Linnéuniversitetet Kalmar Växjö

Examensarbete i Maskinteknik

Robotic 3D Printing of sustainable structures

Robot 3D-printing med hållbara strukturer

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Summary

This report outlines the procedure to be followed when using an industrial robot for 3D printing of sustainable structures made from wood fiber polymer composites.

The procedure was as follows: Traditional CAD (computer-aided design) software was employed to design a three-dimensional model. Subsequently, a different software called a "slicer" was used to divide the model into horizontal planes. Following this, a robot programming software was utilized to generate the programming code necessary for the physical robot to follow a specific path. The code produced by the robot programming software was then transferred to the physical industrial robot, which executed the 3D printing process to fabricate the structures.

The thesis focused on the use of sustainable materials in 3D printing, specifically bio and forest-based materials.

Utilizing the robotic 3D printing cell has been thoroughly documented, including an operation manual and an online video tutorial. These resources are intended for use in student laboratory sessions for manufacturing courses at Linnaeus University.

The thesis provides a step-by-step guide for initializing the 3D printing robot cell, covering the transition from the simulation environment to the practical implementation with the physical robot. Furthermore, the results demonstrate that robot 3D printing can serve as a manufacturing technique for producing structures made from environmentally friendly materials, such as bio and forest-based materials.

Sammanfattning

Den här rapporten beskriver förfarandet som ska följas vid användning av en industriell robot för att 3D-printa hållbara strukturer tillverkade av wood fiber polymer composites.

Följande förfarande användes: Traditionell CAD (datorstödd design) - programvara användes för att designa en tredimensionell modell. Därefter användes en annan programvara kallad "slicer" för att dela upp modellen i horisontella plan. Efter detta användes en robotprogramvaran för att generera den programkod som behövs för att den fysiska roboten ska följa en specifik bana. Den kod som genererades av robotprogramvaran överfördes sedan till den fysiska industriroboten som utförde 3D-utskriftsprocessen för att tillverka strukturerna.

Rapporten fokuserade på användningen av hållbara material inom 3D-printing, särskilt biobaserade och skogsbaserade material.

Användningen av den robotbaserade 3D-printingcellen har noggrant dokumenterats, inklusive en bruksanvisning och en online-videoguide. Dessa resurser är avsedda att användas av studenter i laborationer för produktion- och tillverkningskurser vid Linnéuniversitet.

Rapporten ger en stegvis guide för att starta upp 3D-printingcellen och täcker övergången från simuleringsmiljön till den praktiska implementeringen med den fysiska roboten. Dessutom visar resultaten att robotbaserad 3D-printing kan användas som en tillverkningsteknik för att producera strukturer av hållbara miljövänliga material, som biobaserade och skogsbaserade material.

Abstract

This bachelor thesis aims to integrate and evaluate a 3D printing robotic cell at the Smart Industry Group – SIG lab at Linnaeus University (LNU).

A sustainable structure consisting of wood fiber polymer composites was 3D printed with an industrial robot. Sustainable 3D printing material can be recycled or burned for energy afterwards. The 3D printing material used in this thesis stems from certificated forests.

The objective is to utilise this technology in manufacturing courses and research projects at the SIG lab at LNU. This objective is achieved by creating an operation manual and a video tutorial in this thesis.

The integration and evaluation process will involve offline robot programming, simulation, and practical experiments on the 3D printing robotic cell.

Keywords:

3D printing, Robotic 3D printing, ABB Robotstudio, Robot simulation, Offline robot programming, 3DP PowerPac

Acknowledgement

I found the thesis to be extremely interesting, offering valuable insights into a promising new technology. It sparked a genuine passion within me, and I am committed to further enhancing my knowledge and understanding of robotics and 3D printing.

I would like to express my sincere appreciation to my examiner, Izudin Dugic, for their valuable feedback. Additionally, I am grateful to my supervisors, Jetro Kenneth Pocorni and Osama Ziada, for their exceptional guidance and support. I would also like to acknowledge the contributions of Janka Kovacikova and Daniel Gustafsson, who provided valuable assistance throughout the process.

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Tammam Alkhatib

Växjö, 30 May 2023

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1. Introduction

This chapter aims to introduce the issues investigated in this thesis project. It provides background information and the purpose of this work. Problematization, research questions, and delimitations are also be discussed.

1.1 Background

In the early 2000s 3D printing, also known as additive manufacturing (AM), has become a rapidly evolving technology and one of the most important technologies. Now low-cost 3D printing machines are everywhere.

The origins of 3D printing can be traced back to the 1980s when Charles Hull invented stereolithography (Hull, 1986). Over the years, advancements in robotics and computer technology have significantly improved the efficiency and capabilities of 3D printers. Robotic 3D printing, specifically, refers to the integration of robotic systems with additive manufacturing, offering enhanced precision and flexibility compared to traditional 3D printing methods (Gibson et al., 2021). Figure 1 shows an example of a structure being created during 3D printing.

Figure 1: 3D print in progress (Horvath and Cameron, 2020)

Additive manufacturing is widely used by end customers, research institutions and different industries, including aerospace, automotive, plant engineering, and medical engineering. Robotic 3D printing has the precision of robotics with the flexibility and creativity of 3D printing. Industrial robots have advantages over normal 3D printers, such as higher repeatability and more degrees of freedom (Gibson et al., 2021).

This innovative process utilises computer-aided design (CAD) files to deposit successive layers of materials, such as plastics, metals, ceramics, or a combination of materials, and build objects from the ground up.

1.2 Problematization

The problematization for this study is based on the specific needs and applications of the Smart Industry Group – SIG lab at Linnaeus University (LNU).

The SIG lab has a robot 3D printing cell that will be used for education or research purposes. To start the robot cell, an operation and guiding manual that is user-friendly and easy to read must be created.

The robot 3D printing cell is an integrated system consisting of components from different suppliers, such as a special extruder, a sensor-controlled heating printing table, an industrial robot and a robot controller.

The special extruder enables 3D printing of sustainable structures (such as furniture components and building materials) by using forest-based wood fiber polymer composites. The sustainable 3D printing material can be recycled or burned for energy afterward. The 3D printing material used in this thesis stems from certificated forests.

The author, a student in the mechanical engineering program at Linnaeus University, has been tasked to create a start-up manual of the robot cell and document the procedure (by text or video instruction). The goal is to use this documentation in laboratory sessions for manufacturing courses at LNU. Researchers in the SIG lab will also use the documentation to start the robot 3D printing cell.

1.3 Research question

The following research question is addressed in this thesis by performing both simulations and experiments:

What procedure should be followed in creating sustainable 3D printing structures with an industrial robot?

1.4 Purpose

This project is a task at Linnaeus University’s SIG lab. A student-friendly operation handbook is created to handle the robotic 3D printing cell. The documentation will be used in manufacturing courses at the university. Researchers in the SIG lab will also use the documentation when preparing 3D printing robot experiments in their research. Apart from the above, this project aims to introduce new and modern manufacturing technologies such as robotics, simulation, sustainable 3D printing, and CAM (computer-aided manufacturing) in the mechanical engineering courses at LNU.

1.5 Relevance

The relevance of robotic 3D printing can be seen in its wide range of applications and potential benefits. It is an advanced manufacturing technology adopted by various industries, such as aerospace, automotive, and healthcare.

Robotic 3D printing is gaining popularity due to its versatility and sustainable use of printing materials. As technology advances, it is expected to play an increasingly significant role in shaping the future of manufacturing and other industries, contributing to a more sustainable, innovative, and efficient global economy.

The 3D printing technology studied in this thesis enables the manufacturing of sustainable structures by using bio and forest-based composite material. It is crucial for students at Linnaeus University to acquire knowledge and skills in 3D printing and robotics, enabling them to use these technologies and gain practical experience that will benefit them in their future careers.

This thesis explores the role of robotic 3D printing in promoting sustainability in manufacturing.

1.6 Delimitations

The delimitations of the project include:

- Only one type of sustainable material will be tested in 3D printing experiments.
- Material and destructive testing will not be performed on the 3D printed material.
- Full-scale parameter optimization of the 3D printing process will not be done.

2. Literature and Theory

2.1 Literature review

To acquire accurate scientific information, the author reviewed and studied trusted scientific sources such as books and scientific articles by using specific keywords using scientific websites and search engines such as Google Scholar, ScienceDirect and 'LNU's OneSearch, to get the best search results. The keywords used in this review are outlined below.

- Industry 4.0/5.0
- Industrial robots
- 3D printing
- CAD/CAM
- Extruder and printing material
- Offline robot programming and simulations

Above keywords are used in the following Theory section to describe theoretical background in the project.

2.2 Theory

2.2.1 Introduction

Combining industrial 'robots' abilities with manufacturing techniques can greatly improve the entire production process, resulting in better efficiency, accuracy, and product quality. In this chapter, a short literature survey is given on topics related to robotic 3D with polymer-based material.

2.2.2 Industrial robots

Robots are a central part of the 5th industrial revolution, Industry 5.0. In Industry 5.0, humans are working alongside advanced technology, such as robot applications in manufacturing (De Nul et al., 2021).

Robotic arms can be connected to 3D printing processing tools. In this thesis, the robot is connected to an extruder head. Robots consist of multiple axes and have multiple degrees of freedom in movements that enable the 3D printing of large structures. Robots also enable more flexibility in movement in 3D printing, especially when compared to 3D printing with a gantry (linear axes) system (Puzatova et al., 2022). Robot systems also offer the possibility of exchanging the processing tool with other tools. This makes it possible that a single robot cell can be used in different manufacturing applications (Finkbeiner et al., 2022). For example, a 3D printer tool of a robot can be exchanged for a welding tool or a vacuum gripper tool or a screwdriver tool.

Robots give increased flexibility in movements and enable flexible and sustainable production. Other general advantages of using robots are that products created with them have better quality and consistency. When using robots, maximum productivity is achieved, greater safety for repetitive and dull tasks is ensured, and labour costs are reduced.

Robots are a sustainable solution for different challenges. These challenges can be of engineering background (robots are fast, precise, and flexible) but also challenges facing the wellbeing of humans (robots can perform repetitive, unergonomic tasks in dangerous and dirty environments without becoming tired and without becoming sick) (Valori et al., 2021).

2.2.3 3D printing

The evolution of 3D printing or additive manufacturing (AM) is zrevolutionizing the manufacturing and prototyping sectors. The transformation is chiefly propelled by combining computer-aided design (CAD) methodologies, intricate modelling algorithms, and refined AM technologies (Gibson et al., 2021) (Rosen, D. W. 2007) (Horvath & Cameron, 2020).

CAD methodologies are a cornerstone in the progression of 3D printing, facilitating the creation of highly complex and elaborate models. The exploration of CAD for additive manufacturing of cellular structures underscored the proficiency of CAD in designing intricate, lightweight structures with enhanced mechanical attributes. This development has unlocked new horizons for industries such as aerospace and automotive, where the balance between weight and strength is of major importance (Rosen, D. W. 2007).

Horvath and Cameron (2020) give a detailed analysis of the process of transforming a CAD model into a physical object via 3D printing. The authors stress that it is important to fully understand the entire process, which includes the creation of a digital model, zoptimizing the 3D printer settings, and the selection of the relevant material for prototyping. The authors stress the need for a broad understanding of the AM process, which incorporates the design phase as well as the pre-and post-processing stages (Horvath & Cameron, 2020).

Gibson and Rosen (2021) studied technical facets of AM technologies in depth. They presented a variety of 3D printing techniques, such as Fused Deposition Modelling (FDM), Selective Laser Sintering (SLS), and Stereolithography (SLA), zemphasizing their distinctive advantages and constraints. Additionally, they highlight the importance of material selection and the evolution of materials science in the advancement of AM technologies (Gibson et al., 2021).

In this thesis, experiments are performed with FDM as an additive manufacturing method.

2.2.4 CAD/CAM

The seamless integration and efficient interaction between computer-aided design (CAD) and computer-aided manufacturing (CAM) systems can significantly enhance the efficiency, precision, and overall performance of manufacturing processes, including robotic 3D printing. By zoptimizing the flow of information from the design stage to the manufacturing stage, CAD and CAM aim to streamline production workflows and improve the quality of the final product (Rosen, D. W. 2007).

2.2.5 Extruder and printing materials

Design optimization, careful calibration of operational parameters, and well-thought-out material management are crucial in the execution of a stable and efficient 3D printing process. The extruder, an integral component, significantly influences the quality and characteristics of the final printed product. This mechanism pushes the print material, often a filament, through an optimally designed heated nozzle, transforming it into a semi-liquid state. This softened material is then precisely layered to create the desired 3D object (Gibson et al., 2021).

A well-engineered extruder is equipped with an zoptimized nozzle geometry, an efficient heating system, and a precise material feeding mechanism, which are particularly important in achieving consistent material flow and accurate layer deposition. By fine-tuning the operational parameters, such as temperature, extrusion speed, and layer height, in accordance with the material properties and the desired outcome, one can increase precision, decrease material waste, and zminimize printing defects (Gibson et al., 2021).

