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ROBOTIC CONTROL SYSTEM FOR METAL TUBES PROFILING TO BE USED IN PREPARING WELDING GAPS FOR ANGULAR WELDING JOINTS

Bachelor’s thesis

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PhD
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ROBOTKONTROLLISÜSTEEM METALLIST TORUDE PROFIILIMISEKS, MIDA KASUTATAKSE NURKKEEVITUSLIITMIKE KEEVISLÕIKE ETTEVALMISTAMISEKS

Bakalaurusetöö

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Author’s declaration of originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

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Abstract

The aim of this bachelor thesis was to automate the process of cutting profiles of metal tubes to be used in welding of angled tube joints. Research question was to find a trajectory of intersection of two tubes using vector arithmetic, generate a path as a sequence of 3-dimensional points in conjunction with cutting tool orientation and conducting robot through this path. The research question derives from the need of making the process of welding tube joints fully automated to avoid inaccuracies and defects.

Firstly, the trajectory of tubes intersection was calculated using vector arithmetic and quaternion rotation. Then using integrational functions, the trajectory and angle to be traversed by robot was calculated. Lastly, using quaternions, rotation matrixes and Euler's angles the angles were converted to format which robot can use and using TCP/IP sent to the robot.

The most important result of the work is working programs in Python and FANUC programming language KAREL, which, in simulation, can make the robot cut the desired metal tube profile using gas-oxygen cutter.

While the result programs are fully working there is a lot of places to make it better, because it works only is simulation. There is more work to be done to make it usable in industry. This program will be a part of a bigger system in future development.

This thesis is written in English and is 37 pages long, including 7 chapters, 14 figures and 0 tables.

Annotatsioon

Robotkontrollisüsteem metallist torude profiilimiseks, mida kasutatakse nurkkeevitusliitmike keevislõike ettevalmistamiseks

Selle bakalaureusetöö eesmärgiks oli nurkühenduste keevitamisel kasutatavate metalltorude profiilide töötlemise automatiseerimine. Uurimisülesandeks oli leida kahe toru ristumiskoha trajektoor, kasutades vektoraritmeetikat, genereerida kolmemõõtmeliste punktide järjestatud teegid koos lõiketööriista orientatsiooni parameetritega ning saadud andmete alusel juhtida roboti tööd. Uurimisülesanne tuleneb vajadusest muuta torujuhtmete keevitamise protsess täielikult automatiseeritud, et vältida ebatäpsusi ja defekte.

Esiteks arvutati torude ristmikul trajektoori vektoraritmeetika ja kvaternioni pöörlemise abil. Siis arvutati integreerivate funktsioonide abil roboti poolt läbitav trajektoor ja nurk. Lõpuks, kasutades kvaternioone, pöörlemismaatrikseid ja Euleri nurki, teisendati nurgad vormingusse, mida robot saab kasutada ja robotile saadetud TCP/IP-i kasutades.

Selle töö kõige olulisemaks tulemuseks on tööprogrammid Pythonis ja FANUC-i programmeerimiskeeles KAREL, mis simulatsioonil võimaldavad robotil lõigata soovitud metalltoru profiil gaasi-hapniku lõikuriga.

Kuigi tulemusprogrammid on täiesti töövalmis, on seal palju täiendusvõimalusi, sest see töötab vaid simulatsioonina. Praktiliseks rakendamiseks tööolukorras on vaja programmi edasi arendada. See programm moodustab osa suuremast süsteemist tulevases arengus.

Lõputöö on kirjutatud inglise keeles ning sisaldab teksti 37 leheküljel, 7 peatükki, 14 joonist, 0 tabelit.

List of abbreviations and terms

TUT	Tallinn University of Technology

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1 Introduction

In production the use of robots is highly spread. Robots are useful in all sorts of work from dragging and dropping to cutting and welding. Robot is good in any repeating task, but it needs some sort of serialization and consistency in a task. In Estonia there is no production in such amounts. That's the reason why very often behind a robot there is an operator who controls it because tasks asked from robot is too complex to be straightforwardly programmed, one example of such a task is making a profile of tube to be welded to another tube.

