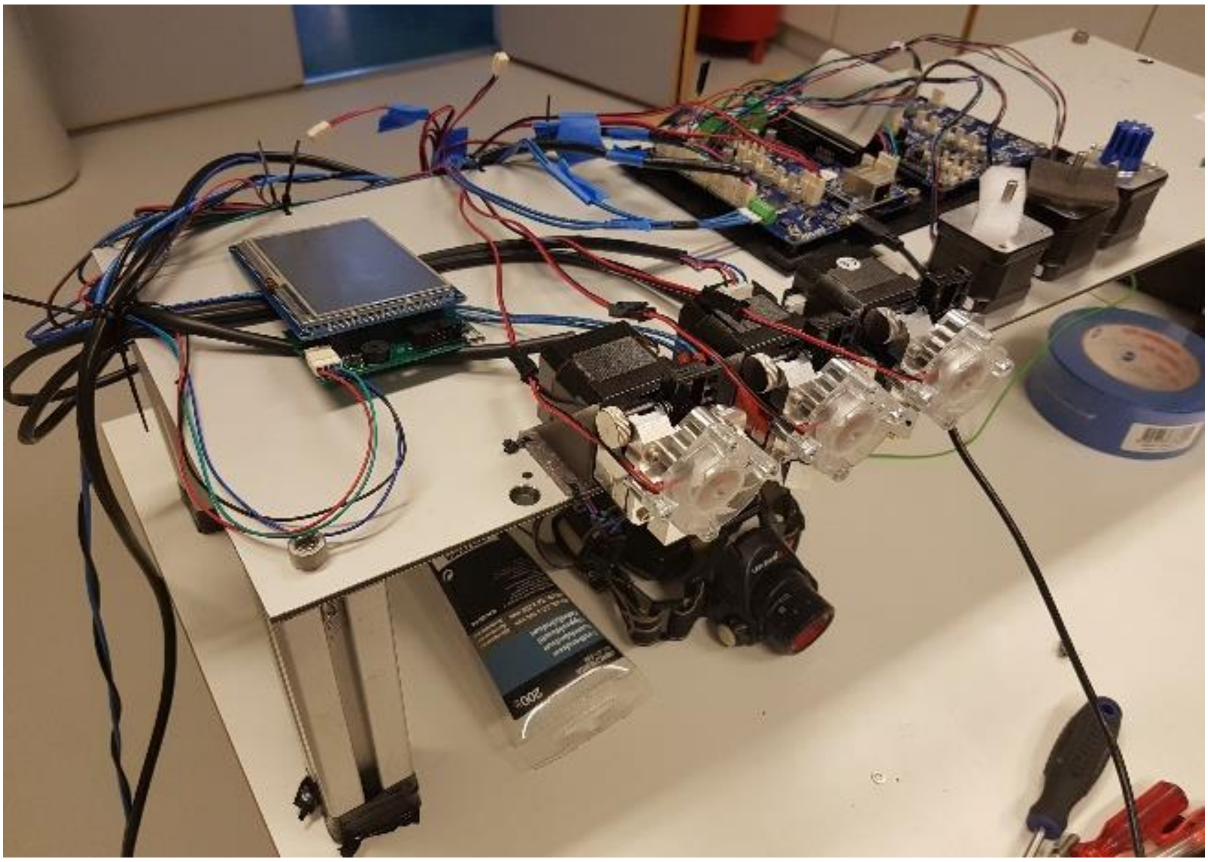


Figure 24. Printer part assembled in the lab for testing

The working order of the new system was tested in the lab with the help of HTML-5 based open source DuetWebControl interface. It allows easy and user-friendly control over the Duet hardware and attached to it equipment. Web interface communicates with the Duet through HTTP GET requests or AJAX calls and sends commands with HTTP POST request. The application is designed to maintain a relatively high loading speed even on slow networks [54]. The DuetWebControl allows to communicate with the RepRapFirmware and control and monitor the machine in real-time, *Figure 25*.

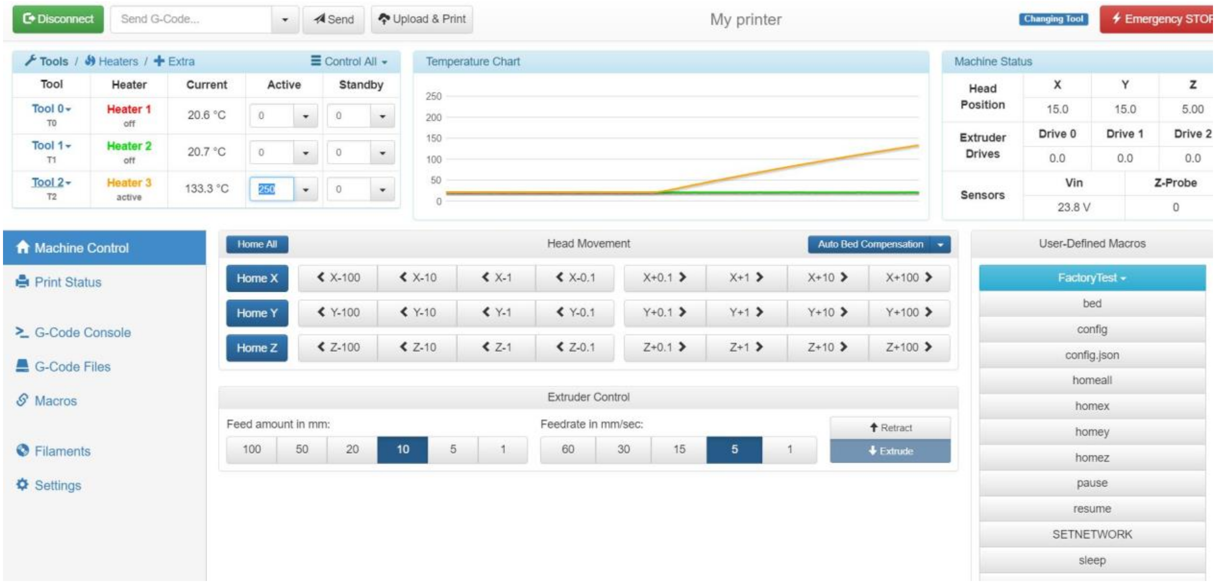


Figure 25. Duet Web Interface configured for the AM

Before the test, the printer system had to be completely put together. The RepRap firmware will not allow any movements until all components are correctly connected as shown in *Figure 24*. The Duet Ethernet firmware must be configured with the official RepRap firmware configuration tool available on (https://configurator.reprapfirmware.org/) before the testing procedure. The tool allows adapting the firmware to the actual components attached to the motherboard to ensure the correct functionality of the machine. After configuration is completed, the tool will create a .zip folder. The Duet Ethernet can be accessed with the PC through ethernet cable and USB cable. When the connection is established, the configuration folder must be uploaded to the card. After the system restart, the firmware will be ready for the new machine. Before the beginning of actual test with the execution of G-code, the X, Y, Z axes must be 'homed' or sent to the defined 'home' position. At the first startup of the system, the system will not understand the position of each axis and the axes will be highlighted with yellow color. When the axes are homed, the yellow color will change to blue and the firmware will accept the movement commands and will respond accordingly. The RepRap will throw an error, and no motion will be performed if the axes are not 'homed.'

The integrity of the AM system was confirmed upon execution of several prints according to the uploaded G-code without filament and with only one active extruder file. The system performed well, and no errors were discovered. The working order of each extruder was confirmed by extruding the PLA filament through the 1.00 mm nozzles and measuring the outer diameter of the extruded material, *Figure 26*.

Figure 26. Measurement of the extruded filament

After performing testing and verifying the working order of the system, all parts were moved and installed on the machine, see *Figure 27*.

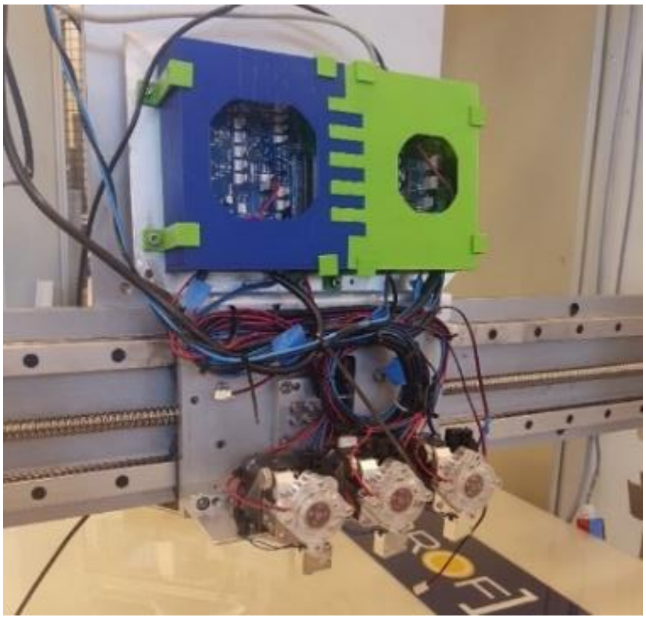


Figure 27. Printer part installed on the machine

The X-axis assembly has the aluminium plate attached to four rollers and worm gear. This plate was chosen as an attachment point for both extruders, wiring, motherboard and expansion board. Three extruders were placed on the 3 mm thick aluminium plate. The plate was designed in SolidWorks with the attachment holes for the extruders. The SolidWorks prototype was printed on the Lulzbot Taz 6 3D printer to verify the holes positions and to use the model as a pattern to drill and tap the holes. The plate was attached to the machined on the milling machine 10×25×244 aluminium plate. The fixture for the motherboard and expansion card was also created from the 3 mm aluminium plate and bent on the plate bending machine. The card box was designed in SolidWorks, sliced in four parts to fit the building table of the Lulzbot Taz 6 3D printer and manufactured from green and blue PLA. The box has two voids on the top for the fans and cut-outs for the wiring on the sides. The top part of the box is held by eight hooks and M4 bolts and can be easily removed if needed.

Three PLA filament rolls were attached to the highest part of the frame above the building table as shown in *Figure 28*. The rolls were hung on aluminum cylinders to ease their rotation. Locks that do not let the rolls to slide out were placed at the end of each cylinder and can be easily removed by hand for the filament change. The outside rolls hang on 40×40×200 mm; the central is placed on the longer 40×40×500 mm profile and supports the power cables lead for the motherboard. Considering that the X-axis has long travel from side to side, such filament and wiring location allows for free movement and only slight deformation during extruder head movement.

Figure 28. Filament rolls and wiring for the Duet

3.6 Adjustment

The design of the machine allows moving all components in every direction to achieve the best possible adjustment results. Levelling laser and the high precision level stock were used for precise calibration of the machine axes position. A ceiling crane and a car jack were used for manoeuvring the heavy weight and large size of the mechanical components and fine-tuning. The adjustment precision is vital and has the direct impact on the printing quality. The most critical parameters are horizontal and vertical levelling and 90 degrees/perpendicular placements of the axes to each other. The manual movement of the axes verified the adjustment precision, and no movement complications were discovered.

3.7 Machine safety

The current machine setup is not using limit switches the axial control. The WHD management system used PLC for this purpose which is excluded from the current setup to simplify the system. The end critical values of all movements will be integrated into the software. The inbuilt safety features will guarantee the additional safety of the movements. Each axis has designed weak links which are meant to fail in case accident. The X-axis has the belt drive and clutch, the Y-axis has plastic safety connection between the worm gear and motor, the Z-axis has the belt drive and clutch. The rubber end bumps will be used to trigger these safety features and save the machine in case of a collision. The machine`s electrical system is equipped with main power supply emergency switch and two automatic circuit breakers.

3.8 Electrical part

The electrical part of the AM machine was extensively simplified compared to the WHD machine. The initial system had a massive electrical cabinet attached to the backside of the frame containing all steering elements for a large number of electrical and pneumatic components. This complex system has been excluded from this project due to the use of only a few components. The new control system has been created and temporarily set up on the table with wheels to simplify its relocation if needed during software developing process, shown in *Figure 29*. The new system is divided into two major parts: mechanical and printer part systems. The key components of the electrical systems are listed below:

Mechanical part

- three motor power cables
- three motor feedback cables
- three servo amplifiers
- three motors
- windows PC
- 24V power converter
- emergency stop switch
- automatic circuit breaker
- ground circuit
- five Sercos interface cables
- 380V main power supply cable
- 220V power supply cable.

