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Optical Path Planning for Welding Robots using Laser Triangulation

Bachelor's thesis

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Acknowledgements

Preface

This thesis is written as the final project for two students attending the bachelor degree in Automation and Intelligent Systems at The Norwegian University of Science and Technology in Ålesund 2023. The main goal of the thesis is to develop a non-contact probe for Møre Trafo AS to help compensate for misalignment in welding process of transformer containers. Møre Trafo AS is the leading Norwegian producer an supplier of distribution transformers and grid stations. They are owned by Møre Electic group which consists of a 66% ownership by the family group Rieve gruppen and 34% by Schneider Electric. The factory is located in Sykkylven, Norway.

Laser triangulation is commonly used for distance probing since it can measure small and large objects without touching the piece. But the probes are often expensive due to robust and high quality components. Using non-contact probes are often used in robot welding due to its high precision and minimal interference with the workpiece. Our aim with this thesis is explore the possibility of using machine vision and laser triangulation to locate features for path calculations.

Abstract

This report documents the solution and findings of a case given by Møre Trafo AS. The case is based on developing a non-contact probe for improved accuracy when robot welding. The current solution uses touch probing and is prone to hitting features on the workpiece and changing the correct path for welding. The developed solution utilizes laser triangulation to locate a seam between two metal plates and used ROS2 to control a Universal Robot UR10. The probe uses machine vision to locate a laser line and finds the seam based on the height profile of the line. The probe was tested on the real product and could find the seam with 80,3% accuracy.

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Terminology

Concepts

3D printing Printers that can print out 3D objects. Usually in plastic.

Blur An image process that removes detail. Commonly used to remove noise from an image.

Collaborative robot Robots designed to work safely within the same space as a human.

Contact probe A probe that uses current flow when touching an object to determine dimensions of a welding part.

Digital clone Using software to create a simulated version of a physical system.

End effector The tool connected to the flange of a robot.

Fork In the context of Git version control, a fork is a copy of a repository that you manage.

Grayscale The process of turning a colored image into grayscale using image processing.

Load cell A sensor that measures the weight of an object.

moveJ Joint move on a robot.

moveL Linear movement on a robot.

Non-contact probe A scanner that measures dimensions using a camera and light.

Touch probe A load cell based probe used in welding application to determine dimensions of a welding part.

Workpiece An object being worked on by a tool or a machine.

Abbreviations

ARM Advanced RISC machine

CAD Computer aided design

CAM Computer aided manufacturing

CPU Central processing unit

CSI Camera serial interface

DH parameters Denavit-Hartenberg parameters

URDF Unified robotics description format

FDM Fused deposition modeling

GMAW Gas metal arc welding

GPIO General purpose IO

GPL General public license

GTAW Gas tungsten arc welding

HSV Hue saturation value

IT Input / output

MIG Metal inert gas

OS Operating system

RAM Random access memory

RGB Red, green, blue

ROS Robot Operating System

SSH Secure shell or Secure socket shell

TCP Tool center point

TIG Tungsten inert gas

UR Universal robot

USB Universal serial bus

1   Introduction

The case for this project is provided and developed at the request from Møre Trafo AS located in Sykkylven, Norway. They asked for a solution to a manufacturing problem caused by a probing program for a welding robot that would sometimes deviate from the welding path.

1.1   Background Information

Møre Trafo is Norway's largest manufacturer and supplier of transformers and grid stations. One of the processes in making the transformers is welding the container for the transformer. The container is a set of heat sinks that contains the transformer and is submerged in mineral oil to prevent moisture, overheating and to maintain efficiency. The welding process of the container is the subject of this thesis and will be further covered in the introduction.

1.2   Research Problem and Motivation

Møre Trafo AS is having problems when using robots to weld. The process today uses touch probing to decide where to weld the edges. As the sizes of the containers vary from under 100x100x80cm up to 180x200x120cm, this is a good method to use a robot in a versatile way. The weld can sometimes be not aligned due the robot hitting production defects when measuring the transformer, for example a spot weld, as can be seen in Figure 1.1. This can cause the robot to miss the weld by a few millimeters causing the weld to melt a hole in the heat sink. This then leads to the transformer leaking oil when submerging. The rest of the robot program performs as intended, but the scanning for the weldable area can be improved. Møre Trafo AS wants a scanner to scan the edges to compensate for these errors while still using the touch probing.
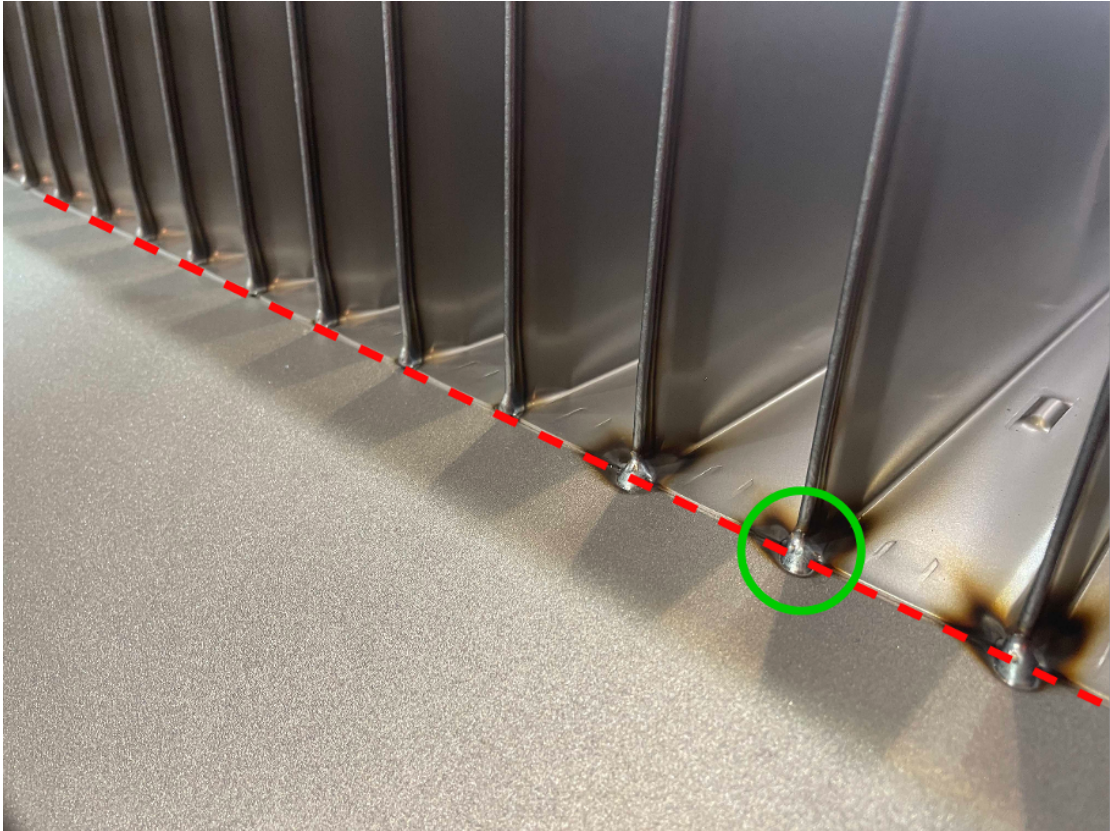
Figure 1.1: Weldable area (Red dotted) and production defects (Green)

1.3   Aim and objective of the thesis

The objective of this project is to see if it is feasible to implement a laser triangulation system to detect the edges of the seam where two parts meet. The main target of this project is to create a sensor to detect the edges and make a robot automatically follow the seam to create a weld.

1.4   Scope and Limitations

The planned goal is to develop and scan the surface of the transformer with a non-contact probe. The probe will locate the seam of two metal plates with the help of laser triangulation. This thesis documents the findings and the process of how the probe works. The thesis will not be focusing on implementing the developed probe into the existing program.

1.5   Methodology

The beginning of the research process is focused on researching similar products to explore what is on the market. The next step is to create a digital clone of the system to simulate the process while ordering parts and designing the physical system.

Creating a digital clone to simulate the system allows us to start creating a program to detect the laser and edge. This has also the added benefit of testing the programs that controls the robot without using a physical robot.

The brackets for the parts in this project will be 3D printed as this cuts down on time while prototyping. Designing the 3D models for the brackets and robot while the ordered parts are in shipping, makes it possible to test the fitment of the brackets as soon as the parts arrive. If any fitments does not fit, adjustments can be made to the 3D model without having to redesign the whole part. This is a fast and cost effective way to prototype parts.

1.6   Significance of the Study

This thesis is solving a client based case, directly benefiting the client. The methods showed use of laser triangulation using easy to acquire hardware. The non-contact probe can be further developed for use in other projects or applciations.

1.7   Thesis Structure

This thesis is structured as a report with the sections referencing each other. Here is the main structure of the text:

- Theory, the relevant background knowledge the thesis is based on.

- Software and Hardware, overview of the software and hardware used in this project.

- Methods, how we used the background knowledge and soft-/hardware to reach our goals.

- Results, what the Method section discovered or generated.

- Discussion, looking back on the choices made in the Method section.

- Conclusion, the findings from the thesis and what we recommend as further work.

2   Theory

This chapter will cover the theoretical basis for the project. The subjects of the chapter is laser triangulation, robot control, and computer vision.

2.1   Laser Triangulation

Extracting height data from a surface is a common task when working with automation and fabrication. There are different approaches to solving this task and the output from the scan will differ based on the selected technique. One of the simple technique is to use a probe consisting of a conductive metal and touch the work piece that is grounded. The probe will register the work piece by measuring the conductivity. By probing the work piece on different locations a more detailed scan can be created. This is called an electrical or contact measurement probe. One of the drawbacks with an electrical probe is that the work piece is not always conductive and cannot be grounded. To solve this problem, a load cell can be installed in the probe. The probe can now detect when the probe contacts the work piece by measuring the amount of force on the sensor. This is called a touch probe and is commonly used in robotics applications.

While these two solutions does work for simple point probing, they both suffer from only probing one point at a time. This can add up the time of the operation on a complex part. By utilizing a camera to sample data the need to make contact with the work part is eliminated. The camera uses a reference point that is projected on to the surface to analyze the surface it is looking at. The reference point can be a single laser dot, a laser line or more complex shapes (Figure 2.1) based on the requirements of the scan. This is called a non-contact measurement probe.
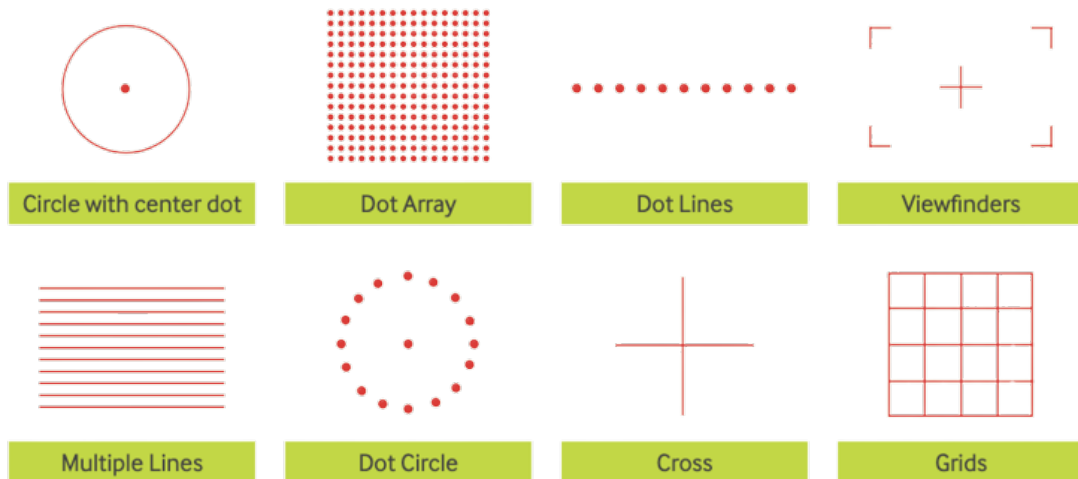
Figure 2.1: Commonly used laser patterns [1]

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[1]Image from `global-lasertech.co.uk` (Line laser manufacturer)

To calculate the distance from the camera to the reference point, a few parameters of the system need to be known. The angle (θ) and the distance (a) between the optical sensor and the laser pointer [1]. Formula 1 and 2 are used to calculate the optimal angle based on the distance requirements of the scanner. Note: λ referees to the Field of View of the selected camera.

$$\theta = \tan^{-1}\left(\frac{D}{D/(\tan(a - (\lambda/2)) + b)}\right) \ \ for \left(\frac{D}{D/(\tan(a - (\lambda/2)) + b)}\right) \geq 0 \quad (1)$$

$$\theta = \tan^{-1}\left(\frac{D}{D/(\tan(a - (\lambda/2)) + b)}\right) + 180 \ \ for \left(\frac{D}{D/(\tan(a - (\lambda/2)) + b)}\right) < 0 \quad (2)$$

(a) Maximum distance   (b) Scanned object hit by laser
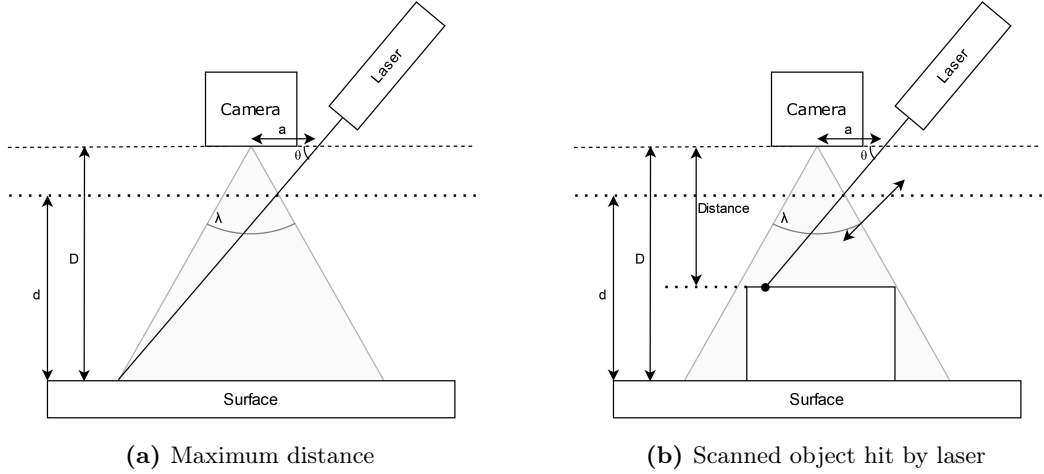
Figure 2.2: Reversed Geometry setup scan. The laser acts as a reference point to calculate distance [2].

With the reversed geometry setup, the scanned object that is closer to the camera will appear at the top, while the surface that is further away will be at the bottom of captured the image.

2.2 UR10 Forward Kinematics

Knowing the position of a robot is a crucial step in controlling it. The Denavit-Hartenberg (D-H) method is a systematic approach to forward kinematics based on joint positions. Forward kinematics is the operations of calculating the position of the end-effector on the robot based on known joint parameters. The first step in the D-H method is to assign coordinate frames to each joint as shown in figure 2.3 [2].

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[2]Information is from [1], but figures are ours.
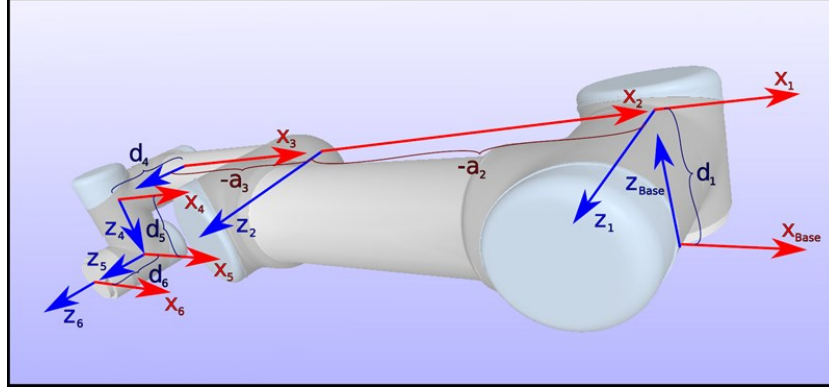
Figure 2.3: Coordinate Frames on UR Robot[3]

Then each joint needs parameters that describes how the joints interact with each other[3].

- θ : Angle, rotation from X_{prev} to $X_{current}$.

- a : Distance, offset from Z_{prev} to $Z_{current}$ along X_{prev}.

- α : Angle, rotation from X_{prev} to $X_{current}$ along $Z_{current}$.

- d : Distance, offset from X_{prev} to $X_{current}$ along $Z_{current}$.

2.3   Denavit-Hartenberg Representation

For each joint of the robot, a transformation matrix is applied. The matrix describes the relationship between the current and previous joint. The 4x4 matrix contains both translation and rotation data.

$$T_{i-1,1} = Rot(\hat{x}, \alpha_{i-1})Trans(\hat{x}, a_{i-1})Trans(\hat{z}, d_i)Rot(\hat{z}, \theta_i)$$

$$= \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & a_{i-1} \\ \sin\theta_i\cos\alpha_{i-1} & \cos\theta_i\cos\alpha_{i-1} & -\sin\alpha_{i-1} & -d_i\sin\alpha_{i-1} \\ \sin\theta_i\sin\alpha_{i-1} & \cos\theta_i\sin\alpha_{i-1} & \cos\alpha_{i-1} & d_i\cos\alpha_{i-1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$= \left[\begin{array}{ccc|c} R_{xx} & R_{xy} & R_{xz} & T_x \\ R_{yx} & R_{yy} & R_{yz} & T_y \\ R_{zx} & R_{zy} & R_{zz} & T_z \\ \hline 0 & 0 & 0 & 1 \end{array} \right] \tag{4}$$

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[3]Image from: `https://www.universal-robots.com/articles/ur/application-installation/dh-parameters-for-calculations-of-kinematics-and-dynamics`

The results of solving the D-H Representation is a 4x4 matrix with a 3x3 submatrix describing the rotation, and a 3x1 describing the translation of the joint (Equation 4).

2.4 Robotics and Automation

There are different types of industrial robots used depending on the task performed. In this text only the mechanical arm type of robot will be covered because of relevance to the theses. When working with a mechanical arm type robot, there are different terms and specifications that shows the capabilities of the robot.

The work space of the robot is a machine drawing that shows the dimensions of the robot, as well as the reach and angle that the robot can move. An example of this can be seen in figure 2.4.
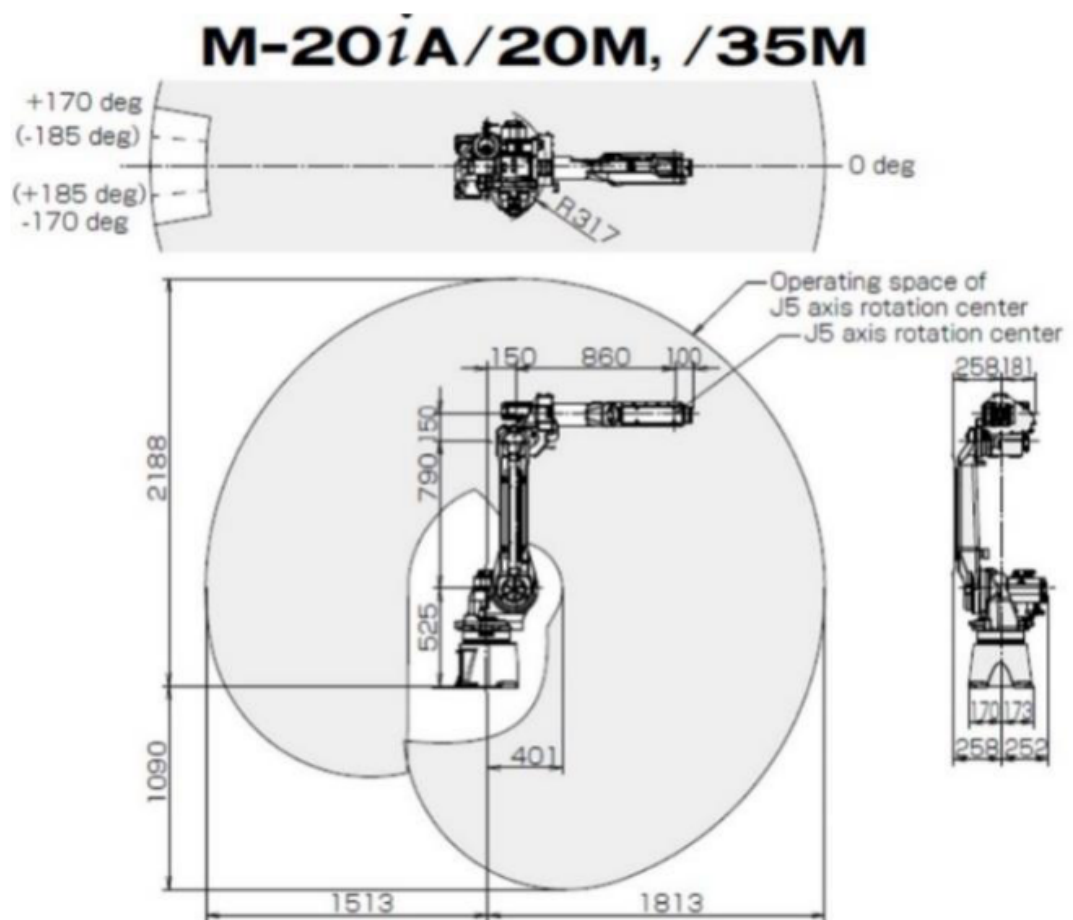
Figure 2.4: Example of a robot work space from a FANUC Robot M20iA/20M/35M [4]

Common terms used in robotics [4]:

The payload of the robot describes the maximum amount of weight an arm can carry, with the same amount of speed, acceleration, accuracy and repeatability.

Coordinate systems are a robots reference point to move in space. The standard coordinate system is positioned at the center of the base of the robot.

The tool center point (TCP) is a coordinate system that is calibrated for the specific tool the robot is using. Doing the calibration for TCP is essential to create an accurate and repeatable process for the robot.

The accuracy of the robot is a number that describes the maximum deviation of the robot when moving the TCP to a specific point.

Repeatability describes how much the robot deviates when bringing the TCP to the same location multiple times.

2.5   Welding Processes

Using robots for welding processes is a method to decrease cost and increase quality of a product. The measure of this however, is determined by the complexity of the part, the production time and repeatability [5]. As the innate repeatability in robots could be as low as 0.02mm this should not be a problem, but depending on the process there could be other factors that degrades the repeatability[4].