The goal of this bachelor's thesis is to create a program which, given needed information about a tube, will calculate necessary trajectory for a gas-oxygen cutter and will send it to a cutter which will perform a task. The information given to program is both tubes sizes and properties of connection between them like angle and standard deviation. When the program gets the information, it connects with a robot and asks for coordinates of the tube in robots' coordinate system. Given all this data the program makes calculations using mostly vector arithmetic to calculate the trajectory robot needs to traverse. Then starts the process of cutting the tube where program sends robot coordinates one by one and cutter is slowly progressing with a task.

Thesis author was approached with this problem and the goal to automate the cutting process by the company ASG Robotics OÜ. ASG Robotics OÜ is located in Narva and offers fully automated complete solutions in automotive industry, shipbuilding and pipe industry fields. The result of this thesis is working programs in Python and KAREL which will be working together to automatically cut the desired tube profile.

2 Problem and today's solutions

2.1 Steel tubes in structures

Steel tubes with circle cross-section is widely used in production of different metal structures. Tubes are used when constructing supports for offshore oil platform, high pressure pipelines for oil and gas transportation, atomic reactors, pumping stations etc. Circle tubes have high moment resistance of cross-section at a relatively low mass. In this way metal structures made of pipes are relatively lightweight, but strong. When transporting liquid medium under pressure bursting force is applied evenly what reduces the requirements for metal thickness. In other words, the use of tubes is economically feasible. However, working with tubes always appear tasks of angular joint welding. This type of joint welding is hard to automate, because weld trajectory represents three-dimensional curve of complex shape. Also, this type of welded joint is poorly amenable to non-destructive testing (when need to check the quality of a joint without opening it, for example, using ultrasonic testing, but this type doesn't always work on this type of welded joints). Furthermore, defect detection after welding leads to large economic losses, because this type of welded joint does not lend itself to mechanized processing when eliminating defects. All of this significantly increases amount of effort. Automation is the only solution to these problems. Creating these joints is a multi-step process and this thesis is focusing on automating one step of this process – tube's cutting.

2.2 Full process

Any automation involves tougher tolerances on the parameters of the process (geometric dimensions, running energy, temperature, speed, acceleration, etc.) with subsequent control of these parameters reaching specified tolerances. The process of manufacturing pipe joints begins with the preparation of production, i.e. pipe manufacturing (steel casting, steel rolling, heat treatment, molding, longitudinal joint welding, calibration and again heat treatment), but this is beyond ASG Robotics competence. ASG Robotics' specialization begins with the processing of blanks, and ends with the finished product.

The quality parameters of the blanks (tolerance for ovality, allowance for taper, tolerance for surface roughness, tolerance for the content of alloying components, etc.) author accepts as an objective reality in the design of further technological processes, but for the scale of this thesis they are left out and a goal for another project.

In terms of welding, the angled connection of pipes can be formulated as follows: one-sided corner or T-joint of saddle shape with full penetration of the root of the seam, with the filling of the cutting with the bevel of one edge. An example of the T-joint is on the figure 1. Welding is carried out in several stages:

1. Manual or automatic welding of the root of the seam (one roller or one pass is applied) and, if necessary, welding of several filling passages;

2. Thermal tempering and non-destructive testing of welding (ultrasonic or radiography) after cooling of the part;

3. Welding filling passages with subsequent thermal tempering.

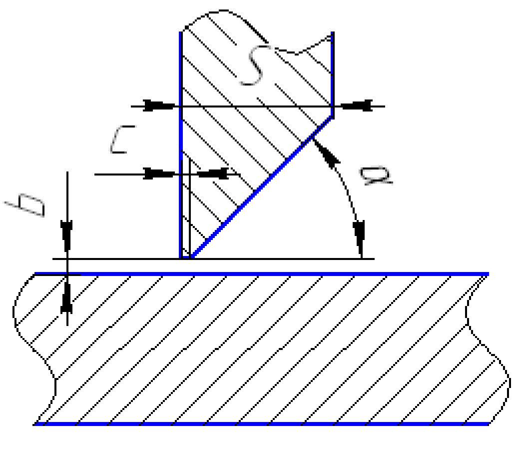

Figure 1. An example of the T-joint.