Printer part

- Duet Ethernet motherboard
- Duex2 expansion board
- three Titan Aero extruders
- three fans for extruder cooling
- three thermistor cartridges
- three heater cartridges
- three stepper motors (X, Y, Z)
- 24V power converter
- 220V power cable
- one limit switch

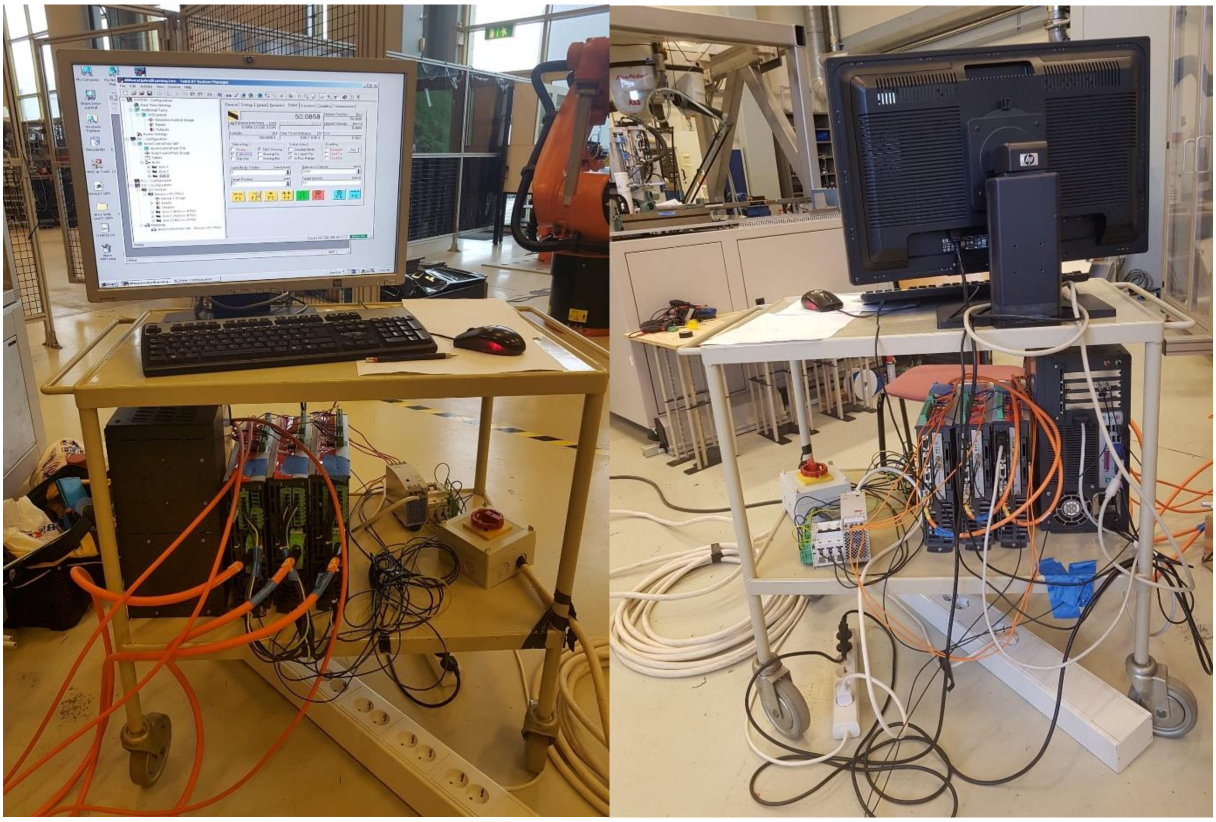


Figure 29. The mechanical part control system

3.9 Software

The typical software choice among hobbyists for the homemade CNC machines or AM machines based on CNC components is Mach3. It is relatively cheap and well-known software adopted for the AM use. In addition to managing the axes, the Mach3 has a function to add an extrusion head instead of the milling head which is set up in the program as an additional linear axis called A-axis [55]. Initially, the large-scale AM machine was supposed to be managed by the Mach3, but due to the complexity of the used components, the original WHD machine software, TwinCAT 2 was used instead.

3.9.1 TwinCAT System

Beckhoff provides automation system solutions based on PC control for industrial machines. The Windows Control and Automation Technology (TwinCAT) is a software system developed by Beckhoff that repurposes a PC into a real-time machine controller. It allows a PC to run PLC programs, NC tasks, and CNC tasks by providing a real-time extension to the Windows kernel, which prioritizes control tasks and monitors the computational load on the system, generating warnings in case the load exceeds some predefined thresholds.

The TwinCAT System Manager is the primary software tool used in this project. It is responsible for the complete configuration of a control system, including I/O interfaces and devices, Numerical Control tasks, PLC tasks and possibly additional tasks accessed via other programming languages not covered by the PLC programming standards. The tool also makes possible the definition of links between task variables and physical device variables [56].

The TwinCAT PLC Control is another software tool provided by the original WHD machine system. It is a complete integrated development environment for the creation of PLC programs in any of the languages covered by the IEC 61131-3 standard [57]. Regarding this project, however, the Numerical Control task variables are manipulated via the Automation Device Specification (ADS) interface, also provided by the TwinCAT system. The ADS describes a device-independent and Fieldbus-independent interface governing access to compliant devices. Here the term “device” is interpreted in a broad sense that includes software modules. A device is uniquely identified by a port number and an AMS network ID, making it accessible to the message router which is part of the TwinCAT system. Variables of a device are addressable by an Index Group and an Index Offset from the C/C++ dynamic linking library, for example.

In another installation level, not available in our current setup, the TwinCAT offers the Numerical Control Interpolation system (NC I). It allows the programming of Numerical Control tasks using a dedicated G-Code program (DIN 66025 standard) or the PLC library TcPlcInterpolation. That could be used to directly feed a G-code file into the system to control the X, Y and Z servos, but would raise the need for synchronization with the G-code running on the RepRap firmware, if any, to control the extruders and heaters.

The setup procedure of the TwinCAT is explained in the *Appendix A. TwinCAT System Manager Configuration*

3.10 Machine test drive

Once the building process was completed, the manual motion tests of the mechanical part were executed to confirm the integrity of the control systems as well as the modified mechanical components and the ability of the designed structure to perform three-dimensional movements. All of the axes were moved one by one with the help of TwinCAT software and testing setup, previously described in the section **“Testing procedure.”** The axes were moved separately with different speed parameters in positive and negative directions to ensure the smooth and problem-free operation of the modified equipment during the FDM process and prepare the machine for the software testing. The video of the test drive is attached to the thesis.

The testing showed that all axes are adjusted correctly and are within the acceptable limits. No vibrations, no binding, no noise, no equipment problems were uncovered during the initial drive test. The machine responded well on all commands as expected. It concluded that no further modification to the machine mechanics is needed and it is ready to accept the software. The hardware selection is confirmed to be appropriate for the machine size and purpose. Once the new software is developed, the new more thorough tests can be performed by executing G-code and extruding material to verify precision and ability to manufacture a 3D structure from PLA.

4. Results and discussion

The built AM machine turned out to be sturdy and well-balanced. All axes are moving freely under their own power. None of the machine parts is subjected to vibrations and deformations. All the adjustments remained in place after the performed motion tests showing the integrity of the construction and the success of the developed design.

After developing the machine design in SolidWorks, selecting the components and implementing the computer model into a physical working mechanism, the project ended up only partially successful. The mechanical part of the machine is believed to be finished and ready for testing with possible small refinements and modifications in future. The electrical system is complete and ready for testing. The software part for the machine control was never fully completed and integrated due to the high complexity of the available WHD machine hardware and software, time limitations and lack of software development knowledge. Other project objectives and goals were successfully achieved, and the good base has been set for the software development project. This led to the fact that not all planned tests were carried out and the machine is not in working order at the project’s end despite the great desire and countless hours spent pursuing the goal.

5. Conclusion and future work

The Additive Manufacturing technology is the future. It develops rapidly for both industrial and desktop users. During the last couple of decades, AM made a huge leap forward and proven to be reliable, widely available, environmentally friendly and rapidly developing technology. It can already now equally compete with the conventional techniques in production quality, speed, availability and cost in various production areas. They allow to create uniform products instead of assemblies, manufacture complex geometries and use different material combinations.

The large-scale additive manufacturing machine is a valuable asset and an excellent addition to the existing AM equipment at the UiT. It will be finished and put to good use in the nearest future.

As with any project, some adjustments can be made to improve the already achieved results. First of all, the assembled machine needs a user-friendly software. The software can be based on the Beckhoff TwinCAT software, previously used by the WHD machine, with the existing Windows PC, Sercos interface, PLC, servo drives, and servo motors as it was pursuit during this project. This task is very complicated and requires a broad knowledge of both software programming and deep understanding of working principles of AM machine. If this task cannot be resolved with the current setup, the machine can be run by big stepper motors fitted to the installed axes and controlled by Duet motherboard. However, some additional electrical components must be purchased to implement this idea.

The frame of the machine is much longer than needed and takes a lot of valuable space in the workshop. One-third of the cabinet can be removed together with the remaining equipment and used for other projects. The cabinet can also be cleaned up and used to accommodate another machine, for instance, a small engraver which can be made from the remaining parts. Plexiglas windows can be placed on the frame to cover all the existing gaps to protect the machine from dust present in the workshop environment and improve its overall appearance.

The machine can be repurposed for the new use. A quick change from an extrusion head to a spindle can be considered. It is believed that the current mechanical setup can support machining of the soft materials like wood and aluminium with the minor modifications. Using both AM and CNC techniques will this AM machine into a hybrid manufacturing machine widening its usability. The wooden table, built during the project, can be replaced with a higher-quality aluminium plate to achieve a better precision of the table, make it more durable and allow hybrid manufacturing as proposed before.

A camera can be installed inside to surveillance remotely the manufacturing process in real time. The extruders can be placed on separate brackets to improve adjustability. The physical limit switches can be installed on either end of each axis to improve the safety of the machine. The machine control module might be permanently placed inside the frame when the machine will be ready to be used.

The other modifications cannot be proposed before the machine is run and adequately tested to identify design flaws and possible ways of their improvement.

References

[1] U. Scheithauer *et al.*, "Droplet-Based Additive Manufacturing of Hard Metal Components by Thermoplastic 3D Printing (T3DP)," *Journal of Ceramic Science and Technology,* vol. 8, no. 1, pp. 155-160, 2017.

[2] S. H. Huang, P. Liu, A. Mokasdar, and L. Hou, "Additive manufacturing and its societal impact: a literature review," *The International Journal of Advanced Manufacturing Technology,* journal article vol. 67, no. 5, pp. 1191-1203, July 01 2013.

[3] H. Bikas, P. Stavropoulos, and G. Chryssolouris, "Additive manufacturing methods and modelling approaches: a critical review," (in English), *International Journal of Advanced Manufacturing Technology,* journal article vol. 83, no. 1-4, pp. 389-405, Mar 2016.

[4] *Standard Terminology for Additive Manufacturing Technologies*, 2012.

[5] F. Calignano *et al.*, "Overview on Additive Manufacturing Technologies," (in English), *Proceedings of the Ieee,* vol. 105, no. 4, pp. 593-612, Apr 2017.

[6] *Selective Laser Melting (SLM)* Available: https://www.additively.com/en/learn-about/laser-melting

[7] *Selective Laser Sintering (SLS)*. Available: https://www.livescience.com/38862-selective-laser-sintering.html

[8] *Direct Metal Laser Sintering (DMLS)*. Available: https://i.materialise.com/blog/direct-metal-laser-sintering-dmls/

[9] *Selective Heat Sintering (SHS)*. Available: https://www.goprint3d.co.uk/blog/selective-heat-sintering-shs-work/

[10] *Electron Beam Manufacturing (EBM)*. Available: https://www.additively.com/en/learn-about/electron-beam-melting

[11] *Laser Engineered Net Shaping (LENS)*. Available: http://www.rpm-innovations.com/laser_deposition_technology_advances_additive_manufacturing_and_repair

[12] *Direct Metal Deposition (DMD)*. Available: https://www.sculpteo.com/en/glossary/dmd-definition/

[13] *Laser Powder Deposition (LPD)*. Available: http://www.additivemanufacturinglaboratory.com/laser-powder-deposition

[14] *Selective Laser Cladding (SLC)*. Available: https://www.slideshare.net/ajith_slide/laser-cladding-and-thermal-spraying

[15] *Laser Consolidation (LC)*. Available: https://www.additivemanufacturing.media/articles/laser-consolidation-one-step-manufacturing-of-metal-parts-and-tools

[16] *Electron Beam Direct Melting (EBDM)*. Available: http://www.sciaky.com/additive-manufacturing/electron-beam-additive-manufacturing-technology

[17] *Fused Deposition Modelling (FDM)*. Available: https://www.livescience.com/39810-fused-deposition-modeling.html

[18] *Robocasting or Direct Ink Writing (DIW)*. Available: https://robocasting.com/index.php/about

[19] *Shaped Metal Deposition (SMD)*. Available: http://www.pomgroup.com/index.php?option=com_content&view=featured&Itemid=435

[20] *Three-Dimensional Gel Printing (3DGP)*. Available: https://www.zmescience.com/research/technology/mit-developed-3d-printing-method-can-create-furniture-vats-gen-within-minutes/

[21] *Inkjet Printing (IJP)*. Available: https://3dprint.com/188092/inkjet-metal-3d-printing/
[22] *Multijet Modelling (MJM)* Available: http://hearinghealthmatters.org/waynesworld/2017/3d-printing-pa/
[23] *Ballistic Particle Manufacturing (BPM)*. Available: http://slideplayer.com/slide/6299450/
[24] *S-Print*. Available: http://www.exone.com/Systems/Production-Printers/S-Print
[25] *Polyjet*. Available: https://www.cati.com/3d-printing/polyjet-technology/
[26] *Thermojet*. Available: http://www.rapidparts.com.au/rapid_prototyping_tj.htm
[27] *Stereolithography (SLA)* Available: https://formlabs.com/blog/ultimate-guide-to-stereolithography-sla-3d-printing/
[28] *Solid Ground Curing (SGC)*. Available: http://www.efunda.com/processes/rapid_prototyping/sgc.cfm
[29] *Laser Chemical Vapor Deposition (LCVD)*. Available: http://fffibers.com/process/
[30] *Ultrasonic Additive Manufacturing (UAM)*. Available: http://www.3dprinterpro.com/ultrasonic-additive-manufacturing-service/
[31] *Laminated Object Manufacturing (LOM)*. Available: https://www.sculpteo.com/en/glossary/lom-definition/
[32] Bas Wijnen, Gerald C. Anzalone, Amberlee S. Haselhuhn, P. G. Sanders, and J. M. Pearce, "Free and Open-source Control Software for 3-D Motion and Processing " *Journal of open research software,* no. 2, pp. 1-12, 2016.
[33] D. Ding, Z. Pan, D. Cuiuri, H. Li, and S. v. Duin, "Advanced Design for Additive Manufacturing: 3D Slicing and 2D Path Planning," in *New Trends in 3D Printing*, I. V. Shishkovsky, Ed. Rijeka: InTech, 2016, p. Ch. 01.
[34] F. Baumann, O. Kopp, and D. Roller, "Universal API for 3D Printers," presented at the Informatik 2016, 2016.
[35] R. Jamieson and H. Hacker, "Direct slicing of CAD models for rapid prototyping," *Rapid Prototyping Journal*, vol. 1, no. 2, pp. 4-12, 1995.
[36] K. V. Wong and A. Hernandez, "A Review of Additive Manufacturing," *Int Sch Res Netw Mech Eng*, vol. 2012, June 17. 2012.
[37] X. Hongwei, J. Weihua, L. Minjuan, and L. Wei, "A slicing model algorithm based on STL model for additive manufacturing processes," presented at the 2016 IEEE Advanced Information Management, Communicates, Electronic and Automation Control Conference (IMCEC), 3-5 Oct. 2016, 2016. Available: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7867489
[38] A. C. Brown and D. d. Beer, "Development of a stereolithography (STL) slicing and G-code generation algorithm for an entry level 3-D printer," in *2013 Africon*, 2013, pp. 1-5.
[39] R. Bonnard, "An Advanced STEP-NC Platform for Additive Manufacturing," in *Industrializing Additive Manufacturing - Proceedings of Additive Manufacturing in Products and Applications - AMPA2017*, M. Meboldt and C. Klahn, Eds. Cham: Springer International Publishing, 2018, pp. 127-136.
[40] I. Gibson, D. Rosen, and B. Stucker, Additive Manufacturing Technologies, Second ed.: Springer, 2015. [Online]. Available: https://link.springer.com/content/pdf/10.1007/978-1-4939-2113-3.pdf. Accessed on 02.11.2017.
[41] D. Ding, Z. Pan, D. Cuiuri, H. Li, N. Larkin, and S. v. Duin, "Automatic multi-direction slicing algorithms for wire based additive manufacturing," *Elsevier,* vol. 37, pp. 139-150, 2016.
[42] C. Hyzin, "Development of an Additive Manufacturing Control System for Multi-functional Material Products," Master, ProQuest Dissertations Publishing, 2016.