There are several different types of welding technologies that are in use in robot welding processes. Gas tungsten arc welding (GTAW), or tungsten inert gas (TIG) as it is more commonly known, is a welding technology that uses an electrode made from tungsten or a tungsten alloy. When weldig with TIG the electrode gives of a constant arc that heats the metal pieces and fuses them together. To fuse two pieces together, a TIG welder can either use the heat from the arc directly, or use filler material for bigger welds. An advantage for this method is that it has low noise, little spluttering and good heat accuracy. The high precision does however come at the cost of speed in the process. As the electrode is made of tungsten and is not consumed in the welding process, TIG is suitable to weld different metals that are electrically resistant or requires precise heat control. A constant stream of inert gas like argon or helium is used when welding to prevent oxidation on the part that is being welded [5]. For a visualisation of a robot TIG welder see Figure 2.5

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[4]Robot repeatability specs: `https://www.ia.omron.com/products/family/3866/specification.html`

TIG process

1 - Electrode
2 - Wire guide
3 - Filler metal
4 - Nozzle

5 - Shielding gas
6 - Arc
7 - Base metal
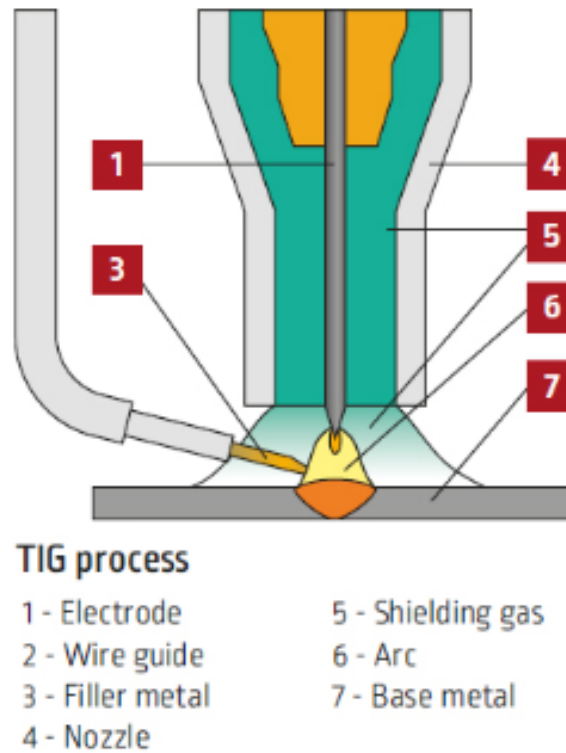
Figure 2.5: Visualisation of a TIG welder used for robots [5]
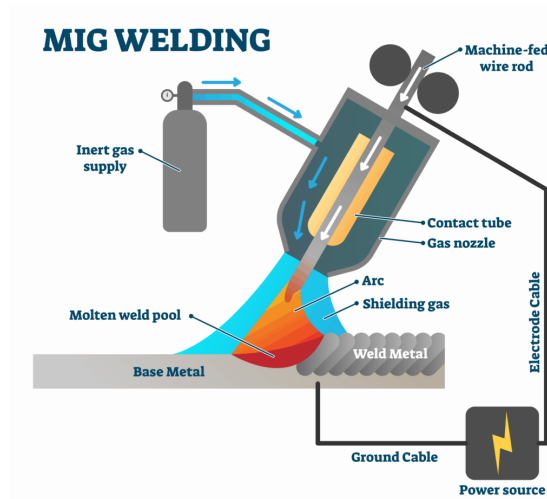
Figure 2.6: Simplified model of MIG welding [6]

Gas metal arc welding (GMAW), or metal inert gas (MIG) welding is a welding technology that feeds a continuous stream of consumable wire electrode. When the wire initiates the arc with the work piece, it itself is consumed in the welding pool. As the material from the wire is melts and is added to the weld, the system needs to be tuned to each weld to optimize wire speed and heat. If the system is not tuned correctly the electrode

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[5]TIG example: `https://robotsdoneright.com/Articles/top-welding-process-for-robotic-automation.html`

[6]MIG example: `https://www.technoxmachine.com/blog/mig-vs-tig-welding/`

can splatter, melt through the material or not combine correctly to the material causing a weak weld [5]. See Figure 2.6 for a visualisation of MIG welding. MIG is the most used method in automated welding processes, due to it being quicker than TIG, and easier for the operator to program[7].

2.6 Safety in Robot Welding

When a new robot manufacturing process is created, it is common practise to undergo a job safety analysis to determine the risk factors to human life. From this analysis safety barriers can be created for the robot. A simple method that is often used is putting up a physical barrier between the operator and robot [6].

The specific safety measures in use when having a robot welder must then be determined from the job safety analysis. An example of this would be to protect the operator from welding arcs, as well as making it impossible for the operator to come in contact with the robot mid operation.

2.7 Computer Vision and Image Processing

This chapter will explain the general theory behind the vision and image processing operators that are used in the thesis.

2.7.1 HSV

Hue saturation value (HSV) is an alternative representation of the RGB colour space. Instead of using values of red, green and blue, it uses values of hue, saturation, and brightness [7]. Hue refers to the colour of a pixel, saturation refers to the intensity or purity of the colour, and the value determines the brightness.
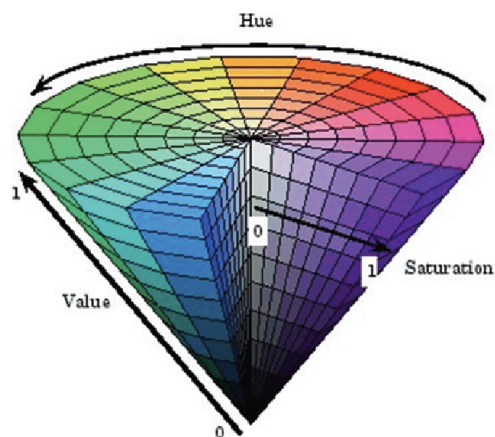
Figure 2.7: HSV colour representation [7]

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[7]Robot welding methods: `https://robotsdoneright.com/Articles/top-welding-process-for-robotic-automation.html`

This process is well suited for image segmentation where HSV can be used to isolate a single colour from an image. The image can then be further processed with other image processing methods. As seen in Figure 2.8 the pink balloons gets segmented from the rest of the image.
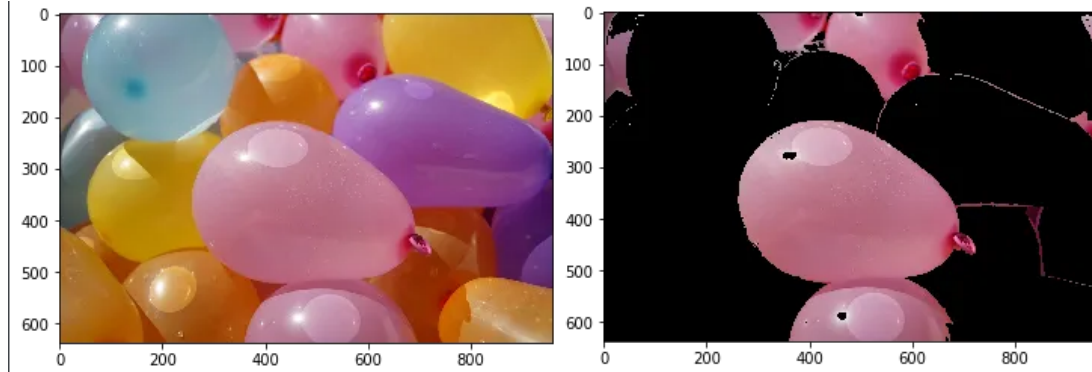
Figure 2.8: Image segmentation using HSV [8]

2.7.2 Sobel edge detection

Edge detection is a useful tool when working with image processing. The sobel edge detection operator is an operator that uses convolution to find changes in pixel value to determine edges in an image. To do this a 3x3 matrix called a kernel is used. This kernel is a filter that computes the sum of values between the filter and corresponding pixels in every point [8]. Figure 2.9 shows how the kernel checks the pixel values in the image. The kernel is overlaid on the image so that the center of the kernel is on top of a pixel in the image. This is repeated for every pixel in the image. For each position of the kernel, the corresponding pixel values of the image and the kernel values are multiplied together. These products are then summed up to get a single number as seen in Figure 2.10. This sum is the new value for the central pixel where the kernel is centered.

The sobel operator is a two stage process that finds edges once in the x-axis, and once in the y-axis using the kernels listed in Equation 5. When combining these however the diagonal edges are not included. To mend this the operator uses trigonometry to find the vectors of the diagonal lines as seen in Equation 6.

$$Horizontal : \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} Vertical : \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix} \tag{5}$$

$$\text{Rate of change: } G = \sqrt{G_x^2 + G_y^2} \text{ Gradient angle: } \Theta = arctan\left(\frac{G_y}{G_x}\right) \tag{6}$$

---

[8]HSV example: https://medium.com/neurosapiens/segmentation-and-classification-with-hsv-8f2406c62b39
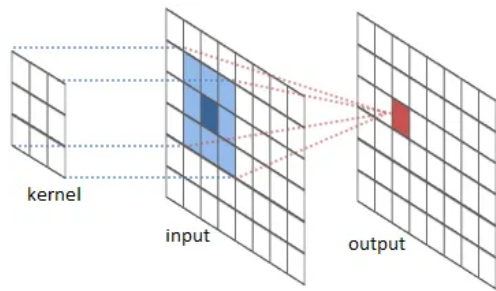
Figure 2.9: Image convolution - kernel filtering [9]
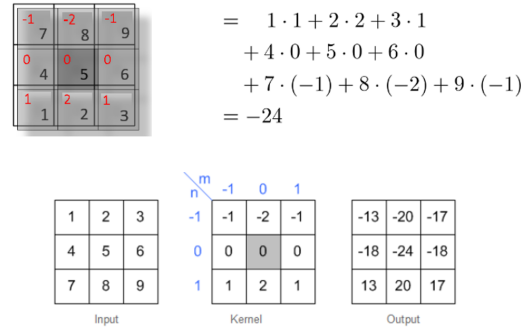
Figure 2.10: Sobel kernel calculating vertical changes [10]

2.7.3   Canny edge detection

To further enhance the edge detection of the sobel operator, the canny edge operator can be used. It uses a hysteresis threshold based process to detect differences in pixel magnitudes to determine the edges in the image . In order to do this, it requires a multi-stage process to find these edges. The first step in this process is to either isolate the object in the image with for example HSV, or to grayscale the image in order to use pixel values in the same colour space. The second step is to use the sobel edge detection on the image. The edges from the sobel processed image are not necessarily imprecise, but they can be several pixels thick. When using the canny edge operator it takes the edges of the sobel processed image and makes them one pixel thick, as shown step by step in Figure 2.12. The way it does this is by using a kernel on the edges to find the highest value in the edge. To determine what values of magnitude counts as an edge, hysteresis threshold is used [9]. This can be visualised in one dimension as seen in Figure 2.11.
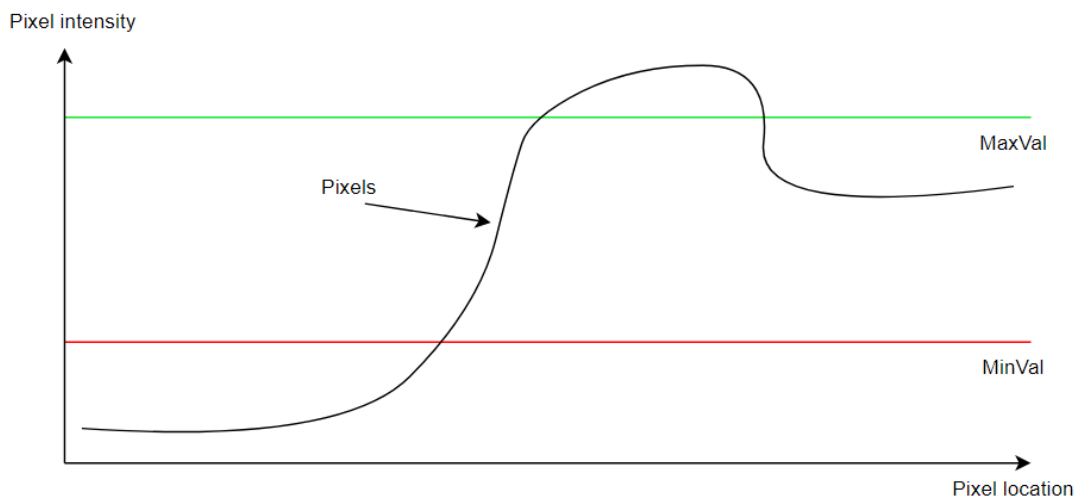
Figure 2.11: One dimension visualisation of hysteresis threshold

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[9]Convolution example: `https://medium.com/analytics-vidhya/image-convolution-from-scratch-d99bf639c32a`

[10]Sobel example: `https://www.songho.ca/dsp/convolution/convolution2d_example.html`
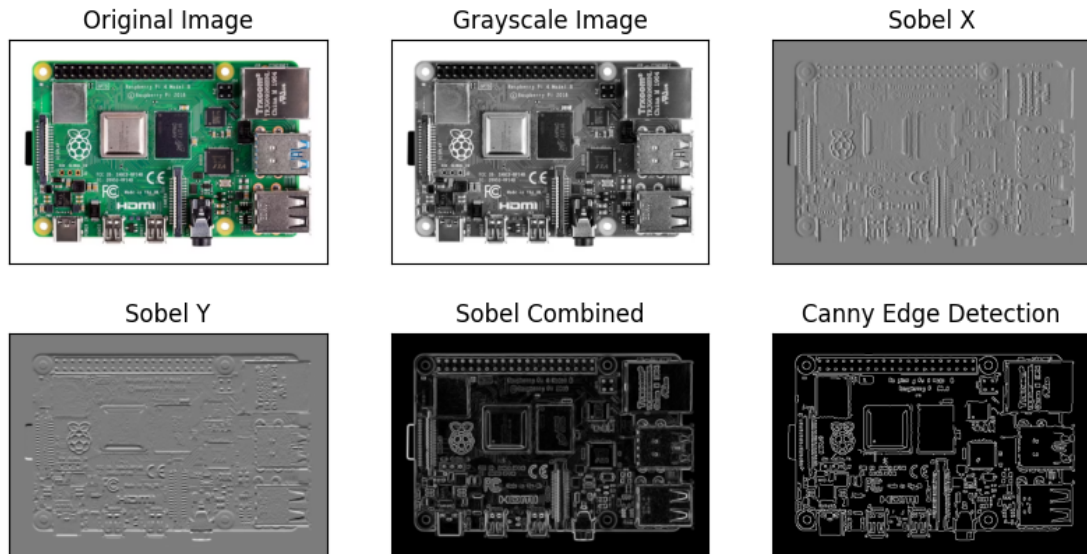
Figure 2.12: Canny edge detection step by step

2.7.4 Dilation and erosion

Dilation and erosion are morphological operators that adds or removes pixels from an image boundary. It uses convolution to add or remove pixels depending on the operator. The number of pixels added or removed depends on the size and shape of the kernel that is used. Figure 2.13 shows an example using canny edge detection on a raspberry pi 4 and dilating the image. The dilated image is then eroded, as eroding the original image would have removed the contours and left a blank image.
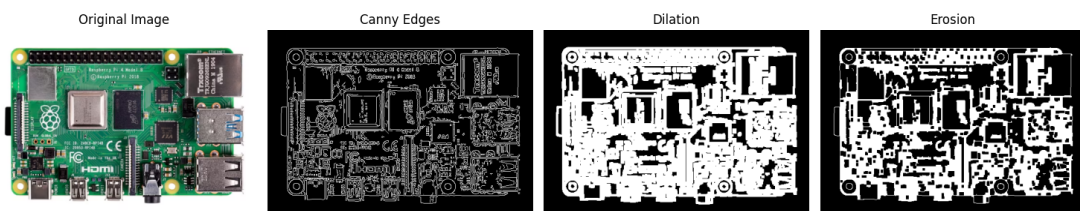
Figure 2.13: Example of dilation and erosion

2.8 Safety Precautions for class 3B laser

NTNU has health and safety guidelines when working with lasers. The strictness of the guidelines depends on the laser class. When working with a class 3B laser, a subject responsible has to decide if the candidates are competent to work with lasers independently. Secondly, suitable protection has to be applied, such as laser safety goggles, covering the laser to protect the surrounding area, and warning signs outside of the room the laser is in. The use of the laser has to be registered in a log book with time and date. The complete set of guidelines for laser handling can be found in Appendix E.

3 Software and Hardware

This section covers all the software and hardware used in this thesis.

3.1 Software

Siemens NX

Siemens NX is a "computer-aided-design" (CAD) and "computer-aided-manufacturing" (CAM) software[11]. It is primarily used to create parametric or solid surface modeled 3D objects, but also has capabilities of analysis using the finite element method. The software is owned and distributed by Siemens Digital Industries Software.

Prusa Slicer

Prusa Slicer is a fork of the open-source toolpath generator Slic3r[12][10]. The software can create G-Code for 3D-printers such as the Prusa MK3(s), Prusa Mini and others. Using the software is a required step when 3D-printing. The printer can only understand motor commands in the form of G-Code. Therefore a slicer is used to convert 3D models into G-Code commands. In the slicer the user chooses machine specific settings like detail, speed and filament.

Blender

Blender is a open-source 3D computer generator content software. The application is free to use and is released under GNU General Public License (GPL) [11]. This includes personal, commercial and educational use. Blender is cross-platform and runs using the OpenGL application programming interface. Everything needed for digital assets creation is supported. Some of the main features of the program is modeling, animation, rendering and simulation. This project used Blender to simulate a digital twin for computer vision training.

Visual Studio Code

Visual Studio code is an industry leading source code editor for Windows, Linux and macOS [12]. It is released and maintained by Microsoft. The application uses extensions to add support for hundreds of programming languages. Visual Studio Code is build top of the Electron cross-platform framework. This is a framework that uses commonly used website technology like JavaScript, HTML and CSS to create native feeling applications while still maintaining just one code-base [13].

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[11]Siemens NX: `https://plm.sw.siemens.com/en-US/nx`
[12]Sli3r Software: `https://github.com/slic3r/Slic3r`
[13]Electron: `https://github.com/electron/electron`

Git

Git, not to be confused with GitHub, is a free and open source distributed version control system. The system was released in 2005 by the creator of Linux, Linus Torvalds [13]. Git needs to be hosted on a server or locally on the developers computer. The system was created under the development of Linux when software changes was distributed around as files and archived files. The system is built on the concept of branches. Like a tree, the software developer can split the software into branches to try changes without affecting the main branch [14]. If a change does not work, the developer can revert back in the version history. And if the change does work, the feature can be merged back into the main branch. This development approach is very beneficial when working in teams, since multiple developers can work on features and always be on the latest up to date code-base. The application uses a command line based interface and can therefore be difficult to use.

GitHub

GitHub used the technology created by Git and hosts the users files and assets on their servers [15]. This enables the users to access the files over internet and removes the need for local servers for version control. GitHub has created a graphical interfaces for a more intuitive interface then pure Git. GitHub is powerful tool for both private and open-source projects. For public projects the owner of the code has the ability to review community changes before merging them into the project. This is called a Pull Request.

Raspberry Pi Imager

The software Raspberry Pi Imager is used to create bootable drives for the Raspberry Pi and other computers[14]. The software is fully open source and derived from the PiBakery tool. The tool is designed to simplify the process of flashing/burning of operating systems onto the drive of a computer. When flashing a drive, the user uses a graphical user interface to choose a desired operating system and a target drive. The software will take care of the formatting and burning process.

ROS2

Robot Operating System 2 (ROS2) is collection of software libraries and tools to aid the development of robotics applications [16]. The system separates the robotic libraries from the communication to the robot. This means that the developed application can be applied to other robots with only changing the communication libraries. The package of communication libraries is called Drivers. The developer can create their own driver or use existing. ROS2 is released in distributions using the Git version control system. The current stable distribution is called Humble and was used for this project [15]. There is an experimental distribution for the latest changes called Rolling, but this can also include breaking changes.

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[14]Raspberry Pi Imager: `https://www.raspberrypi.com/news/raspberry-pi-imager-imaging-uti`
`lity`

[15]ROS2 Distributions: `https://docs.ros.org/en/foxy/Releases.html`

Gazebo

Gazebo is divided into two releases, Classic and Ignition.

Gazebo Classic began development in 2002 as a high-fidelity simulator for robots in different conditions [17]. In 2009 a company called Willow Garage implemented support for ROS. The ROS community embraced the Gazebo simulator and it has become one of the primary tools for developing with ROS. Gazebo 11 is the latest major release of Gazebo Classic and is the one used in this project. Gazebo 11 is build with support of Open Dynamics Engine, Bullet Game Engine, Simbody and DART Physics Engine.

Gazebo Ignition is the successor of Classic [18]. In 2022 Gazebo Ignition was renamed to Gazebo. The main difference between Classic and Gazebo is that the Gazebo version has separated out modules, enabling the user to choose only is required by the project. This makes Gazebo run faster then Classic. The user interface has also received an update.

MoveIt2

MoveIt2 is a path planning software for ROS2 [19]. The software uses the description of the robot to calculate optimal motor movement to follow a calculated path around objects. MoveIt2 is commonly used with Gazebo to simulate physics. The software can also be used to translate Cartesian coordinates to joint positions.

Universal Robots URSim

URSim is a offline simulator for Universal Robots[16]. The simulator runs in a Linux environment either native or through a virtual machine. It can simulate robot movement and setup without a physical robot. The simulator displays the interface of PolyScope to the user. PolyScope is the Graphical user interface that is used to program the robot with the teaching pedant [20]. In PolyScope the settings can be configured to match the preferred robot. URSim can also be setup to use external control with a included Java-based plugin. The plugins are called URCap, and is how tools or other functions are added to PolyScope.

3.1.1 Raspberry Pi OS

Raspberry Pi OS is port of the Debian operative system designed to run on the Raspberry Pi computer. The operative system is made to add a full desktop environment while utilizing the ARM chip on the raspberry[17].

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[16]URsim info and download: `https://www.universal-robots.com/download/software-e-series/simulator-linux/offline-simulator-e-series-ur-sim-for-linux-551`

[17]Raspbian: `https://www.raspbian.org/RaspbianAbout`

3.1.2   Xming

Xming is a X Windows System Server for Microsoft Windows. It works as a client terminal to connect to different machines using X11 Forwarding. This allows a windows machine to open application windows via SSH without the use of a remote desktop. Using this on a Linux server that can't open application windows as standard, would open the application on the windows machine running Xming[21].

3.1.3   PuTTY

PuTTY is an open source Secure Shell (SSH) and telnet client[18]. PuTTY can be used to communicate with remote computers using the SSH protocol.

3.2   Hardware

Universal Robots UR10

The UR10 is Universal Robots medium sized collaborative robot. As the name applies the robot has a lifting capacity of 10 kilograms[19]. Available robots from the same series is the UR3, -5, and -20. The robots are separated into generations as well. CB1 was the first generation released in 2007, CB2 in 2011, CB3 in 2015 and the most recent E-series was released in 2018 [22]. The robot used in this project is from the CB2 generation.

Raspberry Pi 4

Raspberry Pi 4 is the fourth generation of single-board computers from the Raspberry Pi Foundation[20]. The device can be configured with 2, 4 or 8 GB of RAM. It features a Broadcom BCM2711 Quad core ARM CPU. The device started as an affordable approach to general-purpose computing, but gained popularity in the industry due to its capable features and small form factor. The device has been implemented in everything from water fountains to satellites in orbit [23].

Raspberry Pi Camera Module V2.1

The Raspberry Pi Camera Module V2.1 is an 8-megapixel camera for the Raspberry single board computers[21]. The camera has a resolution of 3280x2464 pixels. It can do video and still pictures. It uses the OmniVision OV5647 sensor with a field of view (horizontal) of 62,2 degrees. The module uses a ribbon cable to interface with the Raspberry Pi's CSI port.

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[18]Putty: `https://www.putty.org/`

[19]UR10 manual: `https://www.universal-robots.com/download/manuals-cb-series/service/service-manual-ur10-cb2-english`

[20]Raspberry Pi 4 store page:`https://www.raspberrypi.com/products/raspberry-pi-4-model-b/specifications`

[21]Raspberry Pi Camera store page: `https://www.raspberrypi.com/for-industry`

LM2596 Buck Converter

A buck converter, also knows as a step-down converter, converts DC voltage to a lower DC voltage while increasing the current. The module can convert 4,5 - 40 Volt to an adjustable output of 1,2 - 37 Volt[22].

Prusa Mini 3D Printer

Prusa Mini is the smallest Fused Deposition Modeling (FDM) printer Prusa Research makes[23]. FDM is an additive manufacturing technique that extrudes plastics and other materials in horizontal layers. The layers thickness for the Prusa Mini can range from 0.05 to 0.25 mm. The Prusa Mini uses common 3D-printer materials such as PLA, ABS and PETG.

Laser Module

LYTE-MV-EXCEL-660-50-45-A is a line laser from Global Laser. The laser is projecting a red uniform non-Gaussian line with 50 mW output power. This puts the laser in the 3B category. In this category the risk of permanent eye damage is present, and therefore requires laser goggles when operating. The test report included with the laser and the data sheet can be viewed in appendix C and D respectfully.

