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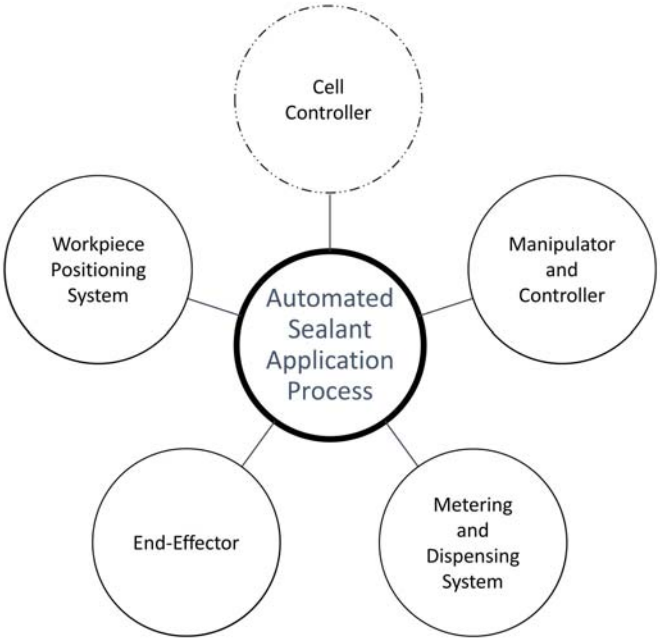

Sealant Process Model for Evaluating Robot Systems in Aerospace Industry

Master's thesis in Production Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: Components associated with a sealant application process.

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Abstract

The aerospace industry in confronted on the one hand with demand regulations from the EU commission to become cleaner, safer, and cheaper. On the other hand, is the change of the manufacturing industry toward more automation in order to pave the way for the next industrial revolution, Industry 4.0. Due to high quality standards and low production volume the aerospace industry has not been able to implement much automation in their production systems. In order to cope with the EU-regulations and to be in the forefront of automation, the aerospace industry now wants to investigate in possible automation solution.

The aim of the thesis is to provide a model that will enable the aerospace industry to systematically evaluate robot solutions. The model is built upon three production efficiency criteria that need to be considered for developing a production system. The model identifies parameters that need to be considered when developing an automated production system. The values of the parameters are determined by means of calculation and simulation. These values are then used to calculate the efficiency of a certain robot solution. The efficiency is used as means for comparison between different robot solutions.

An example for calculating the efficiency of a robot solution is presented in the thesis. The conclusion from the study is that the model can be used for evaluation purposes. However, it is essential for the user to understand the interdependence of the parameters as well as possession of the data that are necessary for the calculation.

Keywords: Robot sealant application, Automated sealant application, Sealant application parameters, Efficiency calculation.

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Abbreviations

TCP	Tool Center Point
OEM	Original Equipment Manufacturer
DoE	Design of Experiments
DoF	Degrees of Freedom
KUKA FRI	Fast Robot Interface
PLC	Programmable Logic Controller

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1
Introduction

Manufacturing contributes to national employment and to the gross domestic product (GDP); and is, therefore, one essential part for a country's wealth creation [1,2]. Governments propose different strategies and concepts for the future of their manufacturing industry in order to provide right circumstances and directions for a sustainable growing economy [2]. The United States put forward the concept Industrial Internet, which aims to add advancements in cyber technologies to the manufacturing industry with the goal of enhancing the processing and exchange of information and improve the current level of control [2,3]. The German Government has a strategy called Industry 4.0, and the intent is to integrate cyber network into the manufacturing environment. Thereby, adding a dimension of intelligent communication between the working cells and making smart manufacturing a trend for future manufacturing [2, 3]. Other developed countries, Japan and South Korea, propose comparable visions to improve their competitiveness. However, every country is just beginning to take their initial steps toward their concepts and strategies of future manufacturing. Paving the way toward the goal are automated production lines in which industrial robots communicate and work in sequence [2].

The use of the word automation in a manufacturing context originates back to the mid-1940s and was first used in the U.S. automobile industry. This phenomenon illustrated the processing and handling of components by machines with little to no human intervention [4, 5]. The general definition of automation, is the execution of a series of predetermined actions with as little human intervention as possible, that is enabled by necessary specialized equipment (computers, control systems, sensors, actuators, etc.). These equipment in turn provide sources of information and process it. The equipment enable the production system to observe, perform, make decisions and control the series of actions on its own [4,5]. The benefits that automation brings into a manufacturing environment are numerous: increased productivity, consistent quality, decreased manufacturing costs and lowered risk for human fatigue [4, 5].

One industry that has not been able to exploit the benefits of automation and is lagging in implementing automation is the aviation industry [6, 7]. The reason lies in the low production volume, and therefore, the efforts towards finding automation solution were not as strongly demanded as in the automotive industry, where a range of automation solutions can be found [6–8]. Furthermore, the high complexity in the aerospace structures as well as the high-quality requirements are additional contributors for the slow advancement of automation solutions in the aerospace industry [6].

1.1 Problem description

Aerospace manufacturers are faced with challenges from governmental future manufacturing strategies [2,3], as well as EU-regulations regarding their vision of future air travel [9]. Confronted with these challenges, manufacturers in the aerospace industry are required to adapt to the demands of future air travel to stay competitive in the market. The advantages of future manufacturing can contribute to fulfilling the demands from EU-regulations. However, as the aerospace industry employs little automation solutions in their manufacturing today, automation of sealant application for aerospace structure remains an uncharted territory [6,7]. Furthermore, research on automated adhesive dispensing systems are lacking,to the best of the authors' knowledge. This indicates that there is a need for analysis of automated solutions in the aerospace industry. The findings in this research intend to contribute in filling the gap of investigations on automated sealant application processes in the aerospace industry.

1.2 Research aim and questions

The aim of this thesis is to develop a model that can be used to evaluate robotic solutions for sealant application processes deployed in the aerospace industry. The model can serve as a tool for comparing different automation solutions and can assist in the decision making process when confronted with automation technology investment choices. This aim is achieved by means of applying a production efficiency perspective to the components for an automated sealant application process. This thesis identifies the parameters that characterize an automated sealant application process. These parameters are then used to develop a simulation model to evaluate the performance of a possible automated sealant process system. The following research questions are posed to achieve the research aim:

- RQ 1) *What parameters can be used to describe an automated sealant application process?*
- RQ 2) *How can these parameters be used to systematically evaluate a sealant application?*

1.3 Brief description of the research project

The aerospace industry is facing challenges and has to respond to the demands from international regulations [9]. These demands require air travel to become more "affordable, cleaner, quieter and safer" [9]. It is predicted that in the upcoming 20 years air traffic will triple. Consequently, the aviation industry must fulfill these regulations as soon as possible in order to satisfy future demands [9].

Automation is a potential contributor to solve these challenges in the aviation industry thanks to its advantages mentioned above. SAAB is active in the aerospace market and additionally it supplies OEM's in civil aerospace industry with high-end aerospace structures. SAAB has recognized these advantages and has therefore commenced a project to automate the process of sealant application in aerospace structures. At SAAB, the sealant application process is currently performed manually and wants to investigate automated solutions for their sealant application process. The aim for implementing automated sealant application solutions is to reduce costs for material and labor as well as improving their own competitiveness on the market.

1.4 Delimitations

The model created in this thesis implements on a production efficiency perspective meaning that the robotic solutions are examined for their efficiency in a production environment. This means that the components that are essential for a robotic solution for sealant application are assessed regarding how efficiently they satisfy the production criteria. This approach delimits the search to parameters regarding cost, time and quality aspect.

The evaluation of the workpiece design and its influence in the decision making for an automation investment is not included in this thesis. This means that the aspects on how the workpiece design affects the development of the production system and its efficiencies are excluded. Furthermore, design aspects of the end-effector and its influence on the production efficiency are not evaluated, although findings regarding end-effector design are discussed in the theoretical framework of this thesis. The experimental equipment, in this thesis is limited to the industrial robot KUKA LBR iiwa 7 R800. Hence, this thesis is delimited to the implementation of manipulators that are characterized by a serial configuration. The thesis focuses on the kinematics viewpoints of the manipulator, although relevant concepts are presented in the frame of reference.

2
Theoretical framework

This chapter provides the necessary background information for understanding the framework of the project and the obstacles and gaps in the research field.

2.1 Sealant

Sealants are imperative in the industry and are an essential part in the products we use in our daily lives. Application for sealants reach from clothing to medical implants, as well as from food to construction structures. It occupies the surfaces of the product's joined area and serves as a layer of protection [10]. Thereby, it prevents external forces and materials to penetrate and cause damage to the united areas. Failing to apply sealants in a correct manner has severe implications [10]. Petrie [10] mentions that the space shuttle disaster of 1986, regarding Challenger, is affiliated to a sealant failure and caused the whole shuttle to explode mid-air. In this section, a description of a sealant is given and its properties as well as application is discussed.

2.1.1 Sealant description

Sealant is a polymer which is of organic or synthetic base. Further, it can also be synthetically produced by letting two or more compounds chemically react in a mixing process [11]. The properties of the base resin in the sealant mix are modified by mixing it with additives and in this manner, desired properties can be produced [12]. Most commonly however, sealants are created by mixing only two compounds [11]. Characteristics of a sealant are that they do not endure high tensile or shear stress and are therefore not the ideal material for structural reinforcement [13]. The main key function of a sealant prevents outer impacts from entering and disturbing the product properties [10, 13]. An alternative application for sealant is to contain a material – mainly liquids or gases – in a confined space [10]. The sealant accomplishes this function by clogging the cavities of two or more surfaces that are joined together and forms a protective layer around these surfaces [10, 13]. Furthermore, sealants can also serve as an insulator, and can even create an obstruction for fire. Additionally, it can enhance the aesthetics of the product [10]. A significant characteristic of a sealant is the quality, meaning it fulfills its key function for the remainder of its lifetime. The lifetime of a sealant is determined with consideration to the environmental impacts that it has to withstand and overhaul services that apply [10]. Further details regarding sealant properties and application considerations can be found in Appendix A – Sealant properties and considerations.

2.1.2 Sealant application: Quality requirements

Quality is defined as a set of product features that meet stated or implied customer's requirements [14, 15]. As this definition states, the expectation on quality is dependent on the customer [14]. Within this thesis the requirements are set by SAAB. For string application SAAB requires the height of the sealant to be between 3-6 mm or 6-8 mm, and the width between 4-8 mm or 8-16 mm depending on application. The appearance of the sealant must have an even and consistent form. The quality requirements regarding sealing of bolts is that the layer that encapsulates the bolt must be between 2,5-5mm in thickness. The appearance of the sealant must have an even and consistent form and should not spread out to an excessive area. These quality requirements must be considered when choosing the components for the automated sealant application process.

2.1.3 Sealant application: Methods

In this subsection, methods for sealant application are discussed, both robotic and manual, and the equipment for the respective application method are reviewed.
Sealant properties must be considered in the choice of application method and equipment in order to achieve a successful sealant application [13]. Further criteria points that influence the choice of application method are the part geometry, including the accessibility perspective to the application area, and the production rate [13].

