1. Ladies and gentlemen, thank you very much for joining my master thesis presentation with the title "Methodical Approach for Analyzing Process Variables and Optimizing Boundary Conditions in Multi-Axis Robot Programs“. Before we jump in, I would like to explicitly thank my two supervisors, Ludwig Siebert and Marius Breuer. Without them, this work would not be possible.
2. In the next few minutes, I will discuss the motivation for this topic, the problem formulation, and highlight the existing research gap in the current state of the art. Furthermore, we will dive into the methodology, implementation, and the obtained results. Finally, I will provide a summary and outlook. Following that, we can discuss any remaining questions.
3. When we look at the annual shipment of industrial robots, we see a significant growth over the last 15 years. In 2010, there were only 100,000 industrial robots shipped, but by 2017, this number had increased to almost 400,000. This growth indicates the increasing importance of industrial robots in the manufacturing industry.  
     
   Not only are the absolute numbers of industrial robots increasing, but the ratio of robots to employees is also steadily rising. This suggests that industrial robots being increasingly adopted by companies to enhance productivity and efficiency.  
     
   If we examine the areas of application, we find that the largest sector for robotic applications is the automobile industry, followed by the electrical and machinery industries. This indicates that industrial robots are being extensively utilized in these sectors to automate tasks and improve production processes.  
     
   Overall, the growth in the shipment and their diverse applications highlight their increasing importance and impact in the manufacturing sector.
4. Even though the number of robots in the manufacturing industry is steadily increasing, traditional manufacturing still heavily relies on CNC machines. CNC machines, which stands for computer numerically controlled machines, are specifically designed for milling operations. They are known for high positional accuracy, which allows them to achieve repeatable precision on the um-scale.  
   Most of the toolpaths executed on CNC mills are defined in 5 degrees of freedom. This means that the position of the endmill is defined by the coordinated X, Y, and Z, while the rotation is defined by the A and B axes. The rotation A and B represent the rotation of the tool around its X and Y axes respectively.   
     
   Industrial robots, in contrast, typically have 6 degrees of freedom, making them well-suited for pick and place or assembly operations. They excel in tasks that require flexibility and adaptability. One notable application of robots in manufacturing is their use in additive manufacturing processes, particularly in wire arc manufacturing. Additionally, robots can also be utilized for milling operations by attaching a spindle to the robot's flange, further showcasing their versatility. One potential disadvantage of industrial robots, when compared to CNC mills, is their lower stiffness. This can pose challenges when trying to produce parts with high precision.  The choice between using industrial robots or CNC mills depends on the specific requirements of the manufacturing process and the desired outcome.  
   It is possible to use the same toolpath designed for a CNC mill on an industrial robot. It is important to note that a 5 degree of freedom toolpath is not fully specifies the robots pose.

Only X, Y, Z, A and B are defined. The rotation C, which represents the rotation around the TCP's Z-axis, is not defined in the toolpath. This rotation can be freely chosen and does not affect the toolpath itself. Regardless of the value of rotation C, the resulting part will be the same. However, the rotation C does affect how the robot behaves while traversing the toolpath and is considered a boundary condition in this example. The same principle applies to applications like Wire Arc Additive Manufacturing (WAAM) where the welding torch can be freely rotated. Regardless of the rotation of the torch, the resulting part will be identical. The rotation of the torch is not critical in terms of the resulting part geometry but may impact the behavior of the robot during the welding process.  
  
Having one degree of freedom more than necessary results in redundancy. The question now is: How does the boundary condition affect the robot, and how can we use the redundancy to our advantage? The goal of this work is to optimize the robot's behavior by optimally setting the boundary condition.

1. The following two videos explain the problem visually.

On the left side, we see how the robot traverses a simple line in the negative y direction.

In this example, the rotations A, B, and C are all held at 0.

It is clearly visible that joint 4 has to rotate significantly to achieve the defined toolpath.  
  
On the right side, however, the rotation C is set to -30°.

It can be seen that the behavior of the robot is significantly different.

To describe the robots behavior, specific process variables are introduced:

The influenced process variables include:

- direction changes in the joints

- accelerations

- energy consumption

- cable positioning

- stiffness

1. After analyzing the current state of the art 3 problems became evident.

First of all:

No currently published method allows the user to select specific (user defined) process variables to evaluate a process.

Second:

As of now, it is not possible to weigh individual process parameters and thus describe the manufacturing process as a singular scalar value

Third:  
No available method provides a solution to optimize boundary conditions based on a user defined goal

The resulting Aim for the Thesis is:

First of all:

Provide a method that can work with specifically selected process variables and rate a manufacturing process

Second:  
Extend the developed method with the option to add user-defined importance factor (weights) for the process variables

For example, that

And lastly,

Provide system that can optimize the boundary conditions while considering the user defined goal

1. The current state of the art offers multiple publications for individual process variables.

For example, singularity avoidance, velocity, acceleration, and jerk, stiffness, or energy usage.

The main problem is that each publication is only focusing on the optimization of one process variable.

Only one publication covers three process variables simultaneously.

No publication is covering the option of user-defined process variables or user-defined importance factors.

The research gap results from the fact that there is only marginal overlap in the publications and no publication takes a holistic approach.

So the missing elements are:

A possibility for the user to select process variables

A possibility for the user to weigh the individual process variables

A possibility to optimize the setting of redundant DoFs towards a user-defined goal.

1. In the developed methodology, the first step is to understand where the individual process variables can be extracted from.

For a given toolpath that must be traversed by the TCP, the inverse kinematic algorithm can give us the exact position of each joint.

These joint positions are in the form of a timeseries that specifies the rotational angle of the joint.  
  
Using these timeseries, it is possible to extract process parameters such as:

Direction changes in the joint

Total travel in the joints

Angular velocity, acceleration, and jerk  
  
With a forward kinematics approach, it is additionally possible to determine:

If all points of the toolpath are reachable

How close the robot is to a singularity.

How the welding torch is oriented.  
  
Further possible process variables include the continuous and total energy use.

1. The first step in rating a manufacturing process is the selection of process variables. In this example, four placeholder variables are selected.

The next step is to determine the importance factor for each variable. It is important that the sum of all importance factors is equal to unity.

The third step is the calculation of the local rating. This is done by analyzing a process variable for multiple variations of the boundary condition.

In this example, the direction changes are analyzed.

The four resulting time series are compared, and it is counted how many direction changes occur in each variation.

After that, a min-max scalar is applied and the values are projected in a range from 0 to 100. The value of the initial variation is now the local rating.

The next step is to obtain the individual local scores. They are the product of the local rating and the individual importance factors.

In the last step, the local scores are summed up to obtain the global score for that specific boundary condition.

This procedure fulfills the first two goals of the thesis. It allows for the selection of specific process variables and, with the help of user-defined importance factors, rates the manufacturing process.

1. The last part of the methodology involves developing an optimization process. The goal is not only to rate a manufacturing process but also to suggest boundary conditions that optimize the selected variables. To achieve this, we first need the specific toolpath in all degrees of freedom, including the redundant degrees of freedom.

Then, we perform a variation of the redundant degrees of freedom. Using an inverse kinematics algorithm, we acquire the time series of the joint movements.

Next, we analyze the individual process parameters and calculate a score as shown before.

The optimization algorithm analyzes how the scores change and suggests a new setting for the redundant degree of freedom, which becomes the new boundary condition.

Possible optimization algorithms are: Genetic algorithms, Particle swarm optimization, Ant colony optimization.

This cycle is performed either until the score converges or a set number of iterations is executed.