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[22]Buck converter datasheet: `https://www.ti.com/lit/ds/symlink/lm2596.pdf?ts=1701207169438`
[23]Prusa mini product page: `https://www.prusa3d.com/product/original-prusa-mini-semi-ass embled-3d-printer-4`

4   Methods

This chapter covers how to project was handled. The beginning covers how the group was organised during the project. The chapter will then cover a overview of the plan, as well as how it was executed. This includes the choice of components, safety, implementation of ROS2, vision process, and the design process of the welding tool.

4.1   Project Organisation

4.1.1   Team Members

Both group members have gained certificate of apprenticeship before starting the bachelor degree at NTNU Ålesund. Peter has done the electrician certificate while Simen has done the automation certificate. Both has experience dealing with electrical systems from PLC's and other similar control systems. One of the group members has done the course Industry 4.0 and has first hand experience of how a robotic system should operate. 3D visualisation in Blender is also a ability the group handles.

4.1.2   Distribution of responsibilities

The group switched group role at a bi-weekly basis. With this approach both group members would get the responsibility of project leader. Tasks for each position can be found in the preliminary project attached in Appendix A.

Time period (week nr.)	Project leader	Secretary
35 - 36	Simen	Peter
37 - 38	Peter	Simen
30 - 40	Simen	Peter
41 - 42	Peter	Simen
43 - 44	Simen	Peter
45 - 46	Peter	Simen
47 - 48	Simen	Peter
49 - 50	Peter	Simen

Table 4.1: Planned Distributed Responsibilities

4.1.3   Planned Meetings With Supervisor

The group decided to have bi-weekly status updates with the group supervisor. At this interval the group could get constructive feedback or guidance at the task at hand. The group invited the supervisors and optional attendees with RSVP through email. The meetings would be conducted online or in person.

4.1.4   Planned Progress With Gantt Diagram

The group used the a Gantt diagram to keep track of milestones and progress. The Gantt diagram was updated live on Microsoft Teams and the planned durations of each tasks could be updated if necessary. Both group members along with supervisors could check on daily progress. The completed Gantt diagram is attached in Appendix I.

4.2   System Overview

The developed system consists of three major hardware components: the optical sensor consisting of the camera and the laser, the Raspberry doing all the calculation with ROS2 and Python, and lastly the Universal Robot UR10. The system is connected to a WiFi-router, enabling the group to SSH into the Raspberry Pi for software changes. The system is represented in Figure 4.1.
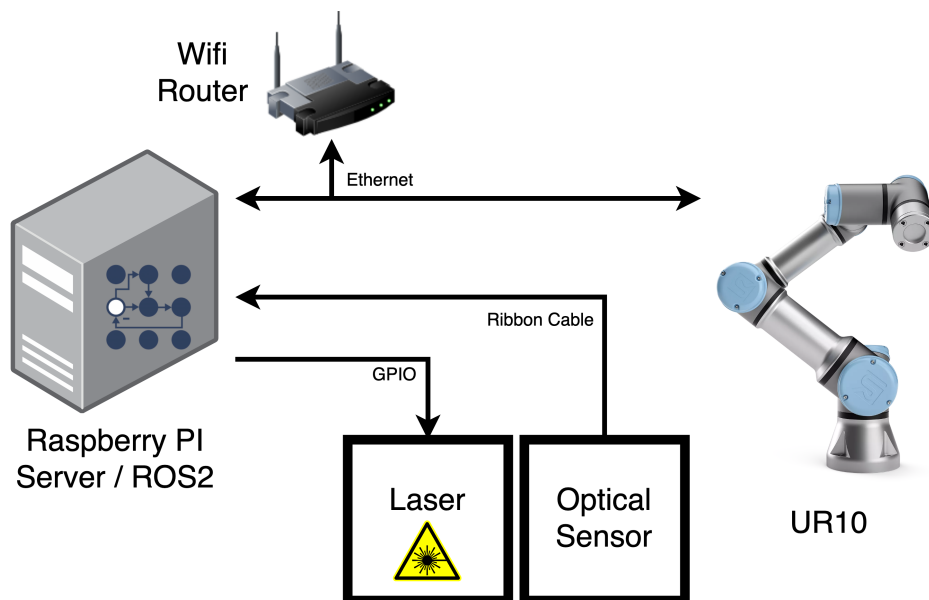
Figure 4.1: Overview of System Hardware

The schematic for the system can be referenced in appendix H. The main program running on the system can be summarized with Figure 4.2.
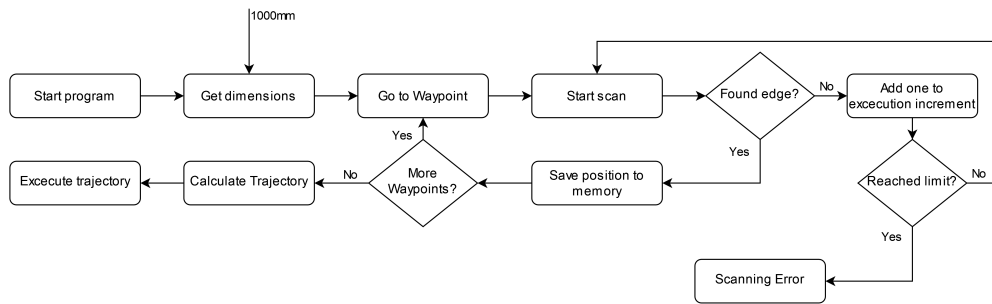
Figure 4.2: Main program flow

4.3   Choice of Components

This chapter covers the reasoning behind the choice of hardware used in the project.

4.3.1   Raspberry Pi 4

The Rasperry Pi 4 was the preferred computing module due to its high price to performance ratio and "General-Purpose Input/Output" (GPIO) capabilities. The Pi can run the Ubuntu operating system, providing an open and stable development environment.

4.3.2   Rasberry Pi V2.1 Camera

Raspberry's own camera module was selected as the optical sensor because the well documented support with the Raspberry Pi 4. The sensor has a high resolution and good performance with vision based tasks. The dedicated hardware connection to the Raspberry Pi 4 is also a good feature, as it frees up the use of USB connections. The cameras resolution and exposure can be adjusted using OpenCV[24].

4.3.3   LYTE-MV-EXCEL Line Laser

The Lyte-MV-Excel series is the preferred choice of line laser. Specifically designed for machine vision tasks this met all the criterias. The availability of the product was a significant factor in its selection. It was in stock at RS-Components, ensuring delivery within a few days. A feature of the Lyte-MV-Excel is its capabilities for modulation of strength and power via 0-3.3 volt signals. This enabled the control of the laser with the Raspberry Pi's GPIO pins. The connections that is needed for laser control with the Raspberry Pi 4 can be seen in Appendix H.

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[24]OpenCV example: `https://docs.opencv.org/4.x/d3/db7/tutorial_hdr_imaging.html`

4.3.4   Universal Robots UR10

Universal Robots UR10 collaborative robot is a great choices for developing sensors for robotic use. The collaborative factor means that the operator can be present and monitor while the robot is running the program. This gives better insight of the behavior and performance of the sensor. The UR10s reach is large enough to reach around the whole workpiece and was therefore chosen as the preferred UR-robots.

4.4   Implemented Safety Barriers

When working with lasers and robotics there is alot of moving parts and unforeseen events can happen very quickly. That's why safety barriers are implemented. Barriers that proactively can protect the users of the system. The chosen robot has collaborative features implemented. This allows for users to be in the robot cell while its operating. The robot will stop when it detects a large enough resistance. To protect from the class 3B laser, the operator inside the chamber has to wear laser safety goggles. These has to be compatible with the laser wavelength to best protect the operator. The laser used in this project had an wavelength of 665nm and the goggles must be designed to filter out this. The test report from the factory, documents the wavelength of the laser and can be found in Appendix C. Lastly a risk assessment of the whole system is available for all the users of the laboratory to read. This includes all the risks involved with the system. The usage of the laser is logged in a laser record that can be referenced in Appendix F.

4.5   Advantages of Choosing ROS2 for Robotics Projects

The scanning procedure requires real-time robotic control and uninterrupted data transfer between the triangulation sensor and the robot. The sensor is crucial for providing ongoing positional adjustments during the scanning. The selection of using ROS2 as the robot interface was also based on the ability to change robot at ease without reworking the communication protocols. ROS2 standardises the communication to and from the robot using interchangeable drivers. The group had multiple robot arms from different manufactures available to choose from, so by using ROS2 the robot could be changed without affecting the triangulation system. The integration of Gazebo simulator was also a key factor of deciding to use ROS2. The simulator enabled early testing of the system without using hardware.

4.5.1   Selecting ROS2 Driver

Universal Robots has developed a ROS2 ready driver for the UR-series of robotic arms.
The driver is still in development and receives updates as new features are implemented.
The driver in its current state is working and has all the necessary features to control
the UR robots. The one used in this project is from Universal Robot's GitHub page
and is called "Universal_Robots_ROS2_Driver" [25]. The library is build on the "Univer-
sal_Robots_Client_Library" which contains all the required components to translate
the interface from the UR10 [26]. The communication library does not contain any infor-
mation about the robot's kinematics or joints, so the driver combines this into a package.

4.5.2   Robot control using ROS2

Robot Operating System 2 (ROS2) uses the mentioned UR-Driver to talk to the Universal
Robots UR10 robotic arm. The developed program can use three different controllers
to send movement commands to the robot. The first controller is the "Joint Trajectory
Controller". This controller is used for joint-space trajectory control. The program
inputs waypoints with joint angles to the controller and ROS calculates and executes the
path between the positions. The second is the "Forward Velocity/Position Controller".
This inputs velocities commands in X, Y and Z axis as well as rotational velocities in
the RX, RY and RZ axis. This can be used for real-time control of the robot. Figure 4.3
shows how the two mentioned controllers interacts with the UR-Hardware.
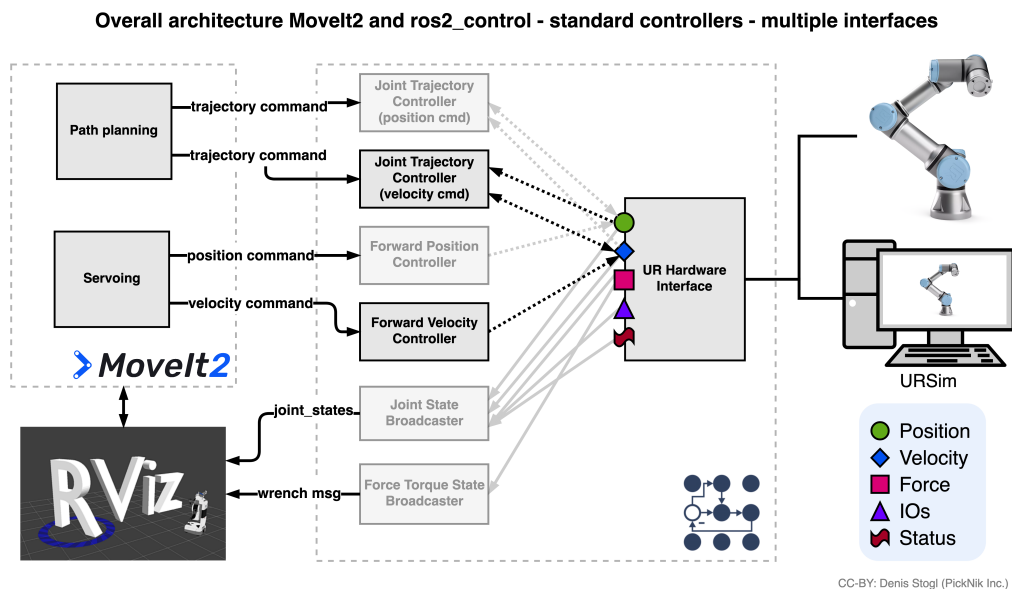
Figure 4.3: ROS2 Controllers interaction with hardware [24]

The last controller uses the Universal Robots URScript interface. This controller can
be used to execute internal UR-Robot commands. URScript is exclusive of the UR-

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[25]Github: `https://github.com/UniversalRobots/Universal_Robots_ROS2_Driver`
[26]Github: `https://github.com/UniversalRobots/Universal_Robots_Client_Library`

series and does not work with robots from other manufactures. There is no feedback when using the URScript commands with ROS and therefore the program must listen to topics to determine if the robot has reached it desired position [25]. Our solution uses a mix of both URScript and the Forward Velocity controller to perform the required maneuvers.

4.6   Calculating Robot Position

The UR10 robot already uses the Denavit-Hartenberg method for calculating its internal position. Therfore the correct values for the D-H matrix is already calculated by Universal Robots.

Joint	θ [rad]	a [m]	d [m]	α [rad]	Link	Mass [kg]	Center of Mass [m]
Joint 1	0	0	0.1273	$\frac{\pi}{2}$	Link 1	7.1	[0.021, 0.000, 0.027]
Joint 2	0	-0.612	0	0	Link 2	12.7	[0.38, 0.000, 0.158]
Joint 3	0	-0.5723	0	0	Link 3	4.27	[0.24, 0.000, 0.068]
Joint 4	0	0	0.163 94	$\frac{\pi}{2}$	Link 4	2	[0.000, 0.007, 0.018]
Joint 5	0	0	0.1157	$-\frac{\pi}{2}$	Link 5	2	[0.000, 0.007, 0.018]
Joint 6	0	0	0.0922	0	Link 6	0.365	[0, -0, -0.026]

Table 4.2: UR10 Kinematic and Dynamic Parameters [26]

The values from the description (Table 4.2) is entered into the Denavit-Hartenberg representation and used to calculate the current position of the robot.

To find the position of joint 1 the following operations was made: Start by getting the parameters from equation 3 and modify it for the first joint.

$$T_{0,1} = \begin{bmatrix} \cos\theta & -\sin\theta_1 & 0 & a_0 \\ \sin\theta_1 \cos\alpha_0 & \cos\theta_1 \cos\alpha_0 & -\sin\alpha_0 & -d_1 \sin\alpha_0 \\ \sin\theta_1 \sin\alpha_0 & \cos\theta_1 \sin\alpha_0 & \cos\alpha_0 & d_1 \cos\alpha_0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}$$

The matrix contains references to α_0. These are relative to the base frame, and can be simplified to 0.

$$T_{0,1} = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{8}$$

The X, Y and Z values can be extracted from the result using the setup from equation 4.

$$Position\,of\,joint : (x_1, y_1, z_1) = (0, 0, d_1) \tag{9}$$

4.6.1   MoveIt2

MoveIt2 serves as a great tool for managing robotic control in both simulated and real-world environments. The framework supports importing elements into the its digital environment, enabling the calculation of navigational paths that avoid collisions with surrounding objects. Furthermore, the MoveIt2 implementation plays a crucial role of computing the necessary commands when using the "Forward Positioning Controller". MoveIt2 uses the URDF description of the robot to calculate the joint movements required to follow paths along the Cartesian coordinate system.

4.6.2   URScript

The ROS2 Driver in its current state is missing a controller for "Cartesian position-based control" [27]. This limits the ability to command the robot with linear moves in Cartesian coordinates. By utilizing the "send custom script commands to robot" feature of the driver we can work around this obstacle. This feature allows sending URScript commands to the robot such as moveJ, moveL or setting the state of digital outputs. The limitation of this feature is that the URScript interface does not provide feedback to the system [28]. The system can however listen to the ROS2 transformation topic called "tf_subscriber" to receive real-time joint position. These can be used with the mentioned Denavit-Hartenberg method from Section 4.6, to determine the Cartesian position of the robot.

4.7   Tool Center Point Calibration

By default the commanded Cartesian position is on calculated from the tool-flange of the robot This is located at the last joint on the UR10 (Figure 4.4.a). When attaching tools to the tool-flange, its important to update the Tool Center Point (Figure 4.4.b). This is done with the teaching pedant on the UR10.

(a) Default TCP   (b) TCP with tool offset
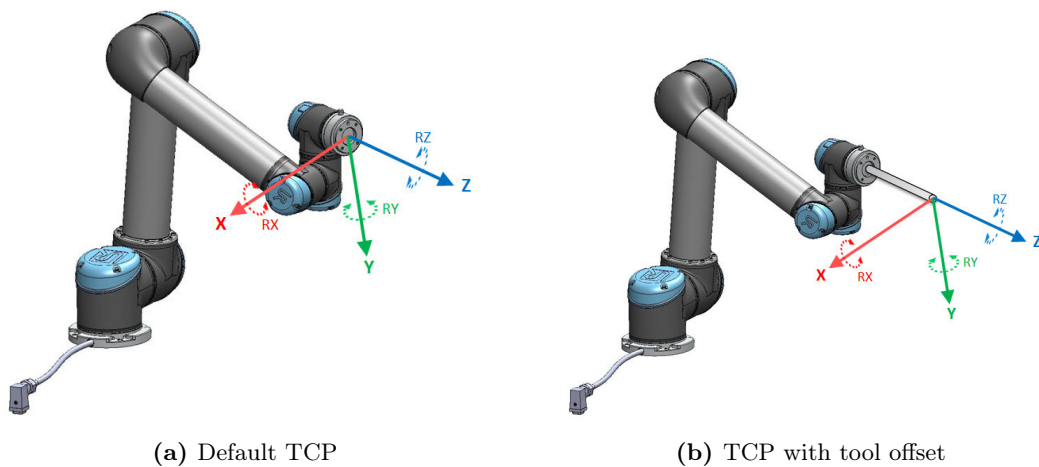
Figure 4.4: TCP Calibration [29]

The Denavit-Hartenberg representation also needs an extra link to account for the tool. The parameters of the link can be found by using the teaching pedants 3-point calibration or by measuring. This gives an offset in X/Y/Z and RX/RY/RZ. These values needs to added to the DH-Parameters. For a tool with offset in the Z axis, like Figure 4.4.b, The new row of Parameters would look like:

- $\theta = 0$: Since the tool is not rotated.

- a = 0 : There is no horizontal offset in X or Y.

- $\alpha = 0$: The tool is aligned with the previous axis.

- d = L : The length of the tool.

The position of the tool can now be calculated using forward kinematics as shown in Section 4.6 Calculating Robot Position.

4.8   Designing the Optical Sensor

When starting the design process of the optical sensor, it was decided that creating a 3D printed model of a welding torch to attach it to was the best choice. A modified version of a welding torch made by Iakov Skoblikov on GRABCAD[27] was used. GRABCAD is a community based webpage where 3D models are free to download and use. The welding torch used can be seen in figure 4.5. As this model was large and had unnecessary details a modified version was created using Siemens NX. The modified version also separated the tip of the torch from the body and made so they thread together. This made it easier to 3D print, and made it more viable to 3D print new parts should any of the parts break during testing. The modified welding torch can be seen in Figure 4.6.

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[27]Original model: `https://grabcad.com/library/welding-torch-robo-wh-pp-w500-1`
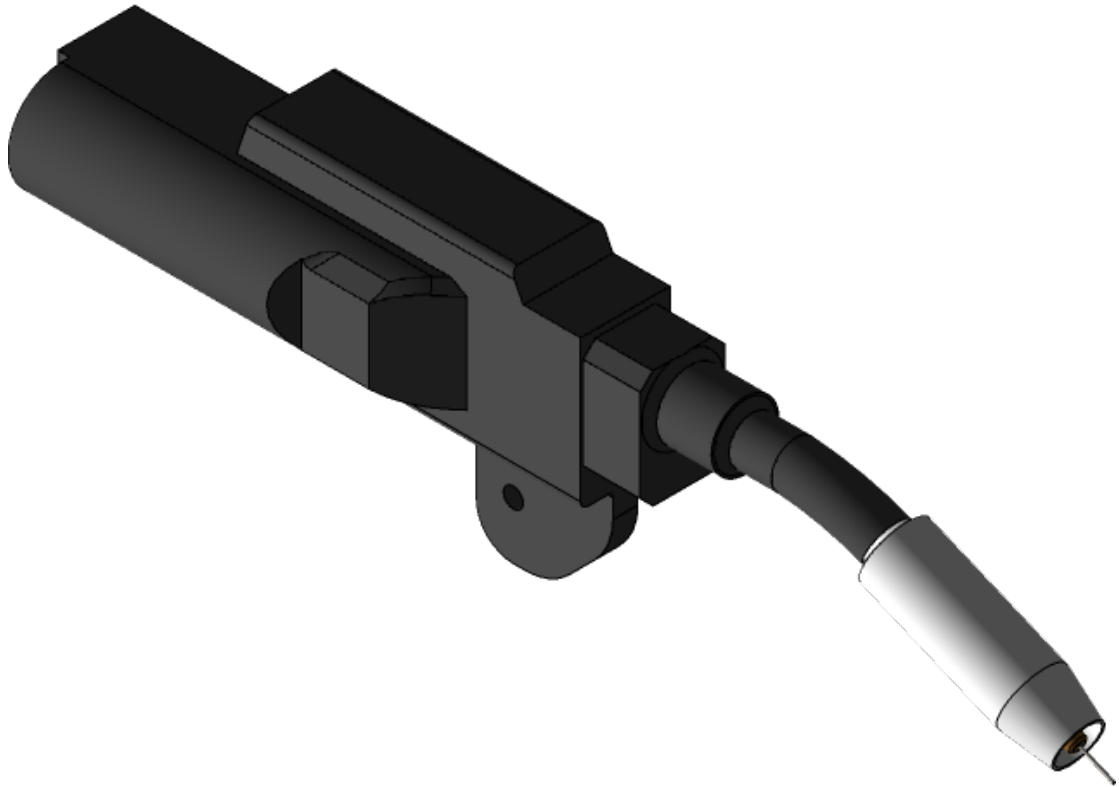
Figure 4.5: Welding torch ROBO WH-PP W500 by Iakov Skoblikov [30]
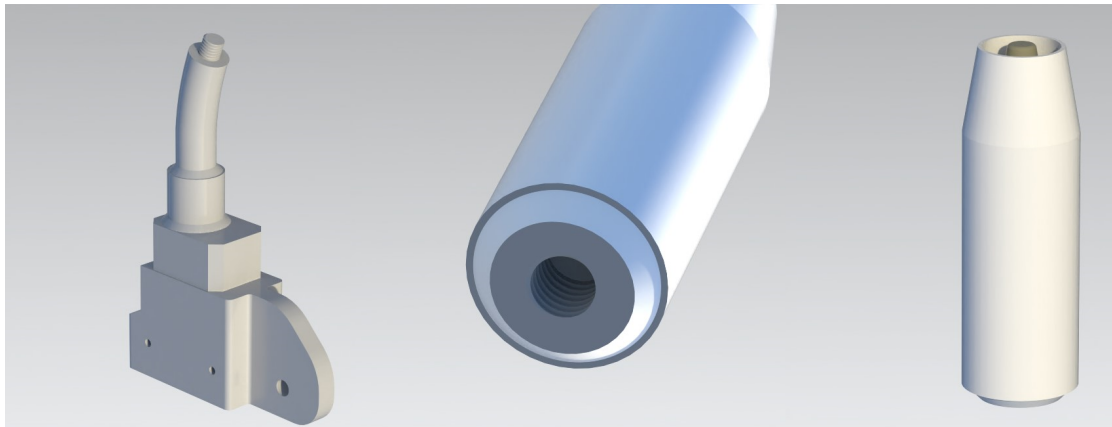
Figure 4.6: Modified welding torch based on the GRABCAD model

As the laser module provider did not have a 3D model of the laser, a simplified version was created in NX from the measurements of the original. After the laser module was created, the bracket of the laser and camera was designed. As heat melting the plastic was not a problem, the choice was made to mount the bracket to the tip of the welding torch. To mount the torch to the robot an adapter for the robot flange was created and is seen in Figure 4.8.