Furthermore, the advancements in polymer-based material science offer exciting opportunities to enhance 3D printing extruder technology. By incorporating advanced polymer materials with unique properties, it is possible to equip the extruder to produce objects with enhanced mechanical, thermal, and chemical attributes. For example, thermoplastic polymers with higher melting points allow for objects to be resistant to high temperatures while those with exceptional tensile strength lead to objects with strengthened mechanical properties (Jiang et al., 2020).

A comprehensive understanding of the printing materials' properties, encompassing melting temperature, viscosity, and tensile strength, is also vital for zoptimizing the extruder's performance, coming together to form an efficient and effective 3D printing process. Hence, the design of the extruder should be capable of handling a wide range of polymer-based materials, each with unique physical and chemical properties (Jiang et al., 2020).

In this thesis, sustainable structures are 3D printed by using bio and wood-based sustainable material.

2.2.6 Off-line robot programming and simulation

The concept of offline robot simulation has roots in the 1980s when computer technology began to boom. 3D modelling, programming languages, and user interfaces play a critical role in the development of offline robot simulation (Wittenberg, 1995).

The field of robotics has experienced significant advancements through the integration of simulations, which have opened new possibilities in design, testing, and implementation. In a paper by Choi, H. S. (2020), the potential and challenges of simulation in robotics are explored, providing valuable insights into how this tool can be optimally utilized. Based on their findings, a new theoretical framework called the Integrated Simulation Theory is proposed, zemphasizing the comprehensive integration of simulation throughout the entire lifecycle of robotic development and operation (Choi et al., 2021).

Simulation plays a crucial role in robotics by providing a safe environment for testing, cost-effective development, and accelerated learning. It proves particularly beneficial for complex tasks that may be expensive or dangerous to perform in the real world. The Integrated Simulation Theory highlights simulations as more than just a stage in the development pipeline; it promotes their ongoing use as an integral part of a robot's lifecycle.

The theory suggests a holistic and continuous simulation application throughout the various phases of robotic systems, including design, testing, learning, and operation. Instead of treating simulations as isolated steps, the Integrated Simulation Theory promotes their integration as vital components within the system. This approach includes "live" simulations during operation, enabling real-time decision-making and continuous learning (Choi et al., 2021).

3D modelling plays a key part in the growth of offline robot simulation. It uses computer-aided design (CAD) to make a digital version of the robot's physical environment. This digital twin allows for precise control of robot movements within a virtual setting (Pan et al., 2012).

3. Methodology

3.1 Research design

This thesis presents the research design in *Figure 2* with the following sections: Plan, Experiment, Evaluation.

The first step is problem formulation, followed by Conducting interviews to understand the problem deeper, then doing a Literature study to find relevant theories. Followed by the experiment phase, which starts with Solving equipment technical problems with manufacturers; after the problems are solved, the simulation begins before moving on to physical 3D printing.

Lastly, during the physical 3D printing process, multiple models are printed to check for optimal conditions (geometer, speed, temperature, etc.). Followed by concluding the presentation and also suggestions for the university and future work applications.

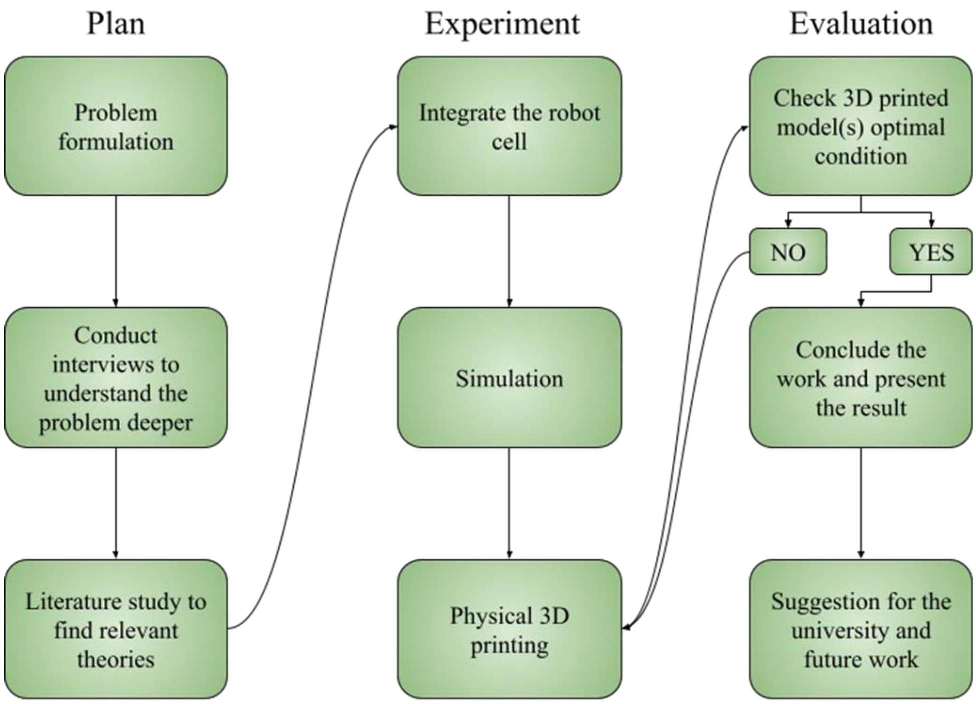


Figure 2: Research design

3.2 Method selection

3.2.1 Research philosophy

Research philosophy includes different perspectives on the development of knowledge during the research process, which impacts the interpretation of the results. Philosophical approaches such as positivism, critical realism, and pragmatism influence interpretation. Realism perceives reality as objective and empirical, while critical realism relates reality to a theoretical framework. Pragmatism focuses on problem-solving, seeing knowledge as a tool (Säfsten, K., & Gustavsson, M., 2020).

Philosophical models guide research, with widely accepted positivism, pragmatism, critical realism, and interpretivism. Positivism combines quantitative research and hypothetical inference methods. Pragmatism zemphasizes practical action, while critical realism looks for fundamental problems (Aithal, G. H. R., & Aithal, P. S., 2022).

Interpretive theory measures unobservable objects by interpreting behaviour. In this case, a positivist and pragmatic approach is chosen due to the technical nature of the task. (Ryan, G., 2018)

3.2.2 Research approach

Research approach plays a significant role in the planning, execution, and reporting of scientific research. This research method aims to explore and zanalyze the concepts of deduction, induction, and abduction as research methods. The selected references provide valuable information on the background and application of these methodologies. The first step in this research approach is to perform a comprehensive literature review based on selected references. The book "Forskningsmetodikens grunder, att planera, genomföra och rapportera en undersökning" provides a fundamental resource for understanding the basics of research methodology. (Patel, Davidson 2019).

In addition, a study by Rodrigues examines the method of scientific discovery in the philosophy of Charles S. Peirce, focusing on deduction, induction, and induction. Another resource discusses inductive and deductive reasoning in children's cognitive development, while another provides an overview of deduction, induction, and abduction in the context of data collection. qualitative data. Based on the literature review, a conceptual framework was developed to define and distinguish deduction, induction, and abduction. This framework serves as the basis for understanding and zanalyzing these research methods. To collect empirical data regarding the use of deduction, induction and abduction in research, interviews, surveys, or observations are conducted. The data collection methods are designed to capture the insights and experiences of the researchers who used these methods in their research (Rodrigues, C. T., 2011).

Qualitative analysis techniques, including coding, classification, and thematic analysis, are applied to the collected data. The data were zanalyzed to identify patterns, similarities, and differences in applying deduction, induction, and abduction as research methods. The results are compared and contrasted with existing literature to confirm or extend current understanding of these methodologies. The results of the data analysis are summarised and presented in a clear and concise manner, and the implications of the results are discussed in the context of the research method. Limitations encountered during the study are discussed and potential areas for further research are suggested. In summary, this research method provides a comprehensive understanding of deduction, induction, and summary as research methods. The strengths and weaknesses of these methods are reviewed and the practical implications of their use in different research contexts are highlighted (Goswami, U., 2004) (Flick, U., Kennedy, B. L., & Thornberg, R., 2018).

3.2.3 research strategy

The goal of this research strategy is to assist engineering students to carry out their graduate projects through a progressive approach effectively. A recommended research method will be used to improve the quality and rigour of the research process. This strategy provides a step-by-step approach for students to successfully carry out their projects. (Säfsten.K., 2020).

The initial phase involves familiarising students with the field of study, identifying topics and goals, and reviewing relevant literature. Students will also conduct preliminary surveys to identify research gaps and potential questions. During this phase, students will develop a comprehensive research plan outlining methods, timing, and available resources. They will define the research questions, choose an appropriate design, and determine the methods of data collection. In addition, students will receive the necessary resources. (Blomkvist Pär & A. Hallin., 2015).

The implementation phase involves carrying out planned research activities, collecting data while maintaining ethical principles and data quality. Students will record all activities and observations. In the final stage, students will zanalyze the collected data, draw conclusions, and report the results. They will zorganize and structure the data, use appropriate analysis techniques, and present the results. A reflection on the research process and future directions will also be included (Blomkvist Pär & A. Hallin,. 2015).

Research strategy is the plan to achieve research objectives. Various strategies exist, such as testing, surveys, and case studies. Case studies involve in-depth study of real-life phenomena, answering what and why questions. They are used for discovery, description, and explanatory purposes. Case studies use both qualitative and quantitative data. However, due to the limited sample size, the results are not generalizable (Saunders, Lewis & Thornhill., 2019).

3.2.4 Methodological choice

In research, one important decision is the choice of research design. There are two main options: qualitative and quantitative. The selection depends on factors such as the research objectives, the nature of the research question, and the available resources.

Qualitative research aims to understand the experiences, meanings, and interpretations of individuals or groups. It focuses on gathering subjective information through methods like interviews, observations, or focus groups (Lowhorn., 2007).

Quantitative research, on the other hand, deals with numerical data and statistical analysis. It is used to measure and zanalyze data, establish relationships, or test hypotheses. Common methods in quantitative research include surveys, experiments, or statistical analysis of large data sets (Lowhorn., 2007).

The choice of research design should align with the research question and desired outcomes. If the goal is to explore subjective experiences, attitudes, or perceptions, a qualitative research design is appropriate. For investigating numerical data, relationships, or hypotheses, a quantitative research design is more suitable (Saunders, Lewis & Thornhill., 2019).

Ultimately, the selection of the research design should consider the specific research objectives and the available resources, ensuring that the chosen design aligns with the desired outcomes of the study.

3.2.5 Data collection

Data collection functions as an important core of research methodology, providing the basic basis for the generation and development of research findings and theoretical frameworks. Effective data collection requires accurate planning, clear objectives, and careful selection of methods appropriate to the nature of the research topic. (Kabir.M.S., 2016)

Explore the many data collection techniques, including observational methods, survey-based approaches, and experimental procedures, which are integral to the process. A firm commitment to ethical principles throughout the data collection phase was emphasized, maintaining the sanctity of the study and the reliability of the results (Kabir.M.S., 2016).

zEmphasizing the integral importance of validity and reliability in data collection further reinforces the quality of the data collected, confirming the overall reliability of the study. Refined data management practices are advocated as an effective way to enhance research authenticity. To zminimize the risk of bias and ensure the reliability and accuracy of the data collected, pragmatic strategies are suggested (Säfsten.K., 2020).

Together, this information provides a comprehensive overview of the complex task of data collection, highlighting its universal applicability in various research fields. The aim is to produce high-quality data that will serve as a solid and reliable basis for further analysis, conclusions, and theoretical development (Säfsten.K., 2020; Kabir.M.S., 2016).

3.2.6 Research quality

The main aspects of research quality, including objectivity, validity, reliability, and trustworthiness, are crucial for conducting rigorous and credible research. Objectivity necessitates unbiased and fact-based writing, while validity ensures that the intended study is conducted within the appropriate context. Reliability entails obtaining consistent results through study replication. Trustworthiness, encompassing credibility, transferability, dependability, and confirmability, contributes to overall reliability and validity (Säfsten.K., 2020).

In this study, a high level of validity is ensured by incorporating only measurable and controllable factors and parameters, such as well-defined components (e.g., geometries) and well-determined parameters (e.g., printing speed), into the 3D model of the simulation. Moreover, the study establishes a detailed research methodology to achieve a high confidence rate. This allows for replication of the experiments by others, ensuring that their results will not differ significantly from those of this study. Additionally, the experiment is repeated to further augment confidence in the obtained results.

4. Experimental procedure

This chapter describes the procedure that should be followed to go from a CAD (Computer-aided design) model to a physical 3D printed structure.

4.1 Offline robot programming and simulation

Before starting with the robot simulation, a 3D CAD model should be created by using any 3D CAD software. In this case, SolidWorks has been used(*Figure 3)*.