[43] B. Wijnen, G. C. Anzalone, A. S. Haselhuhn, P. G. Sanders, and J. M. Pearce, "Free and Open-source Control Software for 3-D Motion and Processing," *Journal of Open Research Software,* vol. 4, no. 1, pp. e2-e2, 2016.

[44] Dyzedesign.com. (2018, 23.05). *3D printing filament size: 1.75mm vs 3.00mm*. Available: https://dyzedesign.com/2018/02/3d-printing-filament-size-1-75mm-vs-3-00mm/

[45] D. Grguraš and D. Kramar, *Optimization of Hybrid Manufacturing for Surface Quality, Material Consumption and Productivity Improvement*. 2017, pp. 567-576.

[46] all3dp.com. (2018, 24.05). *PLA vs ABS Overview*. Available: https://all3dp.com/1/pla-filament-3d-printing/#section-pla-vs-abs-filaments-compared

[47] Andy. (2017). *How Does Multicolor 3D Printing Work?* Available: https://www.scan2cad.com/cad/multicolor-3d-printing/

[48] 3dprint.com. (2018). *Multicolor 3D Printing: Where Is It Heading Next?* Available: https://3dprint.com/203610/multicolor-3d-printing/

[49] 3DPrinterPrices. (2018, 17.05). *Dual Extruder 3D Printers – What you need to know*. Available: http://www.3dprinterprices.net/dual-extruder-3d-printers-what-you-need-to-know/

[50] Alec. (2016). *ORD Solutions' RoVa4D Full Color Blender 3D Printer immediate success on Kickstarter*. Available: https://www.3ders.org/articles/20160727-ord-solutions-rova4d-full-color-blender-3d-printer-immediate-success-on-kickstarter.html

[51] A. P. (2017). *The Da Vinci Color 3D printer: Inkjet and FDM 3D printing in one*. Available: https://www.3dnatives.com/en/da-vinci-color-printer140920174/C

[52] M. Molitch-Hou. (2016). *$350 COLORPOD CONVERTS FDM TO FULL-COLOR POWDERBED 3D PRINTER*. Available: https://3dprintingindustry.com/news/350-colorpod-converts-fdm-to-full-color-powderbed-3d-printer-75420/

[53] Beckhoff, "Digital Servo amplifier AX 2000," ed. Federal Republic of Germany, 2007.

[54] chrishamm. (2018). *DuetWebControl*. Available: https://github.com/chrishamm/DuetWebControl

[55] R. M. Inc. (2018). *Add a 3D Printer to your CNC and Mach3*. Available: https://www.rockcliffmachine.com/3d-print-guide-cnc/

[56] Beckhoff. (2017). *TwinCAT - PLC and Motion Control on the PC*. Available: http://www.beckhoff.com/twincat/

[57] Beckhoff. (2016). *PLC and Motion Control on the PC*. Available: http://www.beckhoff.com/twincat/

Attachments

Attachment 1: Pre-study

The PDF document is attached as a separate file and delivered along with the thesis.

Attachment 2: CAD design

The .zip folder containing all the designed element as well as the complete assembly of the machine is attached as a separate file and delivered with the thesis.

Attachment 3: Motor drive test

See Beckhoff manual and video file attached with the thesis

Attachment 4: Part list

Attachment 5: Process

Photos of the machine building process taken during the project are available in the attached folder.

Attachment 6: Produced CNC parts

Attachment 7: Machine drive test

See video files attached with the thesis

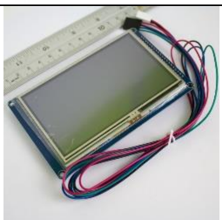
Attachment 8: 3D printed parts

See attached files.

Attachment 9: Printer part drive test

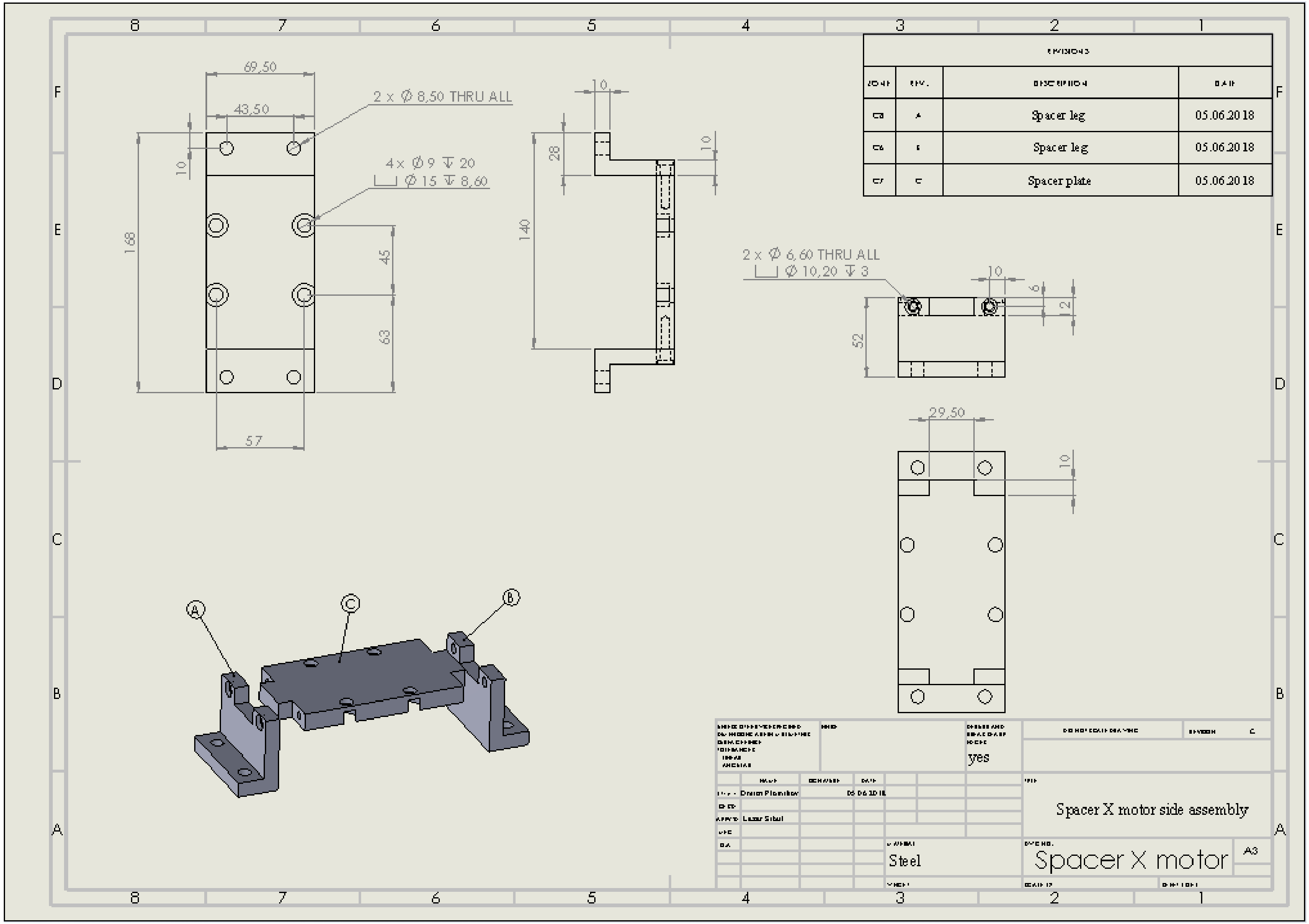
Video of the test is available in the attached folder.

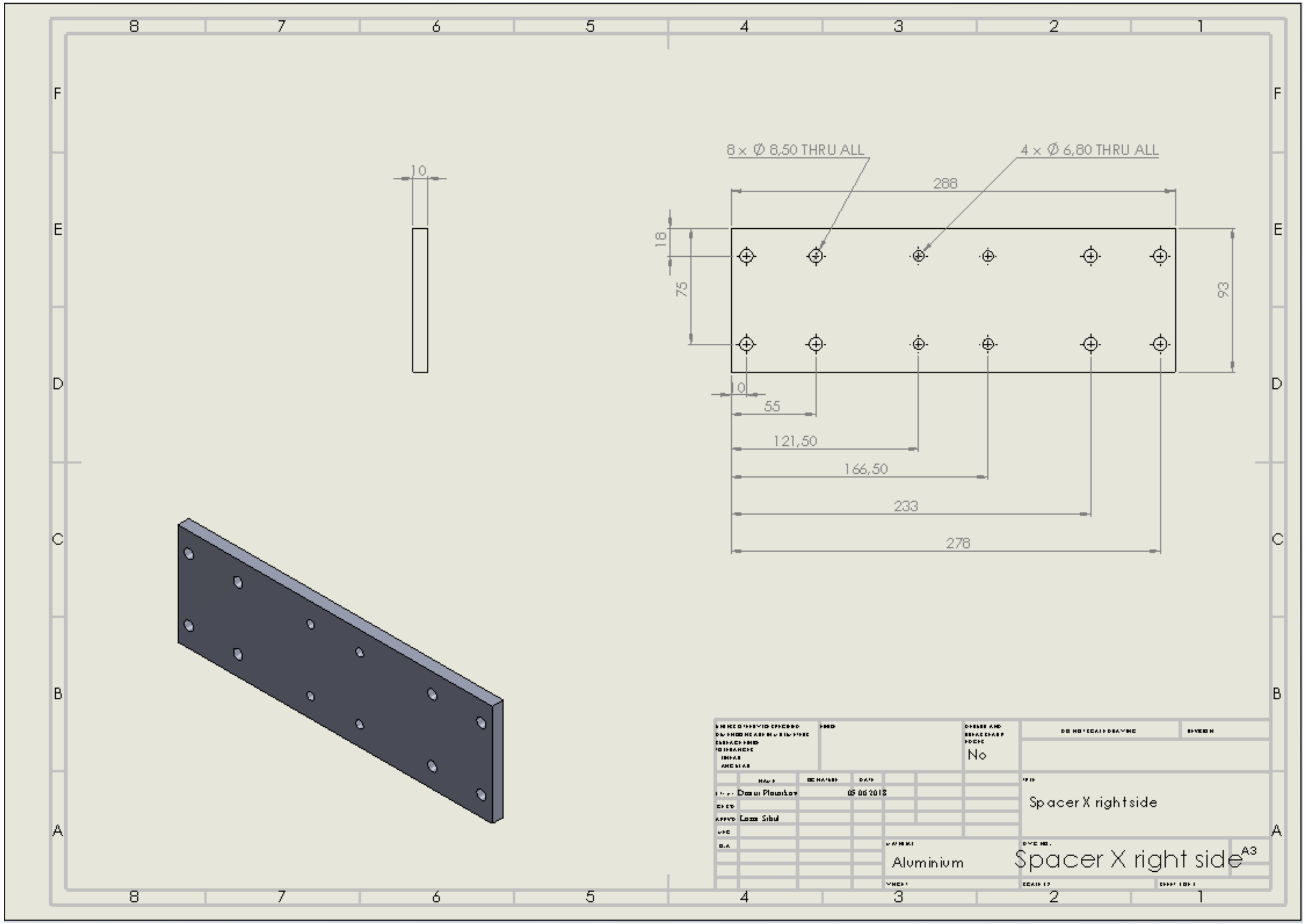
Attachment 4: Part list

Part	Picture	Price in NOK (excluding tax and shipping costs)
3 × Titan Aero Extruder for 3.00 mm filament with V6 heatbreak,V6 heater block and 0.4 mm nozzle		970×3=2 910
3 × Stepper motor		3×119=357
3 × Mounting bracket		3×32=96
3 × V6 silicone socks		38
3 × Volcano hot ends for large prints with 0.6, 0.8, 1.0, 1.2 mm nozzles		270×3+162=972
3 × Volcano silicone socks		58
PanelDue Display touch screen		594

Duet Ethernet mother board		1 404
Duex2 expansion board		624
Plywood 1090×1300 mm		797
Glass plate 1090×1275 mm		819
		Total: 8 669