The non-contract probe was created using two key components: a camera, and a line laser. These were configured in a reversed geometry setup as seen in Figure 4.7. Reversed setup was chosen due to the ability to shield the camera from the welding light. The laser had an angle of 13.5 degrees and a offset of 5 cm to the camera. These values was chosen based on how close we wanted to scan the workpiece.
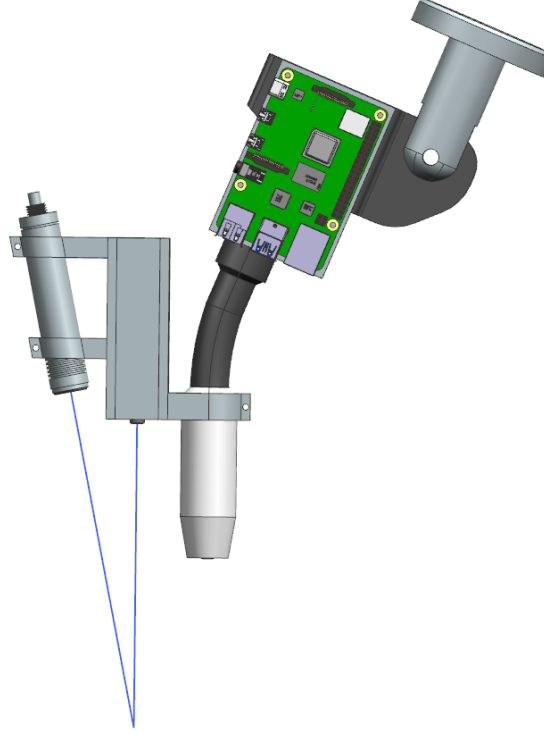
Figure 4.7: Welding module with reversed geometry setup

Due to the short and fragile ribbon cable of the Raspberry Pi Camera, we choose to mount the Raspberry Pi 4 to the tool-flange as well. The UR10 can handle up to 10kg of weight, so this had no impact on the movement of the robot. Power to the Raspberry Pi was provided by the internal 8-pin UR tool interface. This can provide 12 or 24 Volt. The Pi only supports 5 Volt input voltage, so we had to step down the voltage to a usable output. This was done with a buck converter called LM2596. The complete model of the welding module can be seen in figure 4.8. This figure shows the placement of the camera compared to the laser. The hole next to the camera is a tract for the ribbon cable that connects to the Raspberry Pi.
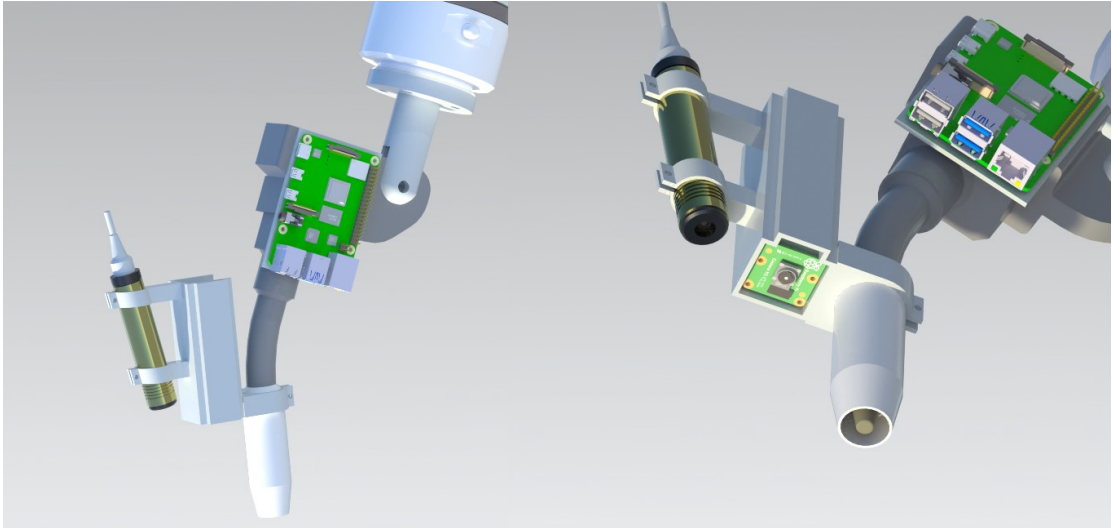
Figure 4.8: The complete welding module mounted to the flange of the robot

The laser also operates on 5 Volt and has a enable line that can be triggered with an 3.3 Volt signal. This was hooked up to the Raspberry Pi to gain control of on/off state of the laser. When hitting the emergency stop switch on the UR10, the 24 Volt line goes to 0 Volt. This makes both the Raspberry Pi and the laser to be turned completely off. This ensures that the laser will not misfire, and the robot does not resume in the middle of the program after the emergency stop switch is released.

The finished model of a robot includes an UR10 robot designed by Nithin P. Anand on GRABCAD[28] and can be seen in Figure 4.9.
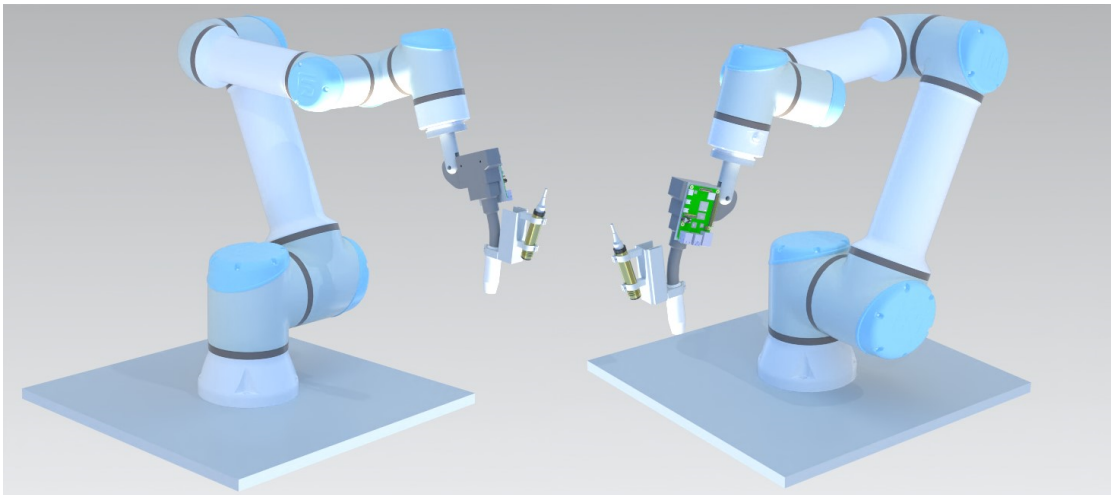
Figure 4.9: The complete assembly of robot and welding module

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[28]UR10 model: `https://grabcad.com/library/ur10-step-1`

4.9   Using Laser Triangulation To Find Seam

The main task of the system was to find the seam of two plates of metal, and provide corrective alignment feedback to the control of the robot. The robot would then use the path to weld the two plates together. A non-contact probe was chosen as the preferred probing technique due to its ability to scan a wide line and find a seam without probing multiple times. The feedback from the probe then commanded the robot to correct its path with a distance value. The developed solution used Python with OpenCV to do the vision based calculations.

The captured image from the optical sensor has to be processed to extract the height map of the surface. The process starts with an input image as shown in Figure 4.10.a and outputs data represented in Figure 4.10.b.

(a) Vision Input   (b) Output of laser height
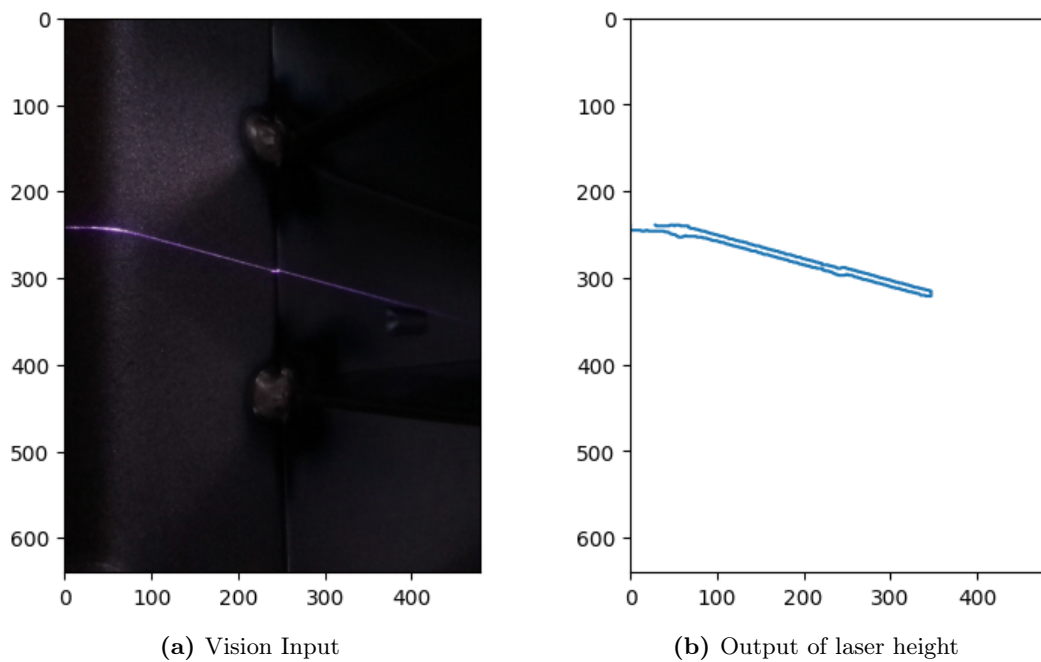
Figure 4.10: Laser triangulation height map

The first step of image processing is using a HSV filter to separate out the values that represent the laser. The HSV filter values has to be calibrated if the environment changes drastically. This can happen if the setup is moved to another location or the sun changes the lighting in the room. The output of the HSV filter after tuning is shown i Figure 4.11.a. The HSV filter helps remove unwanted elements from the image so the canny edge detection in Figure 4.11.b, can focus on the laser.

(a) HSV Filter

(b) Canny Edge detection
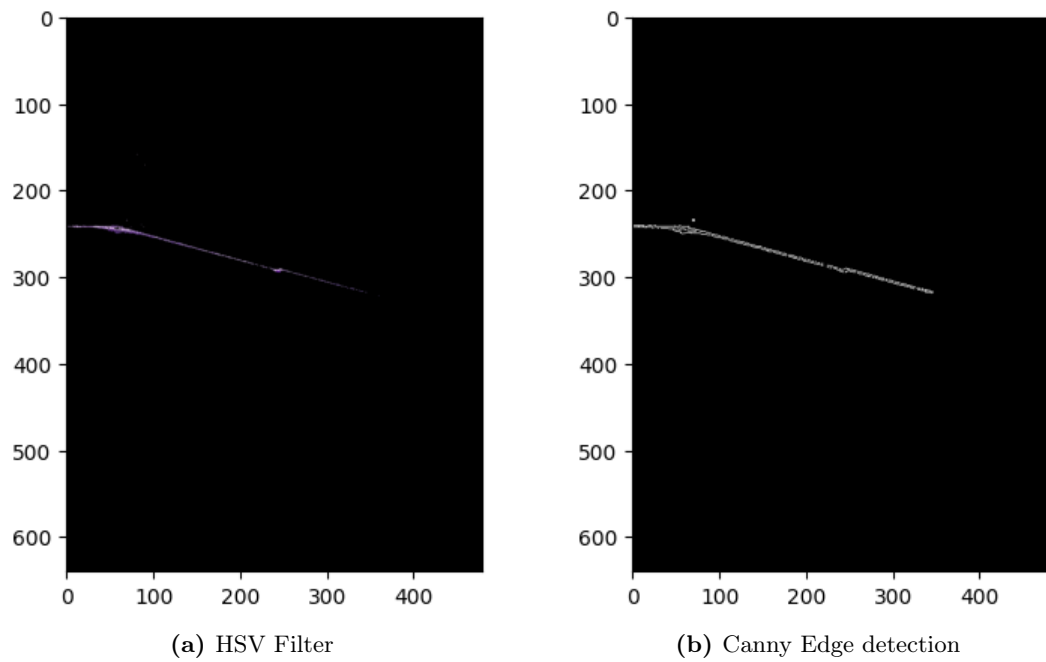
Figure 4.11: HSV and Canny edge detection used to outline laser

With the new contoured representation of the laser, we can apply a blur kernel to fill inn the missing laser inside contour. The effect is shown in Figure 4.12.a. In order to remove noise from the image, only the largest contour is kept, a shown in figure Figure 4.12.b.

(a) Filled in contours with blur kernel

(b) Largest contour on original image
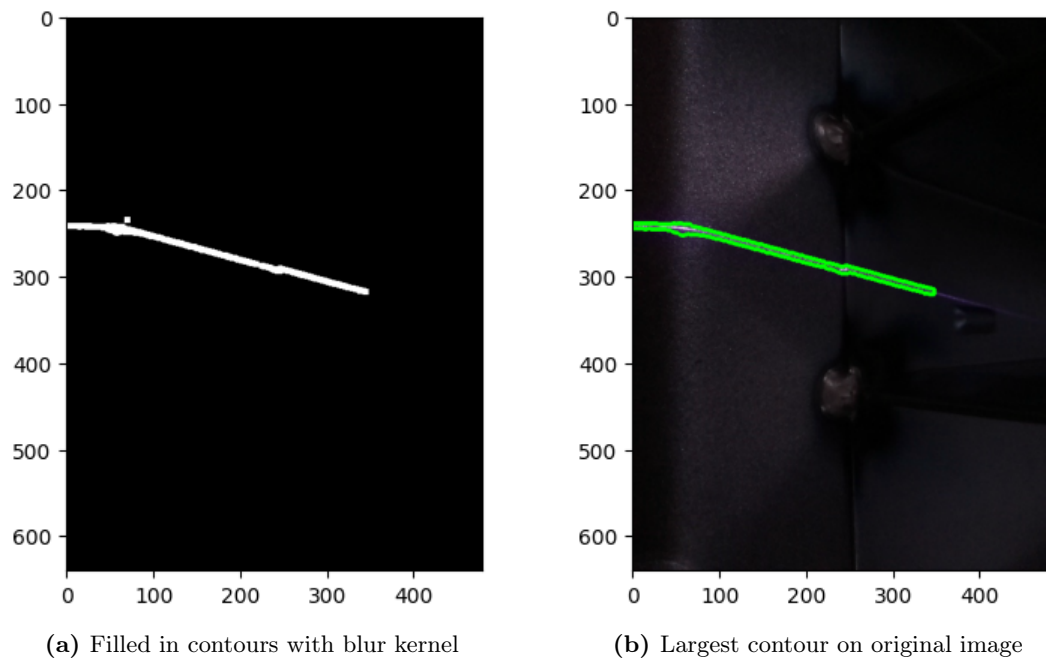
Figure 4.12: Blur Kernel and selective contouring removes unwanted features

The output of the the scan is a height representation of the scanned surface. We found that the most efficient method for finding the seam, is to derivative the output to find the area where slope changes. This is shown in Figure 4.13.
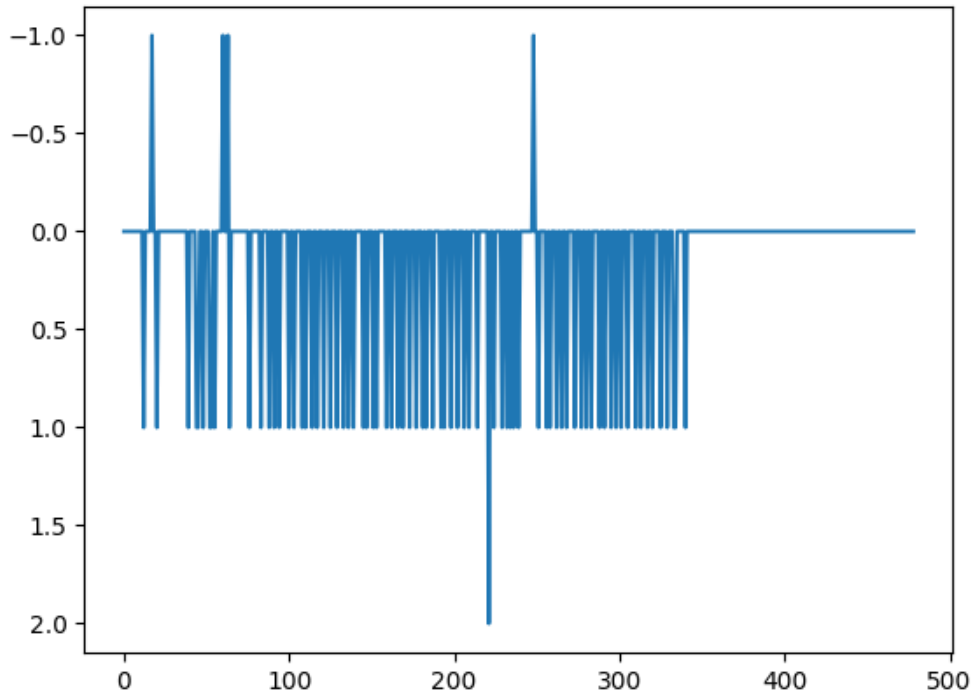
Figure 4.13: Derivative of laser contour. The seam between the plates are represented by the sudden spike on the x-axis at 250.

4.10   Training Vision Algorithm Using Blender

The project required an enclosed robot cell for testing with the class 3B laser. To start with the vision task ahead of schedule, we created a replica of the robot environment in Blender for early testing. Blender was chosen as the best visualizer due to its ability to create realistic renderings with light. The 3D model for the workpiece was provided by the client ensuring we had the highest possible replication. Some post-processing to the workpiece had to be added, such as temporary spot welding or other defects. The simulation started very basic and evolved as the project developed. The first attempts was to replicate a realistic line laser using a Powell lens in Blender. This is a same lens used as the one we have in the real laser.

(a) Powell Lens

(b) Simulation
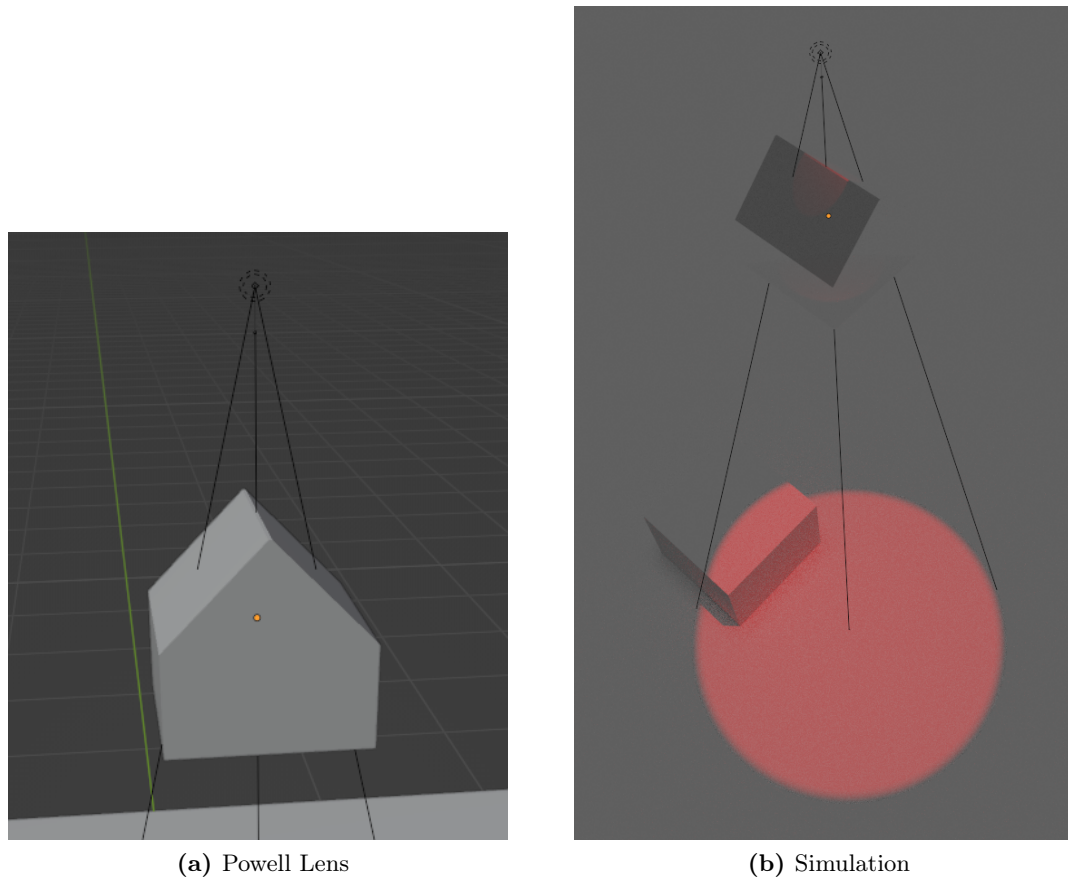
Figure 4.14: Blender Powell lens recreation

As Figure 4.14 shows, the light passed thru the glass without being affected. This is probably because the material of the lens was not setup correctly. The second attempt involved using a area light instead. The area light was set to a rectangle shape and stretched to a line.

(a) Area Light Laser

(b) Box side-profile
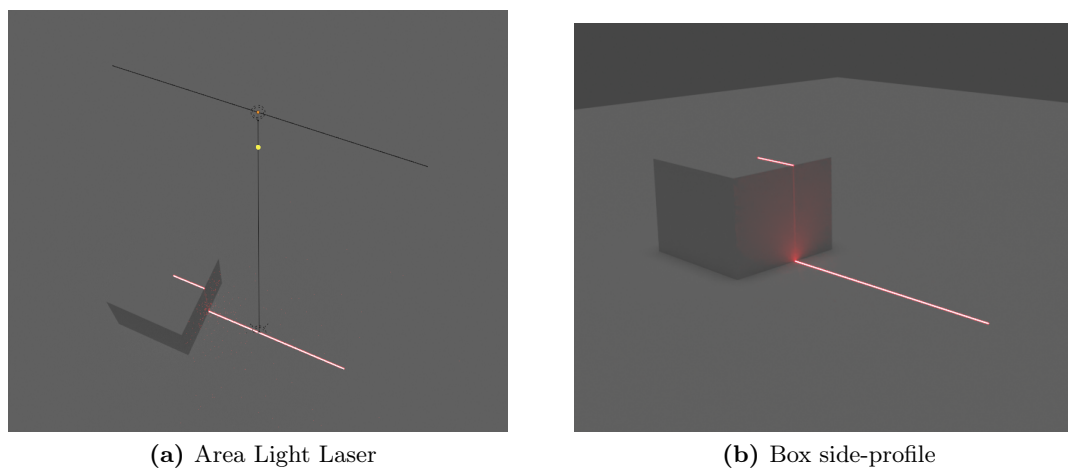
Figure 4.15: Blender area laser

The results showed in Figure 4.15 behaved more like the line laser we wanted. But had a major problem. The light was projected from the whole line parallel down instead of from a single point as shown in Figure 4.16. This resulted in the side of the box not being hit by the laser.