In a manual application environment, equipment such as brushes or rollers are commonly utilized [13]. Also types of squeeze bottles and tubes, as well as dispensing guns and spatulas, are equally commonly employed [13]. With the help of these tools the operator applies the sealant on the components [13].
The robotic or automated application illustrates a far more complex equipment setup [16]. The complexity factor stands in reference to the number of components employed, and further, the communication between those elements [16]. Components employed in the automated sealant dispensing system are of importance for the success of the application process [8,16,17]. Bafunno [16] and Tuner [8] have identified these components. The first component being the cell controller. It initiates and stops the process in the working cell. Then, it governs the signal communication from the cell to other monitoring systems [8, 16]. It checks if every other component in the system is up and running. As soon the part is in place it gives the signal to start [16]. The second component, the workpiece positioning system, is responsible for holding the work piece in place [16]. This system can have different compositions, either a fixture is utilized to secure the correct positioning of the workpiece or external visual equipment are employed that measure and calculate the location of the part in reference to the robot location [16]. The robot manipulator and controller are the third component in the chain, and after receiving the start it applies the right amount of sealant on the locations [8, 16]. The end-effector which is the tool on the robot is an additional fourth component. It is designed for the specific

application process. The design of end-effector contributes to the reachability of the robot as well as to the appearance of the sealant bead [8, 16]. Regarding the design of the end-effector Bafunno [16] has identified the orientation of the nozzle and the size of the end-effector as critical parameters for the end-effector design. An additional design parameter is the size of the orifice [8]. For the sealant to have a continuous flow the velocity signals from the robot are sent to the metering and dispensing system [8, 16]. The metering and delivery system is the fifth component in the chain and is mixing the sealant and adjusting the flow rate of the sealant through the pipes in reference to the application speed [8, 16]. As soon as the robot is finished, it sends a signal to the cell controller that the part can be removed and a new part can be set up [8, 16].

2.2 Industrial robots

An industrial robot is according to ISO 8373:2012 [18] defined as an:

"automatically controlled, reprogrammable, multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications."

The ISO 8373:2012 [18] gives further information on the words used in the definition. With reprogrammable it is specified that changes in the motion program or supporting functions can be made without changing the mechanical structure of the robot [18]. Manipulator refers to the hardware mechanism that is built up by a chain of bodies, called links, that in turn are connected by joints which intend to enable operations in different degrees of freedom (DoF) [18]. The word multipurpose implies the adjustability to various situations by changing the chain of mechanical structure [18]. The serial and parallel mechanical configuration are the two most significant amongst the numerous possible mechanical configuration of an industrial robot [19]. This thesis focuses on serial configurations. The following subsections address algorithms that are relevant for that configuration. In order to design and control an industrial robot, fundamental knowledge about kinematics, dynamics and stiffness are essential [20–22]. In the proceeding subsections, this fundamental knowledge is presented.

2.2.1 Kinematics

A body's position and rotation is described by a coordinate frame (brief: frame) [19, 21, 23]. Each frame has an origin, O, and three orthogonal unit vectors (x, y, z) describing the rotation of the body [19, 21, 23]. The position and orientation of one body in space is captured by putting the body's frame in relation to the *reference* frame [19, 21, 23], see Figure 2.1.

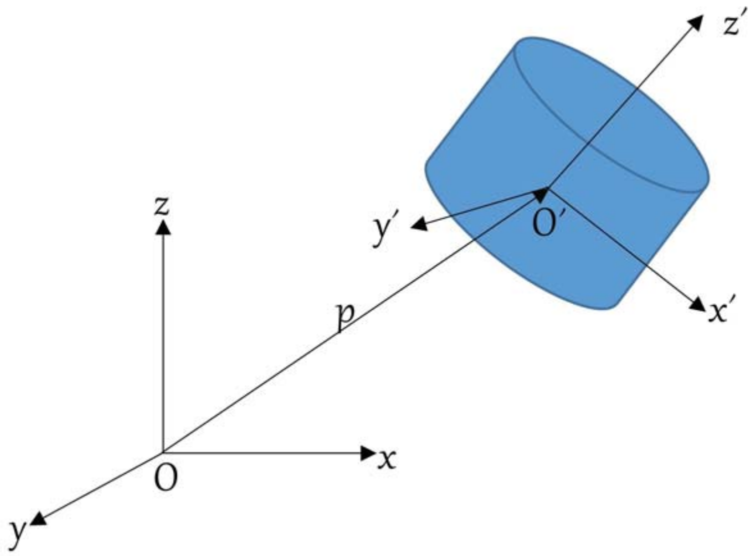


Figure 2.1: Location of a body in space in relation to reference frame

The position of the body's frame in relation to the reference frame is expressed with a 3x1 vector, see vector p in the Figure 2.1. This vector is called translation vector and it gives the coordinates of the position of O' in the reference frame [19,21,23].

The orientation of the body's frame in relation to the reference frame is declared by a 3×3 matrix called the rotation matrix. The rotation matrix manifests the relation of the body's coordinate system to the reference coordinate system. The orientation of the body's frame can be acquired by means of elementary rotations of the reference frame [19, 21, 23]. Thereby a rotation of the reference frame with angle θ about the z axis can be illustrated as in Equation (2.1).

$$R_z(\theta) = \begin{pmatrix} cos\theta & -sin\theta & 0 \\ sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{2.1}$$

Same applies for a rotation about y axis with angleθ and about x axis with angle θ, respectively illustrated below in Equation (2.2) and Equation (2.3).

$$R_y(\theta) = \begin{pmatrix} cos\theta & 0 & sin\theta \\ 0 & 1 & 0 \\ -sin\theta & 0 & cos\theta \end{pmatrix} \tag{2.2}$$

$$R_x(\theta) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\theta & -sin\theta \\ 0 & sin\theta & cos\theta \end{pmatrix} \tag{2.3}$$

It is of importance to note the direction of the rotations [23]. A combination of consecutive rotations is expressed by multiplying the rotation matrices [19]. As there are numerous possible ways to represent an orientation with rotation matrices, applying Euler angles minimize the amount of possible representations [19, 23]. Euler angles consist of a set of three angles and depending on the choice of Euler convention, the orientation is represented by sequencing these three angle rotations [19,23].

Homogeneous transformation matrices (brief transformation matrices) merge the translation and rotation matrix [19,21,23]. The formation of a transformation matrix is illustrated by a 4x4 matrix [19,21,23], see Equation (2.4). The rotation is the 3x3 matrix in the upper left corner of the transformation matrix. The fourth column is the translation vector [19,21,23]. Equation (2.4) displays the transformation matrix of the frame N to the reference frame R.

$$ {}^{R}_{N}T = \begin{pmatrix} r_{11} & r_{12} & r_{1}3 & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{2.4} $$

In robotics, kinematics is used to describe the TCP position and orientation relative to the robot's base frame as a function of the robot's joint angles, θ [20]. There are two types of kinematics approaches, forward – and inverse kinematics [20, 21, 23]. Forward Kinematics addresses the problem of calculating the tool frame relative to the base frame of the manipulator when the joint values are known [20, 21, 23]. The function for the forward kinematics is generated by calculating the transformations matrices, from the base frame to the tool frame in accordance with the order of the frames [19]. For a manipulator with six frames the forward kinematics is as demonstrated in Equation (2.5) [19].

$$ {}^{0}_{6}T = {}^{0}_{1}T + {}^{1}_{2}T + {}^{2}_{3}T + {}^{3}_{4}T + {}^{4}_{5}T + {}^{5}_{6}T \tag{2.5} $$

The purpose of the inverse kinematics is to determining the joint values given a known end-effector orientation and position [19]. The approach of solving the inverse kinematic is more complicated than forward kinematics [20] and there is no existing generic algorithm [22]. Compared to forward kinematics, the inverse kinematics can have multiple solutions [20, 21, 23].

2.2.2 Velocity and acceleration

Differentiating the position and joint vector with respect to time gives us the task velocity vector υ and the joint velocity vector $\dot{\theta}$ [24]. In differential kinematics, the mathematical relation between υ and $\dot{\theta}$ is accomplished by means of the Jacobian matrix (brief Jacobian) [19–22,24]. Thus, the application purpose of the Jacobian in robotics is to define the correlation between the task velocity and the joint velocities [19–22, 24]. The Jacobian is $m \times n$ – matrix, the amount of the degrees of freedom (DoF) that are being considered for the task space determines the value for m and the amount manipulator joints determines the value for n [20]. The Jacobian consists of first order derivatives of transitional and angular values regarding the joint values [19–21]. Given the case in which the joint velocities are known and the velocities of the task space are to be determined, then the differential equation between υ and $\dot{\theta}$ expressed by Equation (2.6) called forward velocity kinematics [21, 22]:

$$\upsilon = J(\theta)\ \dot{\theta} \tag{2.6}$$

Whereas, in the inverse case, where the task velocities are known and the joint velocities are to be determined the equation between υ and $\dot{\theta}$ is acquired with the inverse Jacobian J^{-1} [19]. This differential equation is called inverse velocity kinematics, see Equation (2.7) [22].

$$\dot{\theta} = J^{-1}(\theta)\ \upsilon \tag{2.7}$$

The second order of differentials are obtained by differentiating further with respect to time [24]. The result provides task acceleration, α, and joint acceleration, $\ddot{\theta}$ [24]. The relation of these acceleration terms is expressed with means of the Jacobian [24]. The task acceleration is described by the forward acceleration kinematics equation, see Equation (2.8) [22].

$$\alpha = J(\theta)\ \ddot{\theta} + \dot{J}(\theta, \dot{\theta})\ \dot{\theta} \tag{2.8}$$

The inverse acceleration kinematics determines the joint acceleration $\ddot{\theta}$ and is presented in Equation (2.9) [22].

$$\ddot{\theta} = J^{-1}(\theta)\ (\alpha - \dot{J}(\theta, \dot{\theta})\ \dot{\theta}) \tag{2.9}$$

2.2.3 Kinematic redundancy

Kinematic redundancy exists when the manipulator's DoF is greater than the DoF required to execute the task. In general, the movements of the end-effector in space for the completion of a task requires six degrees of freedom. If the manipulator has seven or more joints, then the manipulator is considered redundant. The motive behind a manipulator design with more joints than necessary is to increase the manipulator's range of motion configurations [21, 24].

The kinematic redundancy of the manipulator has noteworthy implications for the inverse kinematics calculus since the range of solutions are infinite [21]. This trait is based upon the fact that there are multiple configurations of the manipulator that can reach the same point. Hence, with additional joints the configuration possibilities of the manipulator multiplies and for this reason the solution of the inverse kinematics for redundant manipulators may be infinite. Nonetheless, the range of solutions is dependent on the type of joint and the constraints of the joints. As a consequence, manipulator's geometrical configurations in space are dependent on the joint constraints [22].

Determining the inverse velocity kinematics for manipulators requires the inverse Jacobian. However, because of the extra joint, DoF, the Jacobian becomes a non-square. As only square matrices can be inverted, the literature makes use of the pseudoinverse Jacobian, $J^{\dagger}$. The pseudoinverse Jacobian is obtained Equation (2.10) [24, 25].

$$J^{\dagger} = J^T (JJ^T)^{-1} \tag{2.10}$$

The inverse velocity kinematics and inverse acceleration kinematics for redundant manipulators are expressed in the following equations with means of the pseudoinverse Jacobian, see Equation (2.11) and Equation (2.12) [24].

$$\dot{\theta} = J^{\dagger}(\theta)\ \upsilon \tag{2.11}$$

$$\ddot{\theta} = J^{\dagger}(\theta)\ (\alpha - \dot{J}(\theta, \dot{\theta})\ \dot{\theta}) \tag{2.12}$$

2.2.4 Singularity

When determining the velocities, the Jacobian is utilized to define the correlation between the joint velocities and task velocities [19–22,24]. The Jacobian is a function of the manipulators joint values [19–22,24] and for certain joint values a manipulator reaches a configuration which is called singularity [20]. In a singularity configuration, the task space of the manipulator is affected and it loses one or more degrees of freedom [20, 26]. Moreover, the joint velocities increase drastically as the manipulator approaches a singularity configuration [20,27]. These singularities are discovered by analyzing when the determinant of the Jacobian is equal to zero [20]. By using Equation (2.13), it can be seen that the velocity is approaching infinity when the determinant approximates zero. Since the inverse velocity kinematics is the conventional means for manipulator control, the inverse Jacobian has a significance role in the manipulator controlling procedure [27].

$$A^{-1} = \frac{1}{det(A)} \begin{pmatrix} * & * \\ * & * \end{pmatrix} \tag{2.13}$$

Therefore, the singularity phenomenon brings implications to the path control of the manipulator [20, 27]. Aboaf and Paul [27] suggest three employed methods that support the mechanism to control the manipulator when approaching a singularity configuration. The first method is that the control mechanism sets the joint velocities to their maximum physical range but the consequence of this mechanism is that the manipulator executes an unpredictable motion [27]. Second, the manipulator is restricted to come to the proximity to such configurations [27]. Finally, the control mechanism reduces the TCP velocity so that the joint velocities remain within their physical range and without violating the desired straight path [20, 27]. Not deviating from the desired straight path as well as sustaining the TCP velocity is of great interest from a quality perspective in the sealant application process of string sealant application (e.g. string sealant application were deviating from the path can contribute to quality disturbances). To conclude, a motion of the TCP on a straight path with desired velocity that comes within the proximity of a singularity can cause problems that are worth investigating since it can contribute to quality problems.