Attachment 6: Produced CNC parts




8 x Ø 8,50 THRU ALL
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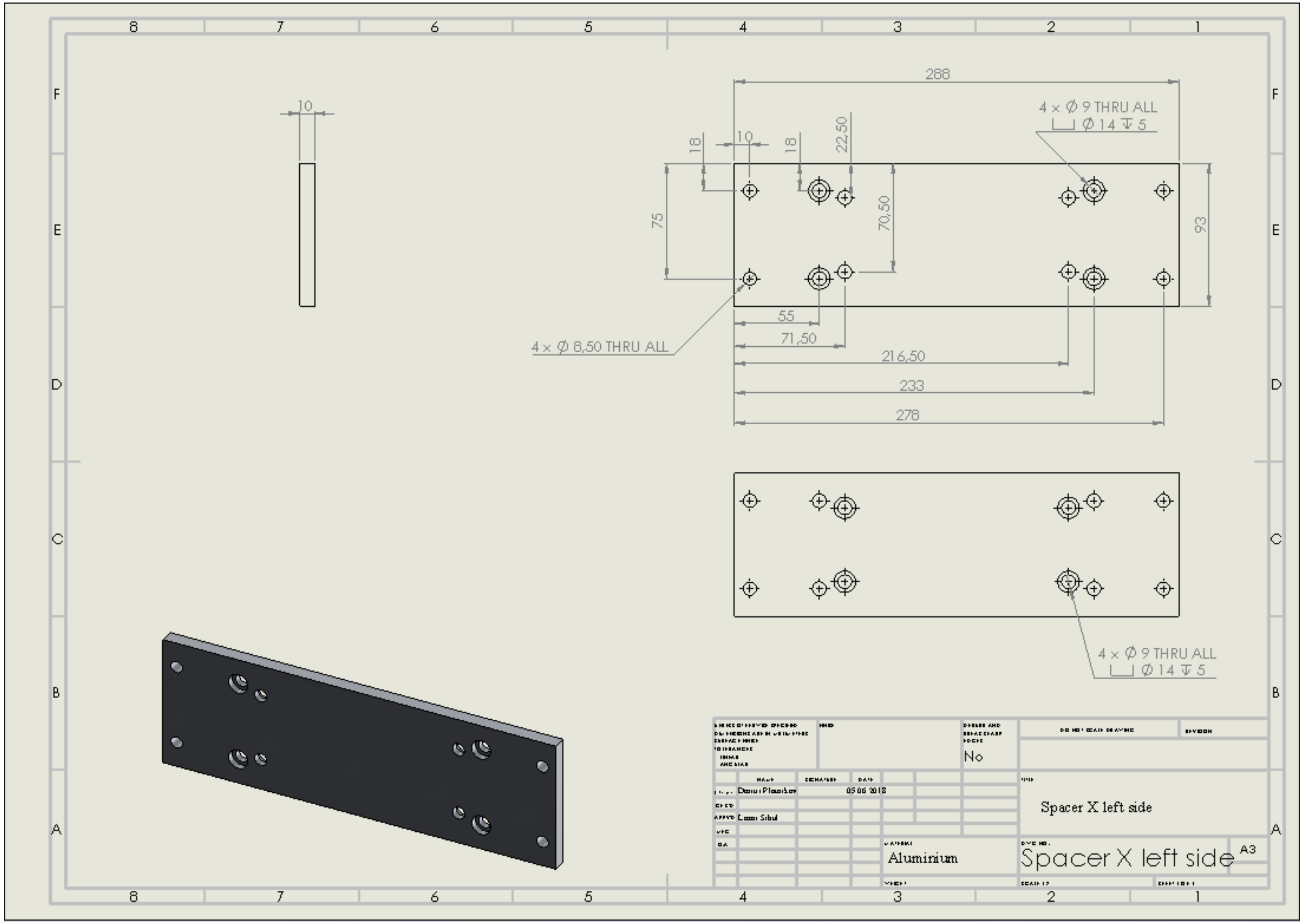
Lazar Sibul
Spacer X right side
Aluminium
Spacer X right side
A3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4 × Ø 9 THRU ALL
Ø 14 ↧ 5
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Spacer X left side
Aluminium
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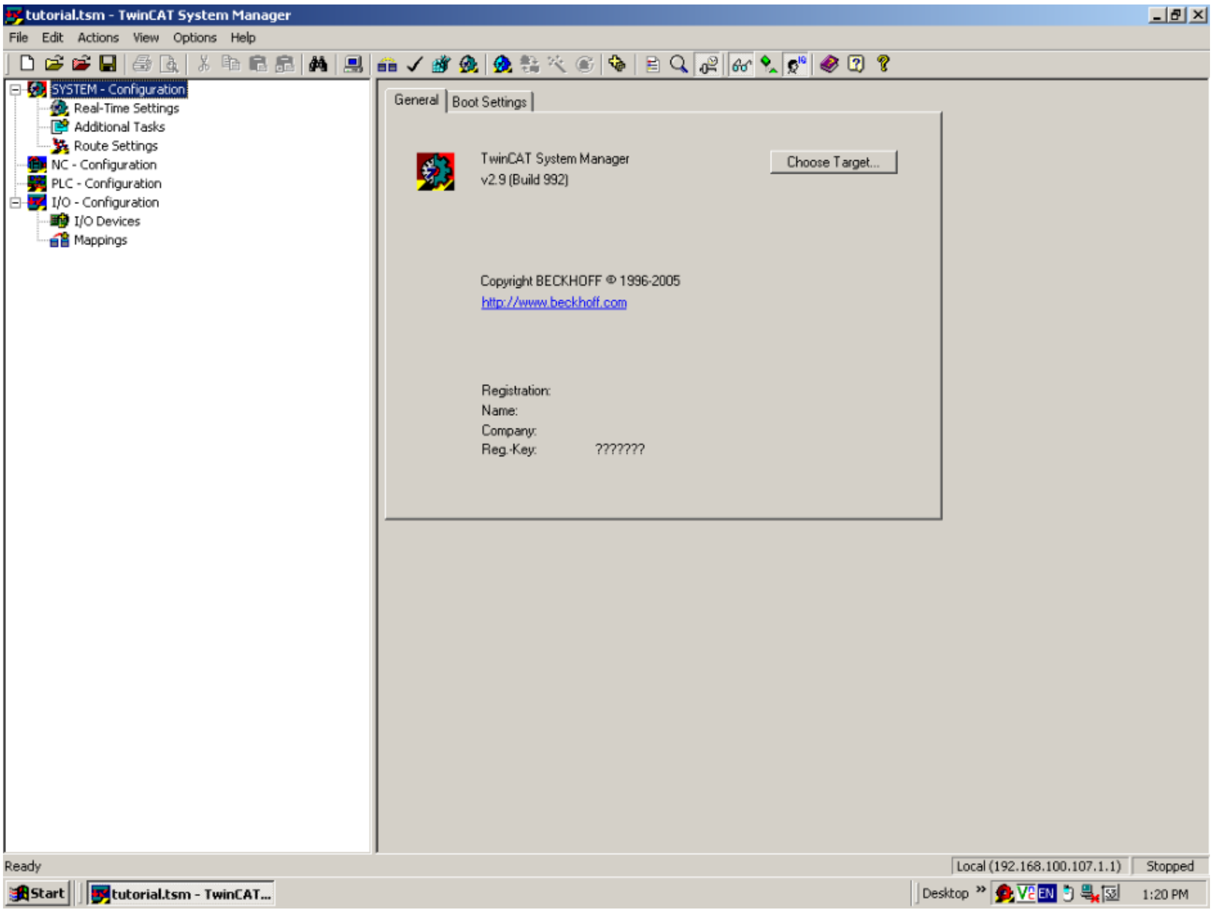
Appendix A

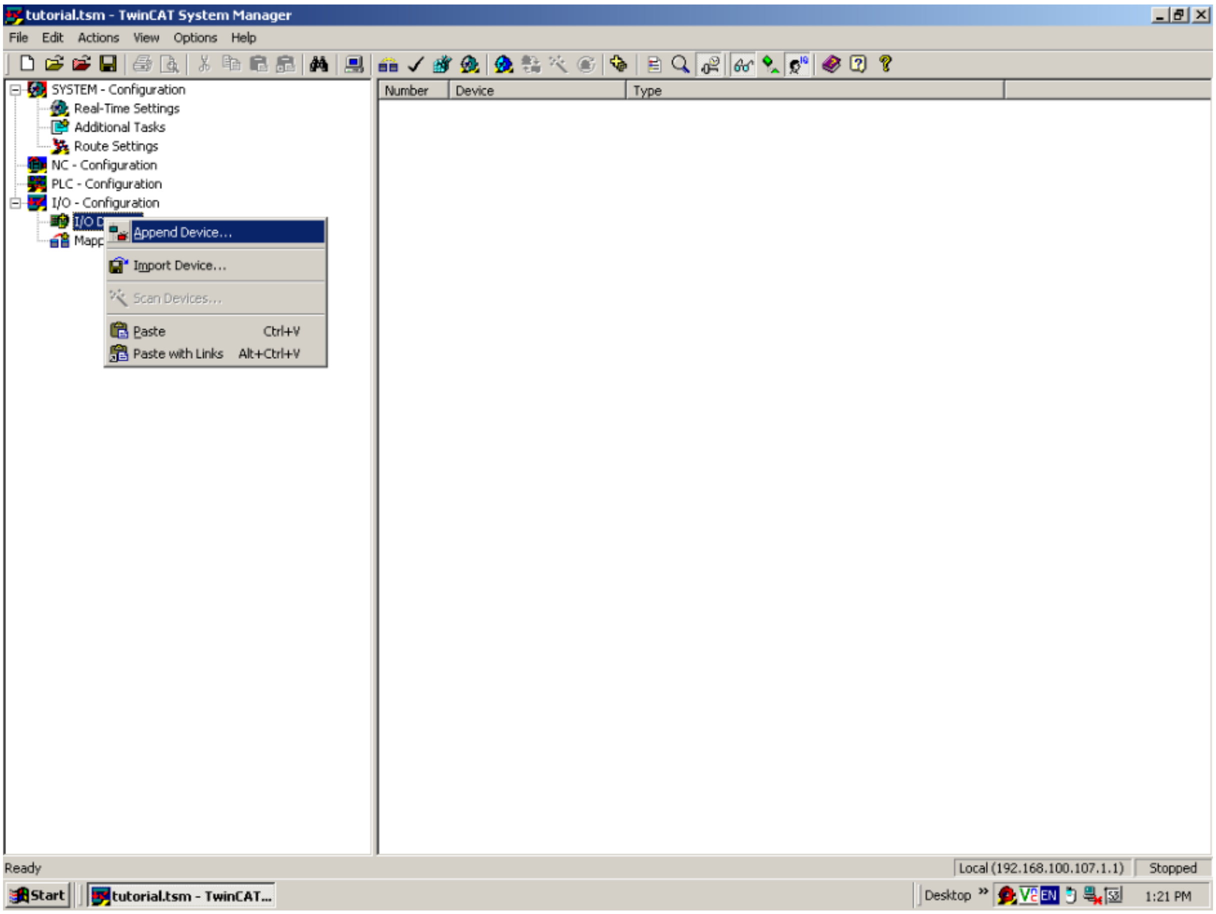
TwinCAT System Manager Configuration

The following tutorial describes the necessary steps to configure the TwinCAT System Manager to control the servo amplifiers corresponding to axes X, Y, and Z.

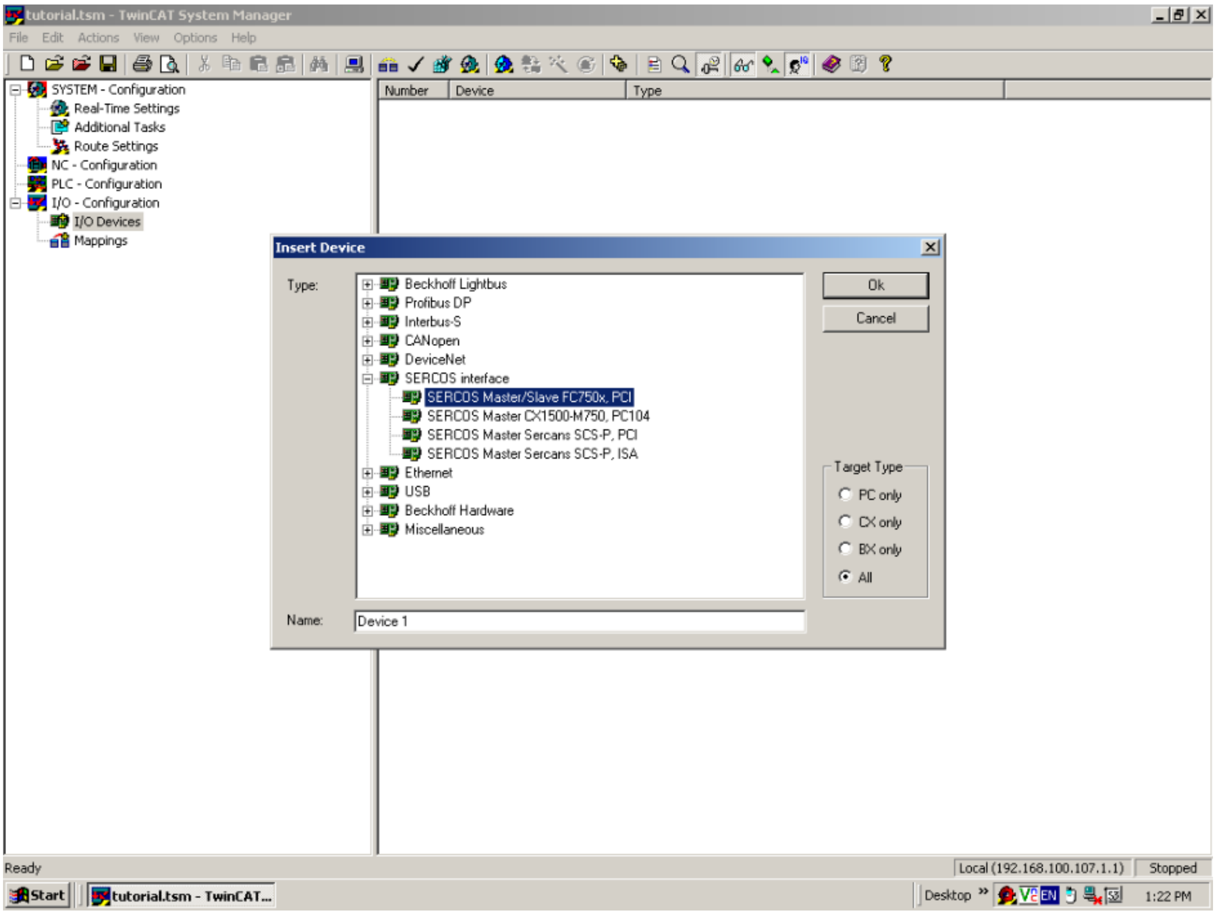
1. The start of the new TwinCAT System Manager configuration.