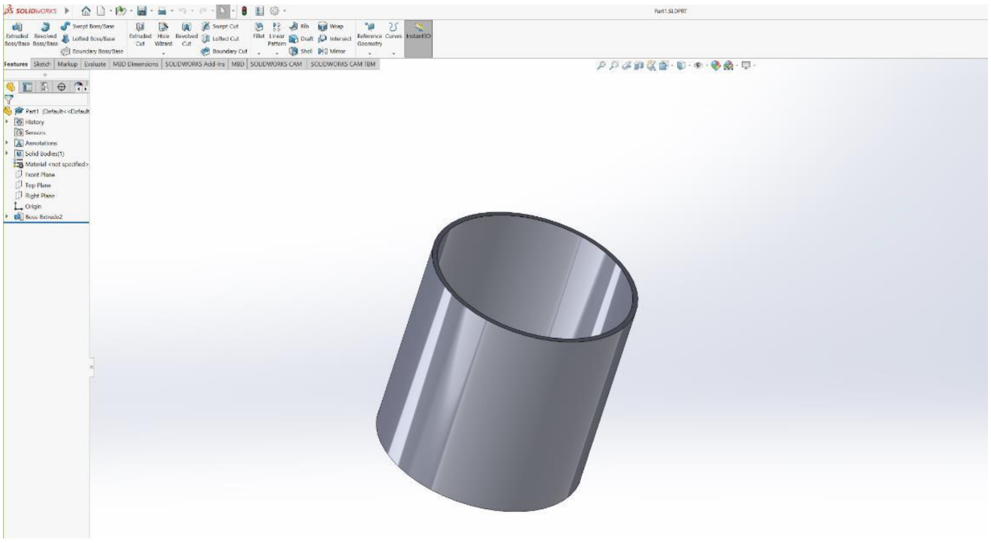


Figure 3: CAD model of a cylinder that will 3D printed

Then the 3D model is sliced using any slicing software, in this case UltiMaker Cura slicer has been used, *see Figure 4*.

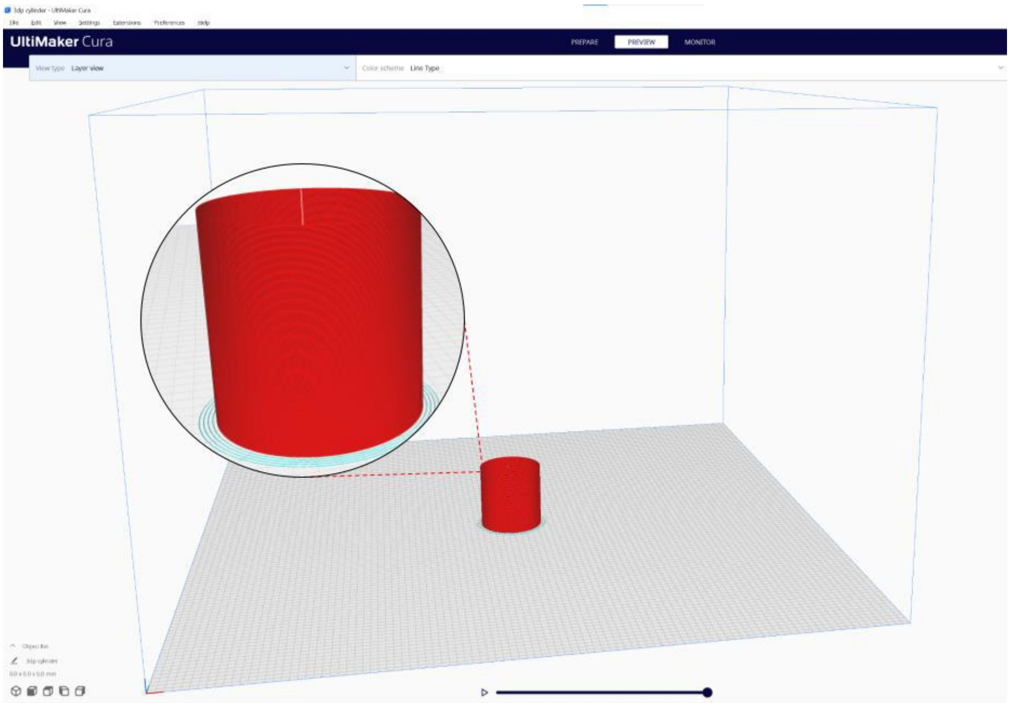


Figure 4: Sliced 3D CAD model in the slicer software UltiMaker Cura

The slicer software exports the coordinates of multiple horizontal ""slides"" as G-code (G-code is a common programming language used in computer numerical control (CNC)).

Now the robot simulation can be built. The robot simulation of the 3D printing process uses RobotStudio software for offline programming and simulation of ABB robots. The simulation started by making a virtual copy of the actual robot cell that the university has. This is done in the following manner. First the physical robot was turned to enable communication between ABB RobotStudio software and physical robot controller. Lastly, the robot model was imported from the physical robot controller to the robot simulation (this is achieved by the ""Go Offline"" function in RobotStudio), *see Figure 5*.

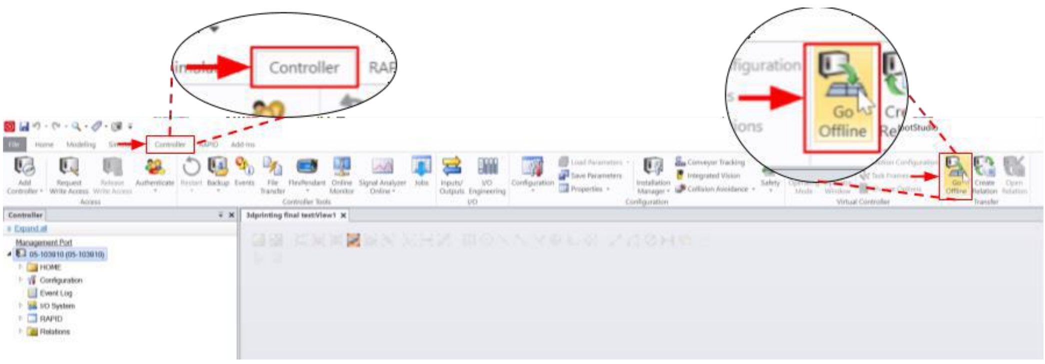


Figure 5: ABB RobotStudio software interface

In *Figure 6* the robot and the extruder are shown. The robot in the simulation is the same one the university has at its lab.

When applying the simulation for the real-world demonstration, the extruder in the simulation should be set up as a mechanism tool instead - the robot controller then recognizes the extruder as an additional axis of the robot arm.

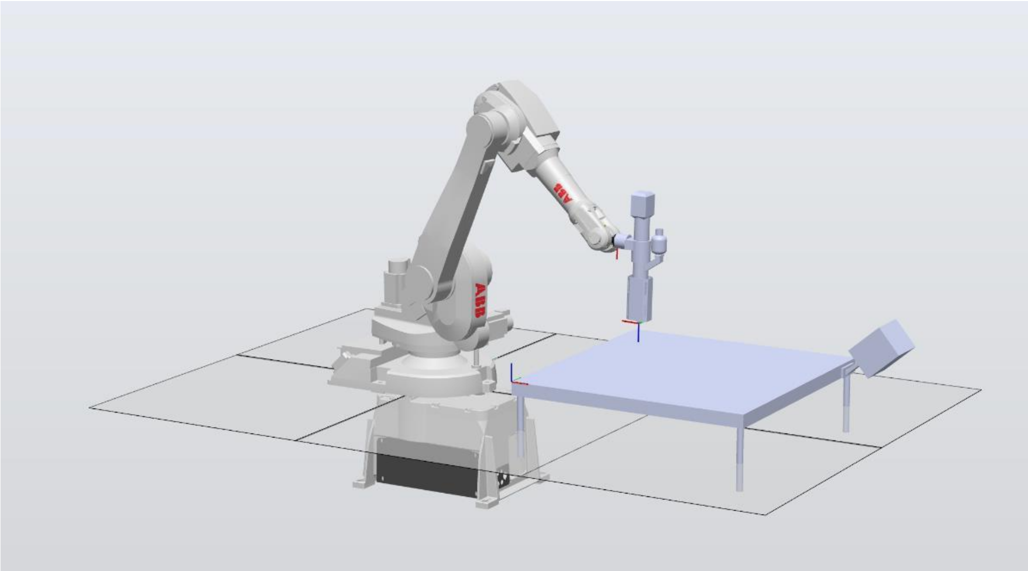
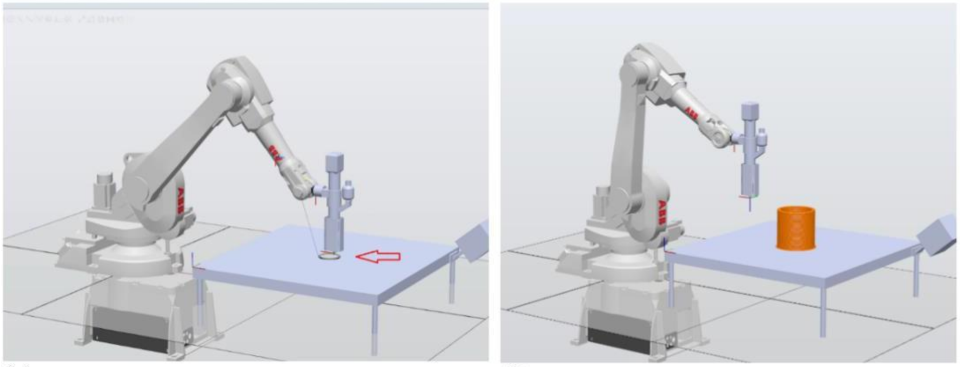


Figure 6: Model of the robot and extruder in ABB RobotStudio

The G-code, which represents the coordinates of the horizontal ""slices"", is now imported into RobotStudio. Importing the G-code to RobotStudio was made possible with the 3DP PowerPac. The 3DP PowerPac is an application in ABB RobotStudio for programming robots for 3D printing applications. 3DP PowerPac enables RobotStudio to be used with different CAD and slicer software.

3D PowerPac then translates the G-code to the ABB robot programming language called RAPID. Now the robot simulation can be run.

Figure 7 (a) shows the start of 3D printing simulation with the robot. To test the simulation, we made the first 3D model as simple as possible (the model has the form of a cylinder). Figure 7 *(b)* shows the complete contour of the 3D printed structure in the robot simulation.



(a) (b)

Figure 7: Simulating the 3D printing contour in ABB RobotStudio

After starting the robot simulation and ensuring that it works, the simulation file, including the RAPID code (RAPID is robot programming language in ABB robots) was transferred to the actual/physical robot for test runs in the real/physical environment. *Figure 8* shows an example of what the robot programming language RAPID looks like.

The physical robot 3D printing environment is outlined in section 4.2.

```
3DP cylinder:View1    05-103910 (05-103910)
T_ROB1/T_ROB1_3DP
!*       GUI related Persistents        *
!****************************************

PERS string st3DP_Version:="3DP version 22.3.10141.1";
PERS num nExtruderRotRatio;
PERS bool bDeleteModules;
PERS num nSpeedMin;
PERS string stSpeedMin;
PERS num nSpeedProgrammed;
PERS string stSpeedProgrammed;

!****************************************
!*   Integrated Extruder Supervision    *
!****************************************

PERS string ExtruderMechUnit:="Extruder";

!*****************************************************************
!** Main Entry for 3D printing with product unique declarations **
!*****************************************************************
PROC main3DP()
    t3DPActive:=TCPKFMextruder;
    wobj3DPActive:=Wobj_workTable;
    nTotalTargets:= 29826;
    nTotalLayers:= 200;
    stFolderName:= "3DP Cylinder";
    nModules:=30;

    v3DPprocess:= v60;
    nSpeedProgrammed:=v3DPprocess.v_tcp;
    nSpeedMin:=v3DPprocess.v_tcp;
    stSpeedMin:=NumToStr(nSpeedMin,0);
    stSpeedProgrammed:=NumToStr(nSpeedProgrammed,0);
    z3DPprocess:= zExtrude;
    z3DPprocessOnOff:= fine;
    v3DPvia:= v50;
    z3DPvia:= z10;
    v3DPwipe:= v10;
    nWipeDelay:= 0;
    bDynamicSpeed:=False;
    nLayerHeight:=0;
    nExtrusionWidth:=0;
    nApproach:=50;
    nDepart:=50;
    nProcess:=4;
    nExtruderRotRatio:=3;
    nExtruderRotOn:=5;
    nExtruderRotOff:=0;
    nLogicalAxis:=0;
    bDynamicFlow:=FALSE;
    !*************************************************************************************************
    !** Extrude factor for position controlled extruder. 1 = no compensation from programmed value **
    !*************************************************************************************************
    nExtrudeFactor:=1;

    WaitSyncTask syncStartInit, taskAll\TimeOut:= 1;
```

Figure 8: Example of RAPID code used in programming ABB robots

A detailed step-by-step procedure of going from computer model to robot simulation and generating robot code is given in *Appendix 2*.

A video tutorial detailing the above steps was also made and can be viewed from the below link.
Video link for the tutorial: https://www.youtube.com/watch?v=J9dO_cpCPv4

4.2 Robot 3D printing setup

To start 3D printing different parts of the robot cell were turned on in a specific sequence. A detailed step-by-step procedure is given in *Appendix 2*. The 3D printing cell is shown *Figure 9* in Figure 9robot, robot controller, extruder, extruder cooler, heated table, and safety sensor.