2.2.5 Dynamics

In the kinematics section, the forces acting on the manipulator that result in manipulator motion were disregarded. However, the field of dynamics studies the forces acting on the mechanism and which thereby generate motion [20, 22, 28]. Similar to the forward and inverse kinematics, the field of dynamics considers with the forward and inverse dynamics. The inverse dynamics refers to the issue of determining the joint torques required to for a given manipulator trajectory. In the opposite case in which the joint torques are given and the manipulator trajectory must be calculated is an issue that is dealt within forward dynamics [20, 28]. Studying the forces that generate motion requires the equations of motion. The literature derives these equations by making use of two methods. One is the Lagrange method and the second is the Newton-Euler method [21,28]. The thesis makes use of the latter method.

The Newton equation in the Newton-Euler method determines the translational motion of link-i of a manipulator at its center of mass [23]. The force required to move link-i is calculated using Newton's second law of motion, see Equation (2.14) [20].

$$F = ma \tag{2.14}$$

The Newton equation in the Newton-Euler method derives from Equation (2.14) and is expressed as follows (see Equation (2.15)):

$$F_i = m\dot{v}_{c_i} \tag{2.15}$$

The force F_i generates accelerated motion, $\dot{v}_c$, and is applied at link-i's center of mass. The subscript i refers to the origin of the link-i's coordinate system [20].

Euler's equation in the Newton-Euler method determines link-i's rotational motion caused by a resulting torque, N [23]. In order to define the rotational motion of the link-i in space about an axis, the moment of inertia of a link-i must be determined. Therefore, the inertia tensor I must be defined relative to a reference frame which provides information of link-i's mass distribution. The relationship between angular velocity ω and angular acceleration $\dot{\omega}$and the torque, N, that causes the rotational motion, is known as the Euler's equation (see Equation (2.16)) [20].

$$N = {}^{C}I\dot{\omega} + \omega \times {}^{C}I\omega \tag{2.16}$$

The superscript refers to reference frame, which in this case has its the origin in link-i's center of mass.

2.3 Production efficiency perspective

The thesis applies a production efficiency perspective in the model creation with the aim to support the evaluation process of automation solutions. The explanation of such an approach is described in this section.

Säfsten and Bellgran [29] mention that a production system must be able to satisfy the customer demands. These demands are cost, time and quality.The company's ability to satisfy these demands efficiently determines a company's capability of staying competitive. The demand for cost requires the production and the supply of the product to the market to be at low cost. The demand fore quality refers to the production's ability produce products that satisfy customer needs and exceeds customer expectations. Lastly, the demand for time requires the production to produce and supply the market at the shortest time possible. It is critical to the company's competitiveness to satisfy these demands efficiently and to fullest satisfaction of the customer because doing so contributes to a competitive advantage on the market. This implies that low cost, high quality and short production times determine the efficiency of a production system. Therefore, are these three demands in this thesis referred to as production efficiency criteria. These production efficiency criteria are the utilized for the model creation to establish an evaluation method for the different automation solutions. The evaluation is done by comparing how efficient each automation solution can satisfy the customer demands.

3
Methods

This chapter describes the authors' approach to answer the research questions of this thesis and bring the aim of the thesis to completion.

3.1 Literature study

The literature study was the first step in the research. It was conducted in order to benefit from past inquiries by learning from established automated sealant application processes and design parameters. For the literature study the databases Google scholar, Scopus, Web of science and Chalmers library search engine were utilized. The keywords used for the literature study were related to the topics aerospace and automated or robotic industrial dispensing solutions. A second literature study was later conducted with a broader scope not limited to aerospace.

3.2 Model building

In this section the creation process and the intention of the conceptual model as well as of the simulation model are explained.

3.2.1 Conceptual model

The findings in the literature study were used to create a model that represented the parameters for describing an automated sealant application solution. The inclusion of the production efficiency perspective in the research is essential in order to establish grounds for the evaluation of the efficiency of the automated sealant application solution in industrial context. The automated sealant application process parameters from the literature study were then categorized into cost, time and quality. The aim of parameter categorization is to display one parameter's influence on a specific category.

3.2.2 Simulation model

The method of assessing the sealant application process was made in two stages: simulation of the robot path and calculation of efficiency values for the process. First the simulation process is described followed by the efficiency calculation.

Robot path simulation

To evaluate how well the robot is following a trajectory, a simulation model was built in MATLAB® and Simulink®. Four major steps are included in the model to be able to simulate the robot path in a kinematic way. The first step of the simulation model is to generate a trajectory for the robot to follow. This is done by using the start point, the desired end-point and the chosen TCP velocity. The result of the trajectory generation is a trapezoidal TCP velocity profile comprising of three parts: acceleration, full speed and deceleration (see Figure 3.1).

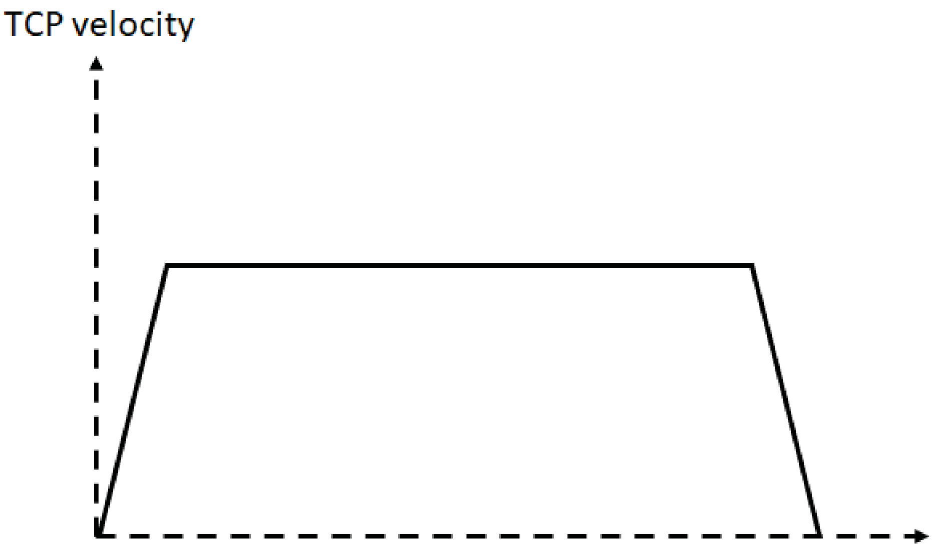


Figure 3.1: TCP velocity profile

Given the TCP velocity, the current joint angles and the inverse Jacobian function, the second step is to calculate the corresponding joint velocities for the robot. The next (third) step is to compute the new joint angles with a numerical integrator. The integrator yields a small angle displacement, $\delta\theta$, which is added to the previous joint angles to get the new joint values. The final step is to calculate the new TCP position by using the new joint angles in the forward kinematics function. The algorithm of the simulation model is visualized in Figure 3.2.

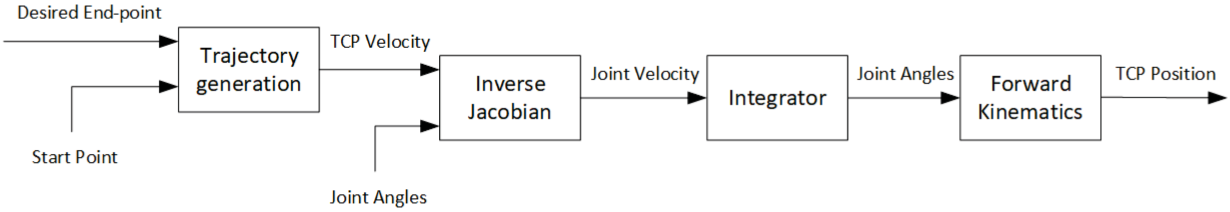


Figure 3.2: Simulation structure

At this point the robot trajectory is evaluated in a purely kinematic approach, meaning that the robot simulation is not impacted by any dynamic effects such as external forces, motor torque and gear box friction as well as the stiffness of the manipulator.

Efficiency calculation

In addition to the kinematic simulation the model also evaluates the efficiency of the sealant application process in the three previously mentioned process aspects, cost, time and quality. These efficiencies are calculated using the robot path data from the simulation in combination with user specific data such as takt time, robot cost, etc. The quality aspect of the system is difficult to quantify, however, since quality errors lead to rework the quality is here regarded as a cost instead. Further calculations are presented in the result section.

3.3 Experiments

In this section the procedure for the experiments are presented. For the experiments, the robot KUKA LBR iiwa 7 R800 was employed.

3.3.1 Singularity experiment

As mentioned in Section 2.2.4, there are three types of methods to control the manipulator when it is approaching a singularity configuration. In any case of those three control mechanisms the outcome has implications for the quality for the sealant application. The possible outcome of a slowdown of the TCP will result in that more sealant will be applied if the end-effector cannot adjust the sealant material flow. In case of workspace restriction the manipulator will be hindered from reaching application areas. This implies that the manipulator might have to change its configuration to continue on the sealant seam. As a result, the sealant seam might not be consistent which is a quality problem as well. The last control mechanism, deviation from the path, can lead to that sealant is not applied on the desired application area and therefore the product must be reworked. To investigate how the control mechanism reacts to a linear motion that approaches the proximity of a singularity configuration this experiment was conducted. In this experiment only the slowdown of the TCP velocity and the workspace restriction were investigated.

For the experiment the manipulator executes a straight motion that comes close to a singularity configuration. As the manipulator executes the linear motion, the data of the joint values are logged via the software KUKA FRI to the computer. The TCP velocity is restricted to 50 mm/s during the whole motion and a linear motion type was performed. The data is then analyzed to evaluate the behavior of the control mechanism. This experiment will help deduce the possible quality implications that are caused by the slowdown of the TCP and workspace restriction when approaching a singularity configuration. A more detailed description of the experiment as well as the design of experiment (DoE) can be seen in Appendix B.

4
Proposed model

This chapter explains the proposed model and introduces the identified parameters that describe an automated sealant application process. Additionally, an efficiency calculation for systematical evaluation is presented as well the reasoning behind it.

4.1 Components

Bafunno [16] and Turner [8] identifies key components that are necessary for designing an automated sealant application process, see Section 2.1.3. Figure 4.1 illustrates these components.