(a) Parallel Light
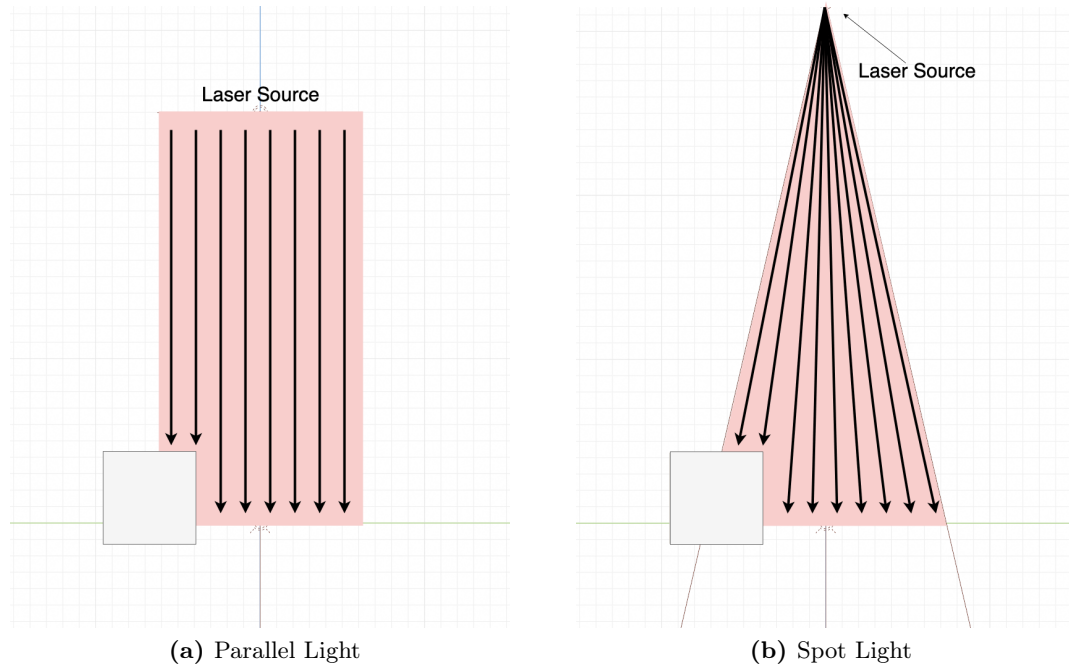
(b) Spot Light

Figure 4.16: Fault with area laser

The third attempt used the spot light feature and pass it through a slot in a box. As shown in Figure 4.17 this resulted in a laser with correct characteristics. The fan angle on the laser can be changed by modifying the spot size of the light.

(a) Box with slot

(b) Light projecting through the slot
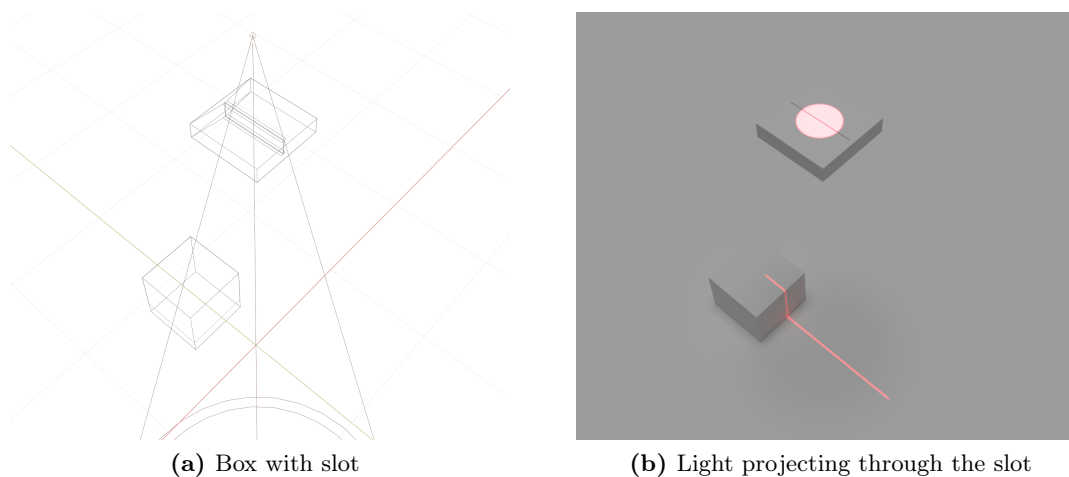
Figure 4.17: Blender spot light line laser

With the laser modeled, the rest of the environment can be created. We attached our developed solution to the Blender model to simulate the lasers effect on the work piece, as shown in Figure 4.18.
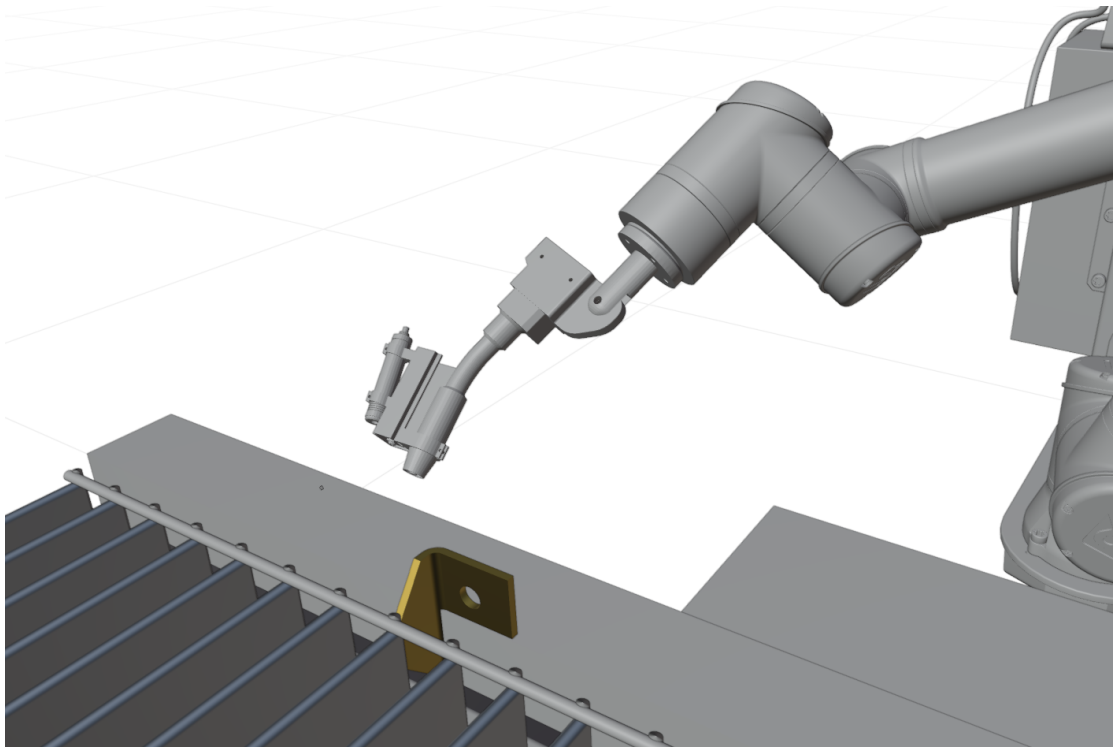
Figure 4.18: The 3D modeled welding attachment and non-contact probe in Blender environment
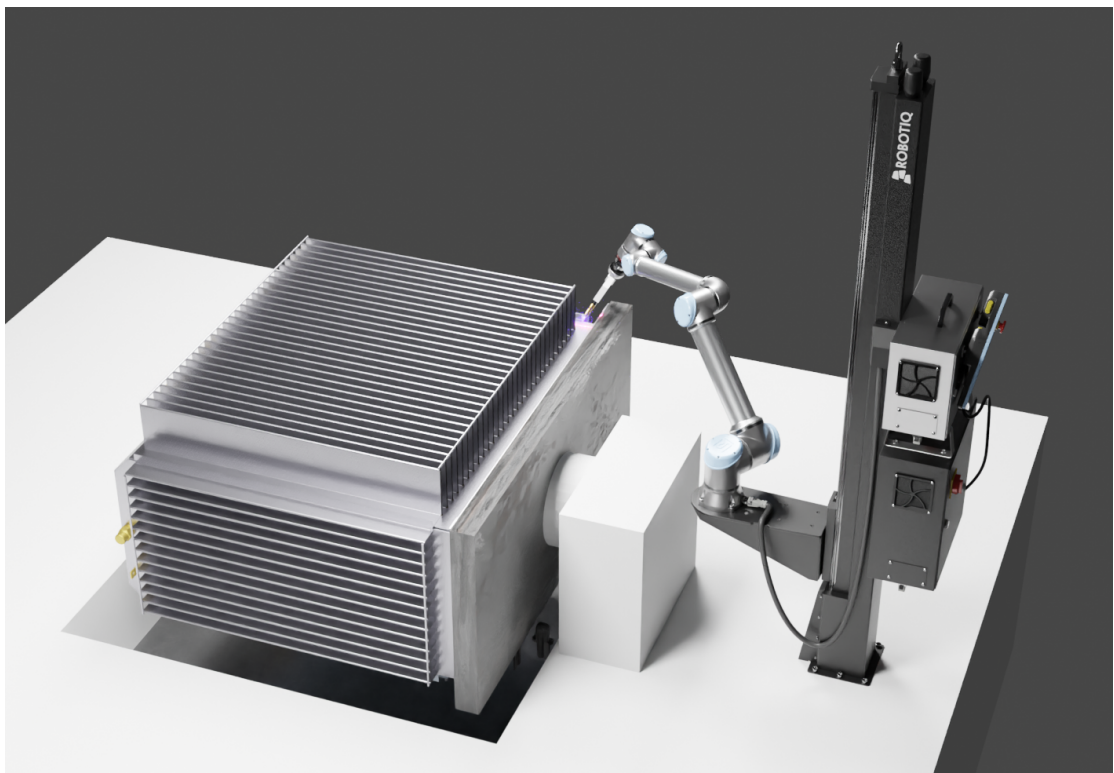
Figure 4.19: Digital twin in Blender

The digital representation was based on how the workpiece was mounted during the on-site consultation with the client. The real version had the robot mounted on a swiveled base to change between two robot cells, but in this representation (Figure 4.19) we simplified the setup. The output from the camera in Blender could then be fed into the python vision algorithm for testing the sensor without hardware.

4.11   Setting Up Raspberry Pi for ROS2 Applications

This chapter covers the steps made to get the Raspberry Pi to work for the project. There are attempts that where not successful, but are covered as they consumed time of the project.

4.11.1   Raspberry Pi Imager tool

A Raspberry Pi automaticly boots from the SD-card inserted to it. The SD-card needs to be loaded with an OS, and needs to be set up using a PC. A simple way of configuring the OS for the Rapsberry Pi is to use the Raspberry Pi imager tool. When launching the tool and inserting an SD-card, an OS can be chosen from a list, as shown in Figure 4.20. After selecting an OS, further customization can be done such as, naming the device, enabling SSH for remote connection, and selecting the wifi SSID.
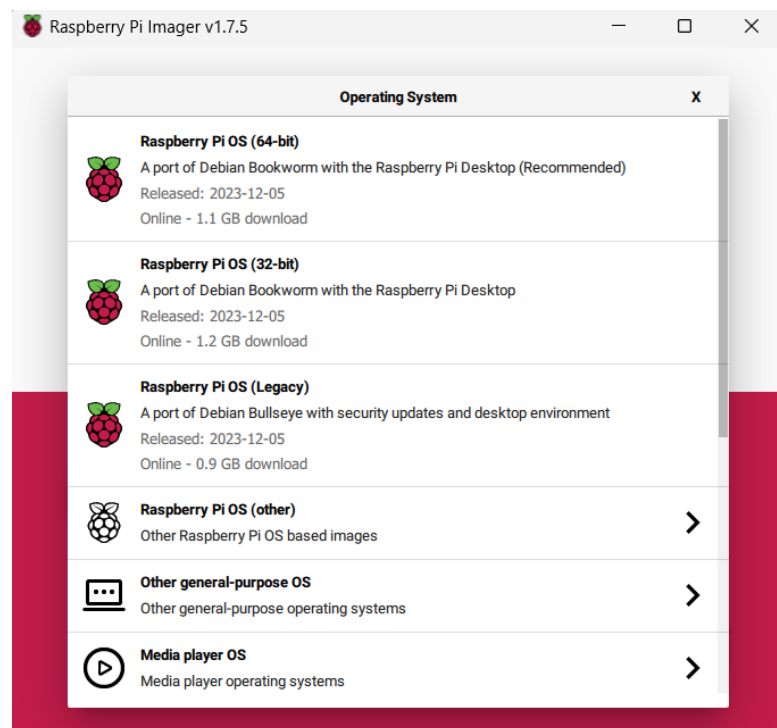
Figure 4.20: OS selection in the Raspberry Pi Imager

4.11.2   Raspbian OS

It was quickly determined in the start of the project that a Raspberry Pi with a Raspberry Pi camera would be used for the vision processes. The first attempt at this was to use the newest Raspberry Pi OS which is a port of Debian bookworm. This however, did not work as expected due to the OS being released in October of 2023 and had bugs which prevented the camera from working. To remedy this an older version of the Raspberry Pi OS based on Debian Bullseye was switched to. After doing the switch, the camera worked, but the OS had to be changed again after deciding to use ROS2 for the project.

4.11.3   Ubuntu Desktop 23.10

After consulting the ROS2 documentation, it was realized that an Ubuntu based OS had to be used. The documentation specified that Ubuntu Server 22.04 was recommended, but not mandatory. The decision to use Ubuntu Desktop was made, as the desktop evironment can open a live camera feed. This would be beneficial when testing the triangulation program. The Raspberry Pi camera does not, however work on an Ubuntu system natively. To get the camera to work a modification to the config.txt file in the boot folder has to be made.

To edit the config.txt file use:

```
$ sudo vi /boot/firmware/config.txt
```

Then add this to the last line:

```
start_x=1
```

After a reboot of the system, check the /dev/ folder if video0 is present. If the camera is present in the folder, it can be used in an OpenCV script.

Running ROS2 on the Ubuntu desktop was not a success, as the desktop environment used too many of the Raspberry Pi's resources and caused it to run slow.

4.11.4   Ubuntu Server 22.04

After the discovering that using the Ubuntu desktop environment was not feasible, the decision to use Ubuntu Server was made as was recommended by the ROS2 guide. After setting it up in the imager tool and booting, the camera had to be enabled. This was the same procedure as the Ubuntu Desktop guide, but when running the server environment the raspi-config package was needed as well.

To install the raspi-config use:

```
sudo apt−get update
sudo apt−get install raspi−config
```

After a reboot type:

```
sudo raspi−config
```

Go to interface options and enable camera. After another reboot, the camera is ready for use.

4.11.5   X11 forwarding

In an attempt at getting a live feed of Raspberry Pi camera while running the Ubuntu Server, X11 forwarding was implemented. X11 forwarding is a method for a user, for example a linux server, to start an application and forward the program window to another computer via SSH. To get the X11 forwarding to work, some editing of the sshd_config.txt file had to be made.

The edit was done using:

```
sudo nano /etc/ssh/sshd_config.txt
```

Then, the "#" from X11Forwarding yes and X11UseForwarding yes was removed to un-comment them, thus enabling them.

Then restarted the SSH service:

```
sudo service sshd restart
```

To make the application windows to show up on a windows PC, two programs must be installed, PuTTY and Xming. PuTTY allows the guest windows pc to connect to the linux server via SSH and X11 forwarding. PuTTY alone, however, can not open application windows.To get the windows to open on the guest PC, a display manager has to be used. Xming is such a program and allows the application windows to show when using PuTTY and X11 forwarding.

The connection to the Raspberry Pi was done as shown in figure 4.21. Before connecting, however, make sure that X11 forwarding is enabled as shown in figure 4.22.
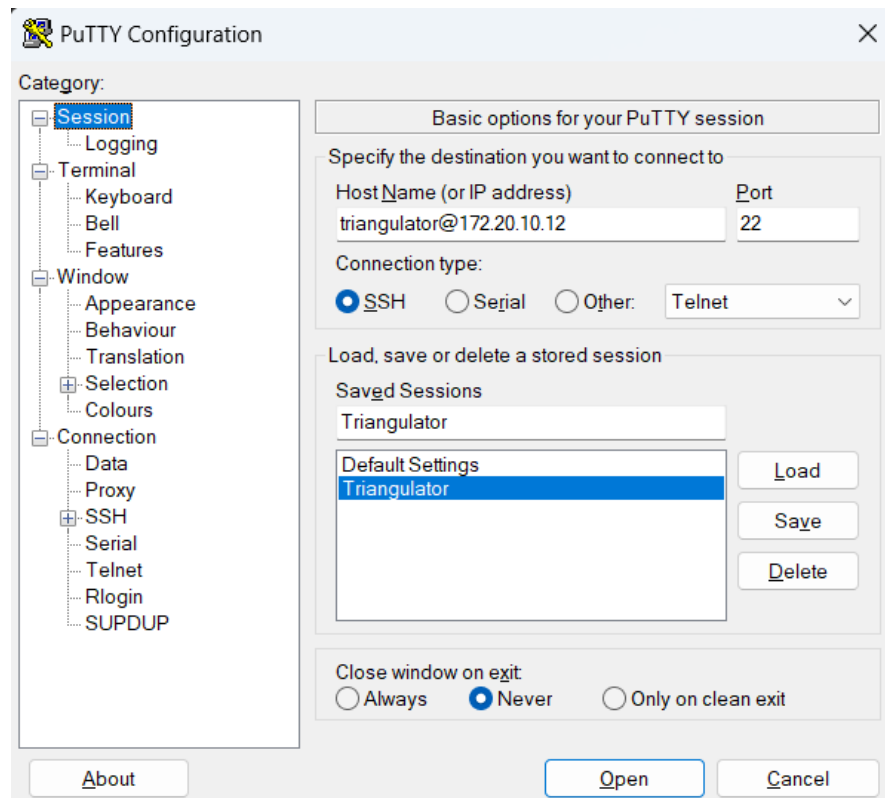
Figure 4.21: SSH connection to the Raspberry Pi using PuTTY
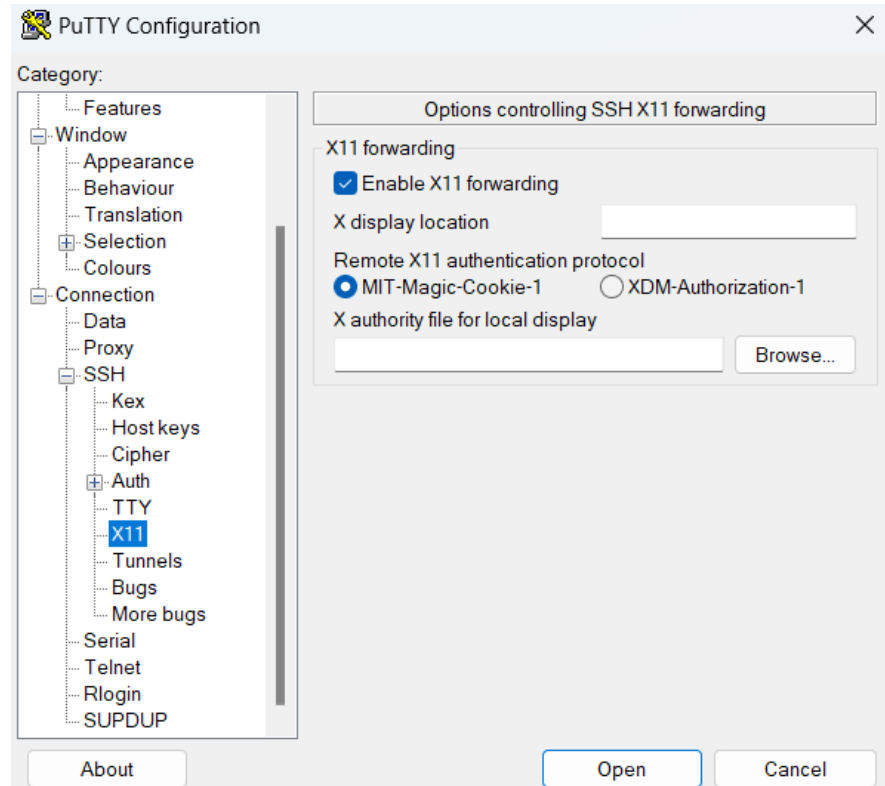
Figure 4.22: SSH settings tab in PuTTY for X11 forwarding

4.11.6   Visual Studio Code SSH

After discovering that X11 Forwarding could not open the application window for the openCV script, another solution to view the camera results had to be done. Using the Remote - SSH extension[29]for visual studio code to connect to the Raspberry Pi allows to view and edit the files via the file explorer. This made it possible to view the frames from the camera, as well as making it easier and faster to edit the Python scripts saved on the Raspberry Pi. The frames of the script would update in real time. This is not a live view of the camera, as there was a limit of how fast it would update the files, but it was quick enough to see how the camera, laser and script acted.

---

[29]Remote - SSH extension is developed by Microsoft

5   Results

5.1   Comparing Blender Simulations Against Developed Solution
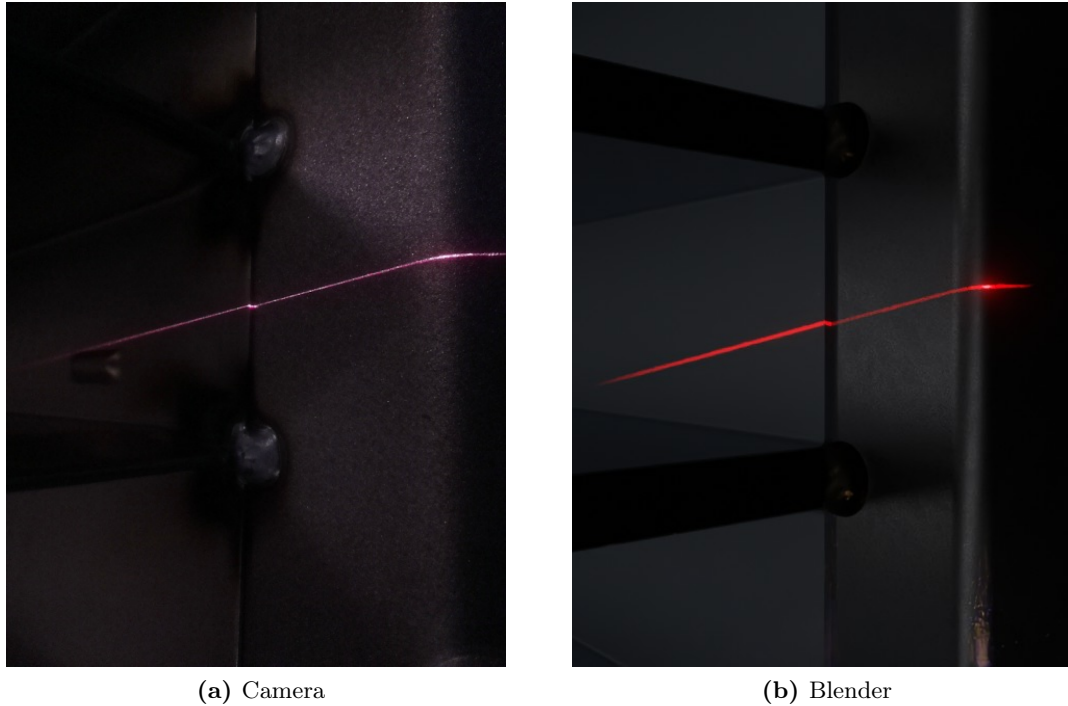
(a) Camera

(b) Blender

Figure 5.1: Comparison of image from camera and rendering from Blender

(a) Welding spatter

(b) Light flash from welding
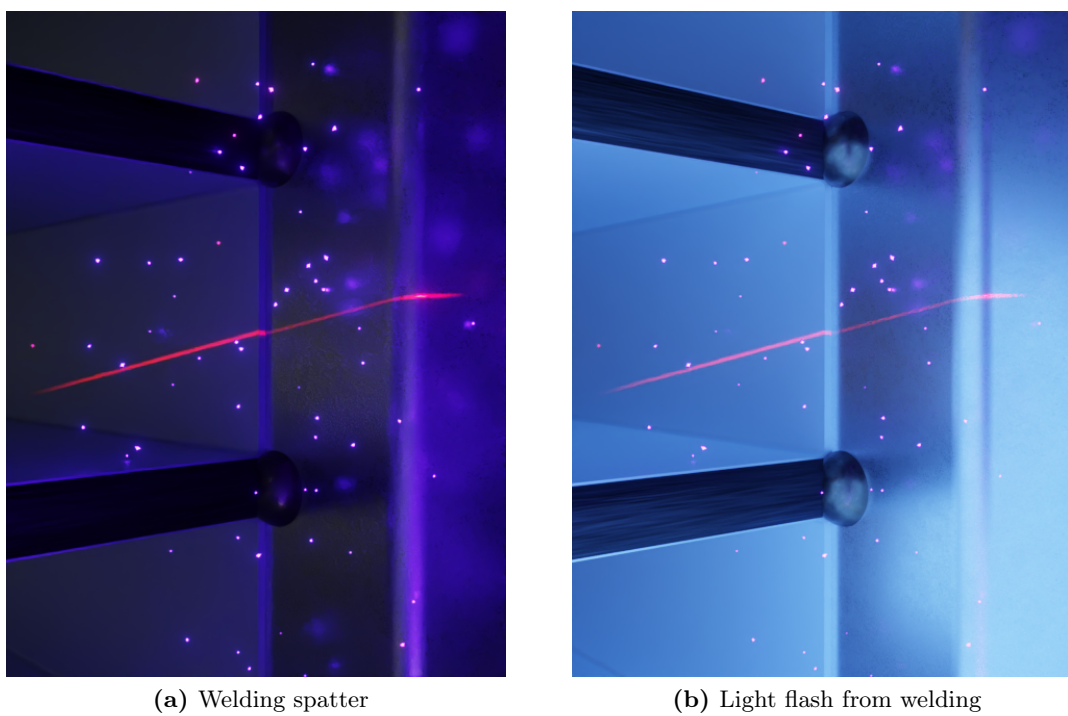
Figure 5.2: Artificially added noise to train algorithm in Blender

Figure 5.1 shows a comparison between the latest versions of the real version and the Blender model. The Blender model had the possibility to add artificial spatter or variable lighting condition to simulate welding, as shown in Figure 5.2. This would be used for testing the vision algorithm under different conditions. The exposure in the Blender model was adjusted to match the camera.