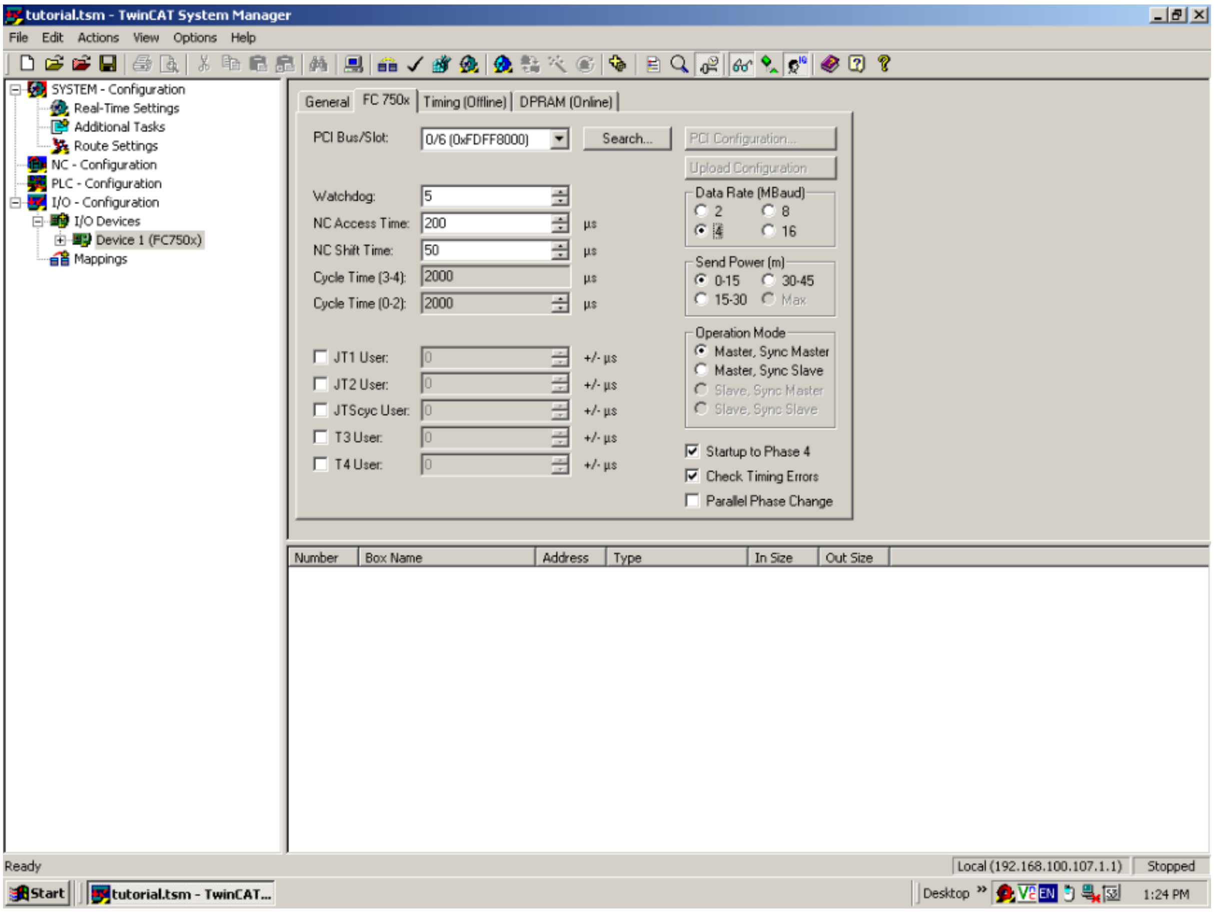
2. Right-click on **I/O Devices** (in the I/O Configuration node) and left-click on **Append Device.**



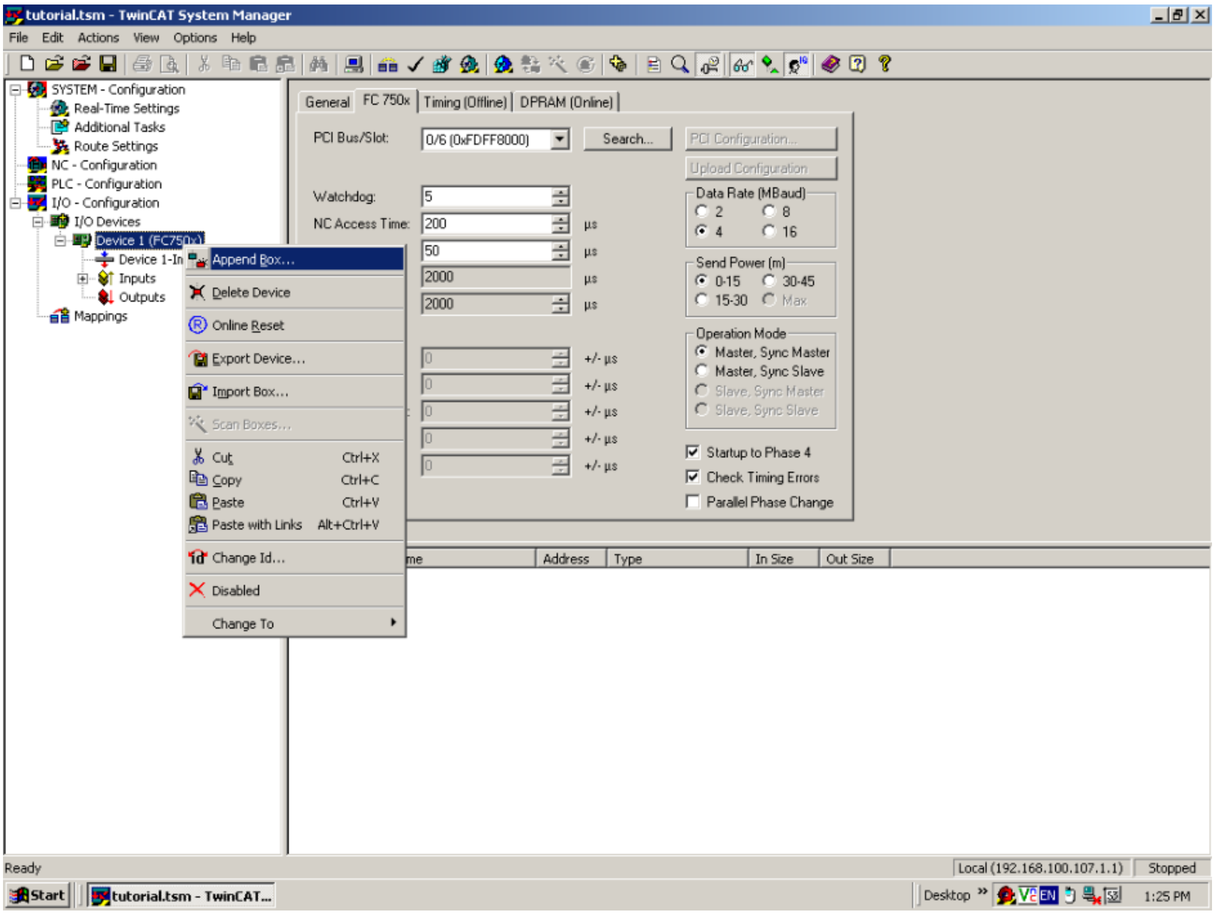
3. Select the device **SERCOS Master/Slave F750x, PCI** and click **OK**



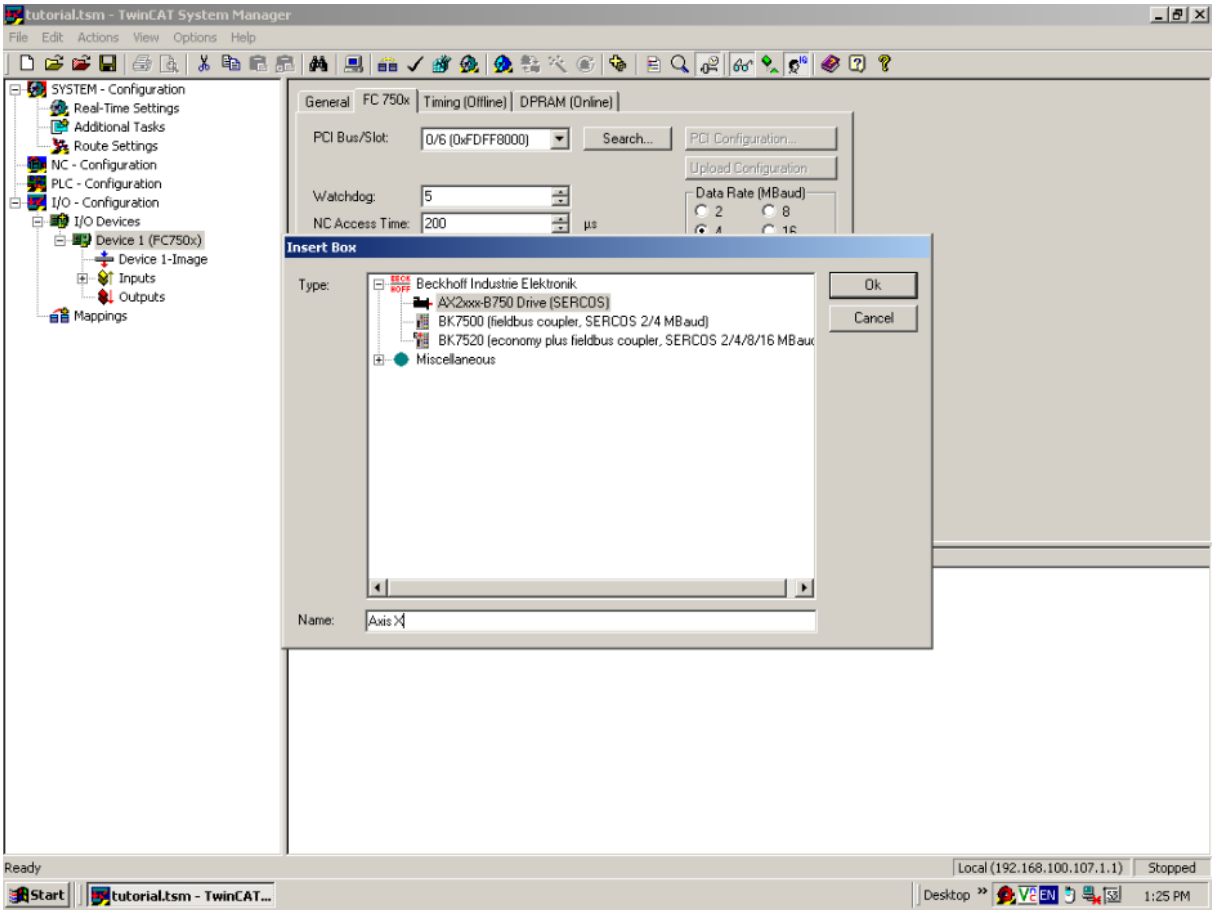
4. Assign a PCI Bus/Slot to the device by clicking on **Search…**. Set the **Baud Rate** to 4 MBaud as shown



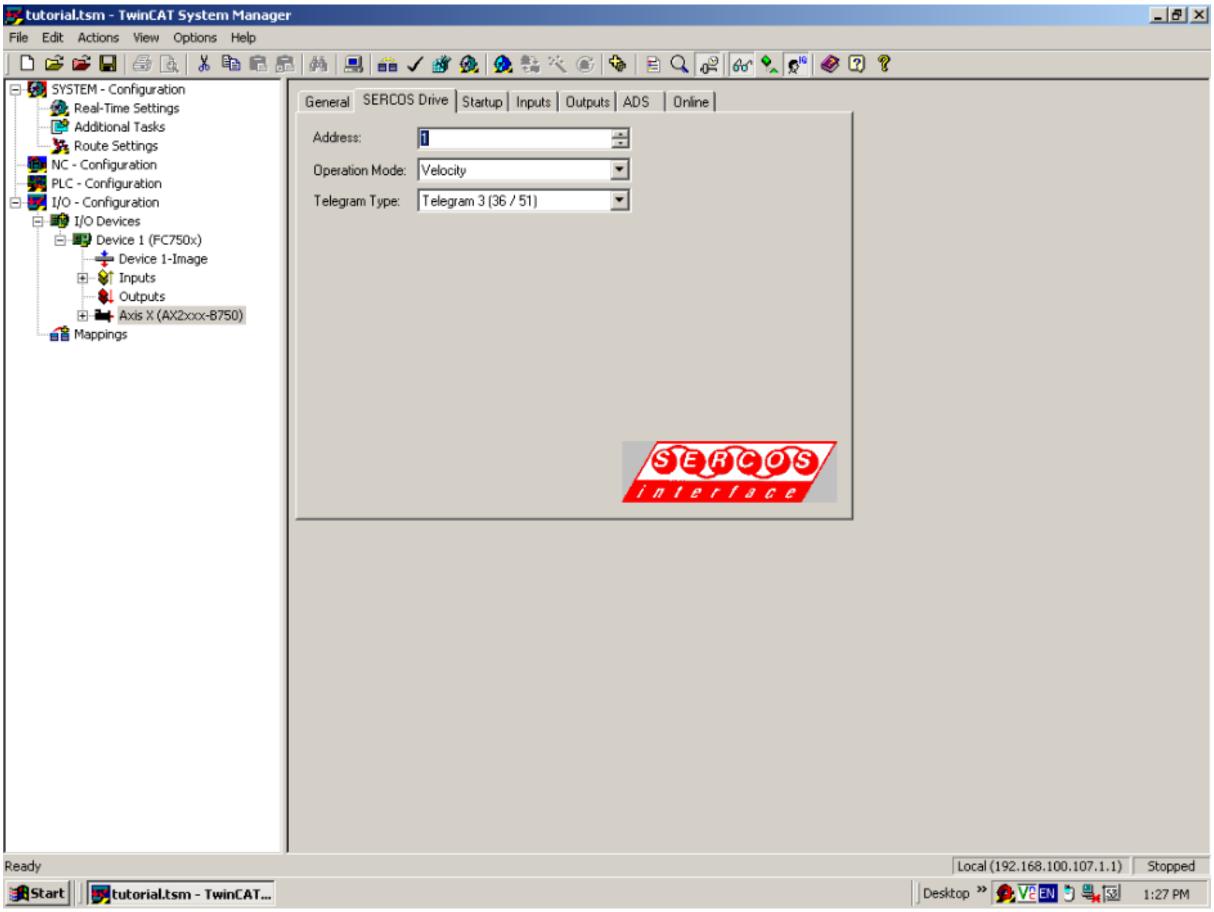
5. To append a new drive, right-click on the PCI device and left-click on **Append Box.**