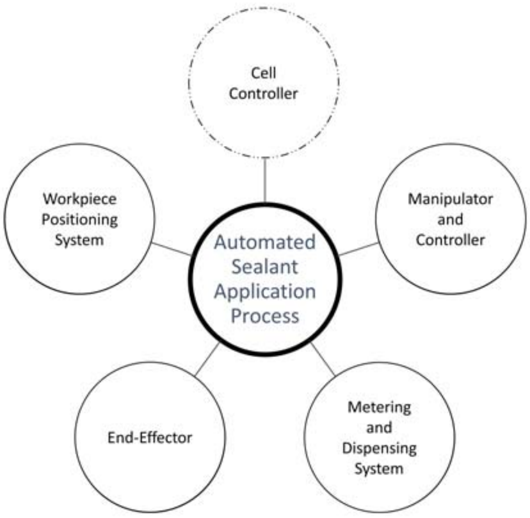


Figure 4.1: Components for the design of automated sealant application process

In Figure 4.1 the cell controller, has a dashed outline since a cell controller is not an essential component for an automated sealant application process to function; the process can also be started from the manipulator's controller and the status of the components can be checked for all components separately. This makes the cell controller an auxiliary equipment. In the proceeding chapters each of these components are analyzed to find the parameters that are critical for designing an automated sealant application process. The cell controller will be disregarded in the analysis process for the reasons mentioned above.

4.2 Parameters

For each of the identified components in the automated sealant application process, see Section 4.1, there are a set of parameters that are associated with a respective component. These parameters are categorized as mechanical or control. The first category includes all the parameters that are related to the machinery and the system of the moving parts. The parameters in this category are the physical attributes related to the machinery. The latter category refers to the system that governs the machinery. Some of these parameters are classified as constraints which implies that these parameters are specifications that must be considered when selecting a manipulator and controller system. Disregarding these parameters when selecting a manipulator and controller system can result in impairment of the system. Parameters that are not classified as constraints do not set any restrictions on the selection of component. The last column illustrates the outputs of the parameters. These outputs are associated with cost, time and quality to demonstrate the respective parameter's impact on a production efficiency criteria cost, time and quality.

The parameters that were identified for the manipulator and control component can be seen in Table 4.1 below. The cross section area refers to the thickness of the links. The DoF refers to the manipulator's flexibility. Operational range is associated with the manipulator's work envelope. The dimensions of the workpiece sets requirements for these three parameters. Disregarding the dimensions of the workpiece in the selection of the manipulator can lead to that the manipulator is not suitable for the task (e.g. cannot reach application areas or is not flexible enough to move in the freely in the workspace. Parameter stiffness refers to the manipulator's capability to endure external and internal loading. The payload capacity refers to the manipulator's capability of enduring external loading at the manipulator flange before the positioning accuracy is affected [21, 23]. These parameters are classified as constraints which means that these parameters must be considered in order to select a manipulator and controller system that is able to complete the sealant application task. Velocity and acceleration of the manipulator relate to the manipulator's motion speed which combined results in the manipulator's path. In the control category the parameter position is listed. This parameter describes the control of the mechanical links executed by the controller and is associated with accuracy and repeatability. All of these parameters have an impact in cost, time and quality. The cost impact of the parameters that are classified as constraints are summed up as hardware costs C_{HW}. The cost for velocity and acceleration C_{Path} as well as the cost for positioning $C_{Position}$ are expenses that needs to be consider in order to improve the time and quality output of the system. The parameters that impacts the quality of the product are stiffness, velocity and acceleration as well as the position parameter. These are respectively characterized by Q_{Path} and $Q_{Position}$. The parameters influences the time needed to complete the task are velocity and acceleration. The effect of the velocity and acceleration parameters on the time criteria is denoted by T_{Path}. It describes how the time for the task execution is affected by the choice of velocity and acceleration.

Table 4.1: Manipulator & Controller parameters

Manipulator & Controller			
Category	**Constraints**	**Parameters**	**Output**
Mechanical	Cross section area DoF Operational range Payload capacity Stiffness	Velocity Acceleration	C_{HW}, C_{Path}, T_{Path} $Q_{Stiffness}$, Q_{Path}
Control	-	Position	$C_{Position}$, $Q_{Position}$

In the following Equation (4.1), Equation (4.2) and Equation (4.3) suggest how to formulate a formula for calculating the total cost,time and quality output of the manipulator and controller system. In Equation (4.4) these outputs are formulated, $O_{M\&C}$, into a overall output formula for the manipulator and controller component.

$$C_{M\&C} = f(C_{HW}, C_{Path}, C_{Position}) \tag{4.1}$$

$$T_{M\&C} = f(T_{Path}) \tag{4.2}$$

$$Q_{M\&C} = f(Q_{Stiffness}, Q_{Path}, Q_{Position}) \tag{4.3}$$

$$O_{M\&C} = f(C_{M\&C}, T_{M\&C}, Q_{M\&C}) \tag{4.4}$$

Table 4.2 represents the parameters identified for the end-effector component. In this system the cross section area, mass, inertia and the operational range are constraints that must be regarded when selecting or designing the end-effector. The cross section area and the operational range parameter are restricted by the workspace of the workpiece. Ignoring these parameter can cause that the end-effector might not be compatible with the workspace. Mass and inertia must be chosen in regard to the manipulator's payload capacity and stiffness. Disregarding these parameters can lead to that the end-effector can not be mounted on manipulator without impairing the manipulator's positioning accuracy [21,23]. The flow parameter refers to the regulation of the material flow of the sealant. The cost impact of the parameters that are classified as constraints are summed up as hardware costs C_{HW}. The influence on the cost of the flow parameter is denoted as C_{flow}. The mechanism that regulates the flow has implications on the time T_{Flow} and quality Q_{Flow}, i.e. the faster the end-effector can regulate the material flow to the workpiece will affect the time for completing the task, T_{Flow}. Further, the force generated from the flow creates forces on the manipulator's flange that need to be dealt. These force is characterized as thrust and depending on its magnitude it can have an effect on the motion of the manipulator, see Section 2.2.5.

Table 4.2: End-effector parameters

End-effector			
Category	**Constraints**	**Parameters**	**Output**
Mechanical	Cross section area Mass Inertia Operational range	-	C_{HW}
Control	-	Flow	C_{Flow}, T_{Flow}, Q_{Thrust}

In the following Equation (4.5), Equation (4.6) and Equation (4.7) suggest how to formulate a formula for calculating the total cost,time and quality output of the end-effector system. In Equation (4.8) these outputs are formulated into a overall output formula, O_{EE}, for the end-effector component.

$$C_{EE} = f(C_{HW}, C_{Flow}) \tag{4.5}$$

$$T_{EE} = f(T_{Flow}) \tag{4.6}$$

$$Q_{EE} = f(Q_{Thrust}) \tag{4.7}$$

$$O_{EE} = f(C_{EE}, T_{EE}, Q_{EE}) \tag{4.8}$$

Table 4.3 represents the parameters identified for the workpiece positioning system. For this system, only mechanical constraints and parameters are identified, since active workpiece positioning systems with embedded control functions are not included in this thesis. The constraining parameter in this component is the load capacity of the structure and it refers to the minimum capacity the structure can endure in order to accommodate the workpiece. The cost output related to the load capacity constraint is denoted as C_{HW}. The position parameter specifies how optimal the workpiece is positioned in reference to the manipulator's capability to reach all application areas. The cost for the workpiece position, C_{WP}, is the cost associated with improved time and quality output. The setup parameter is the time it takes to position a workpiece in the correct place, T_{Setup}. The quality output, Q_{Setup}, of the positioning parameter determines the influence of the position error of the workpiece from the defined position.

Table 4.3: Workpiece positioning system parameters

Workpiece Positioning System			
Category	**Constraints**	**Parameters**	**Output**
Mechanical	Load capacity	Position Setup	C_{WP}, C_{HW}, T_{Setup}, Q_{Setup}

In the following Equation (4.9), Equation (4.10) and Equation (4.11) suggest how to formulate a formula for calculating the total cost,time and quality output of the end-effector system. In Equation (4.12) these outputs are formulated into a overall output formula, O_{WPS}, for the workpiece positioning system.

$$C_{WPS} = f(C_{HW}, C_{WP}) \tag{4.9}$$

$$T_{WPS} = f(T_{Setup}) \tag{4.10}$$

$$Q_{WPS} = f(Q_{Setup}) \tag{4.11}$$

$$O_{WPS} = f(C_{WPS}, T_{WPS}, Q_{WPS}) \tag{4.12}$$

Table 4.4 presents the parameters identified for the metering and dispensing system. The parameter that are classified as constraints in this system is the flow parameter which refers to the force that is required to pump the sealant to the end-effector and to regulate the material flow to the end-effector. The cost impact this parameter is denoted as hardware costs C_{HW}. The influence on the cost of the flow parameter is denoted as C_{HW}. The refill parameter relates to the time required to refill the system with sealant. This parameter stand in direct relation to the time output, T_{Refill}.

Table 4.4: Metering & Dispensing parameters

Metering & Dispensing

Category	Constraints	Parameters	Output
Mechanical	-	Refill	T_{Refill}
Control	Flow	-	C_{HW}

In the following Equation (4.13) and Equation (4.14) suggest how to formulate a formula for calculating the total cost,time and quality output of the end-effector system. In Equation (4.15) these outputs are formulated into a overall output formula, $O_{M\&D}$, for the metering and dispensing system

$$C_{M\&D} = f(C_{HW}) \tag{4.13}$$

$$T_{M\&D} = f(T_{Flow}) \tag{4.14}$$

$$O_{M\&D} = f(C_{M\&D}, T_{M\&D}) \tag{4.15}$$

4.2.1 Influential effect of the parameters

The identified components are in constant communication with each other which contributes to an interdependence between the components [8, 16]. The communication and interdependence between the components is imperative for a successful sealant application [8, 16]. As a results of the interdependence, it can be implied that some of characteristic parameters of a component have an influence on another component. These influential effects is worth mentioning since it can give further input to the decision making when selecting an automated sealant application solution. In this section the influential effect of the considerable parameters will be described, see Figure 4.2.

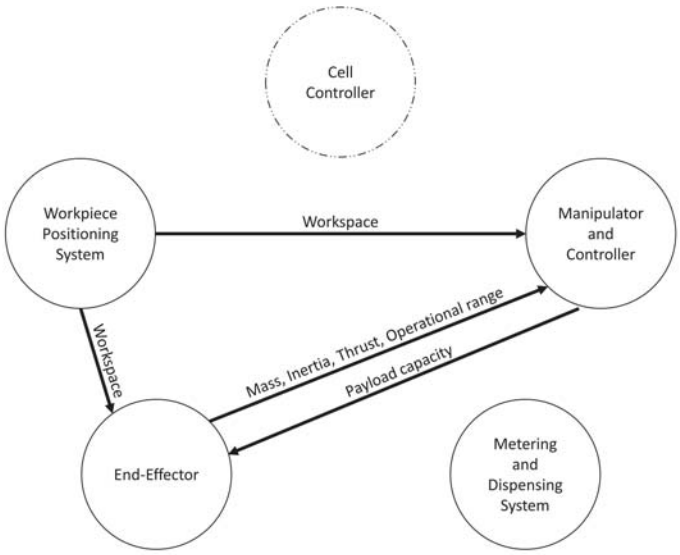


Figure 4.2: Influential effects between components

The component, workpiece positioning system, locks the workpiece in place. The dimensions of the workpiece set a constraint on the mechanical parameters of the manipulator, specifically on the operational range and DoF. This implies for the manipulator that the operational range and the DoF (flexibility of the manipulator) must be chosen accordingly in order for the manipulator to reach the sealant application areas [21,23]. The workspace influences also the design of the of the end-effector, which determines that the cross section as well as the operational range of the must be designed so that the end-effector can fit and be moved in the workspace of the workpiece. The influential effects between the parameters of the end-effector and the manipulator are several. Beginning with payload capacity of the manipulator, this parameter restricts the permitted external loading on the manipulator flange caused by end-effector. Therefore, is this parameter a considerable factor for the mass of the end-effector [21, 23].