5.2   Locating the Seam Using Vision

Of 71 scanning points in different location, the vision algorithm was able to successfully detect the edge with 80,3% accuracy. The value is calculated in Table 5.1. This value is only represents the accuracy of the sensor. Other variables like communication loss could effect the overall success rate and reliability of the system. An example of the probe not finding the seam is presented in Figure 5.3.

Parameter	Value
Total Scans	71
Correct Scans	57
Missed Scans	14
Accuracy	80,3%

Table 5.1: Scanner Accuracy Results

(a) Successfully found edge   (b) Error in scan
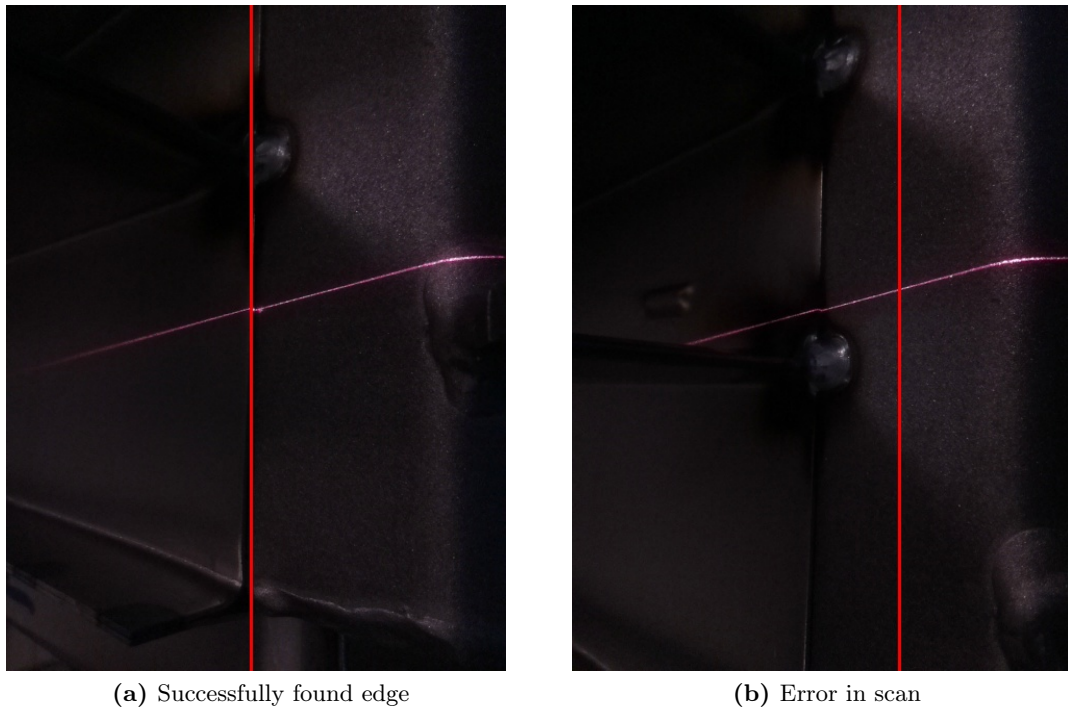
Figure 5.3: Example of missed probing. Selected edge visualized with red vertical line

5.3   Utilizing ROS2 for Motion Command and Control

The Forward Velocity Controller is used for controlling the robot while scanning. The UR10 is set to scan with a velocity of 5 cm/s while continuously trying to compensate for the misalignment in the X-axis. When running the UR10 internal speed at 100%, the system behaved as an unstable system when close to the base, and marginal stable when approaching the maximum reach of the UR10. This was solved by reducing the internal speed of the UR10 to 50% or less. At this rate the UR10 would move smoothly when commanding it with the Forward Velocity Controller. The URScript interface was used to command the robot with "moveL" commands. This was used to set the robot into predefined starting locations for the scans.

The URSim was used to check how programs would function without having a physical robot present.
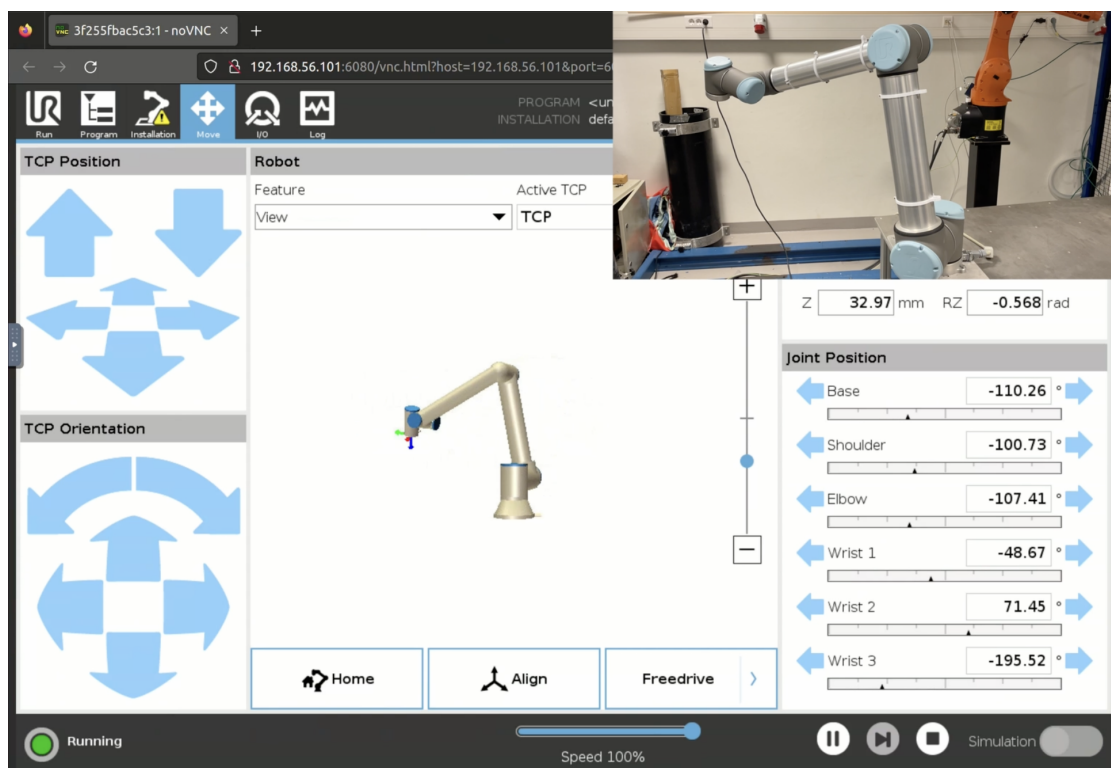
Figure 5.4: URSim and robot at the same spot in the program.

The URSim could also be connected to the Gazebo Classic simulation. Here its possible to import models into the workspace, unlike URSim. This enabled us to check clearances before running the program on the robot.
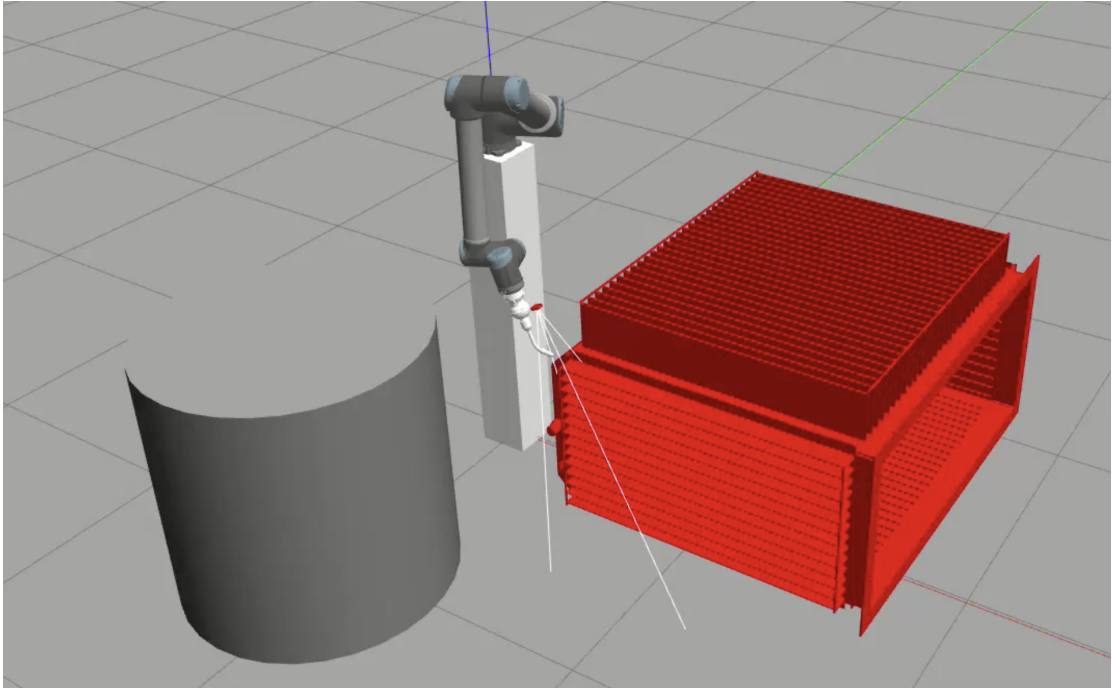
Figure 5.5: Workpiece (red) imported in Gazebo Classic

5.4   Robot Cell

The robot cell is shielded with plastic tarp to protect users of the laboratory from stray laser beams (Figure 5.6). A camera is placed the entry of the robot cell, overviewing the robot. The camera feed could be viewed on an external display outside the cell. The cell is marked with multiple laser warning signs. A risk assessment and record of laser use is present at the entry of the cell. The filled out record is attached in Appendix F.

Figure 5.6: Open robot cell with blue plastic tarp. Door can be closed, sealing the cell.

6 Discussion

6.1 Is Blender Suitable for Training Vision Tasks

The Blender model proved to be a accurate representation of the real setup. The images generated with Blender was useful when training the vision model early in the project. The model also introduced the ability to add artificial noise to the scans to stress the vision algorithm. This was a useful addition since the robotic cell where we conducted the project did not have the necessary ventilation for real welding.

6.2 ROS2 in Robotic Applications

With no prior experience with ROS2, the setup process was challenging and took more time then anticipated to complete. But the ROS2 control system was a crucial part of performing real-time control of the robot. It was considered during the preliminary report to use RoboDK, as can be seen in page 11 of Appendix A. Since RoboDK does not support real-time path compensation, the choice to use ROS2 was made[30]. The ability to simulate the movements with URSim and Gazebo Classic were fundamental to not damaging the robot or the non-contact probe.

During the servoing of the UR10, the jitter problem UR10 with the Forward Velocity Controller was a major problem when developing the control solution. The solution of running the robot at 50% speed introduced new problems. A commanded speed of 5 cm/s resulted in the robot only moving at 2.5 cm/s instead.

6.3 Robot Cell

The plastic tarp around the UR10 acted as a barrier between the users of the laboratory and the class 3B laser. This was a good precaution that allowed testing with the robot even if there was students present at the laboratory without laser goggles. The camera overviewing the cell worked great to monitor the robot without needing laser goggles.

6.4 Hardware Choices

6.4.1 Laser

The selected laser performed great for this task. The ability to turn off the laser while not in use, reduced the chance of stray laser beams when traversing the workpiece. The laser was also sufficiently strong enough for doing scans while not welding.

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[30]RoboDK can not use real time compensation as stated by Albert, a moderator on the RoboDK forum page: `https://robodk.com/forum/Thread-Real-time-path-compensation-using-Faro-Laser tracker`

6.4.2   Camera

The Raspberry Camera Module performed as expected when testing. The camera had parameters for setting the exposure and resolution. This was a important feature when working with high intensity light.

6.4.3   Raspberry Pi 4

The Raspberry Pi 4 performed great for its price point, but this project would benefit of better hardware. The Python algorithm could be optimized to run better on the Pi, but with ROS2 and the vision algorithm running on the system, this would probably only result in a small gain of performance. The main delay in the program was waiting for the vision tasks to find the seam before starting to move. This can be changed to do the calculations while moving to the next scanning waypoint.

6.4.4   UR10

UR10 was a suitable robot choice for this project. With the robots collaborative features, we could be present in the robot cell with laser goggles to monitor the robot. The ROS2 driver for the UR-series is mature enough for use in robotic applications. Some robots does not have the drivers that has transitioned from ROS to ROS2.

7   Conclusions

The main focus of this thesis was developing a non-contact probe for a specific client use case. While the solution was not implemented into the current robot program of the client, the group is satisfied with the performance of the developed non-contact probe. The probe could scan the profile of the workpiece and locate the target seam with over 80% certainty. The sensor can be reprogrammed and updated with new features over time to implement other scanning techniques and better repeatability. ROS2 proved to be a great control solution for real-time control and the group is positive that using ROS2 for this project was the correct decision.

7.1   Further Work

1. Continue developing the non-contact probe. Implementing better calculation of distance for the adjustment.

2. Using the joint trajectory controller instead of URScript for movement between waypoints.

3. Changing the Raspberry Pi 4 to more powerful hardware.

4. Shielding the non-contact probe. Using compressed air and glass to protect the sensor from arcs and splutter.

5. Using a real-time operating on the Raspberry Pi 4.

Appendices

A   Appendix: Preliminary Project Report

PRELIMINARY PROJECT - REPORT

FOR BACHELOR'S THESIS

NTNU

Department of ICT and
Natural Sciences

TITLE:

Optical Path Planning for Welding Robots using Laser Triangulation

---

CANDIDATES (SURNAME, NAME):

ALVESTAD, SIMEN BORGUNDVÅG
BJØRNESETH, PETER NORDAL

DATE:	SUBJECT CODE:	SUBJECT:		DOCUMENT ACCESS:
21.09	**IELEA2920**	**Bachelor's thesis**		- Open
COURSE:			NR. PAGES/ATTACHMENTS:	BIBL. NR:
BACHELOR THESIS AUTOMATION			15/3	- Not in use -

SUPERVISOR(S)/CLIENT(S):

Aleksander Skrede - NTNU - aleksander.l.skrede@ntnu.no
Ottar L. Osen - NTNU - ottar.osen@ntnu.no

Christian Hellebostad - Møre Trafo AS
Fred Alvestad - Møre Trafo AS
Kjetil Monsøy - Møre Trafo AS

SUMMARY:

Møre Trafo AS wants to see if it is feasible to use laser seam tracking for their current welding robot. The group will focus on laser triangulation for determining where the seam is.

A robot will be equipped with the device the group creates and used to test the solution.

This thesis is done by students at The Department of ICT and Natural Sciences at NTNU Ålesund.

This assignment is an exam answer done by student(s) at NTNU in Ålesund.

TABLE OF CONTENTS

1   INTRODUCTION

Møre Trafo AS is a leading manufacturer of distribution transformers and assembled substations in Scandinavia. A portion of the manufacturing is done by robots.

In one of the steps of manufacturing, robots weld together the heat sink sections of the transformer. The robot utilizes a probe to measure the transformer after it has been attached to the welding jig. The program that probes the transformers is universal and works an all the different sizes in the product lineup. The problem that occurs is that the robot sometimes misses the welding line. This causes leaks in the finished product, and leak testing is time consuming. The premade program does not compensate for this error. In this thesis we will be researching ways to correct this error with the help of laser triangulation.

2   PROJECT ORGANIZATION

2.1   Project Group

Candidate number(s)
10005 10016

Table: Student number(s) for all members submitting the assignment for assessment in subject IELEA2920

2.1.1   Tasks for the project group – organization
The group will rotate the roles on a 14-day basis.

Time period (week nr.)	Project leader	Secretary
35 - 36	Simen	Peter
37 - 38	Peter	Simen
39 - 40	Simen	Peter
41 - 42	Peter	Simen
43 - 44	Simen	Peter
45 - 46	Peter	Simen
47 - 48	Simen	Peter
49 - 50	Peter	Simen

The full name of the group members is:
Alvestad, Simen Borgundvåg
Bjørneseth, Peter Nordal

2.1.2   Tasks for the project leader

- Schedule meetings.

- Check time usage at end of week.

- Distribute workload across team members.

- Make sure deadlines are met.

- Quality control

2.1.3   Tasks for the secretary

- Take notes from meetings.

- Keep Gantt chart up to date.

- Save and store communication from client and supervisors.

- Managing documentation

2.2   Steering group (supervisor and client contact person)

- **Supervisors NTNU:**
  Aleksander Skrede - Main supervisor
  Ottar L. Osen - Secondary supervisor
  Hans Georg Schaathun -Vision supervisor

- **Client contact at Møre Trafo AS:**
  Christian Hellebostad - Operations Engineer
  Fred Alvestad - Technical Manager
  Kjetil Monsøy - Production Manager

3   AGREEMENTS

3.1   Agreement with the client

In the Teams meeting 19.09.23 the requirements for the thesis were discussed.
Møre Trafo AS wants a solution for tracking a seam.
The solution is at minimum a report covering the results.
Møre Trafo AS will cover the expenses for the laser.

3.2   Workplace and resources

- Access to workspace
The primary workspace will be NTNU Ålesund. When testing with robots, the
location is set by the location of the robot.

- Access to resources
Robots and other required equipment will be provided by NTNU. The line laser is
provided by Møre Trafo AS. Python and RoboDK is the main programs for data
handling. Some visualizations will be done in Blender.

- Access to individuals
Aleksander Skrede (NTNU) - aleksander.l.skrede@ntnu.no
Ottar L. Osen (NTNU) - ottar.osen@ntnu.no
Hans Georg Schaathun (NTNU) - hasc@ntnu.no

Christian Hellebostad (Møre Trafo AS) - christian.hellebostad@moretrafo.no
Fred Alvestad (Møre Trafo AS) - fred.alvestad@moretrafo.no
Kjetil Monsøy (Møre Trafo AS) – kjetil.monsoy@moretrafo.no

- Data security/confidentiality
No classified information has been exchanged at time of writing the preliminary project.

- Agreed-upon reporting
Møre Trafo AS did not require any reporting but will be invited to participate in every second meeting with the steering group. The steering group will meet at bi-weekly intervals, so every 4 weeks for Møre Trafo AS.

3.3   Group Norms – Collaboration rules – Attitudes

The group will follow normal working hours each week. Some additional working hours may be added at the end of the project. Main working hours: 08:00 – 15:00 (Monday - Friday).

If a group member cannot meet within the working hours, they should inform the rest of the group as soon as possible.

All decisions will be made with both group members present. If the group does not come to an agreement, the group leader has the final call.

No member is to withhold any information they have received. All documents and communications should always be available to the group members.

4   PROJECT DESCRIPTION

4.1   Issue – Goal – Purpose

Møre Trafo AS is having problems when welding the main body of the transformers. The welding consists of 6 parts. Four heatsink pieces, a top flange, and a bottom pan. The pieces are put in a rotary jig that allows the welding robot to access the whole transformer chassis when welding. To prevent having many programs for the robot, due to different sizes of transformers, the current setup uses a probing program to measure the size of the transformers. The program works well to find the dimensions of the transformer, but sometimes the probe can hit a spot weld, which can cause the robot to miss its welding path enough to make the transformer leak. See Figure 1.

The main goal of the project is to create a laser triangulator that can distinguish the different profiles of a steel part and use that data to create a welding path for a robot. Using this in combination with the universal program that is already installed would make this process

much more reliable. Alternatively, a new universal program can be made using the laser instead of a probe, this however falls beyond this assignment.
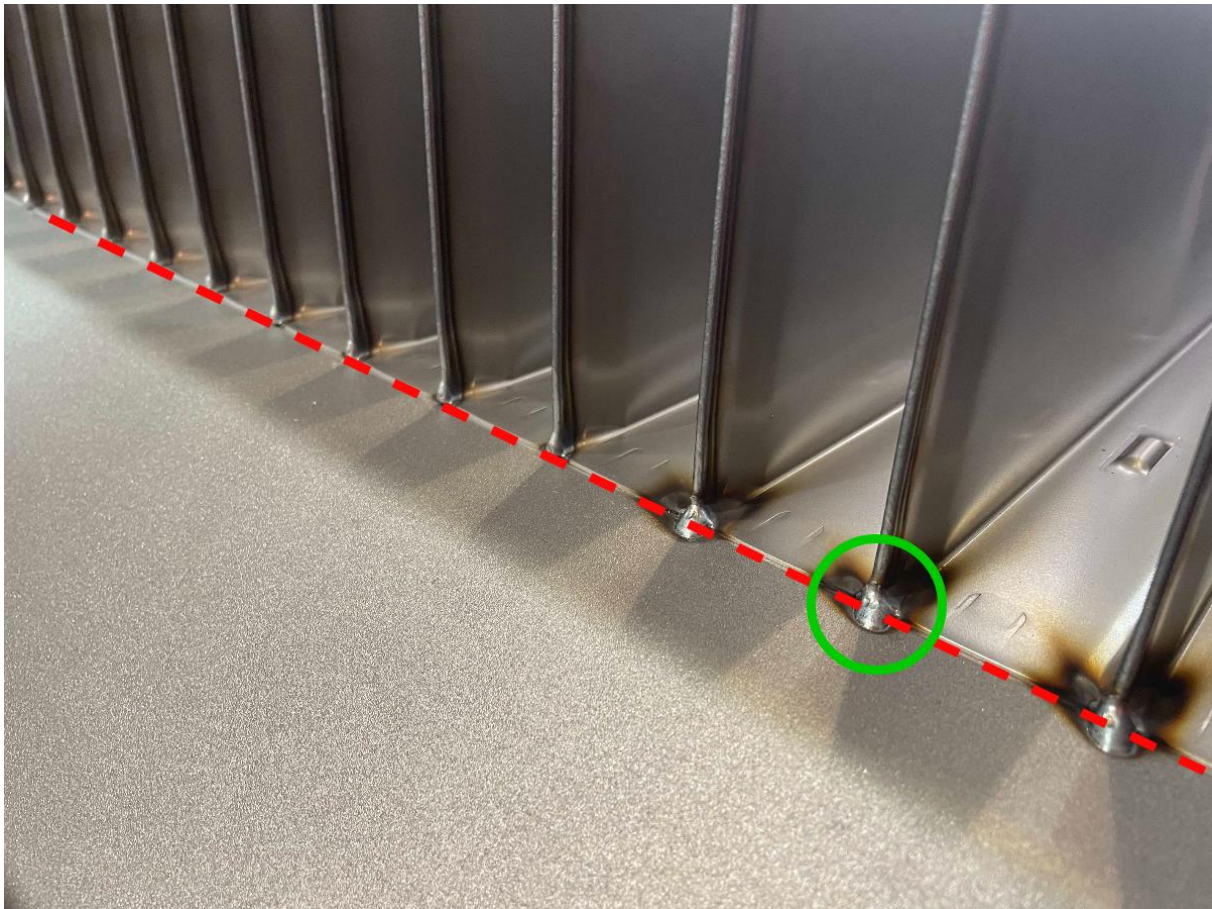
Figure 1: Red line is the welding path. Green circle shows where the probing error can occur.