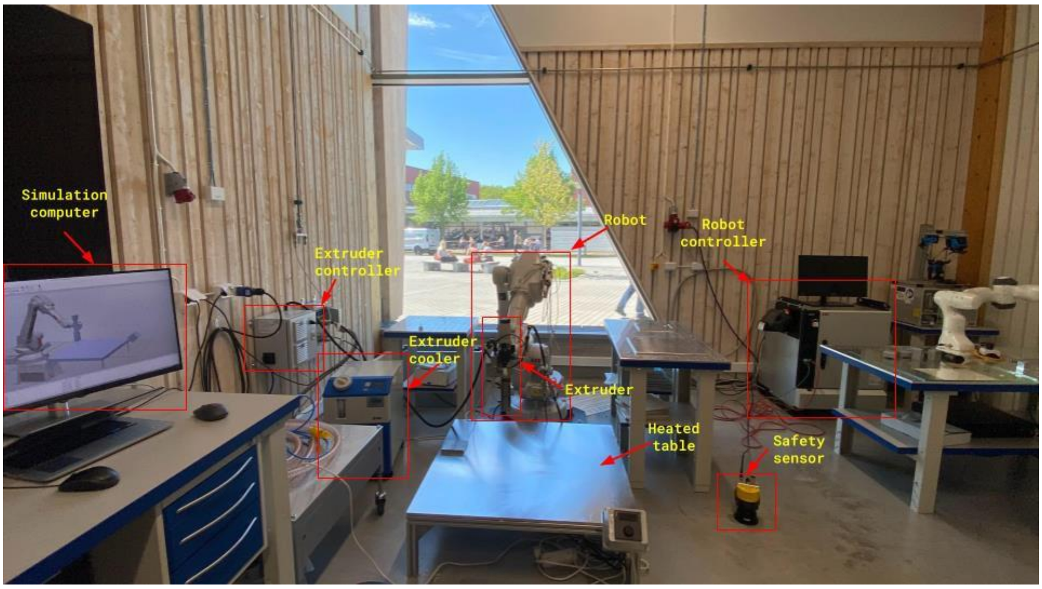


Figure 9: 3D printing industrial robot cell in Smart Industry Group-SIG lab

A schematic diagram displaying 3D printing cell start-up order is shown *Figure 10*.

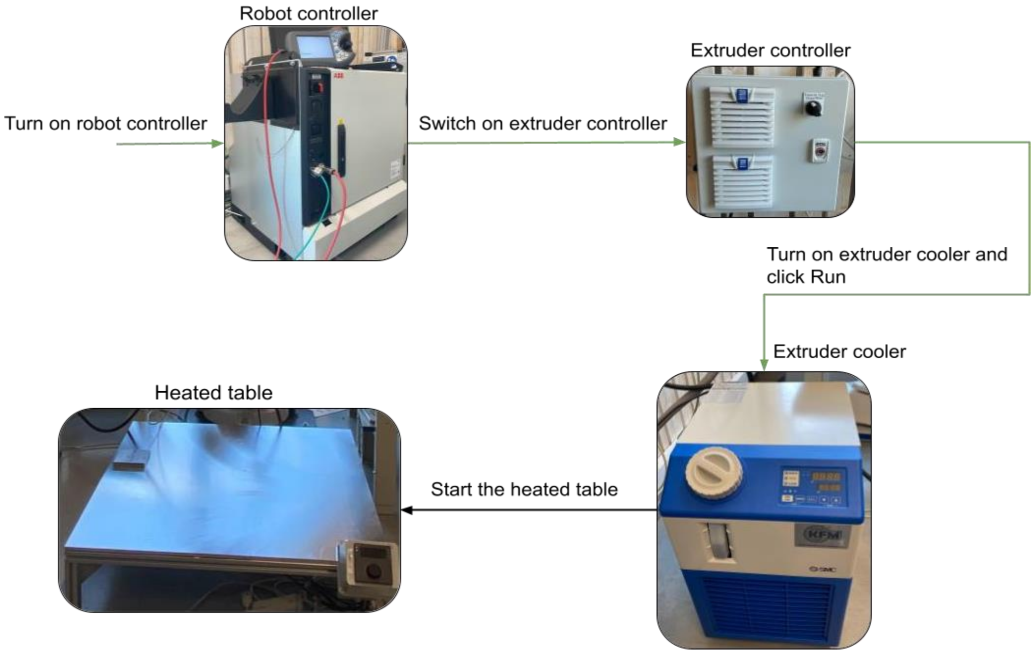


Figure 10: Schematic diagram of robot cell start-up order

A schematic diagram displaying communication flows between the different components inside the 3D printing cell is shown in *Figure 11*.

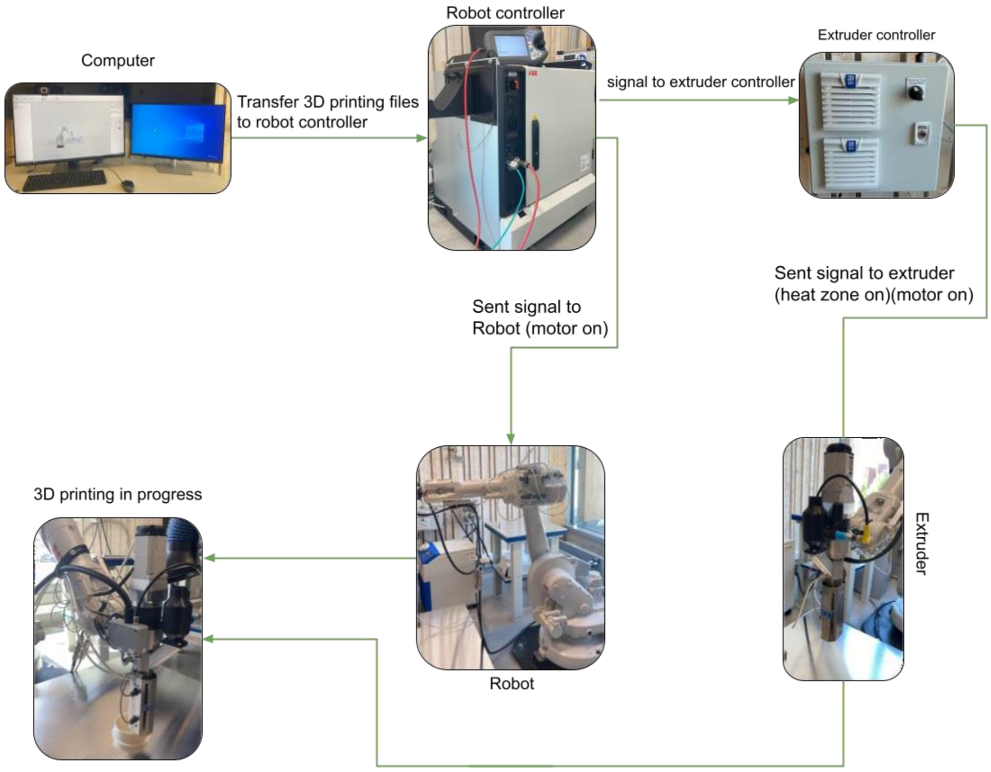


Figure 11: Schematic diagram of the robot 3D printing system

The 3D printing robot cell, shown in *Figure 9* and tabulated in *Table 1*, consists of the following components:

Simulation computer: The CAD and simulation software are installed on this computer, i.e., for CAD: SolidWorks and UltiMaker Cura and for robot simulations: ABB RobotStudio.

Extruder controller: The extruder temperature is controlled from an PID controller installed inside this cabinet.

Industrial robot: The robotic arm is used for moving the extruder head such that three-dimensional structures are printed.

Robot controller: This controller controls the robot movement and also communicates with the extruder and the extruder controller.

Extruder: The extruder is used to melt pellet material to a semi-liquid state that is comparable to a soft paste-like material. Inside the extruder there is screw-mechanism which rotates and pushes the soft paste-like material out of a nozzle. The extruder head is cooled with an **extruder cooler** that pumps water to and from the extruder head.

Heated table: The heated table regulates the cooling process and the material properties of the 3D printed structure. Additionally, the heated table ensures that the 3D printing process is kept stable.

Safety sensor: The safety sensor replaces fences which are usually placed around industrial robots. These safety sensors enable human operators to work close to and even together with industrial robots – this is called human-robot collaboration. In the 3D printing tests in this thesis, human-robot collaboration was not implemented.

Table 1 Components in the robot 3D printing cell

Hardware	**Manufacturer & model**
Simulation computer	Dell, Intel(R) Xeon(R) W-1350P @ 4.00GHz 4.01 GHz
Extruder controller	Gefran PID controller GFX4
Industrial robot	ABB IRB 1600
Robot controller	ABB IRC5 compact
Extruder	KFM (Nozzle diameter: 2 mm)
Heated table	[-]
Printing material	UPM Formi 3D

The sustainable bio and wood-based material composite is shown in *Figure 12*. The technical specification of this material is given in Appendix 1.1.

Figure 12: Sustainable bio and wood-based composite material called UPM Formi 3D used for 3D printing.

5. Results and analysis

Different parameters were used for the 3D printing trials. In *Figure 13,* four-cylinder structures are shown. The printing parameters were changed in such a way as to achieve a printed result with the best surface appearance, i.e., smooth and even surfaces without large colour variations.

Cylinder 1 – 4 are shown in *Figure 13*.

Figure 13: The 3D printed cylinder structures

Cylinder 4 is considered the ""best"" result because of its smooth and even surface appearance. Cylinder 1 – 3 have uneven and burnt surfaces.

For the four experimental trials, base parameters were chosen, see *Table 2*. The base parameters were recommended by the company Addict3D AB from Karlshamn, Sweden. From these base parameters, adjustments were made in the parameter space to achieve the ""best"" result in cylinder 4. The 3D printing parameters for the ""best"" result, cylinder 4, is shown in *Table 3*.

Table 2 Base parameters used for the 3D Printing experiments.

Physical quantity	**Value**
Temperature at top of extruder [Heat Zone 1] [°C]	170
Temperature at bottom of extruder [Heat Zone 2] [°C]	180
Rotation speed of extruder screw [rev/min]	7
Robot speed [mm/s]	70
Temperature of heated table [°C]	90

The printed result of the base parameters is represented by cylinder 1 in *Figure 13*.

The surface in cylinder 1 has zigzag-like imperfections due to increased levels of the robot speed and material flow rate of the extruder. So, the robot speed and the material flow rate were decreased. (The material flow rate is adjusted by changing the extruder screw rotational speed) Additionally, the temperature was also increased. This led to the result represented by cylinder 2, see *Figure 13*. However, the surface appearance of cylinder 2 was unsatisfactory, so the following parameters were adjusted.

First, the temperature was decreased – see the bottom part of cylinder 3 in *Figure 14*. Next, the robot speed and extruder temperature were increased, but this increase led the material to burn – see the middle part of cylinder 3 in *Figure 14*. The robot speed and extruder temperature were decreased after noticing the burn in the material. The material flow rate of the extruder was then increased, which produced a thicker layer than expected – see the top part of cylinder 3 in *Figure 14*.

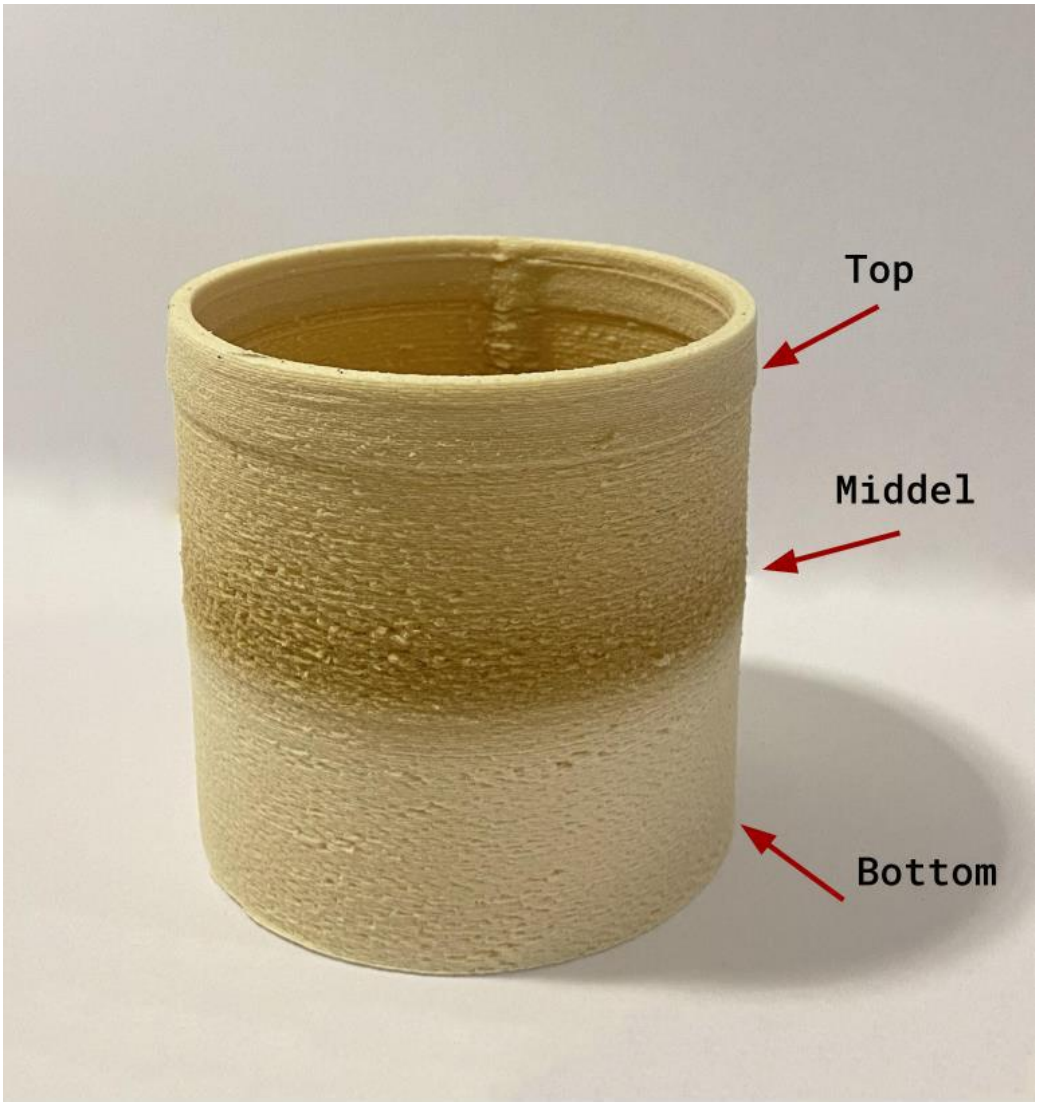


Figure 14: closer look at cylinder 3

The surface appearance of cylinders 1 – 3 was still unsatisfactory; the material flow rate was further decreased to improve the surface appearance. The result of this change in flow rate is represented by cylinder 4. Cylinder 4 is considered the ""best"" result because of its surface appearance, see *Figure 15*

Figure 15 Cylinder 4 is considered the ""best"" result.