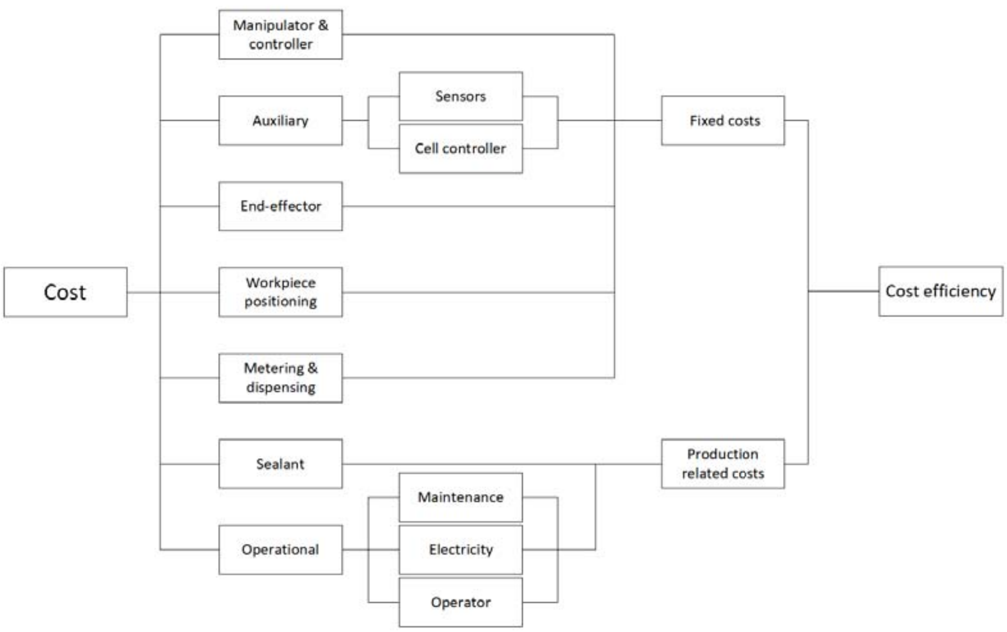
The parameters of the end-effector, mass, inertia and size, influence the manipulator. The mass of the end-effector and the inertia caused by the point of center of gravity affect the manipulator's positioning accuracy [21, 23]. Further, the manipulator is exposed to external forces that act on the end-effector. These forces are generated by the thrust for pumping out the sealant and create a desired material flow. Both, the mass and the thrust, create forces that act on the manipulator and those must be acknowledged when choosing or designing the end-effector [20]. Operational range, as mentioned by Bafunno [16], affects the reachability of the manipulator. Designing the end-effector for the manipulator to reach application areas as easy as possible should be of interest.

4.3 Cost, Time and Quality Efficiency

This section further describes the parameters and constraints derived for each component in Section 4.1, by summarizing them into the three production perspectives - cost, time and quality. In the previous chapter Section 4.1 outputs for parameters were identified for each component. Subsequently, these outputs were put together in formulas, see Equations (4.1) to (4.4) as an example.

The summary of the cost driving outputs are visualized in Figure 4.3. Apart from the former mentioned parameters some additional support functions are included such as maintenance, electricity and operators. In addition to the cell controller, described in Section 4.1, sensors are also added as an auxiliary cost element because neither cell controller nor sensors are necessary equipment for designing an automated sealant application process.

Figure 4.3: Summary of cost associated outputs



The cost outputs are grouped in fixed or production related costs respectively. Fixed costs are those expenditures whose value is independent from production volume and sales [30]. Within the fixed costs classification, the expenditures denoted as C_{HW} in the Section 4.2 for each component are listed. These expenditures are required in order to acquire the necessary components for an automated sealant application process that is functioning well. Whereas production related costs are the opposite, these are expenditures whose value is dependent from production volume [31]. In that classification, applied sealant volume and the operational costs, such as electricity, maintenance, and cost for the operator, are listed. The fixed and production related costs are interpreted as an cost efficiency for the whole sealant application process. The efficiency calculation are presented in Section 4.4. The list for the cost criteria is adjustable to any configuration of components of an automated sealant application process. For example, one might want to design a production system in which the sensor system is so advanced and does therefore not require a workpiece positioning system, because the locations where sealant must be applied are measured and calculated with the help of the sensor system.

Figure 4.4 illustrates all time outputs that were determined in Section 4.2. Subsequently, these time outputs are condensed into time efficiency for the whole sealant application process. The time efficiency calculation is presented in Section 4.4.

Figure 4.4: Summary of time associated outputs

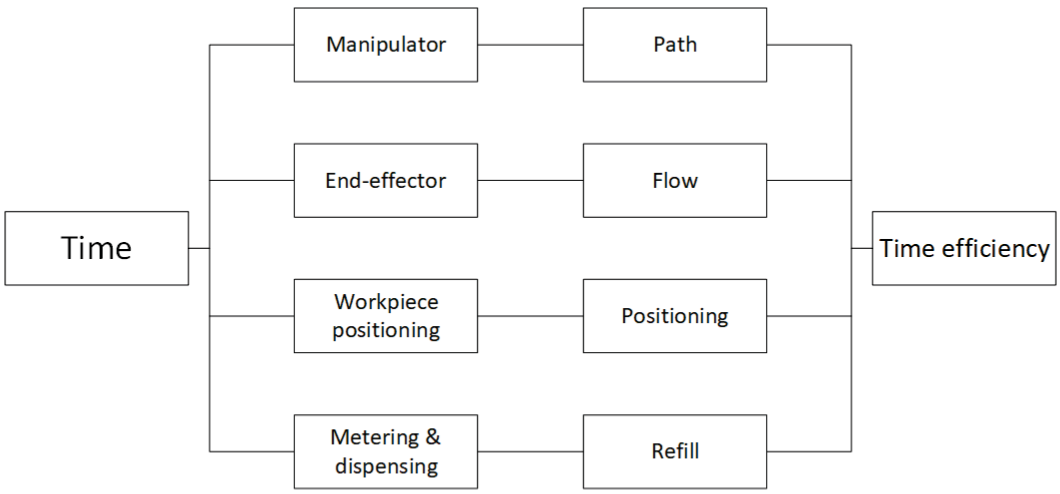
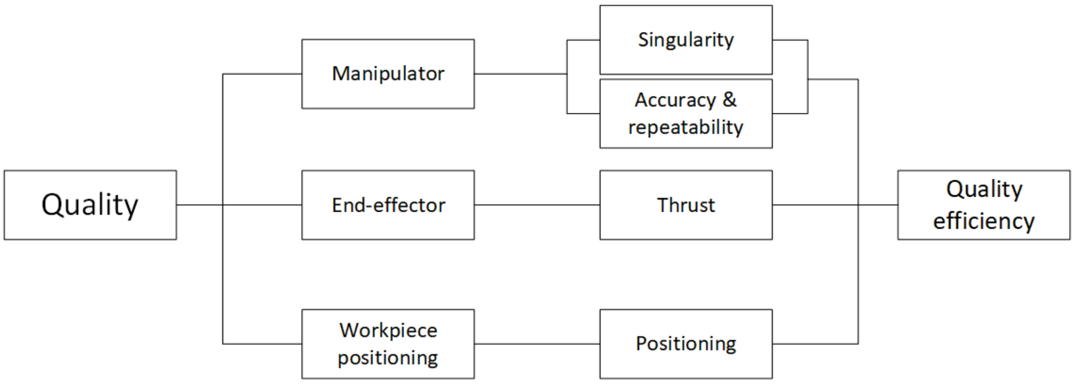


Figure 4.5 demonstrates how the the quality outputs are concentrated into the quality efficiency for the whole sealant system. Apart from the former mentioned parameters singularity parameter is included since it can cause complications for the sealant quality, see Section 2.2.4 and Section 5.3. Singularities must therefore be considered when generating the manipulator trajectory for sealant application. In Section 4.2 the parameters singularity and accuracy & repeatability were identified as time influencing parameters. Whereas, for the end-effector it was the thrust parameter and for the Workpiece positioning system it is the positioning parameter. The time efficiency calculation is presented in Section 4.4.

Figure 4.5: Summary of quality associated outputs



4.4 Efficiency calculation

The previous mentioned efficiencies are here presented as equations of the previous identified parameters. These efficiencies can be used as a measurement, describing how a sealant application process performs in terms of cost and time. The quality aspects of the process are included in the cost calculation, since quality errors require rework, which results in a cost.

The cost is divided into a fixed and production related costs and then merged into a yearly cost. The total yearly cost is compared to a user defined threshold to achieve the cost efficiency.

$$E_c = 1 - \frac{C_{fixed} + C_{variable}}{C_{Threshold}} \tag{4.16}$$

The fixed cost is the sum of the investment costs mentioned in Section 4.3. The fixed costs is the yearly cost of an equipment derived from using straight-line depreciation, see Equation (4.17) [30].

$$C_{fixed} = \frac{C_{Acquisition} - C_{sal.val}}{t_{life}} \tag{4.17}$$

Where $C_{sal.val}$ is the salvage value of the investment and t_{life} is the useful life of the equipment.

The production related costs is dependent on the production rate and quality. Sealant costs, operational costs and quality costs are associated with production related costs. Since the unit for the production related cost is often *cost/cycle* it needs to be recalculated to *cost/year*, using Equation (4.18).

$$C_{production} = \left(\frac{C_{sealant} + C_{op.} + C_{quality}}{t_{takt}}\right) P_{year} \tag{4.18}$$

where t_{takt} is the takt time set in the system and P_{year} is the total amount of production hours in a year.

The time efficiency,E_t, is the ratio between the value adding time and the total time required for the process and is specified in Equation (4.19).

$$E_t = \frac{t_{string} + t_{fastener}}{t_{op.} + t_{rel.} + t_{cal.}} \tag{4.19}$$

t_{string} and $t_{fastener}$ are the time needed to complete all sealant strings and fasteners respectively. The operating time, $t_{op.}$, is the total time needed to perform the cycle, the reload time, $t_{rel.}$, is the time required to refill the sealant and the calibration time, $t_{cal.}$, is the required calibration time associated with positioning the workpiece in the correct position. The reload time can in some cases be included in the total operation time but are here separated for clarity.

The total efficiency for the system is the product of these efficiencies and can be used as a reference when comparing different options for a sealant process.

$$E_{tot.} = E_t E_c \tag{4.20}$$

An example on how to utilize the efficiency equations is presented in Section 5.2.

5

Results

This chapter presents the key findings and answers to the research questions of this thesis. First a model is illustrated that displays the parameters for describing an automated sealant application process. Afterward, a calculation example is shown how these parameters can be utilized for calculating the efficiency for the investigated automation solution.

5.1 Parameters of sealant automation process

Analyzing the components of an automated sealant application process from a production efficiency perspective – cost, time and quality - helped identifying the parameters that are critical for the description of a sealant application process see Section 4.2. The result from applying a production efficiency perspective to the components generated a model with parameters that need to be considered for an efficient production process with automated sealant application. This model is called Conceptual Model, see Table 5.1. Each parameter is categorized in the production efficiency criteria in order to demonstrate that these parameters influence that specific production efficiency criteria.

Table 5.1: Conceptual model

Cost	Time	Quality
1. Fixed Costs: • Workpiece Positioning System • Robot Controller & Manipulator • End-Effector • Metering & Dispensing system • Auxiliary Robot Equipment: o Cell Controller o Sensor System 2. Production Related Costs: • Sealant (Volume per Operation) • Supplementary Costs (e.g. Maintenance, Electricity, etc.)	1. Manipulator Path 2. End-Effector Flow 3. Workpiece Positioning 4. Refill	1. Manipulator Singularity 2. Manipulator Accuracy & Repeatability 3. End-Effector Design 4. Workpiece Positioning

The production efficiency criteria for cost consists of the parameters fixed costs and variable costs. Fixed costs are those expenditures whose value is independent from production volume and sales [30]. Whereas, production related costs are the opposite, these are expenditures whose value is dependent from production volume and sales [31]. Within the fixed costs parameter the individual expenditures for each component are listed. These components are identified as the necessary components for designing of an automated sealant application [8, 16, 17], see Section 2.1.3. The production related cost parameter contains the expenditures that are generated by the activity of the automated sealant application process. In that list, applied sealant volume and the costs, such as electricity and maintenance, are displayed. The list for the cost criteria is adjustable to any configuration of components of an automated sealant application process. Through cost calculation the values for the parameters can be determined.