The sketch on figure 1 indicates the dimensions of the edge blunting (size "c") and the clearance at assembly (size "b"). Control of these dimensions is necessary to ensure high-quality welding of the root of the seam. The very term "one-sided connection" implies low accessibility of the back side of the seam. In other words, welding is carried out only from the cutting side. The term "full penetration of the root of the seam" means that a roller of molten metal should form on the back of the seam. Welding of this root is very technological. It is necessary to ensure full penetration of the metal and, at the same time, not burn the wall of cutting. Welding is carried out with the set mode, which means the constancy of the heat input. That is why it is necessary to ensure the same thickness of the metal at the root of the weld and the specified gap between the parts, so that the same amount of molten metal evenly fills the gap. Additional filling passages in the first stage of welding are necessary to ensure the required stiffness of the seam during thermal tempering and movement of the part for diagnostics. If the diagnostics of the first welding phase is successful, then the remaining filling passages are welded.

The process of preparing the cutting for welding consists of two stages, namely:

1. Thermal or waterjet cutting of the workpiece (figure 2). Here, a preliminary form of cutting is formed;

2. Machining (figure 3). Here, a clean cutting surface is formed, as well as dulling for welding the root of the seam.

Figure 2. Preliminary form of cutting.

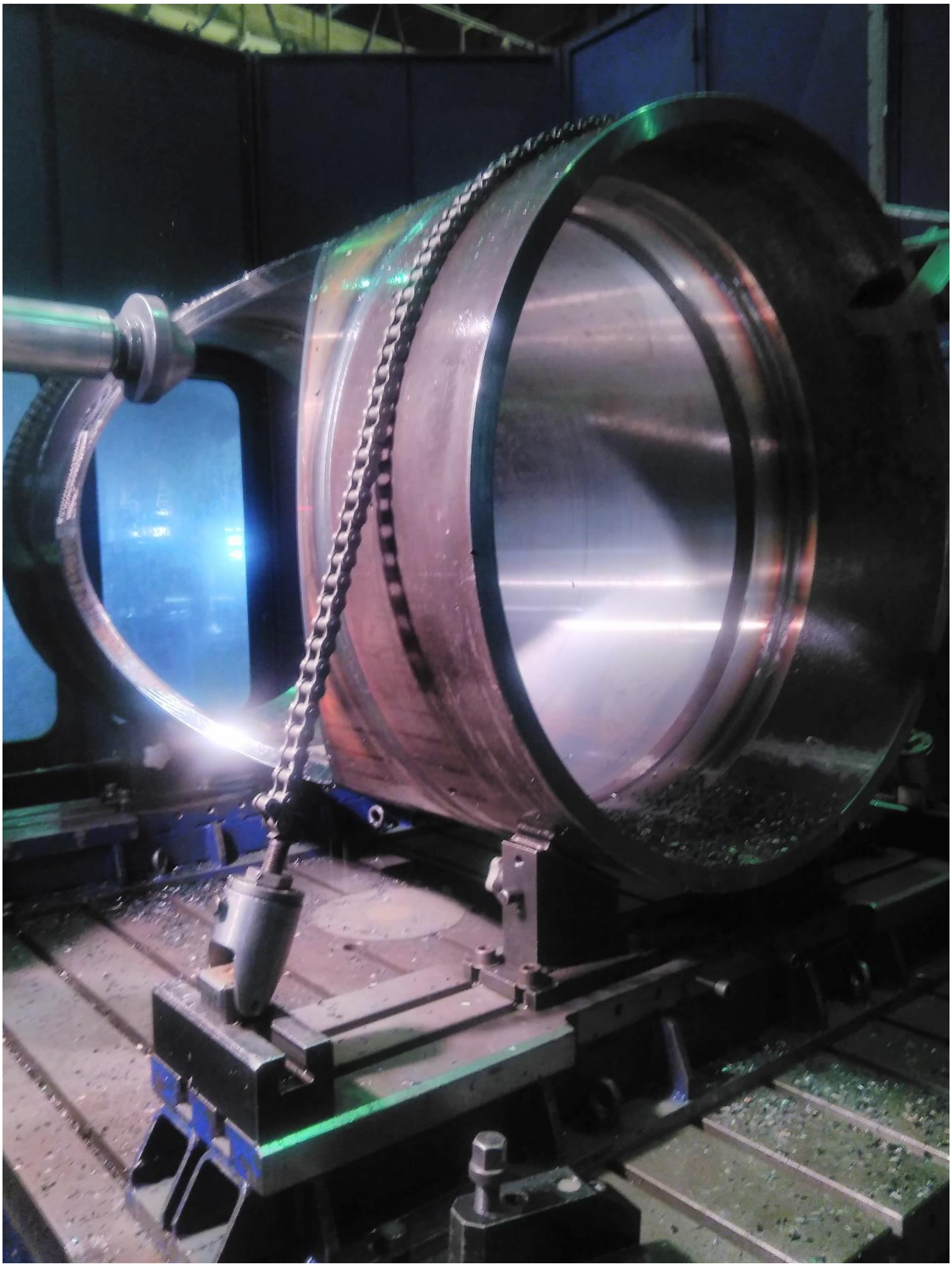

Figure 3. Formation of a clean cutting surface.

2.3 Automated stages

The first stage is carried out by an industrial robot, and the second by a processing center with numerical program control. If the first stage is not performed qualitatively, then for the final processing in the second stage there may be a lack or excess of metal and the operator will have to correct the program, which will disrupt the construction of the cutting geometry and this will entail problems for further welding.

In the framework package, ASG Robotics intends to develop a package of technological solutions for automation of all the listed stages of production from preparing the cutting to welding. It already has a ready solution for welding automation (Figure 4), this solution does not cover all the needs of the industry, because there are a lot of types of pipe joints. Nevertheless, the positive experience of implementing the technology already exists.