In Table 3 the 3D printing parameters are showed which resulted in the ""best"" result, i.e., cylinder 4.

Table 3 Parameters that produced the ""best"" 3D printing results, i.e., cylinder 4

Physical quantity	**Value**
Temperature at top of extruder [Heat Zone 1] [ºC]	150
Temperature at bottom of extruder [Heat Zone 2] [°C]	155
Rotation speed of extruder screw [rev/min]	3
Robot speed [mm/s]	60
Temperature of heated table [°C]	90

In this thesis, the material properties have not been tested, and the ""best"" result, i.e., cylinder 4, should be further improved by fine-tuning printing parameters. These optimization trials were not performed in the thesis.

Figure 16 shows a print screen of the ABB robot interface displaying the different process parameters.

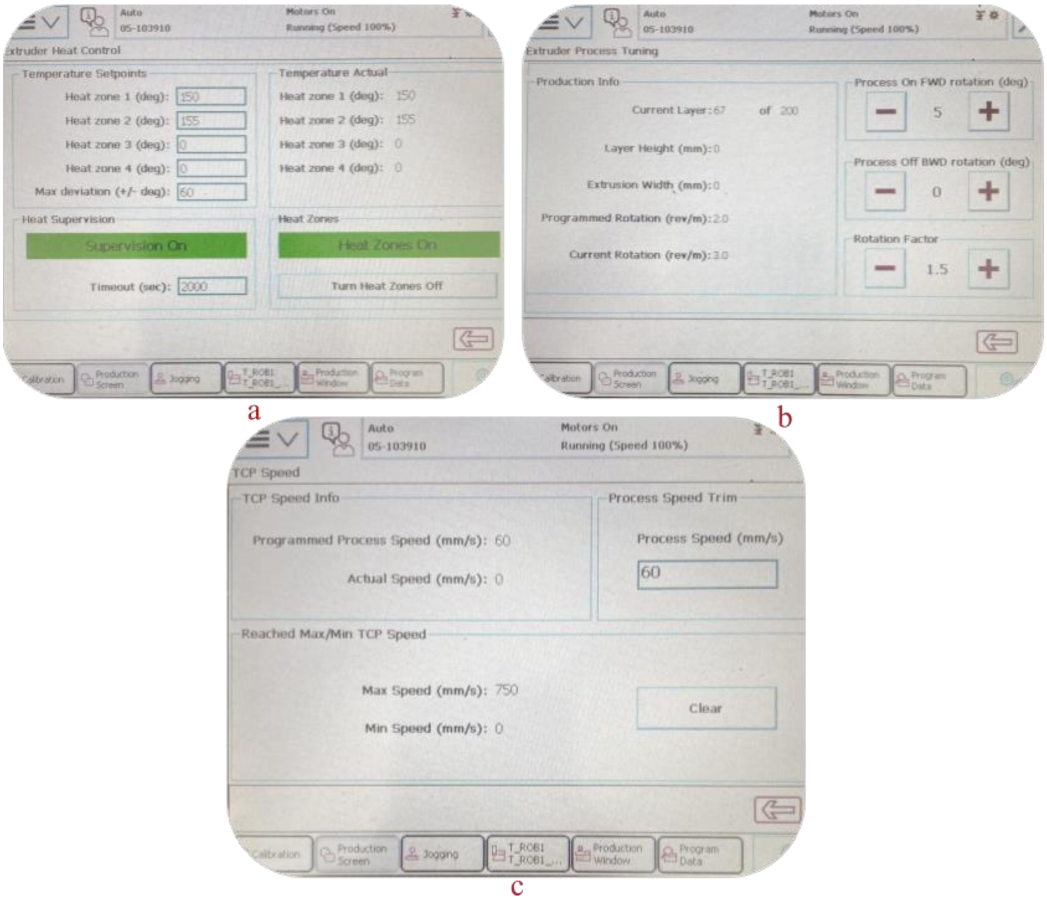


Figure 16 Print screen of the ABB robot interface displaying different process parameters

6. Conclusions and recommendations for future work

The conclusions in this thesis are given by linking them with the research question in Chapter 1. The research question of the this is as follows:

What procedure should be followed in creating sustainable 3D printing structures with an industrial robot?

The procedure of using the robot 3D printing is divided into two parts: simulation and experimental, as is described below.

<u>Simulation</u>

Traditional CAD software is used to design the three-dimensional model. Another design software, called slicer, is used to slice the three-dimensional model into horizontal planes.

Next, robot-specific software should be used to produce the programming codes the physical robot needs to follow a specific path. The software used in this thesis to create the robot code is called ABB RobotStudio.

<u>Experimental</u>

The robot code generated from the above software is then transferred to the physical industrial robot. The robot and a 3D printing extruder head follow the path set out in the robot code. In this thesis, sustainable material consisting of bio and forest-based material is used. Specific 3D printing process parameters are then used to ensure that the extruder can 3D print a sustainable structure with good quality.

The final outcomes are summarized as follows:

- The thesis gives a stepwise guide on the start-up procedure of the 3D printing robot cell – from the simulation environment to the practical implementation with the physical robot.
- Process parameters are given that enable 3D printing of sustainable structures with an industrial robot and extruder.
- The outcomes of the thesis will be used by future students in manufacturing courses at the university. Also, researchers in the SIG – Smart Industry Group lab will use the documentation to start the robot 3D printing cell for related research projects.

The following recommendations are given for future work:

- Different types of materials should be tested in the 3D printing cell. In the thesis, only one type of sustainable material was tested.
- Material and destructive testing should be done on the different printed materials. The results should then be compared to find out which materials have the best material properties after 3D printing.
- A full-scale parameter optimization should be done to find optimal printing parameters for the printing tests done in this study and also for future printing tests with different materials.

7. References

[1] Aithal, G. H. R., & Aithal, P. S. (2022). Why is it called Doctor of philosophy and why choosing appropriate research philosophical paradigm is indispensable during a Ph.D. program in India? SSRN Electronic Journal.

[2] Bellini, A., & Güçeri, S. (2003). Mechanical characterization of parts fabricated using fused deposition modeling. Journal 9(4), 252-264. doi:10.1108/13552540310489631

[3] Blomkvist Pär and A. Hallin. (2015). Method for engineering students: Degree projects using the 4-phase model. Lund: Studentlitteratur. 2&3

[4] Choi, H. S., Crump, C., Duriez, C., Elmquist, A., Hager, G., Han, D., Hearl, F., Hodgins, J., Jain, A., Leve, F., Li, C., Meier, F., Negrut, D., Righetti, L., Rodriguez, A., Tan, J., & Trinkle, J. (2021). On the use of simulation in robotics: Opportunities, challenges, and suggestions for moving forward. Proceedings of the National Academy of Sciences of the United States of America, 118(1), 1-9. doi:10.1073/pnas.1907856118

[5] De Nul, M., Breque, M., & Petridis, A. (2021). Industry 5.0 - Towards a sustainable, human-centric and resilient European industry. Directorate-General for Research and Innovation (European Commission). doi:10.2777/308407

[6] Finkbeiner, M. S., Kühnle, J., & Verl, A. (2022). Towards automatic welding on construction sites: A flexible robotic system for multi-layer welding. In ISR Europe 2022; 54th International Symposium on Robotics (pp. 1-8). Munich, Germany.

[7] Flick, U., Kennedy, B. L., & Thornberg, R. (2018). Deduction, induction, and abduction. In The Sage handbook of qualitative data collection (pp. 49-52). London; Los Angeles: Sage Reference.

[8] Gibson, I., Rosen, D., Stucker, B., & Khorasani, M. (2021). Industrial Drivers for AM Adoption. In Additive Manufacturing Technologies. doi:10.1007/978-3-030-56127-7_21

[9] Goswami, U. (2004). Inductive and Deductive Reasoning. In Blackwell Handbook of Childhood Cognitive Development (pp. 282-283). Malden, MA: Blackwell.

[10] Horvath, J., & Cameron, R. (2020). Mastering 3D Printing: A Guide to Modeling, Printing, and Prototyping (2nd ed.). Nonscriptum LLC, Pasadena, CA, USA.

[11] Jian, Z., Diggle, B., Tan, M. L., Viktorova, J., Bennett, C. W., & Connal, L. A. (2020). Extrusion 3D printing of polymeric materials with advanced properties. Advanced Science, 7(17), 2001379.

[12] Lowhorn, G. L. (2007). Qualitative and Quantitative Research: How to Choose the Best Design.

[13] Pan, Z., Polden, J., Larkin, N., Van Duin, S., & Norrish, J. (2012). Recent progress on programming methods for industrial robots. Robotics and Computer-Integrated Manufacturing, 28(2), 87–94. doi:10.1016/j.rcim.2011.08.004

[14] Patel, R., & Davidson, B. (2019). Forskningsmetodikens grunder, att planera, genomföra och rapportera en undersökning. Studentlitteratur.

[15] Puzatova, A., Shakor, P., Laghi, V., & Dmitrieva, M. (2022). Large-Scale 3D Printing for Construction Application by Means of Robotic Arm and Gantry 3D Printer: A Review. Buildings, 12(11), 2023. doi:10.3390/buildings12112023

[16] Rodrigues, C. T. (2011). The method of scientific discovery in Peirce's philosophy: Deduction, induction, and abduction. Logica Universalis, 1(1), 127-164.

[17] Rosen, D. W. (2007). Computer-aided design for additive manufacturing of cellular structures. Computer-Aided Design and Applications, 4(5), 585-594. doi:10.3722/cadaps.2007.585-594

[18] Ryan, G. (2018). Introduction to positivism, interpretivism, and critical theory. Nurse Researcher, 25(4).

[19] Säfsten, K., & Gustavsson, M. (2020). Research methodology for engineers and other problem-solvers. Studentlitteratur.

[20] Saunders, M., Lewis, P., & Thornhill, A. (2019). Research methods for business students. Pearson.

[21] Valori, M., Caccavale, F., & Siciliano, B. (2021). Validating safety in human-robot collaboration: Standards and new perspectives. Robotics, 10(2), 65.

[22] Vaezi, M., Seitz, H., & Yang, S. (2013). A review on 3D micro-additive manufacturing technologies. The International Journal of Advanced Manufacturing Technology, 67(5-8), 1721-1754. doi:10.1007/s00170-012-4605-2

[23] Werner, J., et al. (2021). MeshSlicer: A 3D-Printing software for printing 3D-models with a 6-axis industrial robot. Procedia CIRP, 99, 110-115.

[24] Wittenberg, G. (1995). Developments in offline programming: An overview. Industrial Robot, 22(3), 21–23. doi:10.1108/EUM0000000004186

8. Appendices

Appendix 1

Technical specification printing material

Technical Specification

UPM BIOFORE BEYOND FOSSILS

UPM Formi 3D 21.10.2019

Material UPM Formi 3D is cellulose fiber filled plastic composite. Principal ingredients are specially selected cellulose fibers and native polylactide acid.

Applications UPM Formi 3D grades are suitable for production of 3D printing filaments to be used in Fused Granular Fabrication (FGF).

Environment UPM Formi 3D is manufactured from renewable cellulose fibers. Material can be recycled or burned for energy. All cellulose fibres are from certificated forests.