The production efficiency criteria for time is determined by the process time of the manipulator to complete the sealant process. This process time is dependent on the velocity and acceleration values of the manipulator. The value for the time is obtained through a PLS-based simulation in which the time for the sealant application process is measured.

Lastly, the production efficiency criteria for quality lists parameters that are affecting the quality of the sealant during application process. From a production efficiency perspective, the goal is to produce outputs that have minimal deviation from the defined quality characteristics [29]. The parameter robot singularity refers to the impact on the TCP caused by the increase of the joint velocities as the manipulator approaches a near singularity configuration. The parameters accuracy and repeatability are manipulator specific parameters. According to Atkins and Escudier [32] accuracy refers to the capability to move as close as possible to a specified point; meaning the preciseness of an obtained measurement. The manipulator repeatability on the other hand, is defined as the deviation in obtained measurements when moving repeatedly to a specific position [33]. These parameters can be obtained from manipulator’s list of technical specifications.The parameter design of end-effector which is determined by its dimensioning, nozzle orientation, and orifice size [8, 16]. As Bafunno [16] mentions that the design of the end-effector is critical for reaching the application points with desired tool orientation in the workpiece, thereby increasing the manipulator’s workspace. Additionally, the design of the end-effector is equally critical for the appearance of the sealant bead [8, 16]. Designing an ideal end-effector requires iterative drawings and simulations of the application process [16]. In this thesis the design of the end-effector is assumed to be perfect. Lastly, the parameter workpiece positioning. This parameter determines the influence on the quality output caused by the position error of the workpiece from the defined position.

5.2 Systematical evaluation of solutions

To illustrate how the efficiency of a sealant application system can be calculated, an example is described utilizing the equations stated in Section 4.4. The efficiency for this example is calculated when the robot is applying sealant in a straight line at constant velocity. Some additional simplifications are made to lower the complexity of the calculations. By combining the end-effector and the metering and dispensing system into one device these parameters can be consolidated into the end-effector. The rest of the simplifications are described in the following text. There is a large amount of input data required to perform this calculation, even for a simplified example, these parameters are presented in Table 5.2.

Table 5.2: Example values used to calculate sealant process efficiency

Parameter	Value
Useful life T_{life}	7 years
Manipulator & controller cost, $C_{man.\&cont.}$	$ 0.5M
End-effector cost, C_{EE}	$ 0.1M
Workpiece location system cost, C_{WPL}	$ 0.3M
String length, L_{string}	2.3 m
String volume, V_{string}	15 ml/m
Sealant cost/ml, $C_{seal.vol.}$	$ 4/ml
Operational cost, $C_{op.}$	$ 50/cycle
Quality cost, $C_{quality}$	$ 4/cycle
Takt, t_{takt}	0.5 hrs/product
yearly production hrs, P_{year}	3840 hrs
Threshold cost, $C_{threshold}$	$ 2.5M
Robot velocity, υ_{robot}	50 mm/s
Operation time, $t_{op.}$	72 seconds

5.2.1 Example cost calculation

The first part of the cost calculation is to determine the fixed costs for the process. In order to make the calculations simpler it is assumed that the life span for all equipment is seven years and that it is used for the entirety of that time with no salvage value. The calculation is further simplified by assume that no auxiliary hardware is needed. This results in no impact from the salvage value (Equation (4.17)) and auxiliary cost. By putting the values from Table 5.2 in Equation (5.1) the total cost of the yearly fixed cost is $ 0.1286M/year.

$$C_{fixed} = \frac{C_{man.\&cont.}}{t_{life}} + \frac{C_{EE}}{t_{life}} + \frac{C_{WPL}}{t_{life}} = \$0.1286\text{M/year} \tag{5.1}$$

The second part is to calculate the production related cost by identify the cost of the sealant. Here, it is assumed that there is no waste of sealant in the process. The total cost of the sealant when applying a string of sealant is \$ 138/cycle.

$$C_{sealant} = L_{string}V_{string}C_{seal.vol} = \$138/cycle \tag{5.2}$$

To simplify the production related cost the cost for maintenance, electricity and operators are presented as operation cost rather than individual costs. The production related cost is \$ 1.4746M/year.

$$C_{production} = \frac{C_{sealant} + C_{op.} + C_{quality}}{t_{takt}} P_{year} = \$1.4746/year \tag{5.3}$$

The cost efficiency for this particular example is 35.9 %.

$$E_c = 1 - \frac{C_{fixed} + C_{production}}{C_{threshold}} = 0.3587 \tag{5.4}$$

5.2.2 Example time calculation

The first step in the time calculation is to identify the value adding time, which in this case is the time required to perform the string sealant application. The value adding time in this process is 46 seconds.

$$t_{string} = \frac{1000 \times L_{string}}{v_{robot}} = 46\text{sec.} \tag{5.5}$$

When calculation the total process time for the cycle, the reload time for the sealant and calibration time is assumed to be included in the operation time, $t_{op.}$. The operation time can be acquired by using a PLC simulation or similar. The total time efficiency for the sealant application process is 63.9 %.

$$E_t = \frac{t_{string}}{t_{op.}} = 0.6389 \tag{5.6}$$

Combining the cost and time efficiencies a total efficiency can be determined for the sealant application process. By using Equation (5.7), the total efficiency is calculated to be 22.9 %.

$$E_{tot} = E_c E_t = 0.2292 \tag{5.7}$$

5.3 Singularity experiment

The behavior of the manipulator when approaching the singularity point is examined. The goal is to acquire insights about the reaction of the control mechanism to handle such phenomenon.

Figure 5.1 illustrates how the TCP velocity slows down as the determinant of the Jacobian approaches the zero value. The TCP velocity is shown on the y-axis that is on the left-hand side and the value of the determinant is shown on the y-axis on the right-hand side. The TCP velocity is programmed to be at 50 mm/s. As the TCP approaches the singularity point the determinant starts to get closer to the value zero. Then, at a certain value of the determinant, the TCP velocity is seriously affected and reduced to approximately 3-4 mm/s. Interestingly, the determinant never reaches the value zero.

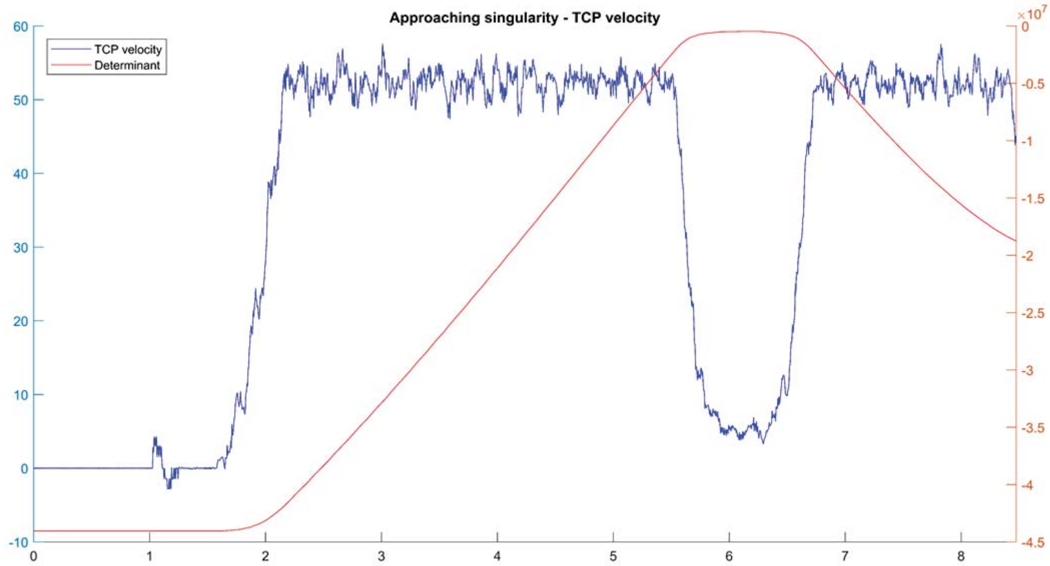


Figure 5.1: Approaching singularity point - TCP velocity

Figure 5.2 illustrates how the joint velocities are affected by the determinant approaching the zero value. This figure displays only the joints that are affected by the singularity. The joint velocities increase exponentially and are then suddenly stopped. The joint velocities start to decrease again as soon as the determinant increases.

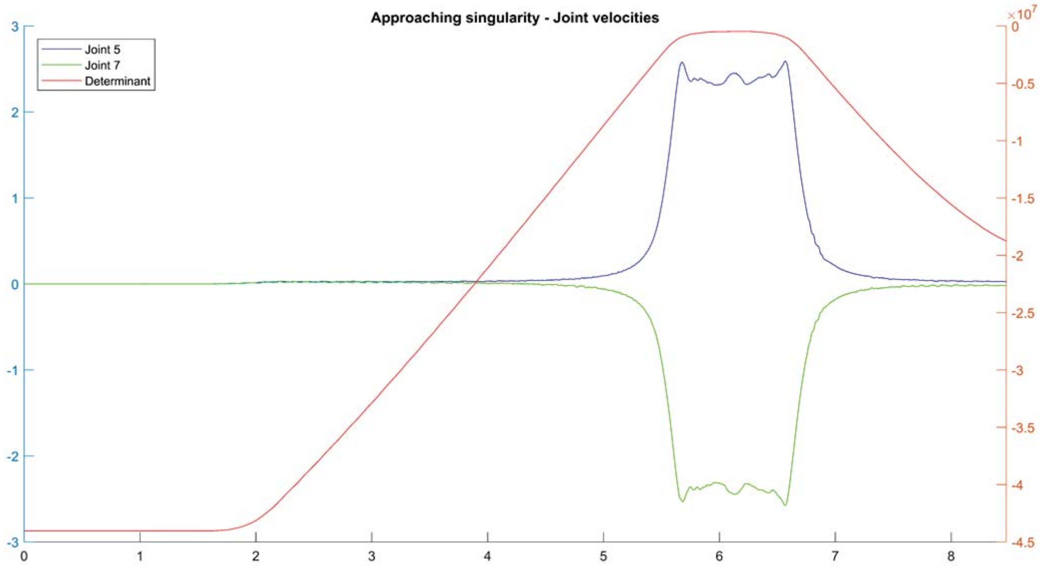


Figure 5.2: Approaching singularity point - TCP velocities

To conclude, it was demonstrated that the parameter robot singularity is important parameter that needs to be considered in the description of a robotic sealant application process. This parameter is an influential factor for the production efficiency criteria quality and should therefore be included in that production efficiency category.

5.4 Simulation validation

To be certain that the results of the simulation is good enough data from KUKA FRI was compared to values obtained from the simulation. The comparison is made between joints since that is the most relevant data obtained from the FRI. Here, two comparisons are presented, the full comparison can be found in Appendix C.