Figure 4. Ready solution for welding automation used by ASG Robotics.

3 Research question. Thesis goal

3.1 The process to be automated

Within the framework of cooperation with the university, ASG Robotics defined the following target production sector for the development of technology, namely: production of supports for offshore oil platforms. An example of such a platform is presented on Figure 5. With close examination, the support looks like it is shown on Figure 6. As seen, there are a lot of corner joints of pipes, welding of which does not lend itself to automation.

Figure 5. Offshore oil platform ASTRA in the Russian sector [1].

Figure 6. Close examination of the support joint on Eureka oil platform [2].

By the welding method, the welding joints are divided into rotary and non-rotary joints. The word "rotary" means that the part can be rotated, and the welding gun can remain in place. This is a very important point in multi-pass welding, because in which case welding can be carried out continuously.

In the case of welding non-turning joints, the part is stationary, and the welding gun must move around the seam. The gun has a wire feeder and a welding current feeder. All this cannot be twisted indefinitely and process should be stopped to return the gun to its original position. Stopping and starting the welding leads to the appearance of a transient process when the welding arc is stabilized, and this leads to potential defects. Nevertheless, that’s how all these joints are welded now.

How to make the non-rotational joints turn into rotary joints? Angle joints of pipes can be welded in the form of a subassembly, i.e. at the welding plant, in workshop conditions, an angular joint is made, consisting of short pipe fragments, while the opposite ends of these pipes are prepared for orbital welding (i.e., in a circle) with the ends of the pipes of the remaining assemblies of the structure.

Total number of welded joints is increasing, but orbital welding is the most common and well-studied technology. This welding method is well amenable to nondestructive testing and can be accepted, including in the field. An example of orbital welding is presented on Figure 7 and an example of the subassembly is presented on Figure 8.

Figure 7. An example of orbital welding [3].

Figure 8. An example of the subassembly [4].