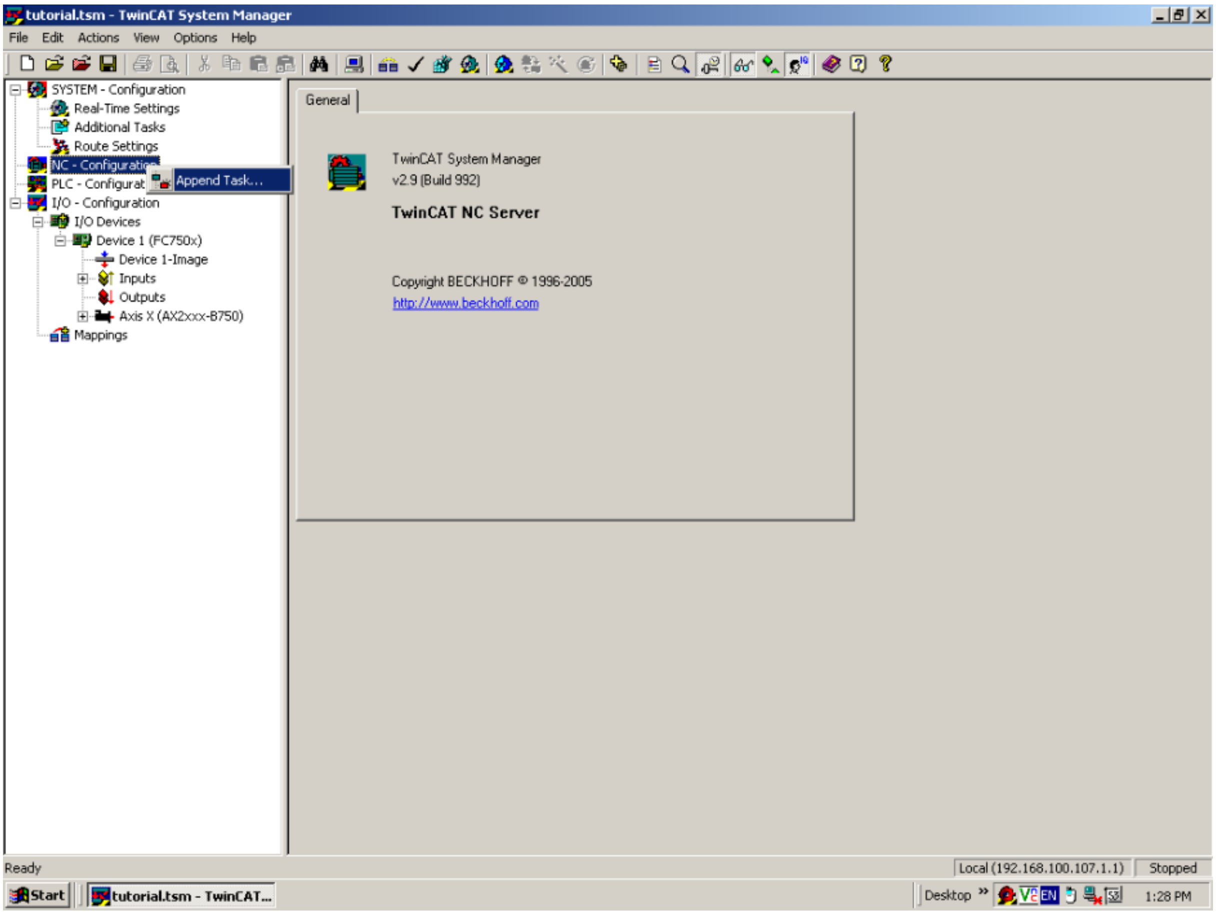
6. Select the **AX2xxx-B750 Drive(SERCOS)** and click **OK**.



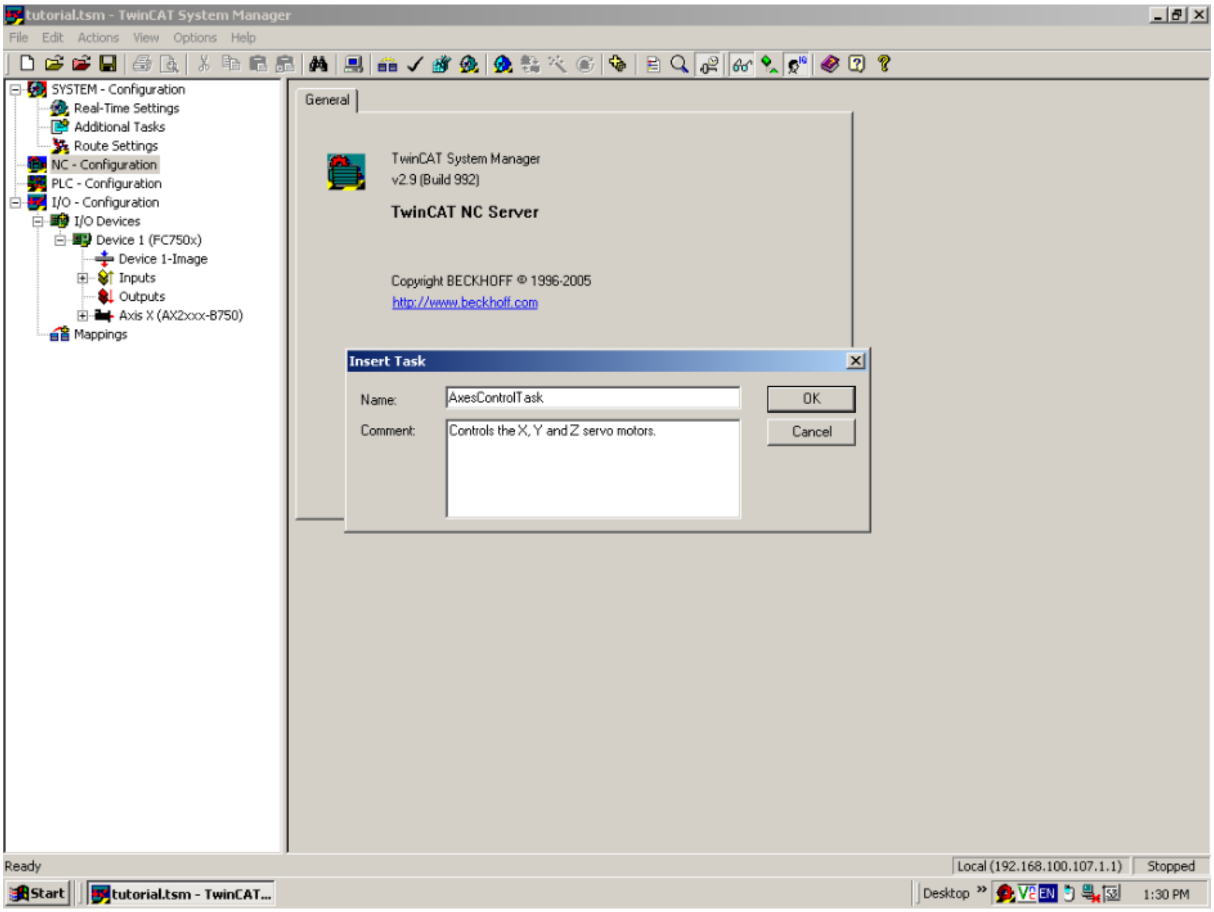
7. **Address** assigned to the drive has to be the same as the one shown by the DRIVE.exe configuration program. Select **Velocity** as the **Operation Mode** and **Telegram 3 (36 / 51)** as the **Telegram Type**.



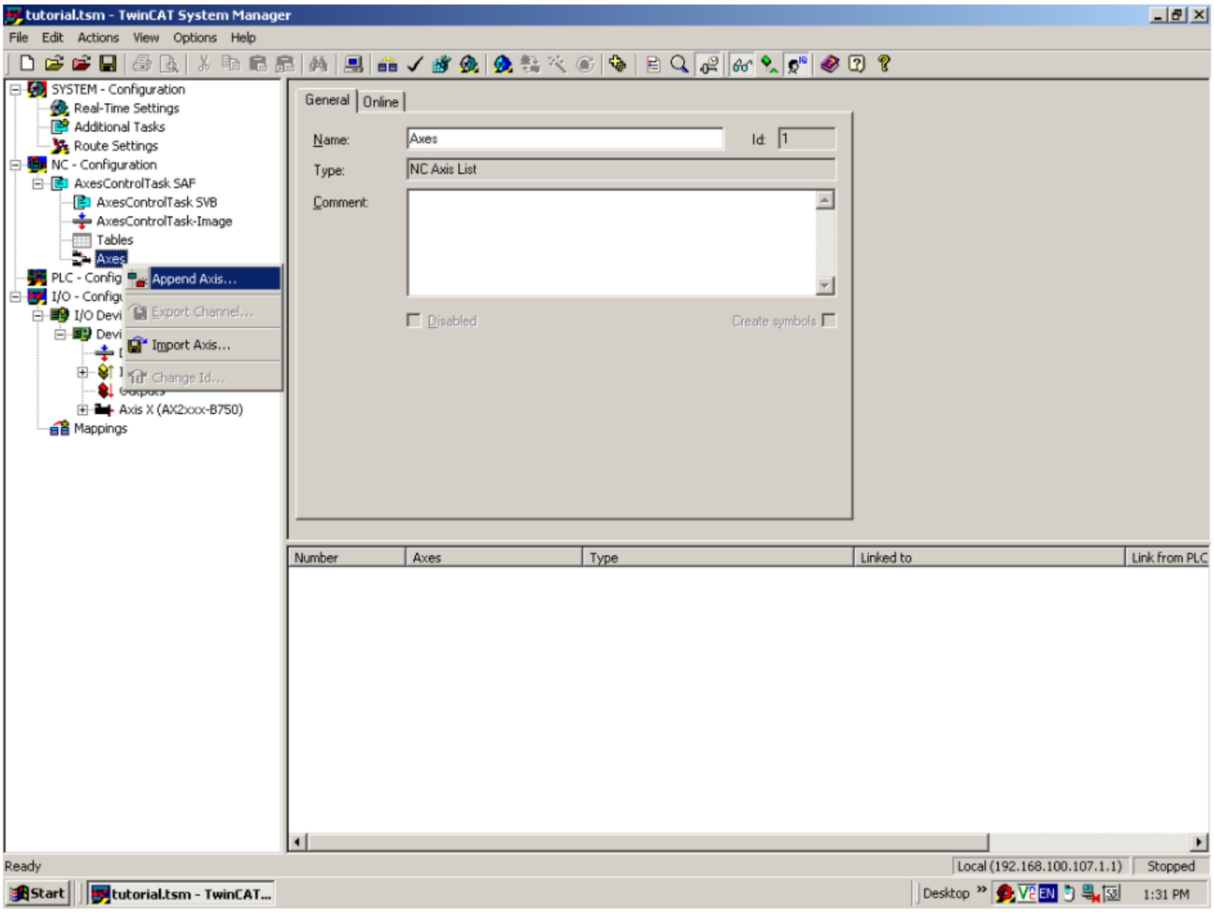
8. Right-click on **NC – Configuration** and left-click on **Append Task.**



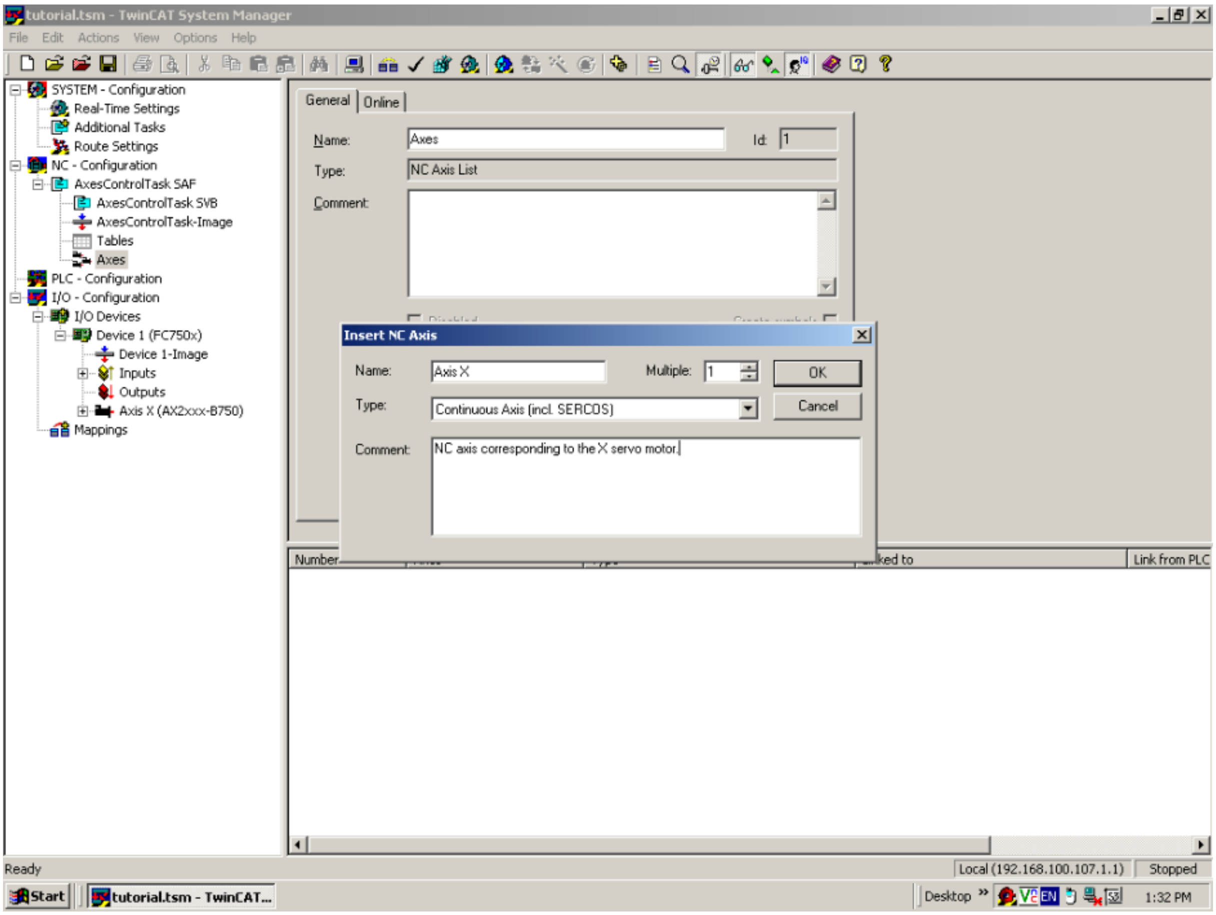
9. Enter a name for the task and optionally some description. Click **OK**.