Physical and mechanical properties

Property**	Test method	3D 20/19	3D 40
Density, g/cm^3	EN ISO 1183	1,2	1,2
Tensile strength, N/mm^2	ISO 527	39	48
Tensile modulus, N/mm^2	ISO 527	3600	5400
Strain (tensile), %	ISO 527	4	2
Impact Strength, Charpy, kJ/m^2	ISO 179/1eU	20	14
Peak melt temperature, °C	ISO 11357	140-180	135-180
Glass transition temperature,°C	ISO 11357	65	60
Melt flow index (granulates)*	ISO 1133	16	7
Fibre content (%)		20	40

* 190 °C/10kg ** Measured from injection moulded test specimens

Colours Lignin free fibres enable richer colors which, whilst gently lightening over time. The light color remain bright. In filament extrusion, recommended amount of added PLA-based color masterbatch is 0.75% or lower.

Blending UPM Formi 3D 40 can be blended with native PLA plastic or wood plastic composites. Recomended blend ratio: < 25% 3D 40 with PLA.

Pretreatment UPM Formi contains cellulose fibres which may absorb moisture if the package is open. Close the package at all times when possible. UPM Formi composite should be dried for minimum of 3 hours at 80 °C (dehumidifying dryer preferred).

Safety Maximum recommended processing temperature is 200 °C. Overheating may cause risk for thermal degradation. Auto-ignition of UPM Formi material is possible after purging the moulding machine. Recommended to purge into cool water. Product is non-flammable under normal conditions of storage, manipulation and use. In the case of inflammation as a result of improper manipulation, storage or use preferably use polyvalent powder extinguishers (ABC powder) or water, in accordance with the regulation on fire protection systems.

Appendix 2

Simulation operation manual

For a detailed explanation concerning the steps and procedure followed in programming of the 3D printing robot cell, click on the video link below.

Video link describing above steps: https://www.youtube.com/watch?v=J9dO_cpCPv4

The steps described in above video link are also summarized in text form below.

First of all, a 3D CAD model should be drawn using a 3D CAD drawing software. In this case SolidWorks has been used, see *Figure 17*.

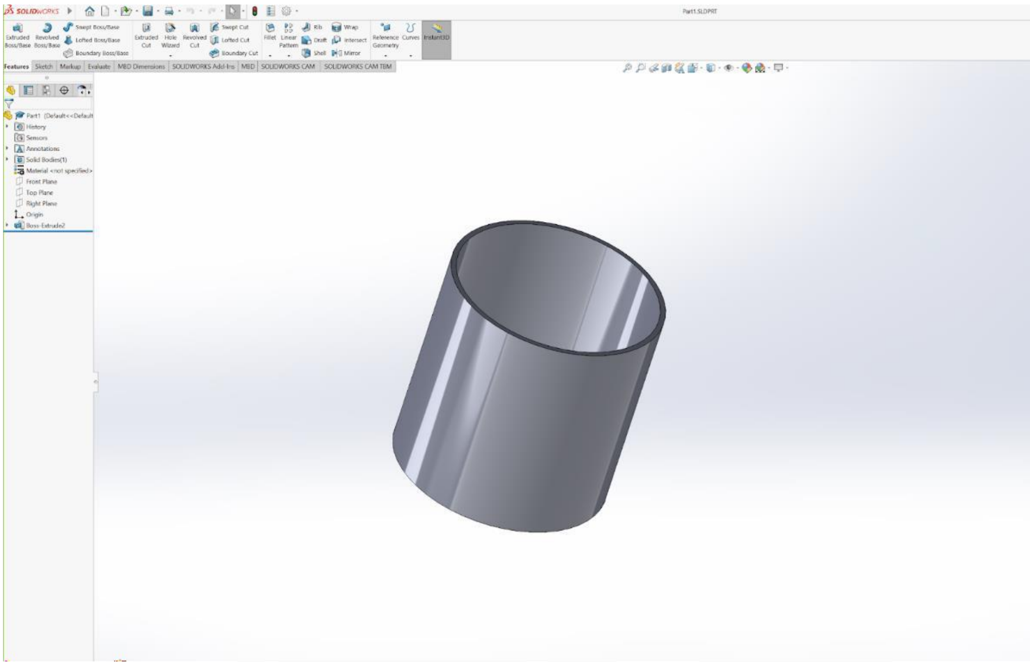


Figure 17 SolidWorks 3D CAD Drawing

Then slice the 3D CAD model using as slicing software. In this case UltiMaker Cura Slicer has been used, see *Figure 18*.

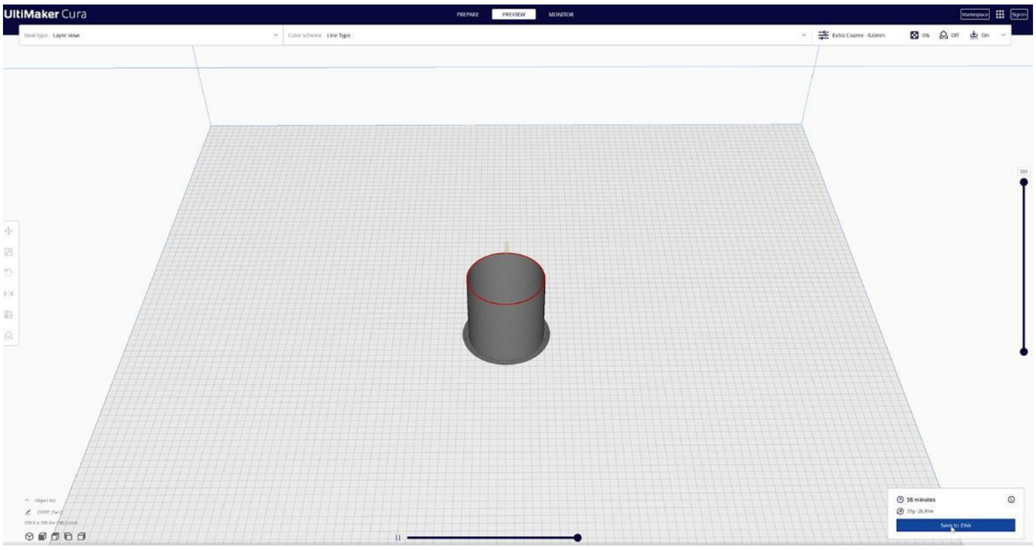


Figure 18 Sliced 3D CAD model

To begin the simulation, start-up *ABB RobotStudio*, from ""controller"" click on ""Add controller"", choose ""One click connect"" to connect to the actual controller, see *Figure 19*.

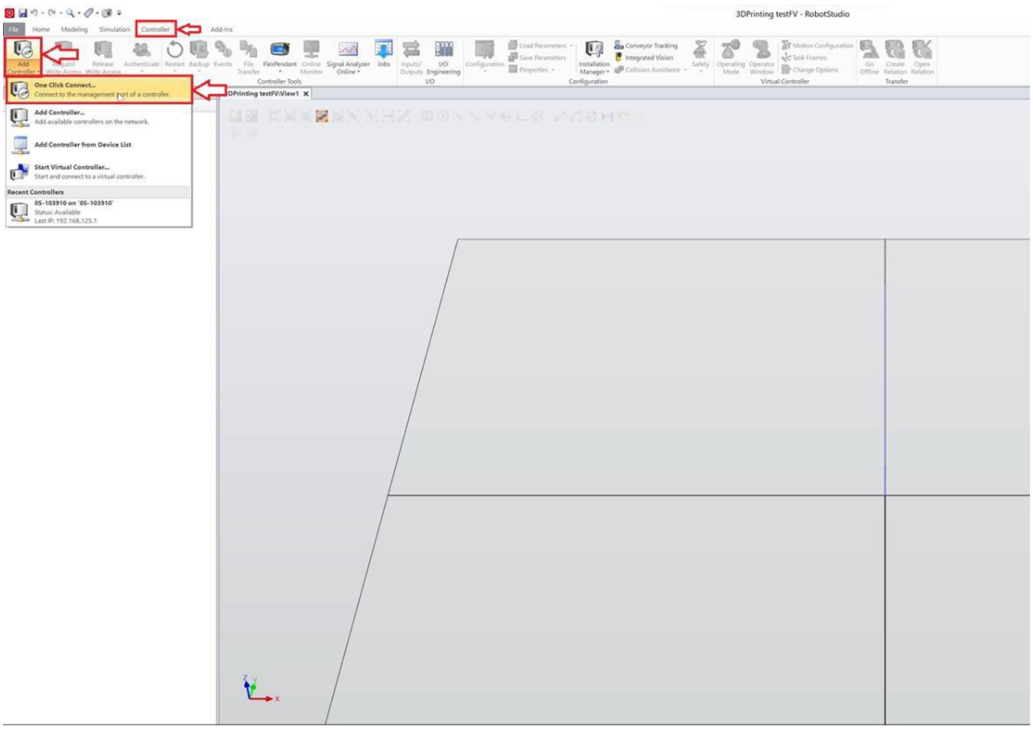


Figure 19 Connecting robot controller to RobotStudio

To add the Extruder and working table, click on ""import library"" and then choose ""browse for library"", see *Figure 20*.

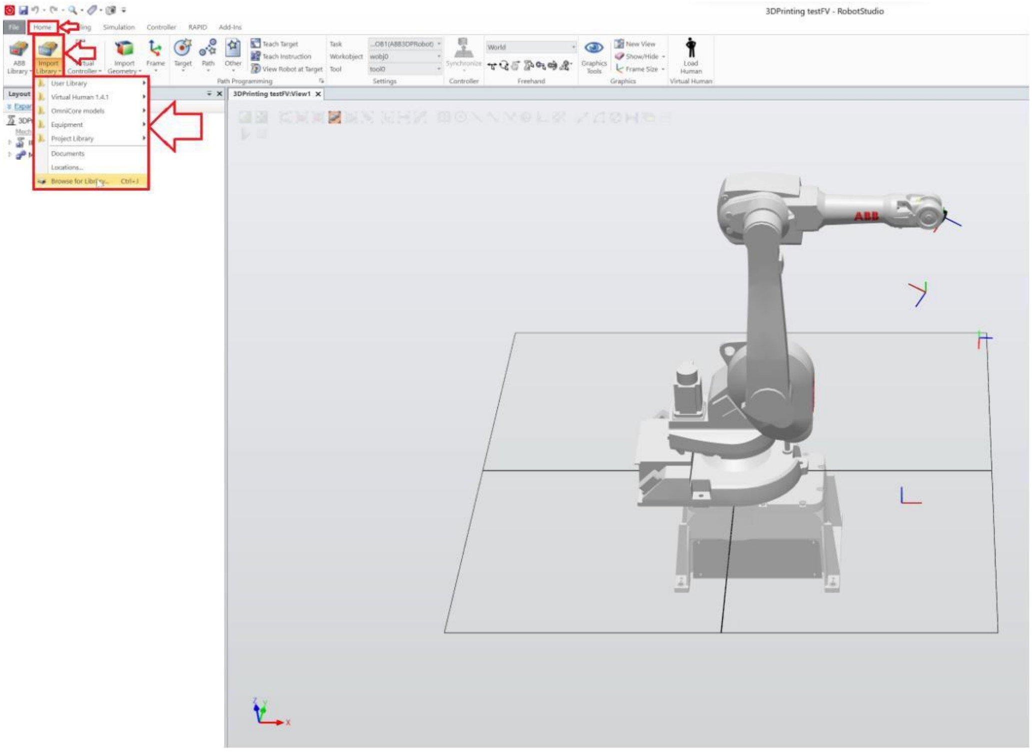


Figure 20 Importing 3D printing tools

From ""Add-Ins"" open ""3DP"" to import the sliced 3D CAD model file, *Figure 21*.