3.2 Goal of this thesis

In the framework of cooperation with the university, ASG Robotics intends to execute a series of student projects in order to develop an integrated technology for the production of marketable products under the name: "Assemblies of the corner joints of steel pipes for the construction of supports of offshore oil platforms." This thesis focuses on developing the technology of automatic gas-oxygen cutting of steel pipe billets in accordance with the specified profile for further use in welding of these subassemblies.

At the beginning this goal was set to a group of TUT students and it was meant to be a group project. But after short amount of time all other students realized that this project is too hard for them and they are not ready for such a complex task. The author of this thesis was the only one who decided to stick with it. But because it is only one person working on that project scale of a task was reduced to make it possible to finish.

The purpose of the project was to develop the technology for launching mass production. As an object of production, it was proposed to produce a connecting branch pipe for the angled connection of steel pipes, with the formation of a cutting for welding, by gas-oxygen cutting. The cutting path is a spatial curve formed by the intersection of the inner surface of the connecting pipe and the outer surface of the main pipe. To construct the cutting path, it is necessary to determine the spatial position and geometry of the workpiece billet in the coordinates of the robot, as well as the position of the main pipe relative to the workpiece of the connecting branch pipe.

The accuracy of the cutting path is determined by the accuracy of measuring the actual spatial position of the workpiece billet. The accuracy of the cut-out, in addition to the accuracy of the cutting path, is also determined by the accuracy of the calibration of the cutting tool. In other words, the final accuracy of the technological operation is determined by the sum of such factors as: accuracy of positioning of the robot, accuracy of measuring the spatial position of the billet of the connecting branch pipe, accuracy of calibration of the cutting tool. The geometry deviations associated with the thermal expansion of the metal are compensated by additional input parameters of the mathematical model of the trajectory cutting based on the analysis of the output statistical data.

In the framework of the project, it was necessary to develop and test in practice the method of calibration of the cutting tool, the method of measuring the actual spatial position of the workpiece, the method of constructing the cutting path, the method of control measurement of the cut-out part, which, incidentally, also has a certain accuracy.

Because of the development of these techniques, the final (expected or claimed) accuracy of the technological process must be formed. To verify the technology and collect statistical data, it is necessary to produce the necessary and sufficient number of connecting pipes to assess the quality of the process in accordance with the method of Sigma. Based on the results of the assessment of the quality of the technological process, it is necessary to identify the factors that have the greatest impact on the accuracy of the process and provide appropriate recommendations for stabilizing these factors.

This would be the result of the group project, but it was reduced to completing the task of calculating the trajectory and cutting without taking the inaccuracies into account. This choice was done because with working piece of software it’s easier to add more additions later. As a result, ASG Robotics OÜ should get working software which they can use in next projects and develop additions which will be focusing on higher accuracy.

3.3 Positioning of the robot

When a workpiece is cut out on a robot, the shape of the part cannot be easily based on subsequent processes, which means that some installation equipment could be used to transfer the technological base to the next process. In practice – a steel plate in the form of an equilateral triangle is cut. At the corners of the plate, the same holes are placed, the centers of which also form an equilateral triangle. On the faceplate of the robot positioner, machining center, assembly conductor and welding station, guide pins are installed, which will enter into these holes. Three points uniquely determine the plane of basing. Thus, this fitting will be fixed on the guide pins in the same way at all stages of the production line.

Then binding of a certain local coordinate system to this installation snap-in is needed. To do this, it is sufficient to establish three identical pins (a cylinder with a cone at the end) at the corners of a right-angled triangle, the vertices of which will denote the origin and direction of the two axes of coordinates lying in the base plane. The third axis of the coordinate system is perpendicular to the reference plane and is applied to the origin.

With the help of these pins, it is possible to define local coordinate systems at all other stages of production. This is the transfer of technological base. To fix the workpiece on the mounting tool, we can place on it a certain expansion, three cams. To meet the needs of production, a certain number of these adjusting rigs are manufactured with periodic monitoring of their geometry in the course of production.

The technological bases for constructing the trajectory of the cut, as well as the trajectory itself, must be defined in the coordinates of the local coordinate system of the rigging.