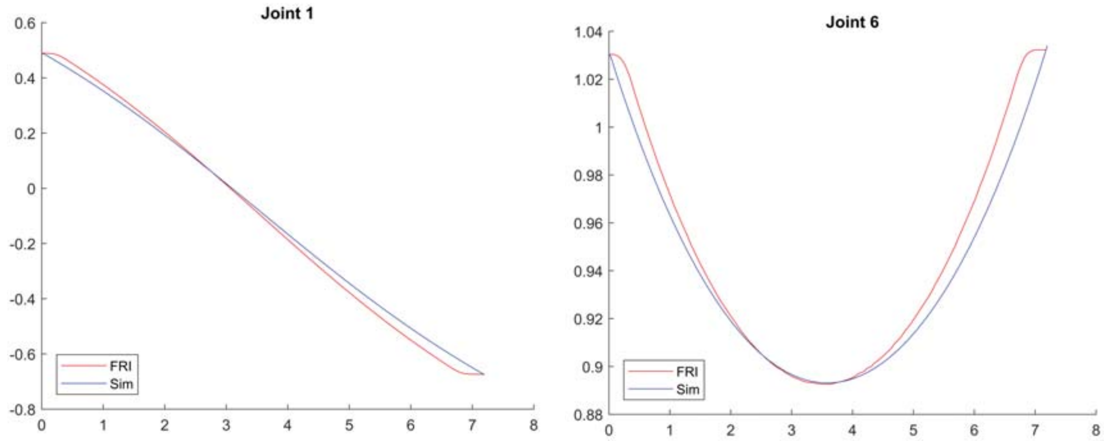


Figure 5.3: Joint value comparison for joint 1 and 6

As seen in Figure 5.3, the simulated values are very similar to the real values obtained from the KUKA FRI. The simulated joint vales does not follow the real values exactly but the initial and final values are the same as well as the time it takes to complete the motion.

6
Discussion

This section discusses the findings and the overall approach to the thesis. Additionally, it evaluates the answers for the research questions.

6.1 Results

This section discusses the answer for the research questions.

6.1.1 Conceptual model

The conceptual model presents a list of identified parameters for each production efficiency criteria. The advantage of the model is that the list can be arranged to any configuration of automated sealant application process. However, these parameters are interdependent and this requires the process planner to comprehend the interaction between the parameters. For instance, it was concluded that the parameter singularity affects the quality of the sealant application. However, this parameter depends on the technology embedded in the end-effector. If the end-effector is equipped with a velocity feedback sensor, the end-effector can adjust the flow of the sealant to the TCP velocity. Thereby the end-effector can apply the right amount of sealant on the workpiece and fulfill the specified quality characteristics.

6.1.2 Simulation model

The simulation model is a simple way to assess the robot motion. However, being a simulation the accuracy of the result compared to the real case is always an issue. Firstly, there is always some inherited accuracy problems associated with numerical errors in the simulation environment. It is consequently not realistic to expect a 100 % accurate simulation model. Apart from the inherited errors, there are some design choices that also impact the result of the model, the first being the way the TCP trajectory is generated as well as the omission of dynamical and stiffness aspects.

Normally, a real robot is calculating the trajectory by utilizing the inverse kinematic functions for all intermediate points between the current and desired position. The robot control system then calculates the needed joint torques in order to move the respective joints in such a way that the desired TCP is reached. In our model, the TCP speed profile is first generated and then the resulting joint velocities are calculated. The big difference is that our model utilizes the task velocity directly instead of the task position. It is possible that some information is lost during this simplification, but the simulation and KUKA FRI yields similar results regarding joint and TCP position. The profile for the joint and TCP positions is not the same for the simulation and the reality but the simulation end up in the same position as the real robot. The reason for the difference in behavior can partly be described by the assumed TCP acceleration when calculating the TCP speed profile. KUKA does not provide any information regarding the TCP acceleration so data from similar robots is used instead.

To produce a functional dynamic model, a large amount of data needs to be collected in order for the dynamic calculation to be correct. These are very specific robot data, such as mass and inertia matrices of each individual link. This data is normally not given by the manufacturer, consequently have we not been able to acquire trustworthy data regarding these parameters. In addition to the dynamics of the links there are several other parameters that needs to be included to construct a more accurate model, such as friction coefficients in drive units and gearboxes. These parameters have not been measured and are therefore not included in the model.

The stiffness is another aspect that can greatly affect the accuracy of the manipulator. Again, the correct stiffness data has not been acquired since it is not only robot specific but also configuration specific for the manipulator. Meaning that the stiffness values differs depending on posture of the robot.

The user-friendliness of the model is something that needs to be discussed as well. A large amount of time need to invested to obtain and calculate the robot specific parameters, only to be able to simulate the path. Considerable more time is needed to be able simulate the impact of dynamic and stiffness. The same is true to be able to calculate the efficiency of the system. Product related data need to be obtain, such as takt time and maintenance frequency, as well as all the cost aspects related to the system. The characteristic of this model is that it represents a framework and equations to be able to calculate the efficiency for the process, but it is required of the user to gather the necessary data.

6.2 Experiment

To begin with, in all experiments only linear motions of the TCP were performed since these generate predictable motion paths and because that motion type is relevant for the string sealant application.

Further, the lack of proper of equipment has affected the progress of the experiments. For example, in order to measure the vibration on the TCP during the singularity experiment a vibration measuring equipment would have been beneficial in order to conclude about the path deviation during a motion in the proximity of a singularity. The lack of equipment did also affect thrust experiment. The air flow measuring equipment was defect and did not show the magnitude of the air pressure that was going through the system. Also, the force sensor equipment that was used for the same experiment did not measure the thrust which was applied through the air flow. For this reason, a numerical analysis of the thrust experiment could not be performed. As a consequence, the thrust experiment was canceled.

Regarding the singularity experiment, the determinant of the Jacobian never reached zero in the experiment. The author's have tested to go as close as possible to the singularity point with restricted TCP velocity and a linear motion. However, the control mechanism does not allow the TCP to go close to the singularity point under these conditions. It is therefore believed that the control mechanism has a priority protocol that is triggered as soon as the TCP approaches the singularity point. This protocol may prevent such motion to a singularity in order to sustain TCP velocity as well as the TCP position & orientation and the linear motion of the TCP. This belief is based on illustration of the determinant in Figure 6 and Figure 7. In both figures the determinant is seemingly prevented from reaching the zero value. In both graphs the determinant suddenly forms a plateau. Further, it can be seen that as the determinant approaches zero the joint velocities increase exponentially and are then suddenly reduced by a small amount in order not to exceed the physical range. Then, as soon as the determinant increases again the protocol is released and the joint velocities start to decrease again.

6.3 Verification and validation

As stated in the methodology section of this thesis, the verification and validation was accomplished mainly by means of peer review. This process depends on the level of expertise and experience of the reviewers.

The validation for the simulation model on the other hand, was attempted by means of comparing the simulation results with the data collected from the KUKA FRI. Since the simulation does not include all the system constraints of the control mechanism of the manipulator, the results were not completely the same as the analyzed data which was gathered from the KUKA FRI.

Some constraints regarding the KUKA FRI also hindered the validation. Software did not provide crucial data such as joint velocity, joint acceleration TCP velocity. The lack of comparable data made the validation process more difficult. Further, KUKA AG did not provide this data either, when the author's asked to.

6.4 Future research

It was concluded that the design of the end-effector has an effect on the quality of the sealant bead, see section 2.1.3. The investigation on how the design parameters of an end-effector are correlated with the quality sealant bead is not within of the scope of this research. Regardless, the authors are convinced that the study on end-effector design parameters that affect the quality of sealant application would be a contribution to the research field since the aerospace industry has to fulfill high quality requirements [6].

Furthermore, the design and assembly of workpiece are viewed as constraints for this research. The authors suggests that the research field would benefit from a study regarding how design and assembly of aerospace structures can ease the implementation of robotic automation solutions. The findings and results of such research can facilitate the industrial robot implementation in the aerospace industry since the complexity of aerospace structures are an obstacle for the implementation of robotic automation solutions [6].

In this thesis, the concept of singularity was presented in the context of the quality. The authors suggest that a more in-depth analysis of the singularity identification should be made. Possible research questions could be: How close can the TCP path be to a singularity without affecting the TCP-velocity? Is it possible to generate an algorithm that generates a path which avoids being close to singularities and bypasses them totally? How can singularities be taken into consideration in the algorithm for the path generation?

The parameters presented in the conceptual model list are only referring to the kinematic viewpoint of the manipulator. The implication of forces and torques, internal as external, that are acting on the system are not included in the list. Therefore, the authors believe that the list can be extended to include parameters of manipulator's dynamic viewpoints. For this a study must be conducted on how the manipulator's dynamics impact the production efficiency criteria.

Admittedly, it is possible to use different approaches to identify the parameters for describing the automated sealant application process as well as different approaches to evaluate the various automation solutions. Therefore, the authors suggest an area for future research that gathers the different possible approaches for parameter identification and evaluation methods and proposes, through comparison of the possible approaches, a suitable approach for engaging in the research topic.

6.5 Ethics aspect

The work ethics for this research were followed up by not mentioning the project members and the confidential aspect of the project.

7
Conclusion

This thesis presented a model that illustrates the parameters that need to be considered for describing an automated sealant application process. These parameters were derived from the the components, which in turn form systems, necessary to create an automated sealing application process. These parameters are categorized in the the categories cost, time and quality. These categories were chosen because they are production efficiency criteria which means that the efficiency of a production system can be evaluated by analyzing how efficient a production system is able to satisfy these criteria. The parameters are categorized in order to demonstrate that the respective parameter influences the category it is assigned in. In this manner, the parameters' influence on the efficiency criteria can be studied.

Secondly, this thesis conveys a method for calculating the efficiency for different automated sealant application solutions in form of efficiency calculations. The result of these calculations can be used as means to compare the efficiencies of the different solution to systematically evaluating these solutions.

With the model and the efficiency calculations the authors proposed a method for the aerospace industry to evaluate different automated sealant application solutions. With an example the authors demonstrated the application of the efficiency calculations.

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A

Appendix I - Sealant properties and considerations

A.1 Sealant properties

Sealant properties can be divided into three categories: Chemical, physical and mechanical properties [10, 34]. These properties constitute a significant role in the selection of a sealant, as well as in the application procedure of the sealant [10, 34]. Sealant properties that have an impact on the application procedure are here studied.

In regard to the chemical properties of a sealant Petrie [10] mentions the cure rate, the depth of cure, and shrinkage are important for application purposes. The duration it takes for the sealant from being mixed to the state it loses its applicable condition is referred to as the cure rate [10, 34]. The duration can vary between minutes and a day [10]. Within the duration the sealant slowly loses the applicable condition as it hardens gradually [35]. The terms pot life and working life illustrate the concept cure rate [34]. Pot life is the time from when the sealant leaves the mixer and is ready for application until the time the sealant's viscosity measure doubles [34, 35]. Whereas, working life is the time span in which the sealant still poses the capability to wet the surface [34]. This property is important in a production context because it sets a time limit on when the application of sealant must occur [34].

Regarding the curing mechanism, certain sealants cure by diffusing moisture. As the most outer layer of the sealant can transmit moisture easier and thereby cures faster, it creates a layer of skin which impedes the transmission of moisture for the deeper layers of the sealant. In consequence, further moisture transmission is restricted and the complete solidification of sealant is constrained by this phenomenon. This phenomenon is referred to as the depth of cure [10, 34].

During solidification, sealant can shrink up to 10 % in size. For sealants that diffuse moisture on the other hand, the shrinkage is higher [34]. The shrinkage can contribute to the creation of flaws (e.g. cracks) on the seal which in turn negatively affects the function and even the durability of the seal [10, 34].

Concerning the physical aspects of sealant properties, rheology, is an influential factor for the sealant application [10]. Rheology is the term that specifies the material's deformation and flow property [10, 34, 36]. This property defines appropriate application methods and application surfaces for the sealant. There are two classes of rheology: self-leveling and non-sag [10,34]. A sealant that is self-leveling spreads out evenly on the surface [10,34]. In contrast, a material that is non-sag is a thixotropic material that can be deformed by applying force [10, 34]. For instance, if the material is self-leveling then an extrusion gun might be the tool of choice compared to a spatula, because the material is fluid and spreads out evenly by itself [10,34]. However, in this case the sealant may not be ideal for vertical or upside-down horizontal application surfaces [10, 34].