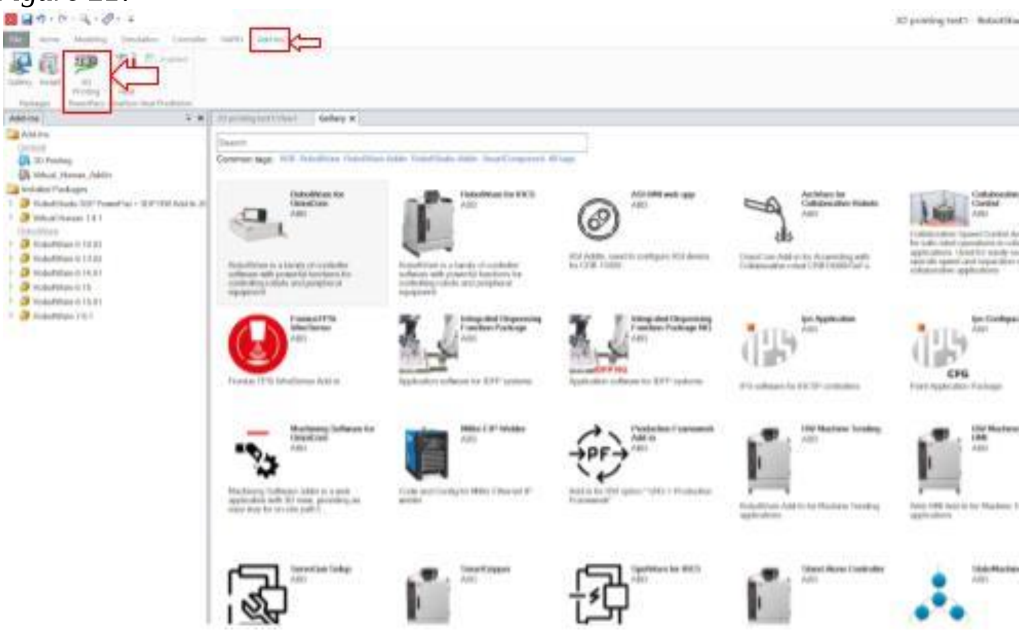


Figure 21 Open 3DP PowerPac

After ""3DP"" has been opened, click ""open"" choose the file with the extension ""Gcode"" then click import, see *Figure 22*

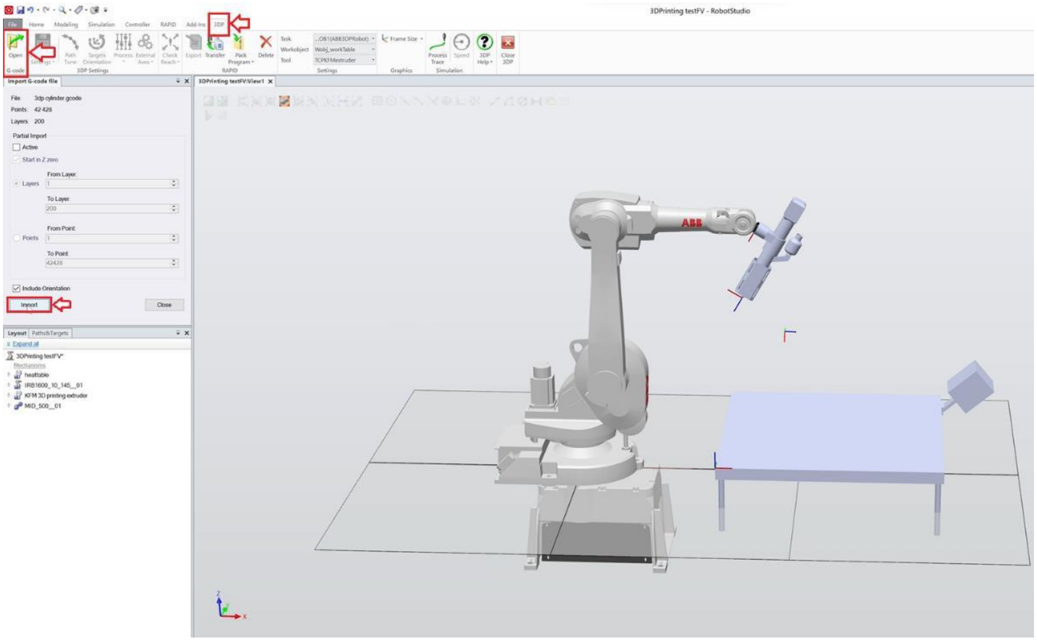


Figure 22 Importing G-code file

Then check the extruder orientation by clicking on ""Target Orientation"" if any changes are needed. These changes can be done from the field ""Rotation (deg")", see *Figure 23*.

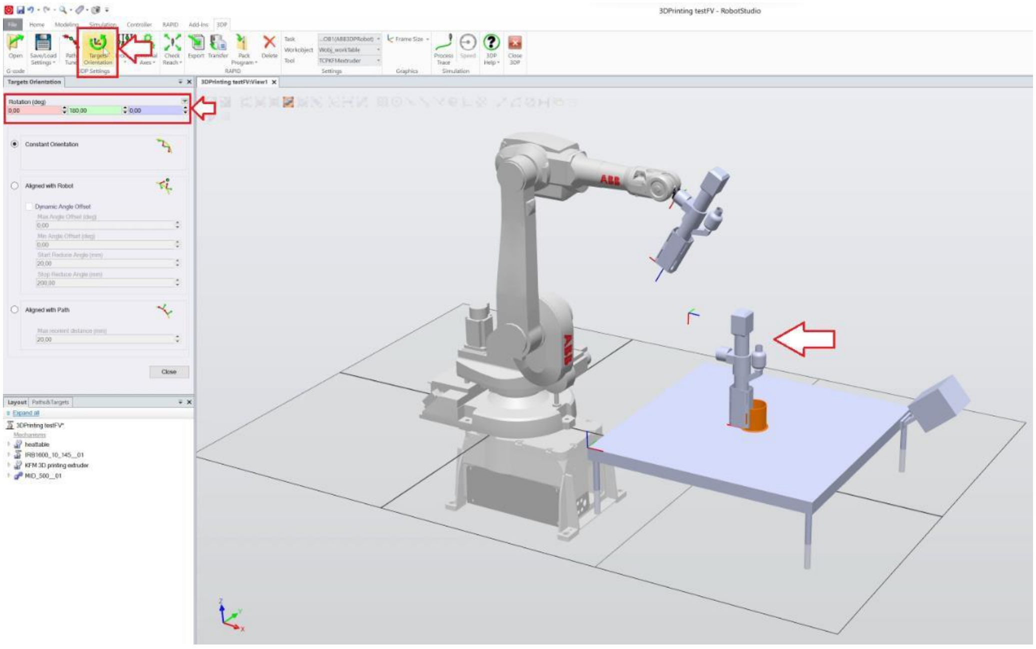


Figure 23 Check extruder orientation

To choose the process settings, click ""Process"" and from the ""Process Settings"" bar choose the optimal settings for the project, *Figure 24*.

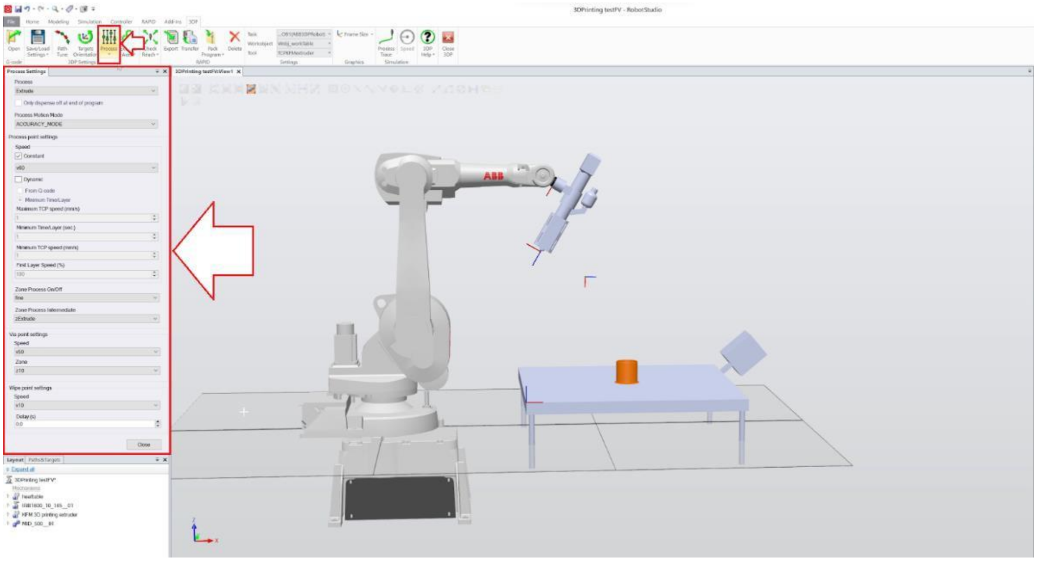


Figure 24 Choose process settings

Set extruder screw parameters by clicking ""External Axes"", choose ""Extruder Axis"", see *Figure 25*.

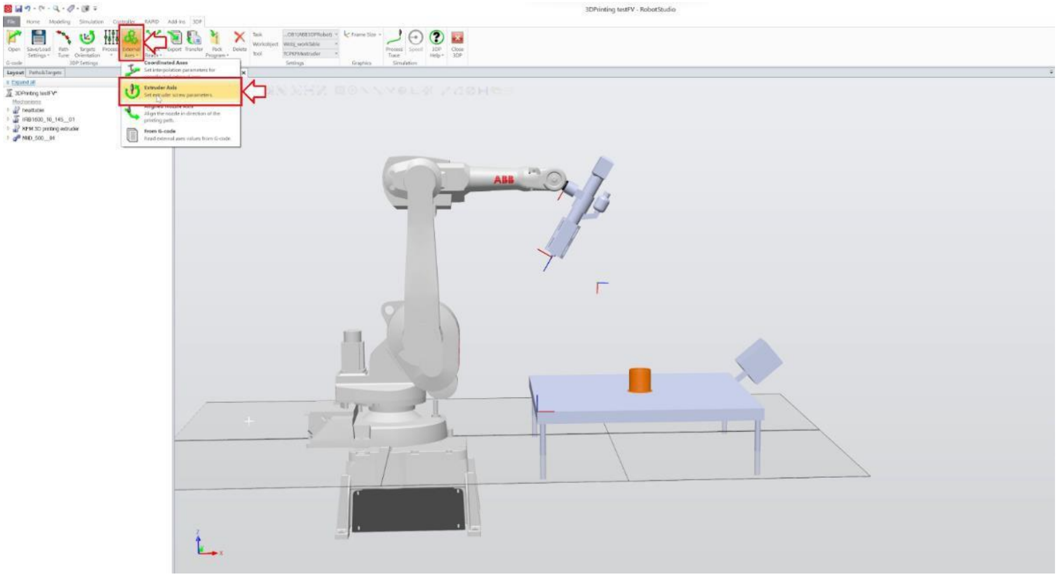


Figure 25 Setting extruder screw parameters

Check the reach from ""Check Reach"", choose ""Check Points"", see *Figure 26*

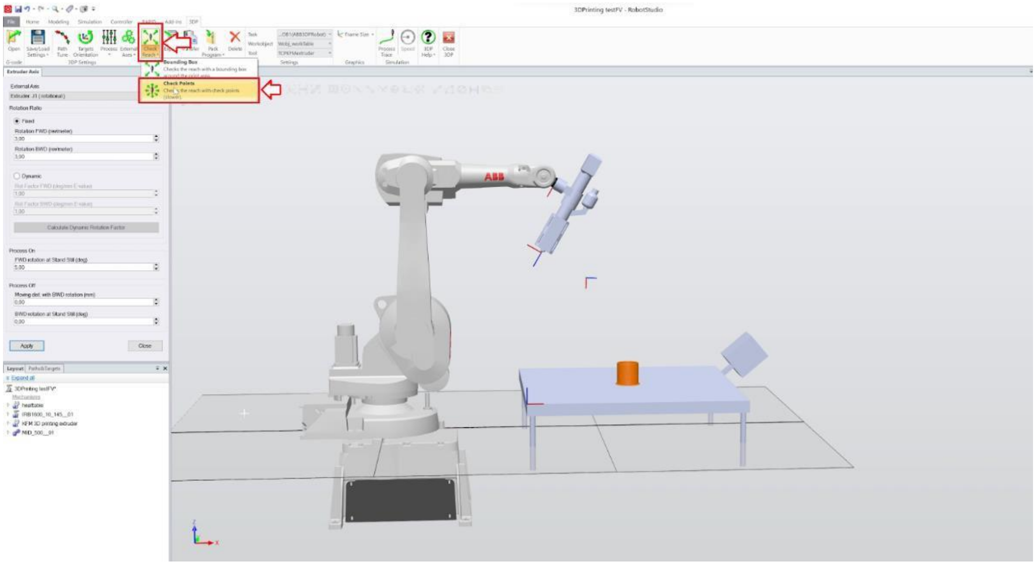


Figure 26 Check reach points

After setting and parameters has been entered, export the files by clicking ""Export"", see *Figure 27*.

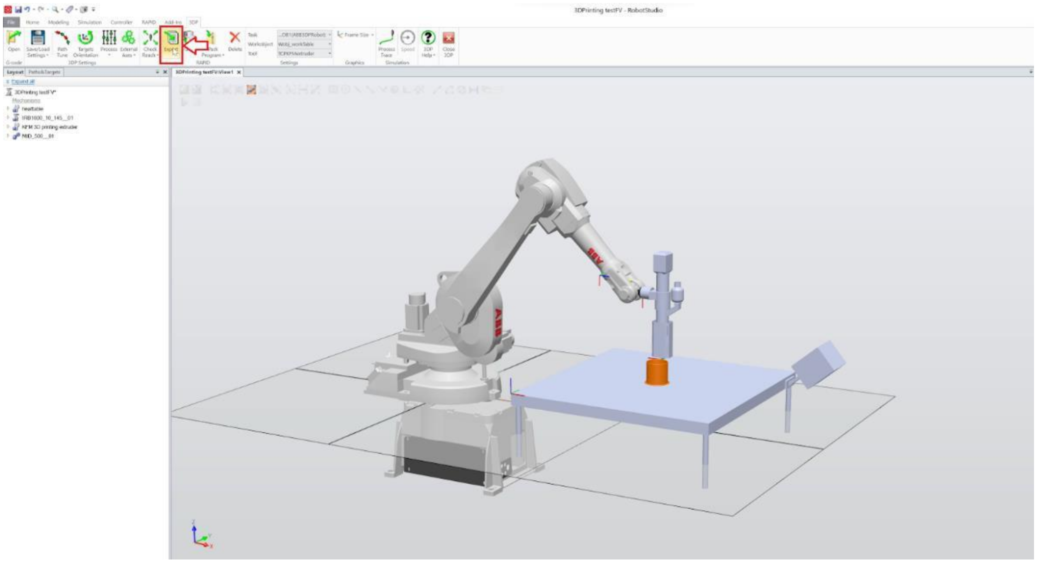


Figure 27 Exporting 3D printing files

Click ""Process Trace"" to trace the simulation movement lines, see *Figure 28*.