These data will already be used in the next stages of production. Thus, the data of the process of thermal cutting of blanks determine all the remaining stages of production. This is a big responsibility, which means that we must ensure that the final geometry of the workpiece falls within the specified limits. It is necessary to integrate quality control directly into the process itself.

The positioning itself was taken out when deciding where to reduce the scale of project. It was assumed that positioning of a robot is accurate and not questionable which is not always the case. There is a lot of different challenges with that, for example, the end from which robot grabs a tube can be at an angle, the shape of a tube can be not perfect circle, taper level, etc. This is a part which may be done in another project.

4 Methodology

4.1 Robots

All modern robots are able to work independently. Robots perform the task of moving a working tool in a given coordinate system. In other words, moving the working tool is the essence of the technological process. In case of this thesis, the robot moves the gas-oxygen cutter in accordance with the specified trajectory. The program for the robot is a set of points and interpolation functions when moving from point to point, but the term "task" can be expanded as follows: moving the working tool from the current position to the specified one, in accordance with the specified interpolation function. Interpolation functions:

- Joint. Move to the specified position without controlling the orientation of the tool. The trajectory of the tool movement is obtained proceeding from the principle of equalizing the speeds of the robot drives. This method of moving is used in welding automotive industries. Simply this is the fastest way to move a robot. Used for contact welding, where we are only interested in the final destination.

- Linear. Move from the current point to the specified one in a straight line.

- Circular. Movement from the current point to a given point along the arc through some intermediate point. Just to build an arc, you need 3 points.

Using the interface of manual movement of the robot, the working tool is installed in the target positions through which the trajectory of motion is built. The program is written into the robot's memory and it can repeat this program an infinite number of times.

In practice, robot programs require adaptation to the actual position and geometry of the workpiece. For this, the surface feel function is applied.

An example of the operation of this function: [5]. In this example, the robot detects the position of the part by touching the surface when the electrical circuit closes between the end of the welding wire and the part. At the moment of touch, the robot receives a touch signal and stops. The stop position is recorded and used for further calculations.

The position of the working tool on the robot arm also requires adaptation. Various calibration devices and methods are also used for this. For examples [6] [7].

The principle of operation of the robot can be described approximately like this: moving the relative coordinate system attached to the working tool, relative to the base coordinate system.

The basic coordinate system can be either an absolute (world) coordinate system that is linked to the robot's design, and a local coordinate system that is attached to the installation jig and is described in the absolute coordinate system. In other words, to determine the position of a solid body, you need to attach to it a certain coordinate system whose displacement, in a fixed coordinate system, determines the motion of this solid body. This describes the movement of aircraft, satellites, etc.

4.2 Vectors and quaternions

All the calculations are done using vector arithmetic. Quaternions are used to rotate vectors.

Because robot uses 3-dimensional coordinate system it was very natural to use vectors when calculating the cut trajectory. It was possible to use only quaternions because they have all the properties vectors have, but author together with co-supervisor decided to use vectors because it would be more understandable and convenient. Program code would be more readable as well.

While searching for a solution of the problem of finding trajectory it became obvious that vectors would be needed to rotate. There are two common ways to rotate a vector: using rotation matrixes or using quaternion rotation. There are some other rotating methods, but most of them are worse when it comes to rotating multiple vectors at once. For this project quaternions were chosen for vector rotation. When using matrixes for vector rotation there is a problem named gimbal lock. Gimbal lock occurs when two axes in a three-gimbal system align. When that happens, the object's movement is limited. An entire range of motion becomes impossible [4]. Because we always do a full circle it was certain that gimbal lock would appear and it would take extra time to go around it. For that reason, quaternions were chosen for vector rotation.

During development results were controlled using 3D modelling software and Roboguide.

4.3 Python, KAREL and ROBOGUIDE

For this project Python programming language was used. Python is programming language often used for scientific researches, it is easy to both write and read. It is a good choice for project like that because Python makes it easier to focus on mathematical functions not on programming challenges which problem brings.

KAREL is a lower-level language very similar to Pascal used by FANUC robots. Thesis' co-supervisor has a manual which was used to write KAREL programs.