A.2 Sealant application considerations

The sealant is applied to the joint surfaces whilst the sealant is in liquid form. This ensures that the sealant can penetrate through all gaps and cavities of the joint [11, 13, 37]. The liquid form also wets the surfaces, meaning that the sealant accomplishes an intermolecular contact with the surface which provides optimal conditions for the sealant to adhere to the surfaces [11,13,38]. The concept of adhesion is the intermolecular forces that are present between two dissimilar substances [10,39]; in this case the sealant and the surface. Whereas, the intermolecular forces that exist within a material itself are encapsulated in the concept of cohesion [39]. The intermolecular forces in both adhesion and cohesion are identified as van der Waals forces [39]. The sealant is transformed into a liquid state by heating it with proper equipment or by applying a solvent to dissolve the sealant [13]. Additional alternative is that the monomer of the sealant material begins in a liquid state and undergoes a polymerization process and stays in its liquid form afterwards [13].

A key component for a successful sealant application is the preparation of the surface. Preparation operations on the surface contribute to enhancement of the adhesion mechanism [10, 40]. Beneficial for the adhesion of the sealant are flaws in the adherent surface, such as cavities and pores. This allows the sealant in its liquid state to fill these flaws and achieve a mechanical interlocking [41]. By roughening of the surface with adequate equipment these flaws can be applied to the surface. Furthermore, a clean surface improves the wetting ability of the sealant [10].

After the sealant has been applied in its liquid form is must harden. Different sealants require different methods for the hardening process. In its hardened form the sealant reaches strength and durability [37, 39].

B

Appendix II - Singularity experiment details

The model of the experimental process is depicted in Figure B.1.

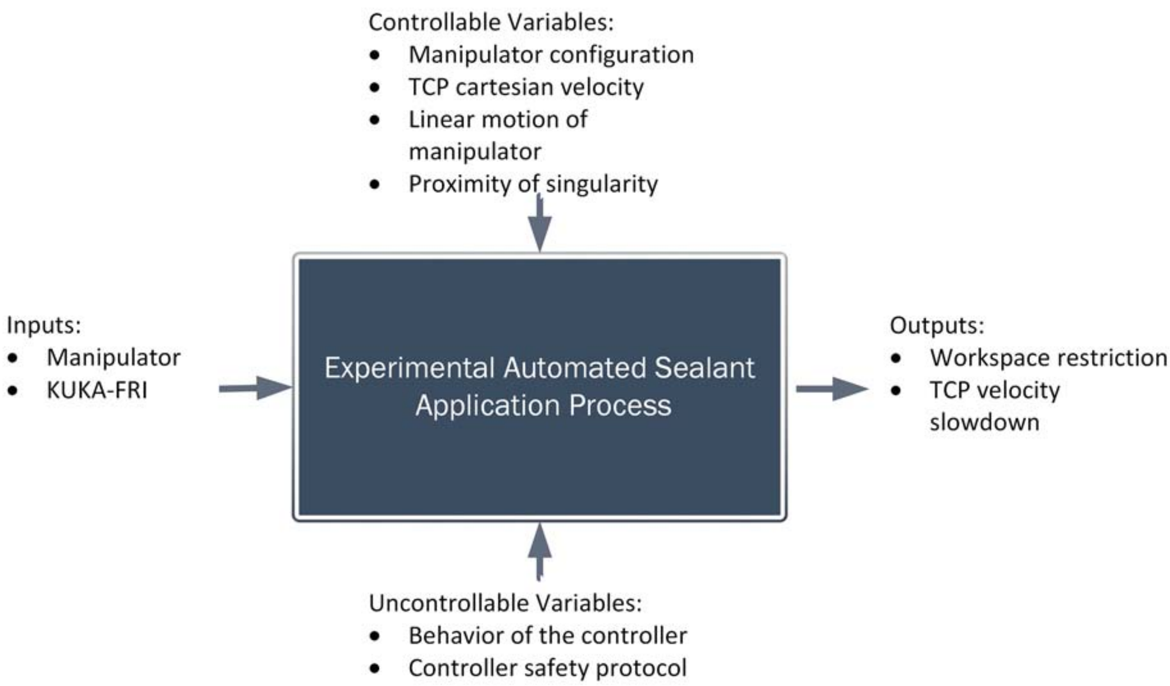

Figure B.1: General Model of the singularity experiment

The process variables for the experiment were identified by means of brainstorming and screening the experiment [42]. These variables were then classified as either controllable or uncontrollable [42]. Controllable implies that the variables can be attuned by the experimenter and uncontrollable implies that variables cannot be attuned [42]. The disturbance effects caused by uncontrollable variables that might influence the experiment are averaged out by applying the three principles of designing an experiment; randomizing, replication and blocking [42].

For the experiment the manipulator is needed and the KUKA-FRI. KUKA-FRI is a software that logs the joint angles. These angles can then be used to calculate the TCP-velocity as well as the joint velocities. In the experiment, the controllable variable TCP Cartesian velocity will be limited to 50 mm/s and the motion type of the manipulator will only be linear. Regarding the configuration, only one singularity configuration was performed since the behavior of the controller will be the same for all singularity configurations. The proximity of the singularity was controlled by adjusting the joint angle of the redundant axis (Joint 3). For the selected configuration, the joint angle of the redundant axis was set to 5° since this was the closest we could get to a singularity configuration before the controller would restrict the workspace. The aim of the experiment is to only investigate the behavior of the controller and the possible implications for sealant application not to find the singularities. Uncontrollable variables are the behavior of the controller and the safety protocol embedded in the program of the controller.

C

Appendix III - Joint values for validation

The following figures show the comparison between the simulated joint values and the real values. As can be seen in the graphs, the simulated values and the real values are not exactly the same. However, the start-point and end-point are the same as well as the required time for the motion.

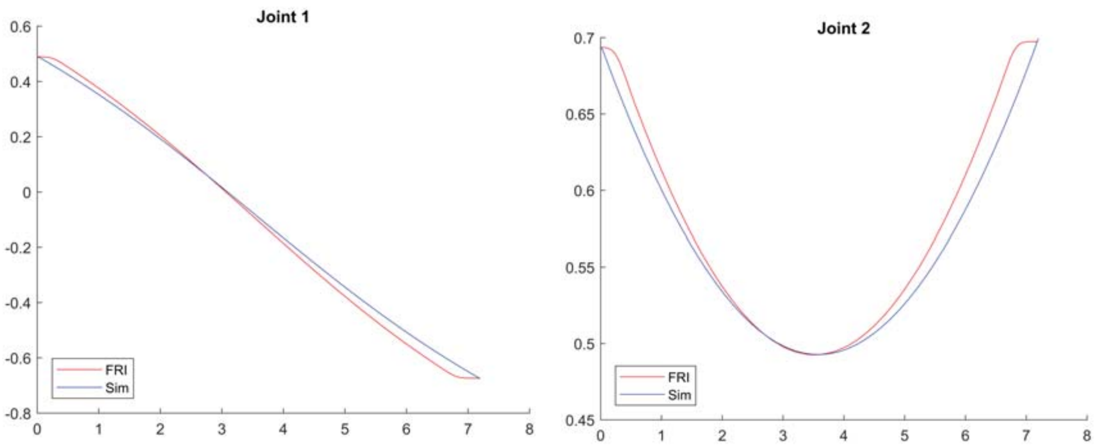

Figure C.1: Joint value comparison for joint 1 and 2

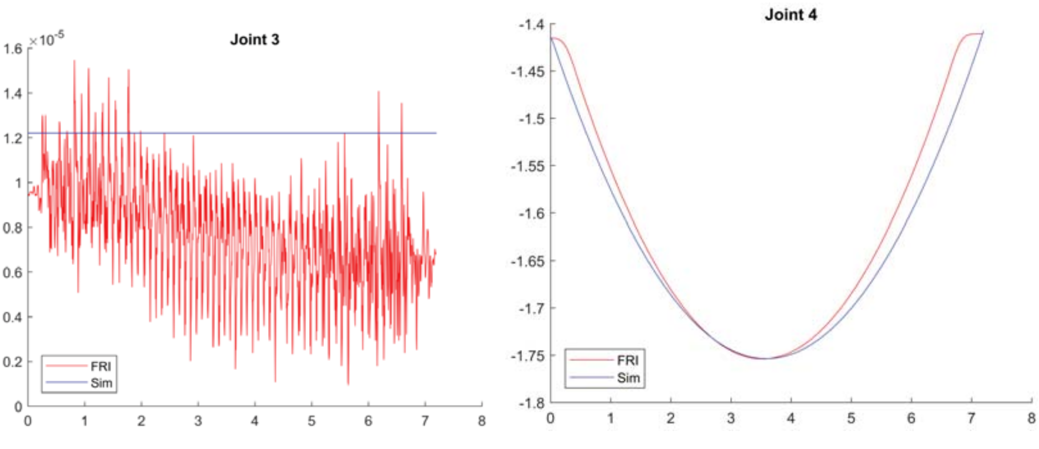

Figure C.2: Joint value comparison for joint 3 and 4

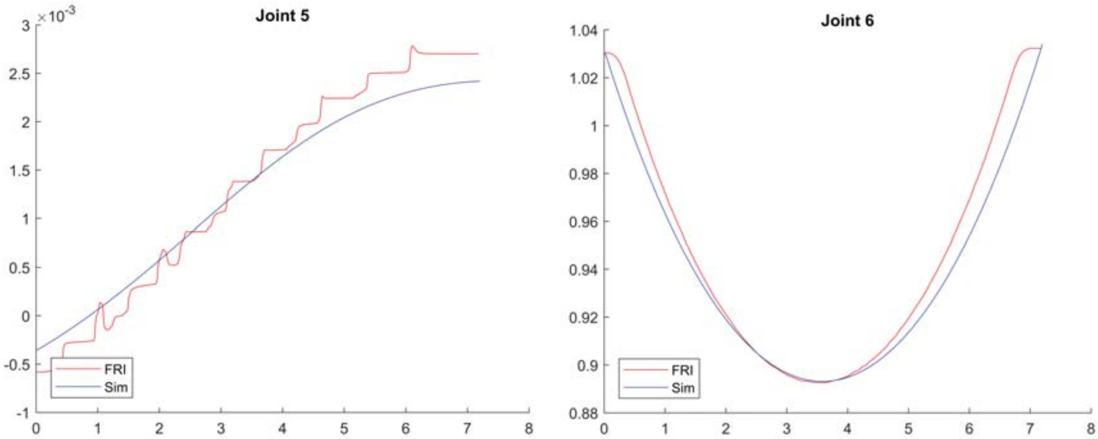

Figure C.3: Joint value comparison for joint 5 and 6

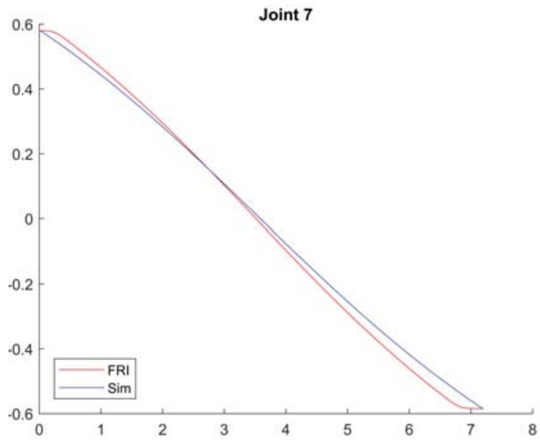

Figure C.4: Joint value comparison for joint 7