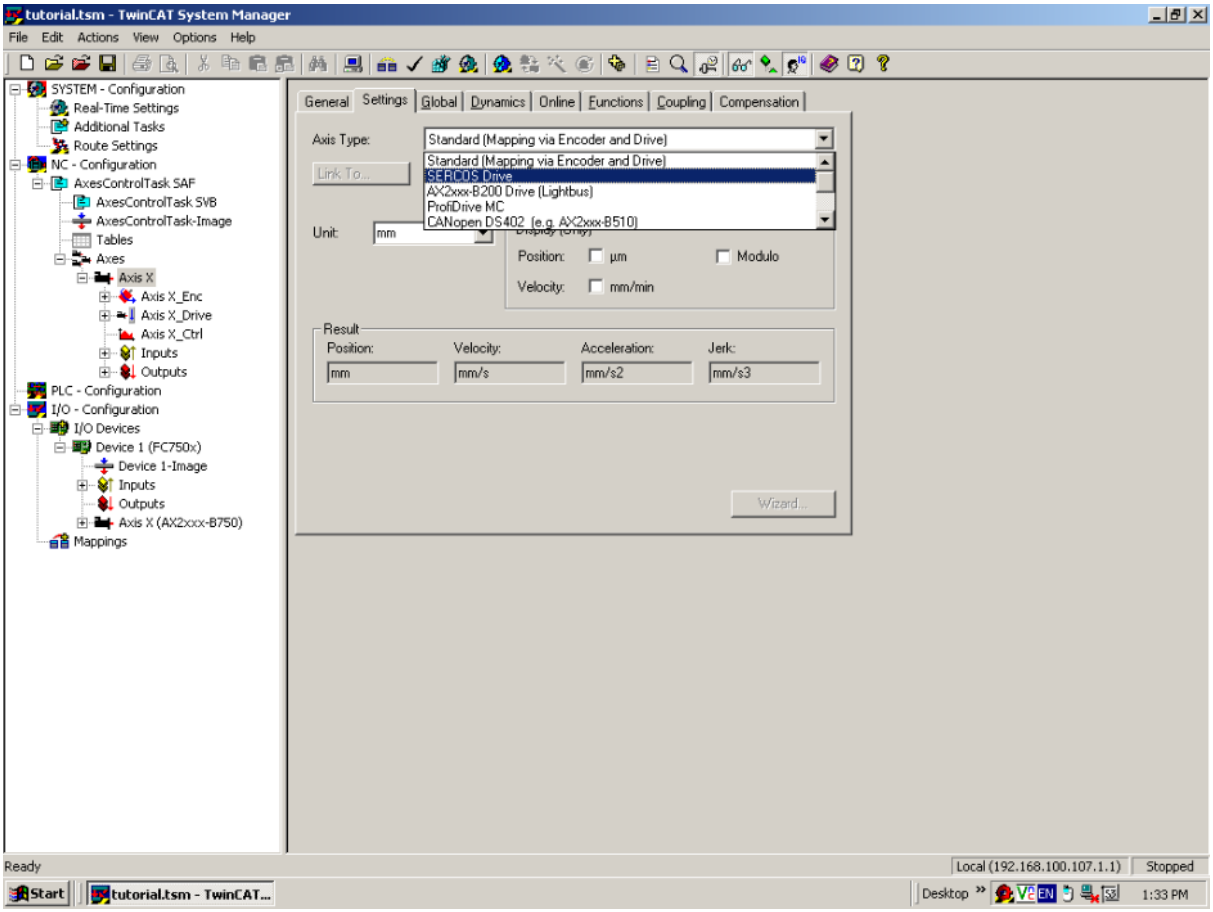
10. In the NC task just created, right-click on **Axes** and click on **Append Axis.**



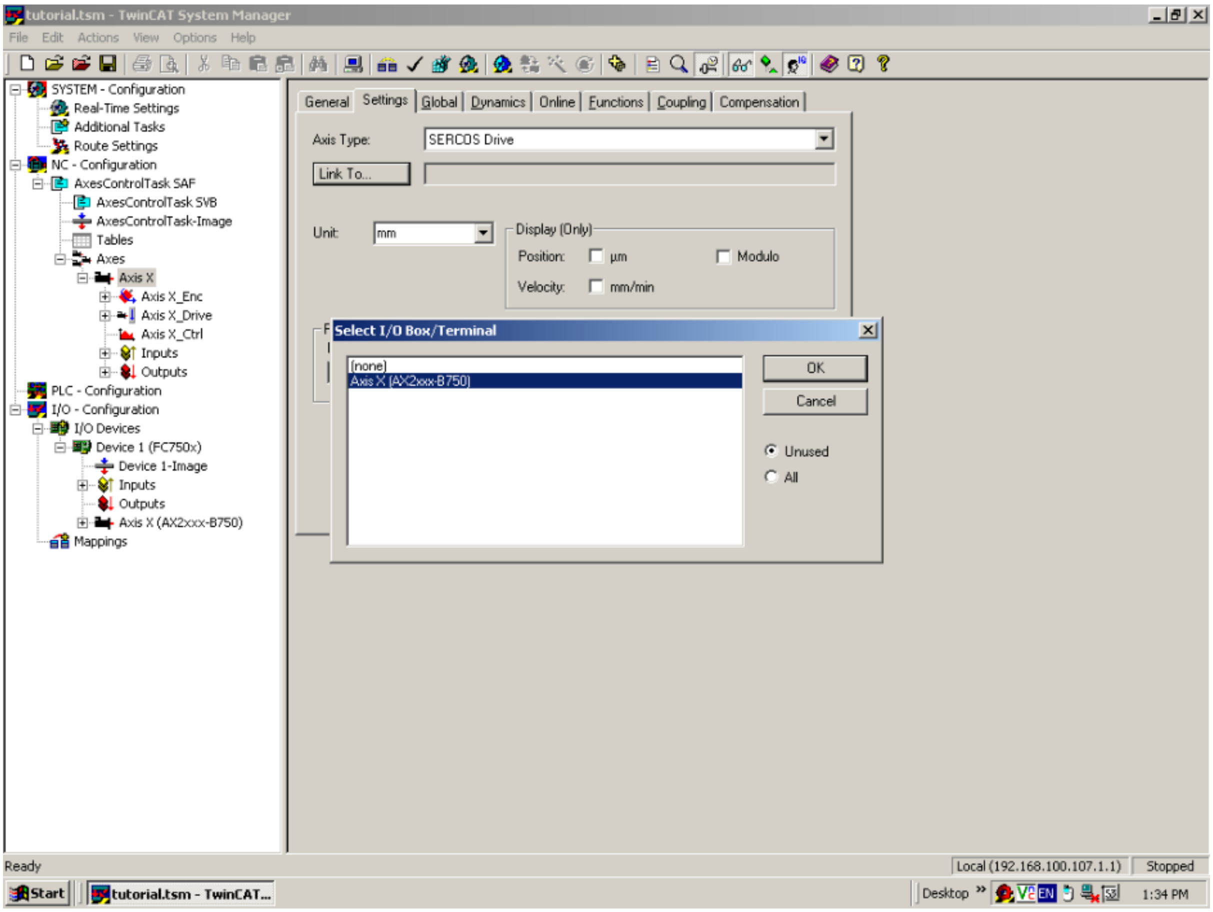
11. Give a name to the axis and set its **Type** to **Continuous Axis (incl. SERCOS)**.



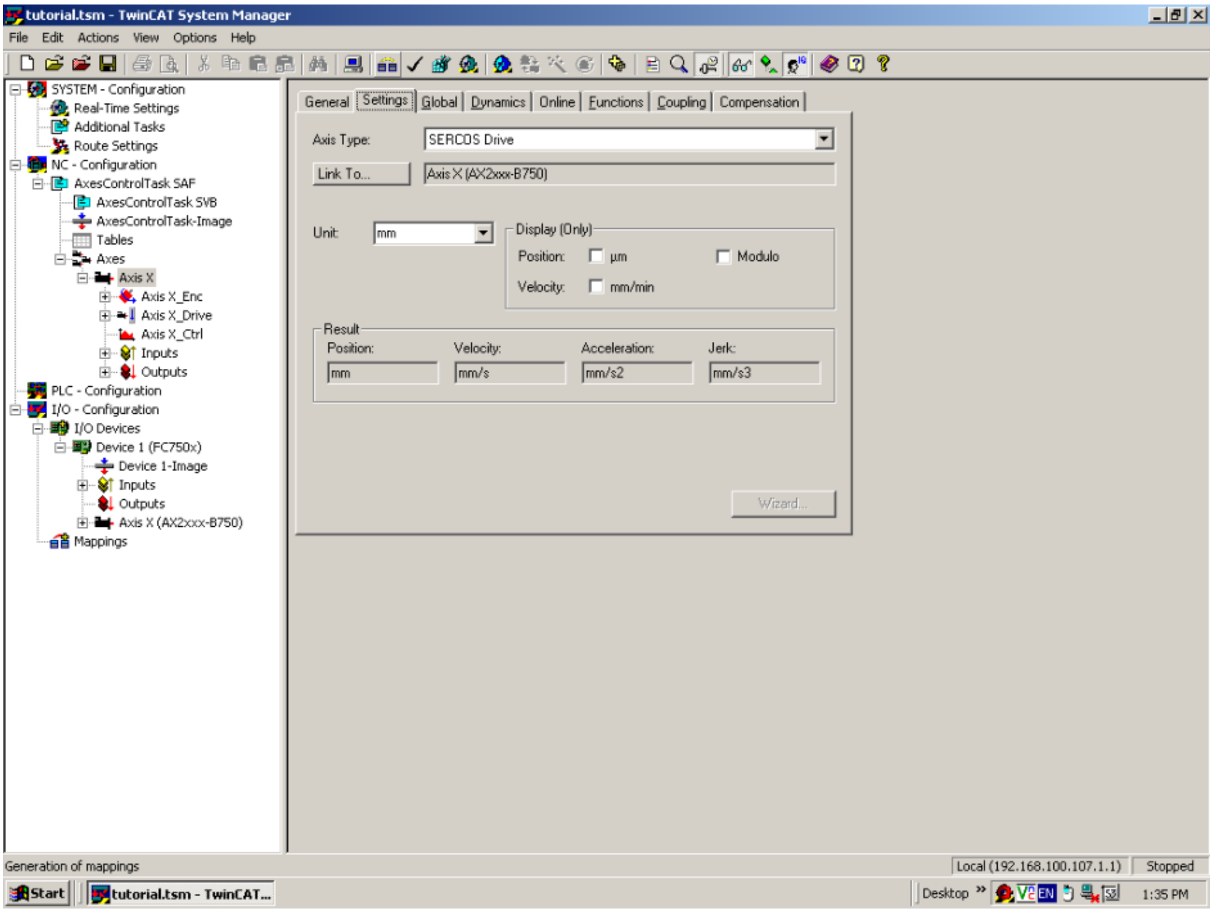
12. In the **Settings** tab, set **Axis Type** to **SERCOS Drive**.