The achievement goals for the project are as follows:
- o Locating the laser with OpenCV
- o Utilizing a camera-grid system to define shapes from the laser
- o Creating a housing for the camera and laser
- o Making a digital twin for prototyping
- o Physical prototype
- o Using the data from the grid to position the robot

4.2 Solution or project outcome requirements – specifications

Møre Trafo AS wants a laser for their current welding robot to correct small errors in its welding path. There is, however, different ways to complete this task. One way is to use the CAD model of the transformer to generate the paths, but this would still not be an ideal solution as there are still real-world margins to compensate for. This would also require several new programs considering the different CAD models there are.

Another solution would be to use 3d vision and machine learning to create the welding paths. This would, however, be a much more expensive solution and would require more time and investment. This solution would also still need a laser to compensate for errors in the generated 3d model.

A third solution is to redo the probing program in a way which creates less errors. The group is not familiar with the current probing program, so it is uncertain if this is feasible.

When weighing the different options, the group has concluded that implementing a positioning laser is a good and cost-efficient solution. This would be easier to implement to the existing robot, without much downtime relative to the other solutions. This might increase the production time of an assembly, but overall decrease labour due to fewer defects.

The specifications from Møre Trafo AS of the finished project is to see if it is viable to use laser seam tracking for this purpose. If the seam tracking takes too long, or if the unwanted geometry cannot be filtered out then the conclusion will be that it is not feasible.

4.3   Planned approach(es) for development work – methods

The group plans on using the agile development methodology with the Kanban framework. This allows the members for the group to be more flexible in their work, as they work on separate tasks, and not be to dependant on each other. One downside of using this methodology is that deadlines are not defined. To remedy this, a combination of the Kanban table and the Gantt table is used. This will give a visual representation of what the group members are working on as well as when they are supposed to be done with a task. To get an overview of the Gantt and Kanban tables, see section 9.1 and 9.2.

4.4   Information gathering – performed and planned

A visit to Møre Trafo AS was conducted on 08.09.23. There the group was shown the current solution. The possible solutions were discussed with both Christian Hellebostad (Møre Trafo AS) and the operator of the welding station. There we got first-hand experience of the problems that delays the manufacturing process.

Laser triangulation for welding is a mature technology in the industry. Off the shelf solutions does exists but tend to be bulky. The use case in this project does require some special made algorithms and may benefit from a custom solution. The Department of ICT and Natural Sciences have experience from using vision in industry cases. Therefore experts in the field should not be hard to come by.

The group has little experience with robot welding. The thesis will mainly focus on the laser triangulation and algorithms. Since scanning can be done when welding, the group must be familiar with how to perform a good quality weld. Things like speeds, thickness of material and other factors may impact the result. Møre Trafo AS has a lot of expertise in robot welding and can be a good resource to the group.

4.5 Assessment – analysis of risk

Strålevernskoordinator NTNU Ålesund:

Koordinator:
Hans Christian Giske
hcgi@ntnu.no
70161557
Ankeret, A428, Ålesund

Vara:
Harald Jan Skarstein
harald.j.skarstein@ntnu.no
70161380 97040051
Kompasset, K-244, Ålesund

Consequence - harm to humans or material.						
Risk			**Description**			
Grade	Category of risk	Measures to prevent accident / solution.	What	Damage to human	Damage to material	Price
10	Serious	Never look directly into laser. Incapsulate the laser. Use certified laser goggles when inside the robot cage. Keep record of laser use. If exposed to laser, report to radiation protection coordinator.	Class 3B Laser	Permanent eye damage	None	N/A
4	Moderate	Use collaborative robots under research.	Robot crushing hazard	Broken bones	Damage to robot, laser, camera.	< 10K NOK
2	Small	Work from home if possible Update the other group members.	Ill group member	Weakness	N/A	N/A
1	Small	Use safe manufacturing techniques. Outsource work to qualified personnel (E.g. Møre Trafo AS).	Prototyping of equipment		N/A	10K
2	Small	Stretching.	Long sessions of writing	Ergonomics	N/A	N/A
6	Moderate	Use the Gantt diagram to manage time.	Not enough time	Stress	N/A	N/A
3	Small	Status meetings.	Not reaching deadlines	Mental and reputation	N/A	N/A
12	Serious	Limit welding under testing.	Welding with robot	Blindness, Burns	Damage to electronics or mechanical components	< 50K NOK
12	Serious	Backup files	Losing computer files	N/A	N/A	N/A

4.6   Laser Usage Log (Class 3B) (Template)

Date	Time Start	Duration	Sign

4.7 Main activities in further work

No	Activity	Responsibility	Date / Deadline	Allocated days
A1	**Preliminary report**		**07.09 → 21.09**	**14 d**
A1.1	Contract meeting	Simen	20.09	
A1.2	Writing	Peter	07.09 → 21.09	14 d
A1.3	90% delivery	Simen	21.09	
A1.4	Final delivery	Peter	29.09	
A2	**Research**		**21.09 → 04.10**	**13 d**
A2.1	Laser	Simen	21.09 → 27.09	6 d
A2.2	Vision	Peter	21.09 → 27.09	6 d
A2.3	UR Course	Both	27.09 → 28.09	2 d
A2.4	Robot control	Simen	27.09 → 04.10	7 d
A2.5	Robot welding	Peter	27.09 → 04.10	7 d
A3	**Design**		**04.10 → 25.10**	**21 d**
A3.1	Laser Scanner	Simen	04.10 → 12.10	8 d
A3.2	Welding robot	Peter	04.10 → 12.10	8 d
A4	**Testing**		**25.10 → 10.11**	**17 d**
A4.1	Simulator	Simen	25.10 → 01.11	7
A4.2	Vision	Peter	25.10 → 01.11	7 d
A4.3	Robot control	Simen	30.10 → 03.11	4 d
A4.4	Robot welding	Peter	06.11 → 10.11	4 d
A5	**Status presentation**		**15.10 → 17.10**	**2 d**
A5.1	Preparations	Simen	15.10 → 17.10	2 d
A6	**Thesis report**		**10.11 → 15.12**	**35 d**
A6.1	Draft 1	Simen	10.11 → 01.12	21 d
A6.2	Draft 2	Peter	04.12 → 08.12	4 d
A6.3	Complete report	Simen	15.12	
A7	**Project deadline**	**Both**	**20.12**	
				Total Days: 104

4.8   Progress plan – management of the project

4.8.1   Master plan

The plan is to create a solution for compensating robot welding errors. By using lasers and vision, a 3D path can be created and followed. The main activities for the project will be:

- Develop a compensation system for robot welding.

- Use vision and laser triangulation to find path.

- Simulate with digital twin.

- 3D-print models to test with robot.

- Deliver project report.

4.8.2 Management tools

- **Notion**

  Will be used to take document and take notes throughout the project. The application has support for Gantt schemes that shows milestones in the calendar, as well as the kanban table.

- **Microsoft Office365**

  Communications tools from Microsoft's Office365 package. Mail will be used to convey messages to and from the group. Calendar has support for RSVP meetings.

4.8.3 Development tools

- **Python**
  The project contains a lot of signal processing. Python can be a very powerful tool for this with the right packages. OpenCV, NumPy and Matplotlib is some of the required packages.

- **Siemens NX and Autodesk Fusion360**
  To create 3D models, a CAD program is required. NX and Fusion360 is similar, but NX is more capable for larger assemblies. Fusion360 is great for quick parts and generative design.

- **RoboDK**
  RoboDK is used to simulate and create Gcode instructions for the robot. Gcode is series of commands used to make the robot move.

- **Overleaf**
  The final report will be written in latex. Overleaf enables multiple collaborators to work on the same project with live updating text.

- **ROS2**
  A universal robot framework for controlling robots from different manufactures. A code written for a Kuka robot can work on a robot from Universal Robots.

- **Blender**
  A 3D visualizing and modelling tool. The tool can be used to generate training data for the laser.

4.8.4 Internal control - evaluation

The Gantt scheme in Notion can be used to remind the group of upcoming deadlines. If deadlines are not met, the group should discuss the problem and allocate more resources if needed.

When arranging meeting, the RSVP function in Microsoft Outlook will be used to invite all the group members. This will ensure the meeting gets noted in the calendar of the participants.

4.9 Decisions – decision process

The group will vote for any decisions that has a large impact on the project. If the group cannot agree, a meeting with the steering group can help the decision process. For smaller and less important decisions, the group leader will have the final vote.

5   DOCUMENTATION

5.1 Reports and technical documents

The group should produce a "end-of-week" status report every 7 days. This should contain what work has been done and what's next on the agenda. If milestones are not met, they should be included in the report. The reports should be stored in shared file storage (OneDrive, Teams or Notion).

All technical documents must be stored in a shared file storage.

6   PLANNED MEETINGS AND REPORTS

6.1 Meetings

6.1.1 Meetings with steering group

The group will meet with the steering group at bi-weekly intervals during the thesis. A report from each meeting must be written by the current secretary. Meeting logs can be viewed in section 9.3.

6.1.2 Project meetings

An "end of week" meeting will be conducted on Friday each week. A short summary must be written by the current secretary. If one of the group members cannot meet on Friday, an alternative day will be selected.

6.2   Periodic reports

6.2.1   Progress Reports (incl. milestones)

A progress report must be created at the last Friday of each month.
There will be created 4 status reports:
September, October, November and December.
The report should include what has been done, and what should be done.

7   PLANNED DEVIATION TREATMENT

If an unexpected problem does appear, the person responsible for the task should first try to solve it.

If the problem is not solvable, the group should discuss alternative approaches.

If the problem is not solvable by the group, the steering group should be contacted for further discussion. Any unexpected problem that is not solvable from the responsible should be noted in the end of week summary.

8   EQUIPMENT REQUIREMENTS / REQUIREMENTS FOR IMPLEMENTATION

- Raspberry pi 4 (or similar)
- Raspberry pi camera (or similar)
- Line laser
- A six-axis robot
- Access to 3D-printer
- RoboDK
- CAD software

9   ATTACHMENTS

9.1   Gantt Chart

9.2 Kanban Chart

To do	In Progress	Complete
+ Add task	+ Add task	+ Add task
○ A3 Design	○ A2.4 Robot Welding	Completed tasks 6 ∧
○ A4 Testing	○ A2.3 Robot Control	✓ UR Course
○ A5 Status Presentation	○ A2.2 Vision	SA Completed by Simen Borgundvå…
○ A6 Thesis Report	○ A2.1 Laser	✓ A1.4 Final Delivery
○ A3.1 Laser Scanner	○ A7 Project Deadline	SA Completed by Simen Borgundvå…
○ A3.2 Welding Robot	○ A2 Research	✓ A1.3 90% Delivery
○ A4.1 Simulator RoboDK	○ A1.2 Writing	SA Completed by Simen Borgundvå…
○ A4.2 Vision		✓ A1.1 Contract meeting
○ A4.3 Robot Control		SA Completed by Simen Borgundvå…
○ A4.4 Robot Welding		✓ A1 Preliminary Report
○ A5.1 Preperation		SA Completed by Simen Borgundvå…
○ A6.1 Draft 1		✓ A1.5 Visit Møre Trafo AS
○ A6.2 Draft 2		SA Completed by Simen Borgundvå…
○ A6.3 Complete report		

9.3 Meeting Logs from Pre-liminary project

Date	Participants	Location	Recap
28.08.23	Simen, Peter, Ottar Osen.	Zoom	The group discussed the available thesis. Deadlines was not set in stone, the preliminary project should be 90% done in 2 weeks.
29.08.23	Simen, Peter, Paul Steffen Kleppe.	Manulab	The group talked with Paul Steffen about using laser triangulation for 3D scanning. Paul Steffen showed interest in being a supervisor.
08.09.23	Simen, Peter, Christian Hellebostad.	Møre Trafo AS	A guided tour of Møre Trafo. We were presented with the case.
15.09.23	Simen, Peter, Aleksander Skrede, Ottar Osen.	Teams	First meeting with supervisor. Discussion about deadlines, requirements and whos is going to pay for equipment. Aleksander wanted status updates bi-weekly. The group could choose if we wanted early or late in the week. Ottar suggested that we explored other solutions in case there is a better one. Using Manulab and Paul Steffen was dismissed since IIR recently got new robots.
19.09.23	Simen, Peter, Christian Hellebostad, Kjetil Monsøy.	Teams	The meeting was about agreements with Møre Trafo AS. Møre Trafo AS can cover the expense of a line laser. The group will report to Christian. We report when we have something to show or something we want to ask about. Møre Trafo AS wants a solution for following a seam at the end of the thesis. Existing solutions is often to bulky.
28.09.23	Simen, Peter, Aleksander Skrede	Teams	Bi-weekly status meeting. The group went over the current status of the thesis. We discussed using an UR robot for testing. When using ROS2 the choice of robot is not locked in since ROS2 can run on most robots.

B   Appendix: Meeting Logs

Date	Participants	Location	Recap
12.10.23	Simen, Peter, Ottar Osen, Aleksander Skrede, Hans Georg Schaathun	Teams	Bi-weekly status meeting. The group was introduced to Hans Georg. There was a suggestion that he could help on the machine vision. This meeting was planned to include Møre Trafo AS, but due to their busy schedule the meeting was only with the supervisors. ROS2 was chosen as a suitable control system.
17.10.23	Simen, Peter, Cristian Hellebostad, Kjetil Monsøy.	Teams	Møre Trafo AS was invited to a recap of last week's meeting. The group also showed the progress made this far, 3D models, ROS2, etc. They were asked by the group if a model transformer container could be made to use for testing. They were able to, and would send an email with suggestions of the size we wanted.
26.10.23	Simen, Peter, Ottar Osen, Aleksander Skrede, Hans Georg Schaathun	Teams	Bi-weekly status / Midway presentation. The group had a presentation that show their findings to the supervisors.
09.11.23	Simen, Peter, Aleksander Skrede	Planned	Meeting canceled. The meeting was canceled since the group did not need any help from the supervisors this period. The supervisors informed via E-mail and no major changes had happened from the midway presentation.
01.12.23	Simen, Peter, Aleksander Skrede	Tunglabben	Last scheduled with supervisor. The group is transitioning into only writing report. The topic was troubleshooting ROS2, and some tips and tricks for report writing. Aleksander wanted a draft of the report thus far, and the group promised to deliver by next week.

C   Appendix: Laser Test Report

Global Laser
Acceptance Test Report
Product: LYTE MV EXCEL 660 / 50 / 45 / A / 300
RS

Serial Number:		39454 - 3	
Customer Requested Wavelength (nm)	660	Passed	✓
Customer Requested Diode Power (mW)	50	Passed	✓
Customer Requested Fan Angle (°)	45	Passed	✓

Driver Board   Linear ✓   DNI ☐   DI ☐

Power after Collimation (mW)	31.6
Measured Wavelength (nm)	664.9
Pre-Set Working Distance (mm)	300
Line width at pre-set focus (um at 1e2)	114
Modulation	Passed ✓
Line uniformity	Passed ✓
Test Temperature (°C)	23
Tested By:	AD
Date:	20/06/2023

D   Appendix: Laser Datasheet / User Guide

Lyte-MV-Excel
Machine Vision Laser

Features

Unique user adjustable focus without removing line optics

Max powers Red up to 100 mW & IR up to 200 mW

Uniform non-Gaussian line with fan angles from 15 to 90 degrees

Laser classification maintained during focus adjustment

CW, Linear modulation or TTL control

Excellent focus & line quality

Rugged design

Case electrically isolated

Improved line thickness

Accurately aligned

Applications

Automotive

Ceramics

Timber & packaging

Aerospace

Triangulation

Tomography

The Lyte-MV-Excel range of laser modules provides reliable high power, industrial laser light sources with well-defined line illuminations. Used primarily with industrial cameras, they are suitable for a wide range of inspection, measurement and control systems.

Available in visible wavelengths up to 100 mW, infrared up to 200 mW, the laser beam output is a uniform intensity line with excellent focus control.

Conventional machine vision lasers are adjusted in focus by removing the line optics and inserting a focusing tool into the laser to adjust the position the collimating lens. This process is time consuming and also can result in the laser changing power classification. The unique focusing mechanism of the Lyte-MV-Excel allows the focus to be adjusted without the need for removing line optics by simply rotating the rear end of the laser. This novel design produces improved line quality whilst maintaining accurate alignment.

Line lengths from a few mm to several metres are available from a variety of standard optics, with custom optics to suit specialised requirements.

Requiring only a standard low voltage supply the Lyte-MV-Excel range is ready to use in arduous environments and demanding applications.
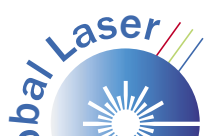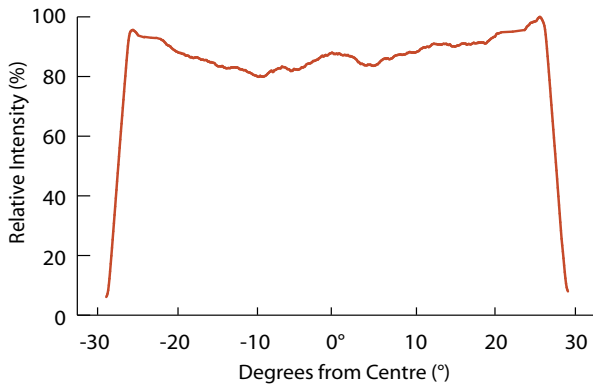
UNIFORM INTENSITY

The profile opposite shows the typical intensity along the length of the line. The uniform power distribution in the centre with sharp ends makes this laser suitable for use with of a wide range of commercial CCD cameras.

FOCUSING AND DEPTH OF FIELD CHARACTERISTICS

The following charts show the typical focusing and depth-of-field performance of the Lyte-MV-Excel laser. The focus charts indicate the minimum line thickness (at $1/e^2$) achievable for a specific projection distance. The depth-of-field is defined as the distance between two points either side of the pre-set focus at which the linewidth increases by a factor of $\sqrt{2}$.

Focusing

Short range
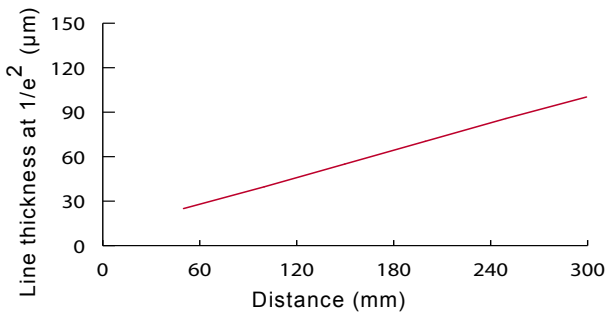
Long range

Depth-of-field (Rayleigh range)
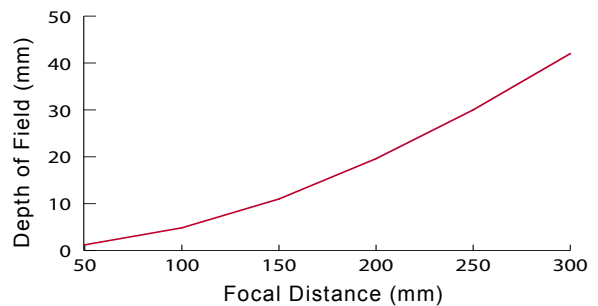
Short range
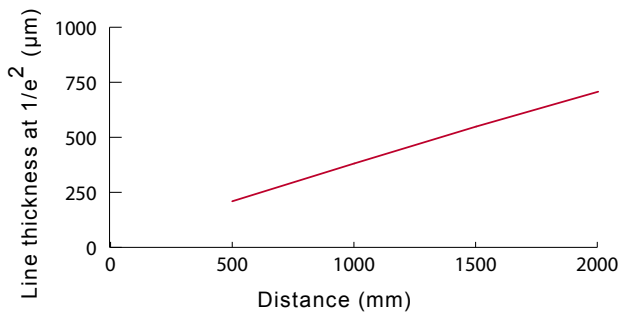
Long range
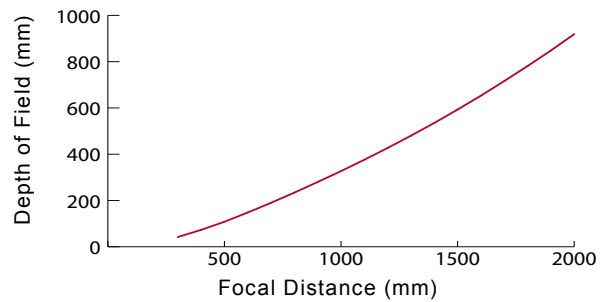
SPECIFICATIONS

MECHANICAL SPECIFICATIONS

Weight	52 grams
Dimensions	19 mm dia x 88 mm *(not including connector)*
Housing	Bronze anodized Aluminium
Isolated Body	Yes
Input Leads	4, Red (+ve), Black (0 V), Yellow (Control), Blue (Enable switch)
Lead length	250 mm

OPTICAL SPECIFICATIONS

Diode Power	1 mW to 200 mW *
Wavelength	635 nm to 980 nm *
Intensity distribution	Uniform along length, Gaussian along width
Fan Angles	15 degrees to 90 degrees *
Line Thickness	Varies with distance & wavelength
Bore sighting	< 3 mrad

ENVIRONMENTAL SPECIFICATIONS

Operating case temperature	-10°C to +50°C
Storage temperature	-10°C to +80°C
Operating Humidity (%RH)	90 (non condensing)

ELECTRICAL SPECIFICATIONS

Input voltage	5 Vdc (+ 10%) (standard) 12 Vdc or 24 Vdc ** (via optional 11-32 Vdc adaptor) 110 Vac/240 Vac ** (via optional adaptor)
Connector type	4 pin BINDER
Reverse - Polarity protection	Yes

Specifications are typical at 25°C unless otherwise stated

* = varies with model

** = CW operation only with these power adaptors

MOUNTING CLAMPS

The optional heavy duty mounting clamp allows the Lyte-MV-Excel to be securely fixed at any required direction or angle. The base plate has a series of threaded holes which allows the clamp to be fixed directly onto a machine or workbench.

STANDARD DRIVER TYPES

Two driver boards are available for the Lyte-MV-Excel either a Linear or TTL control.

• LINEAR INTENSITY & ANALOGUE MODULATION CONTROL

User adjustable intensity control
Via the yellow control lead output power may be linearly controlled from the maximum factory set value to all lower values including off. This may be changed via a simple resistor or by a control voltage. 0 Vdc is off, +1 Vdc is on, all values in-between are linear.