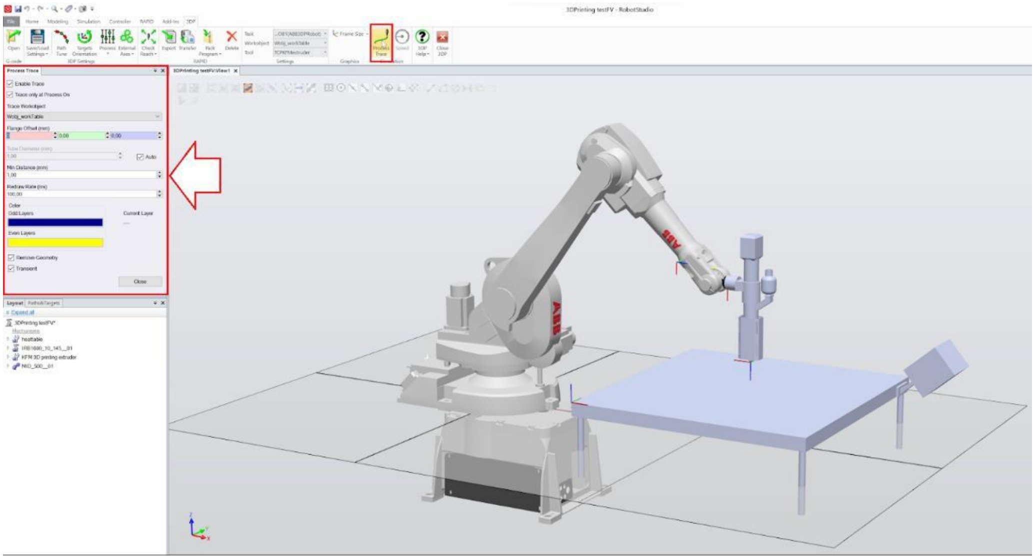


Figure 28 Tracing 3D printing process

From ""Controller"", choose the virtual controller then click ""Operator Window"" to mirror the virtual FlexPendant, see *Figure 29.*

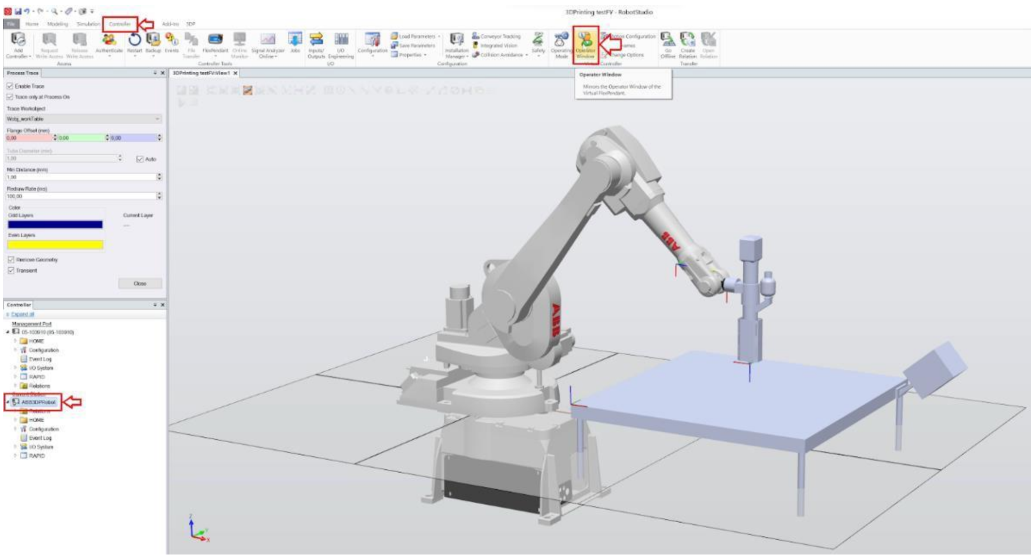


Figure 29 Opening Operator Window

To start the simulation, click on the ""Play"" button then from the Operator Window choose ""Purge"" if extruder cleaning is needed before printing otherwise choose ""Print"", see *figure 30.*

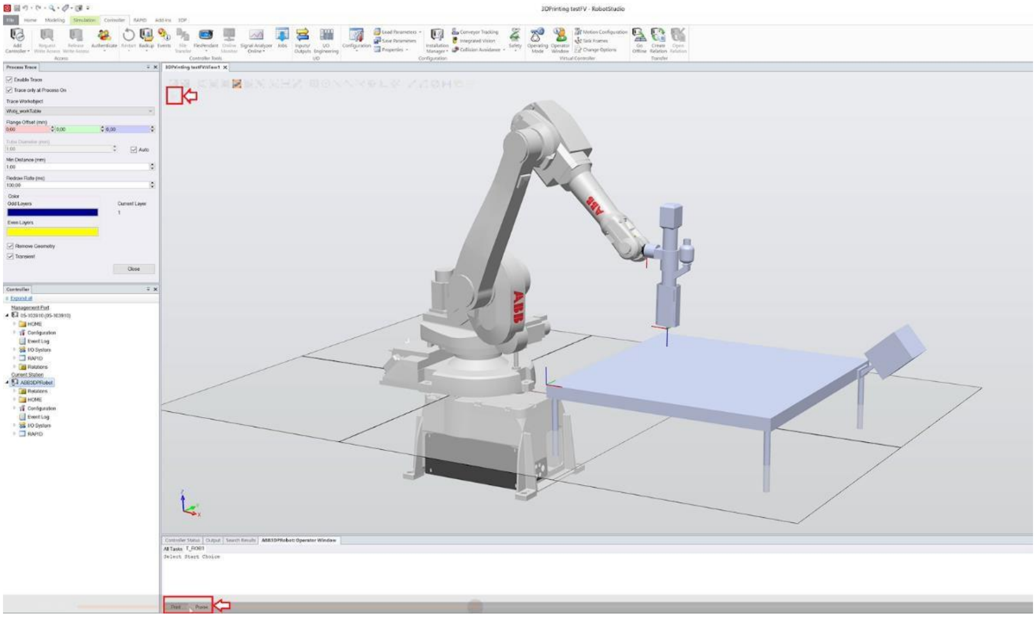


Figure 30 Starting 3D printing simulation

Figure 31 shows the movement tracing lines on Work Object which represent the simulation, Output window shows the simulation process.

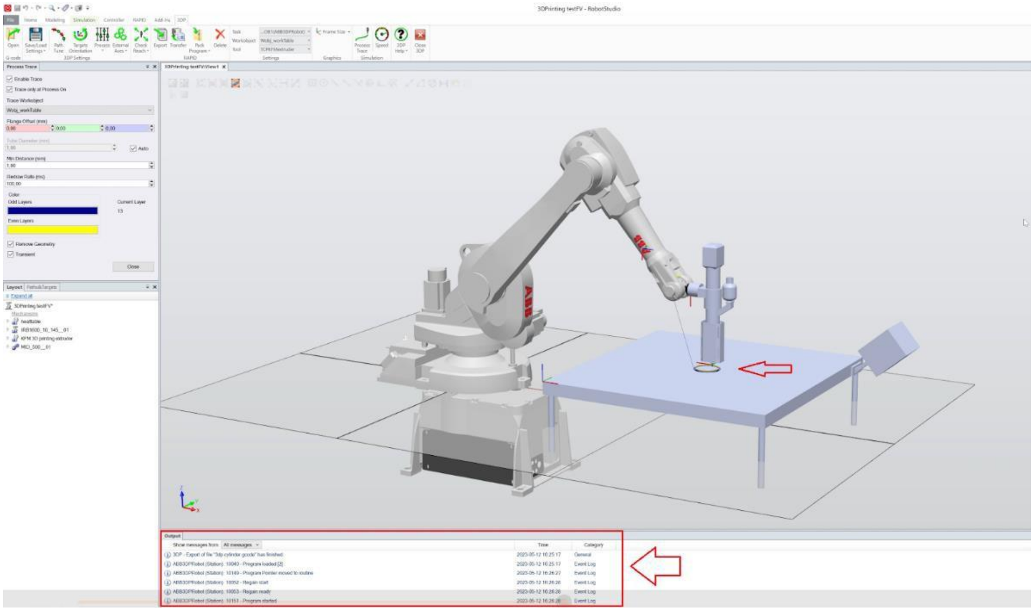


Figure 31 Movement of tracing lines

Figure 32 shows simulation results.

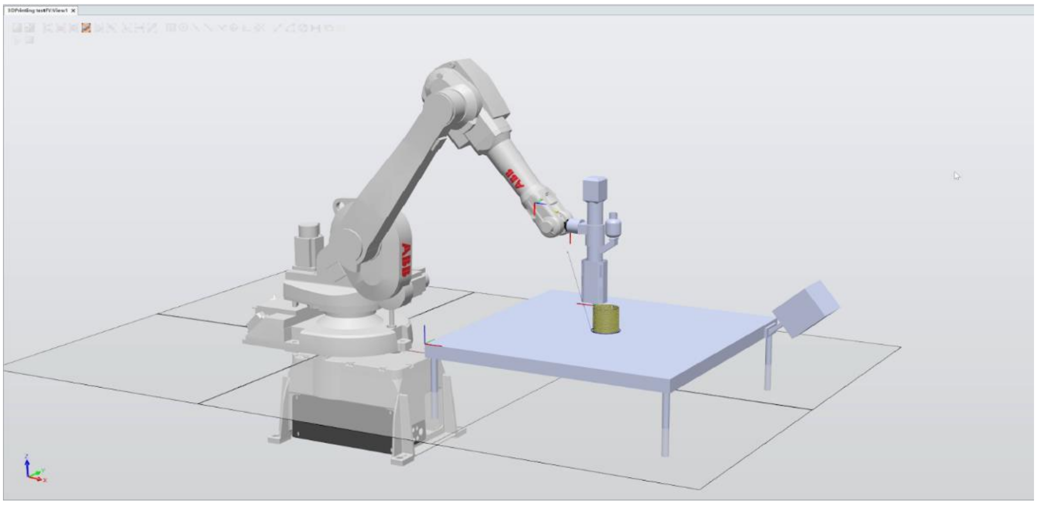


Figure 32 simulation results

After the simulation has been completed, choose the actual controller in the ""Controller"" tab, then click ""File Transfer"" to transfer the files from the virtual to the actual controller, see *Figure 33*

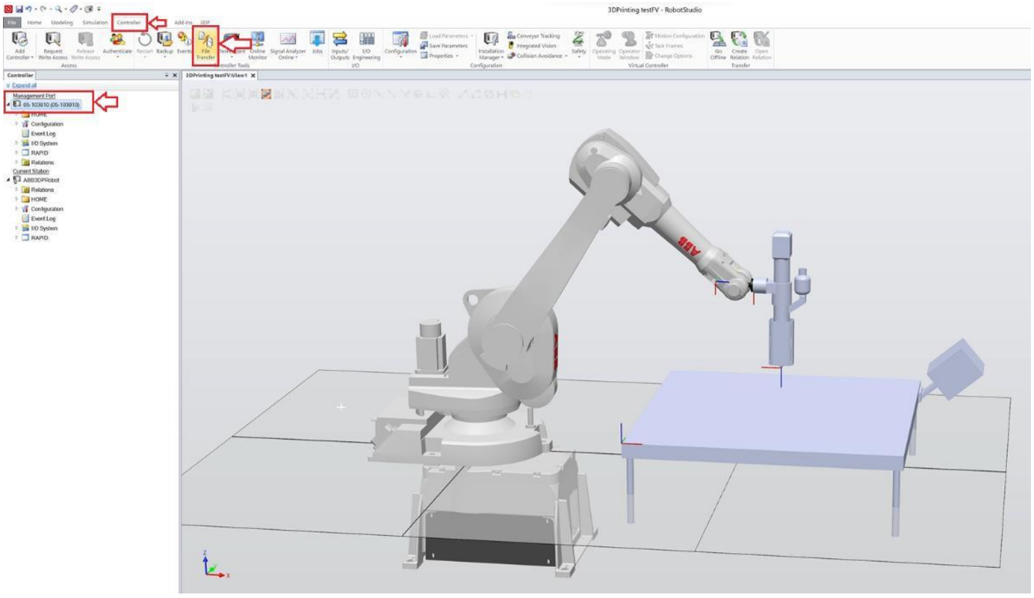


Figure 33 Transferring 3D printing files to actual robot controller

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