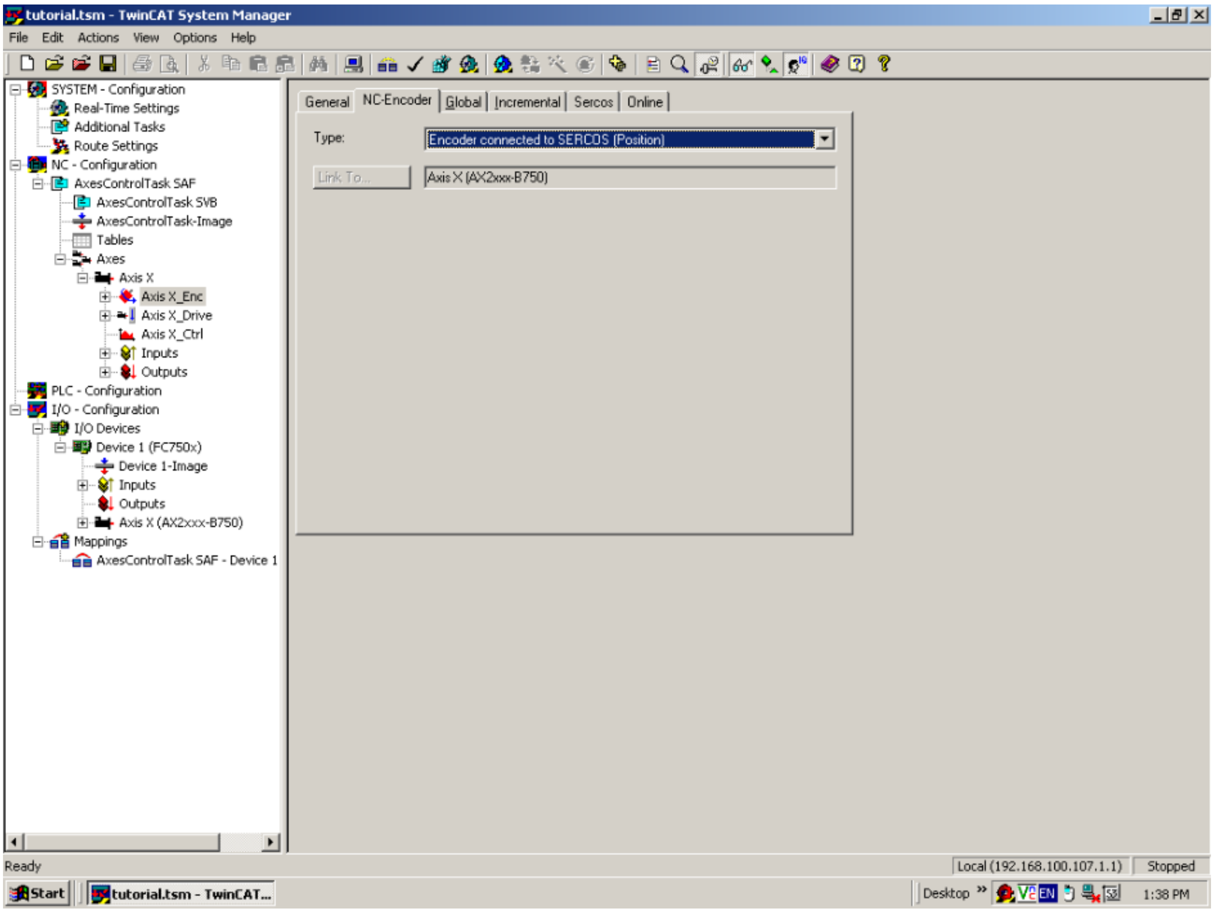
13. Still, in the **Settings** tab, click on **Link to…** Select the corresponding I/O Box/Terminal defined previously. This action will automatically link task variables to physical device variables.



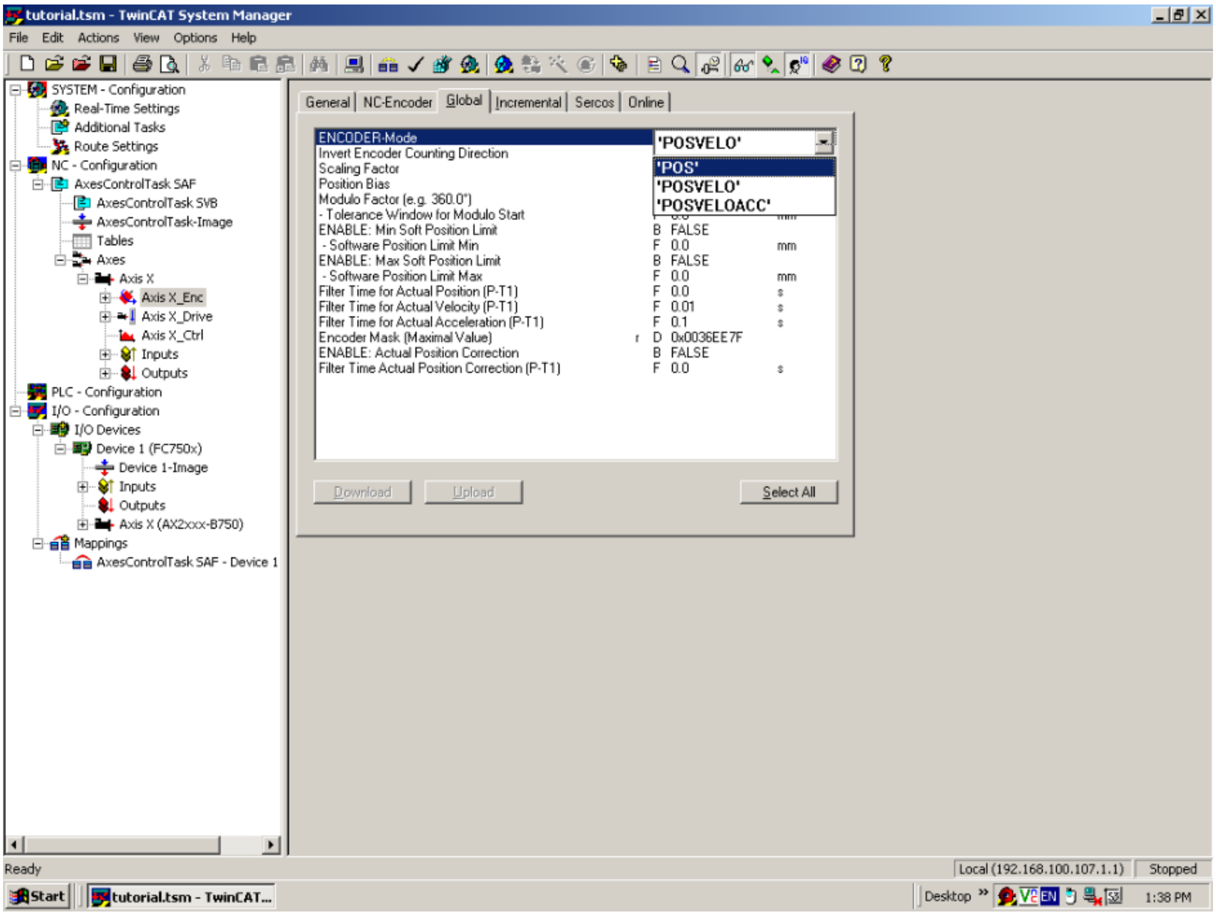
14. Click on the **Generate Mappings** button in the toolbar. A new entry will appear under the **Mappings** object.



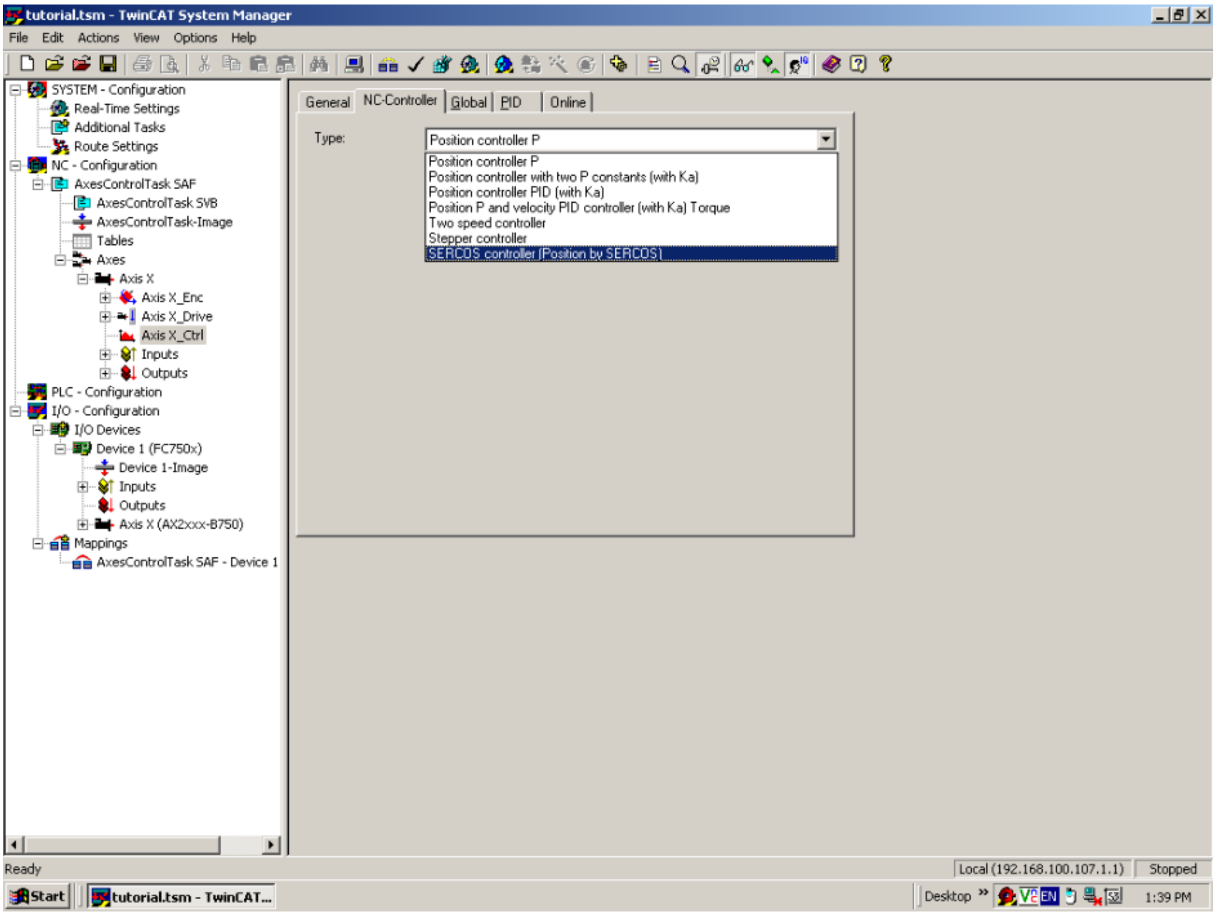
15. In the encoder object, under the **NC-Encoder** tab, set **Type** to **Encoder connected to SERCOS (Position)**



16. Under the **Global** tab, set **ENCODER-Mode** to **POS**

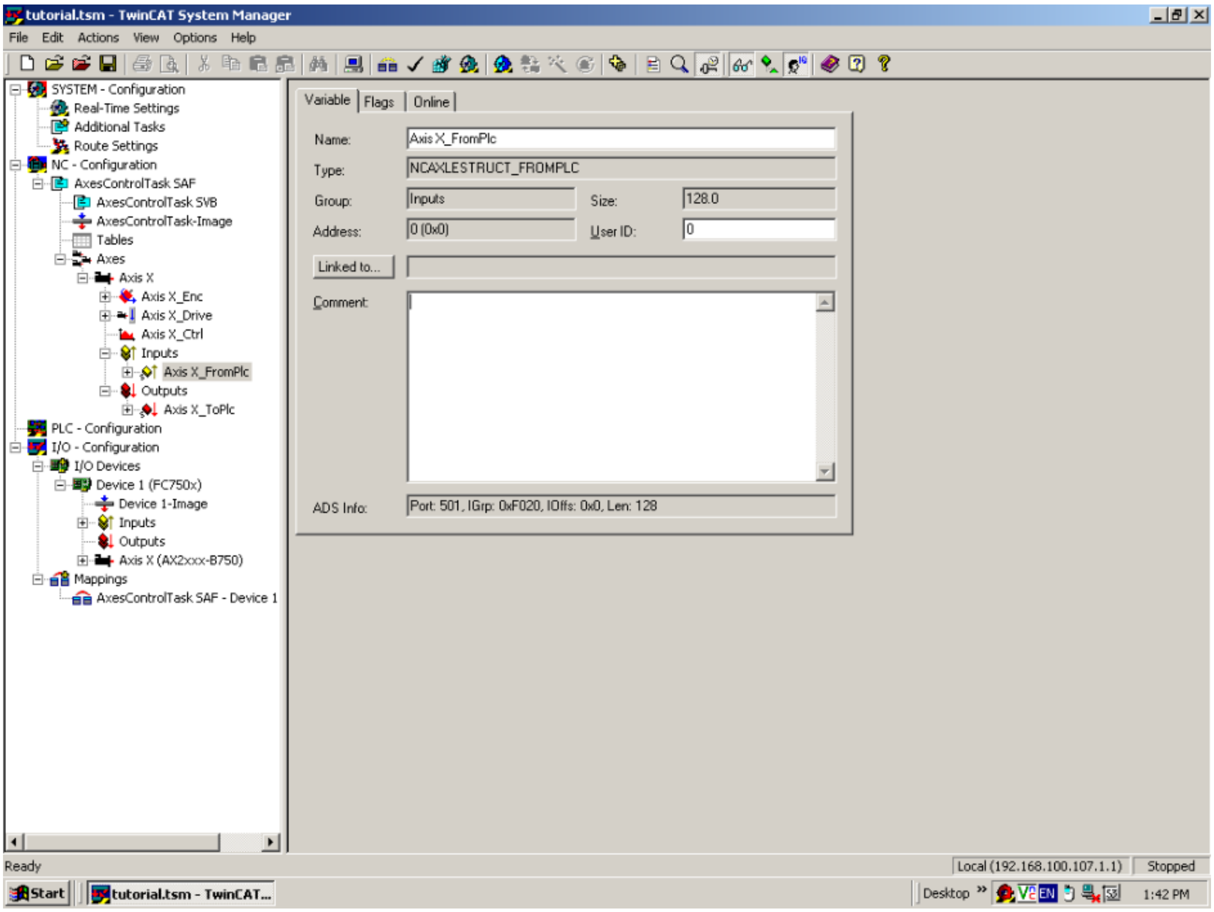


17. In the controller object, under the **NC-Controller** tab, set **Type** to **SERCOS**



controller (Position by SERCOS).

18. In the axis inputs, the structure of type **NCAXLESTRUCT_FROMPLC** defines the data that flows from a PLC program to this axis in the NC task.



19. Under **Mappings,** variables in the I/O Configuration are associated with the NC task. The procedure to add the Y and Z axes is the same, but each axis must have an ID equal the shown in the DRIVE.exe setup program.