See power adjustment curve below.
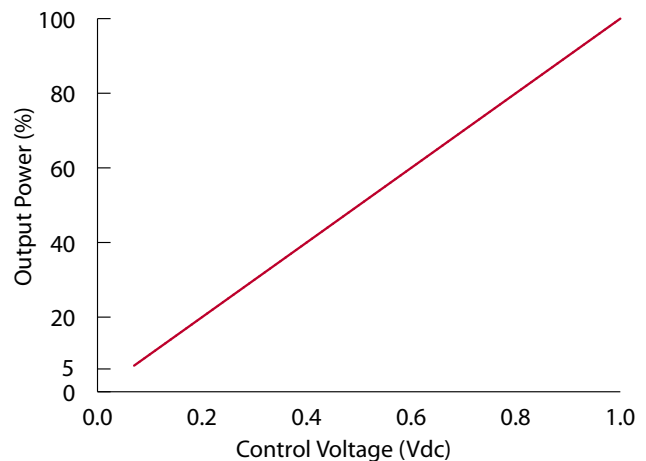
Modulation & Synchronization
Using the yellow control lead the laser may be modulated or synchronised to the camera by using an external signal. Required voltage range is 0 to +1 Vdc (to set the maximum intensity), frequency range is DC to 200 KHz

Please note: Intensity control and modulation functions may be used together.

• TTL DIGITAL CONTROL

The Lyte-MV-Excel is also available with a TTL driver board that allows the unit to be gated on and off, or pulse-width modulated at TTL voltage levels via the yellow control lead. Two versions are available either non-inverting TTL or inverting TTL. For non-inverting < 0.4 V = off and > 2 V = on and vice versa for the inverted model.

Rise Time: < 0.5 µs *
Fall Time: < 0.5 µs *

* = Varies with model

STANDARD WAVELENGTHS AND POWER OPTIONS

635 nm	1, 3, 5, 10, 15, 35 mW
650 nm	1, 5, 10 mW
660 nm	20, 30, 35, 50, 100 mW
670 nm	1, 3, 5, 10 mW
685 nm	20, 50 mW
780 nm	5, 20 mW
785 nm	35, 50, 75, 90 mW
980 nm	200 mW
Custom	Please call for further details

Please note wavelength tolerance can vary typically by ± 10nm.

FAN ANGLE OPTIONS

The Lyte-MV-Excel is available in the following fan angles. These angles are full angles.

15°
20°
30°
45°
60°
75°
90°

ORDERING GUIDE

To order the correct Lyte-MV-Excel please follow the guidelines below:

Wavelength (nm)
Fan Angle (°)

LYTE-MV-Excel/ 660 / 50 /60/ A / 500

Working Distance (mm)
300mm if not specified

Power (mW)

Driver Board
DNI -TTL (non inverted)
DI - TTL (inverted)
A - Linear Modulation

LASER SAFETY

Our lasers are compliant to IEC 60825-1 standards. The lasers fall within one of the following classifications depending on power, wavelength and fan angle. The labels supplied with the units are shown below.

OEM Laser Label

OEM COMPONENT FOR USE IN A CERTIFIED LASER SYSTEM
>5mW CW 630-980nm
IEC 60825-1 Amendment 2 / 2001

Class 2M Laser Label

LASER RADIATION
DO NOT STARE INTO BEAM
CLASS 2 LASER PRODUCT
<1mW CW 690-700nm
IEC 60825-1 Amendment 2 / 2001
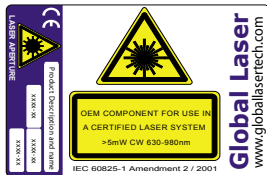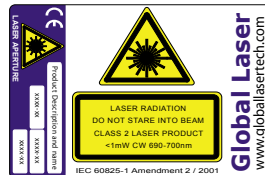
Class 3R Laser Label

LASER RADIATION
AVOID DIRECT EYE EXPOSURE
CLASS 3R LASER PRODUCT
<5mW CW 630-690nm
IEC 60825-1 Amendment 2 / 2001

QUALITY & WARRANTY

The Lyte-MV-Excel is supplied with a 12 month parts and labour warranty. Our manufacturing operations are certified to ISO9001.

Global Laser *Are a ISO9001:2000 registered company*

DIMENSIONS

120 mm
19 mm
88 mm Adjustable
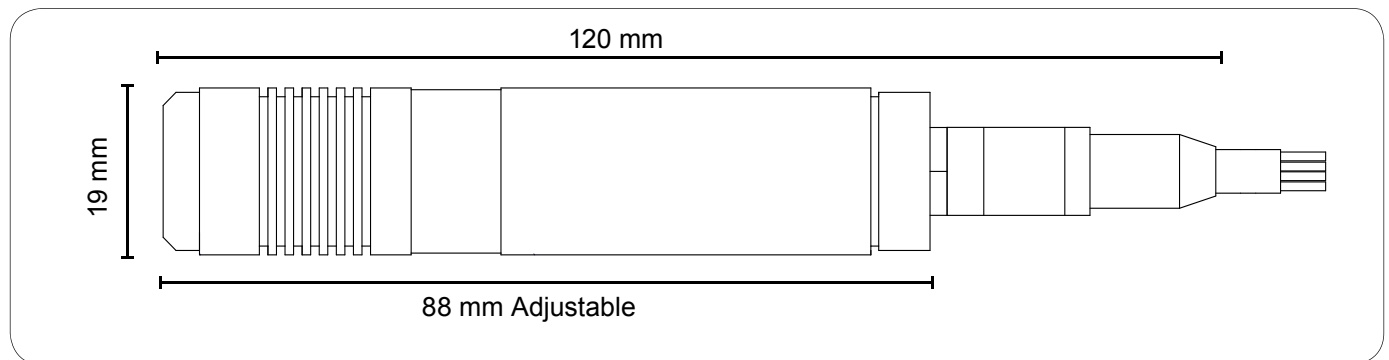
Please note: Global Laser reserve the right to change descriptions and specifications without notice

Global Laser Ltd
Cwmtillery Industrial Estate
Abertillery. Gwent. UK. NP13 1LZ

T: +44 (0)1495 212213
F:+44 (0)1495 214004
E: sales@globallasertech.com
www.globallasertech.com

For further information about the Lyte-MV-Excel you can contact your local distributor or you can contact Global Laser in the UK.

Your Local Distributor Is:

10
RADIOACTIVE SOURCES
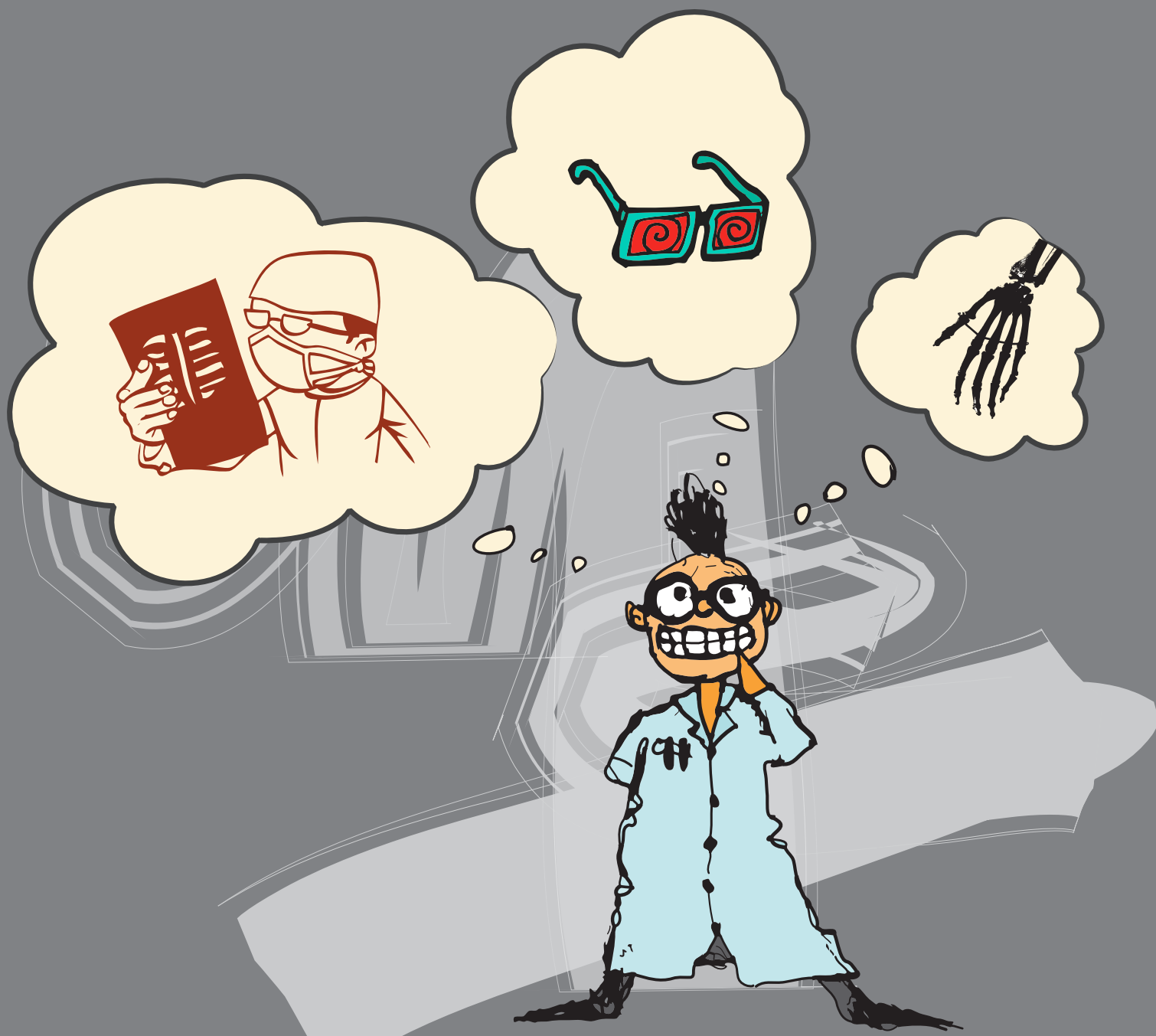
10.1 Radioactive sources

There are two main categories of radioactive sources:
- Ionising: Radioactive substances, X-ray apparatus, electron microscopes
- Non-ionising: Lasers, short-wave ultra-violet radiation (UVC) and sources emitting potentially harmful electro-magnetic radiation, among others.

Radioactive sources must be handled in compliance with local regulations and in such a way as to minimise the risks to your own health and safety and that of others, the working environment, and the external environment

The use and handling of radioactive sources are regulated by separate statutory regulations, standards and HSE guidelines.

Innsida: Radiation protection

10.2   Prior to the commencement of work

- The local radiation protection coordinator must be kept informed and be consulted regarding radioactive sources and their use, location, movements, procurement and disposal, etc.
- Necessary training shall have been completed
- The employee health and safety representative and relevant third parties must be notified of the activity in question, and of any precautions which must be taken
- A risk assessment of work involving the radioactive source(s) in question must be carried out
- Essential shielding, technical safety systems, personal protective equipment and appropriate measuring devices for carrying out radiation protection checks must be readily accessible
- Prior to procurement or use, personnel must be made aware of the proper storage and disposal procedures for the radioactive source(s) in question
- Emergency procedures/a contingency plan must be prepared. Accidents involving radioactive sources must be reported without delay to both the local and central radiation protection coordinators, together with standard notifications to the relevant managers
- The radiation protection coordinator must be informed of the procurement of new radioactive sources. He or she will then register the source with the Norwegian Radiation Protection Authority, or submit an application for approval for use if the source in question is not included among NTNU's general licences for use.

10.3   Sources of ionising radiation

- Service and maintenance must be carried out by qualified personnel
- Users must have training in locally prepared guidelines, handbooks and contingency plans, in the use of measuring devices and protective equipment, and in the disposal of waste

- Make an assessment of whether it is possible to employ methods which do not involve the use of ionising sources
- Access to laboratories containing sources of ionising radiation must be restricted
- Use the minimum levels of radiation possible
- A contamination check must be carried out when using open sources
- All purchases, usages and disposals must be recorded
- Signs and notices must be posted in compliance with statutory regulations on all sources and equipment, and at the workplace (parts of, or the entire laboratory)
- Radioactive sources and waste must be stored correctly
- Personnel who become pregnant must inform their technical supervisor without delay.
- If you are pregnant and intend to work with ionising radiation, the doses shall be calculated and must not exceed 1 mSv for the remainder of the pregnancy.
- The central radiation protection coordinator must be notified of all users who may be at risk of levels of exposure in excess of 1 mSv/year

Open radioactive sources
- All work carried out above the contingency thresholds described in the attachment to the statutory regulations governing radiation protection and the use of radiation (strålevernforskriften) must be carried out only in approved laboratories (Classes B or C). Applications must be made to the Norwegian Radiation Protection Authority for discharge permits for these labs.
- For more detailed information, we refer to the various types of ionising sources as described in Innsida

10.4   Non-ionising radiation

The use of sources of non-ionising radiation must be registered in a log book that accompanies the source. In compliance with local guidelines, an information folder must accompany the source.

Lasers – classes 3B and 4

- The person responsible for the equipment must make an assessment as to whether likely users are sufficiently qualified to use the lasers without supervision. In the case of class 4 lasers, the assessment must be documented in writing
- The most relevant protective equipment comprises laser goggles designed specifically for the laser radiation in use and its application. In addition, for Class 4 lasers, there may be a specially-designed visor, fire-proof clothes, gloves, etc., in order to protect the skin from exposure, fire risk, etc.
- Every effort must be made to provide maximum enclosure of the laser beams
- The procurement, movement or disposal of Class 3B and 4 lasers must be reported to both the local and central radiation protection coordinators.
- Lasers stronger than Class 2 (1mW) shall not be used as laser pointers at either NTNU or SINTEF.

10.5 UVC sources

- The division in question must ensure that UVC tubes are used correctly
- Protective equipment may include eye and face protection (goggles/visor), appropriate protective gloves, and long-sleeved work clothes
- The division must have its own equipment for, or know where to find assistance in relation to, the measurement of UVC
- All exposure must be kept to the minimum levels possible. Systems should be in place to ensure that open UVC sources are turned off automatically when a person enters an area where harmful UVC radiation is in operation
- All apparatus and laboratories where harmful UVC radiation in use must be indicated with signs and notices.

F   Appendix: Laser Usage Record

4.6   Laser Usage Log (Class 3B)

Date	Time Start	Duration	Sign
13/11	12:00	2h	Peter
14/11	09:30	6h	Peter
15/11	10:00	5h	Peter
16/11	09:30	6h	Peter
17/11	10:30	4h	Peter
20/11	09:00	5h	Peter
21/11	09:00	4h	Peter
22/11	10:00	4h	Peter
23/11	09:00	3h	Peter
24/11	10:00	2h	Peter
29/11	09:00	4h	Peter
1/12	09:00	2h	Peter

G   Appendix: Monthly Status Reports

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Ålesund, Norway

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PROJECT STATUS REPORT

Reporting period:	07.09.23 - 25.09.23	Project title:	Optical path planning for welding robots using laser triangulation
Date of report:	26.09.23	Report author:	Simen Borgundvåg Alvestad, Peter Nordal Bjørneseth

SUMMARY

The group have not had any major problems during the starting weeks of the project.The preliminary report is almost complete and should be entirely finished before the deadline. In the coming weeks the group will focus on researching laser triangulation and vision control, as well as designing a mounting bracket for the laser and camera.

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Ålesund, Norway

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PROJECT STATUS REPORT

Reporting period:	October 2023	Project title:	Optical path planning for welding robots using laser triangulation
Date of report:	27. October	Report author:	Simen Borgundvåg Alvestad, Peter Nordal Bjørneseth

Tasks this period

- Robot control

- Design laser scanner

- Testing simulator, hardware and robot control

- Mid way presentation

Completed tasks

- A first draft of the laser scanner was made, but will probably be changed under testing.

- Connection to UR10 via ROS2

- Simulating UR10 using Gazebo classic

- Mid way presentation

Challenges and issues

ROS2 is difficult to set up and use.

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Ålesund, Norway

Upcoming tasks

- Integration with UR10 and laser scanner

- Mounting laser scanner to UR10 including wiring

- Functional demo

- Start writing thesis report

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Ålesund, Norway

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PROJECT STATUS REPORT

Reporting period:	November 2023	Project title:	Optical path planning for welding robots using laser triangulation
Date of report:	24. November	Report author:	Simen Borgundvåg Alvestad, Peter Nordal Bjørneseth

planned tasks this period

- Integration with UR10 and laser scanner
- Mounting laser scanner to UR10 including wiring
- Functional demo
- Start writing thesis report

Completed tasks

- Integration with UR10 and laser scanner
- Mounting laser scanner to UR10 including wiring
- Start writing thesis report
- Working laser triangulation with edge detection
- Got a miniature trafo from Møre Trafo to test in the project
- Covered the robot cell with blue plastic tarp and safety markings

Challenges and issues

- Forward velocity controller in ROS2 proved to be difficult to use. URscript will be used instead
- Raspberry Pi got too low power delivery and turned off
- Raspberry Pi kept loosing network connection

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Ålesund, Norway

Upcoming tasks

- Get robot to move to correct position from laser

- Continue writing thesis

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Ålesund, Norway

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PROJECT STATUS REPORT

Reporting period:	December 2023	Project title:	Optical path planning for welding robots using laser triangulation
Date of report:	15. December	Report author:	Simen Borgundvåg Alvestad, Peter Nordal Bjørneseth

Tasks this period

- Write first draft of bachelor thesis

- Complete bachelor thesis

Completed tasks

- First draft complete with feedback from supervisor

Challenges and issues

We dropped the idea to get the robot to move correctly, to focus on writing the thesis. After a meting with the supervisor it was encouraged to include the theoretical basis to get the robot to move correctly.

H   Appendix: System Schematic
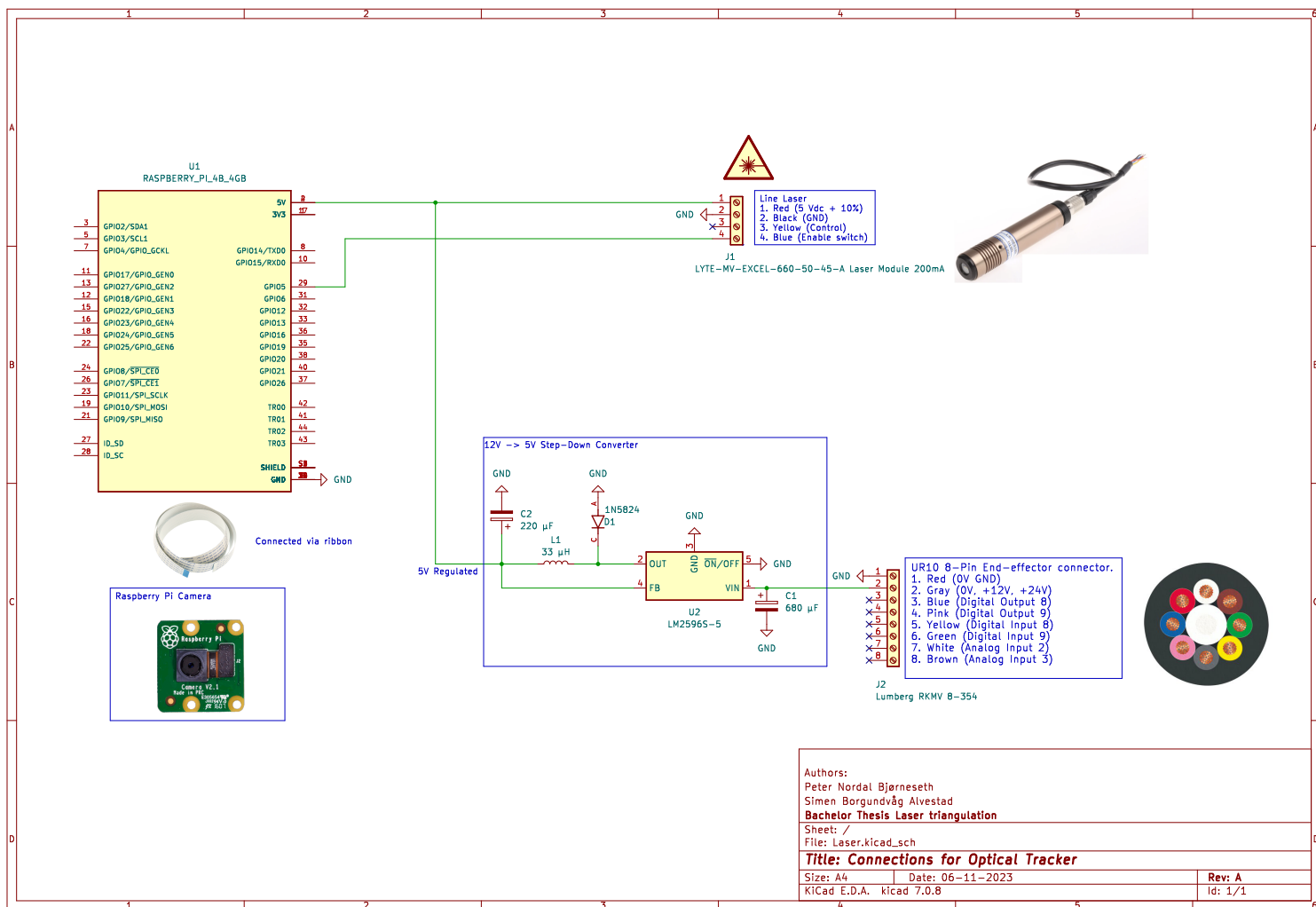
I   Appendix: Gantt Project Plan

Bachelor Thesis - Optical Path Planning For Welding Robots Using Laser Triangulation

NTNU Ålesund
Autumn 2023   **NTNU**

Candidates: ALVESTAD, SIMEN BORGUNDVÅG BJØRNESETH, PETER NORDAL	Project Start:	7-Sep-23		
	Display Week:	1		

TASK	ASSIGNED TO	PROGRESS	START	END
A0 Status Meetings			Every 2 weeks	
A1 Preliminary Report				
A1.1 Contract meeting	Simen	100%	20-Sep-23	20-Sep-23
A1.2 Writing	Peter	100%	7-Sep-23	21-Sep-23
A1.3 90% Delivery	Simen	100%	21-Sep-23	21-Sep-23
A1.4 Final delivery	Peter	100%	29-Sep-23	29-Sep-23
A1.5 Visit Møre Trafo AS	Simen	100%	8-Sep-23	8-Sep-23
A2 Research				
A2.1 Laser	Simen	100%	21-Sep-23	27-Sep-23
A2.2 Vision	Peter	100%	21-Sep-23	27-Sep-23
A2.3 UR course	Simen, Peter	100%	27-Sep-23	28-Sep-23
A2.4 Robot Control	Peter	100%	27-Sep-23	4-Oct-23
A2.5 Robot Welding	Simen	100%	15-Oct-23	22-Oct-23
A3 Design				
A3.1 Laser Scanner	Peter	100%	27-Sep-23	7-Oct-23
A3.2 Welding Robot	Simen	100%	4-Oct-23	14-Oct-23
A4 Testing				
A4.1 Simulator Gazebo/URSim	Peter	100%	25-Oct-23	1-Nov-23
A4.2 Hardware	Simen	100%	25-Oct-23	1-Nov-23
A4.3 Robot Control	Peter	100%	30-Oct-23	3-Nov-23
A4.4 Integration	Simen, Peter	100%	6-Nov-23	10-Nov-23
A4.5 Functional demo	Simen, Peter	100%	10-Nov-23	19-Nov-23
A5 Status Presentation				
A5.1 Preparation	Peter, Simen	100%	23-Oct-23	25-Oct-23
A5.2 Presentation	Peter, Simen	100%	26-Oct-23	26-Oct-23
A6 Thesis Report				
A6.1 Status Report	Peter, Simen			
A6.2 Draft 1	Peter, Simen	100%	10-Nov-23	1-Dec-23
A6.3 Draft 2	Peter, Simen	90%	4-Dec-23	8-Dec-23
A6.4 Complete report	Peter, Simen	95%	11-Dec-23	15-Dec-23
A6.5 Project Deadline	Peter, Simen	0%	20-Dec-23	20-Dec-23

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