Programs in robot's memory and Python programs communicate through TCP/IP.

ROBOGUIDE is a FANUC Simulation Software and System Animation Tool specifically developed for the production and maintenance of FANUC robot systems [5].

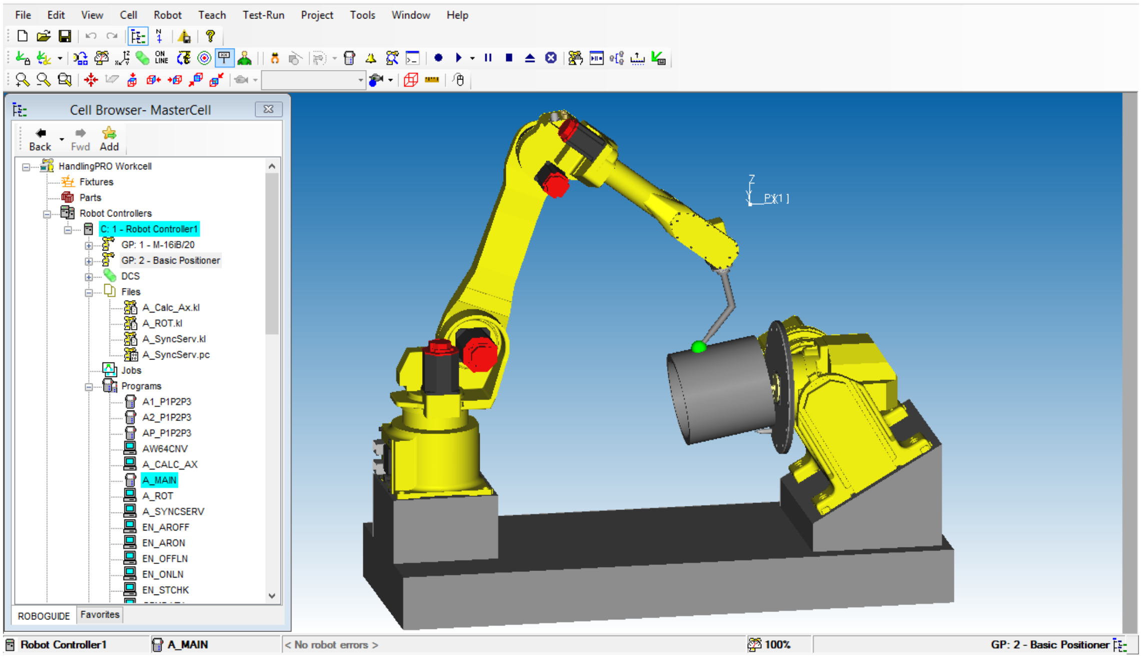

Figure 9. An example of ROBOGUIDE interface.

5 Realization

5.1 Input data

When starting to work on a solution for a problem the first thing which should be done is deciding what information is needed for a program to calculate proper trajectory. The decision was based on a goal of making as flexible system as possible which would not have hard-coded sections in it.

First of all, coordinates of a tube to be cut are needed. A tube is two cylinders with the bases in the same plane and common center of its' bases. For the representation of a tube, the coordinates of the center of the base and the direction of the normal vector to the plane of the base is needed. They are named **VA1** and **Va1** respectively. V means vector, capital A means it's a point, not a vector (radius-vector), small a means it's a vector, not a point, and number 1 means it's the first tube (first is smaller one which will be welded to a bigger one, which is numbered 2).

Both radiuses of the first tube and outer radius of the second tube are needed. Because first tube will be welded to the second one form outside, inner radius of the second tube isn't needed. The inner radius of the first tube and the outer radius of the second tube is needed to calculate the initial intersection trajectory. The outer radius of the first tube is needed to calculate the angle of a cutter and for distance at which cutter will be moving around trajectory. **sr1**, **sR1** and **sR2** are inner radius of the first tube, outer radius of the first tube and outer radius of the second tube respectively. s means it's a scalar, r and R are inner and outer radiuses respectively.

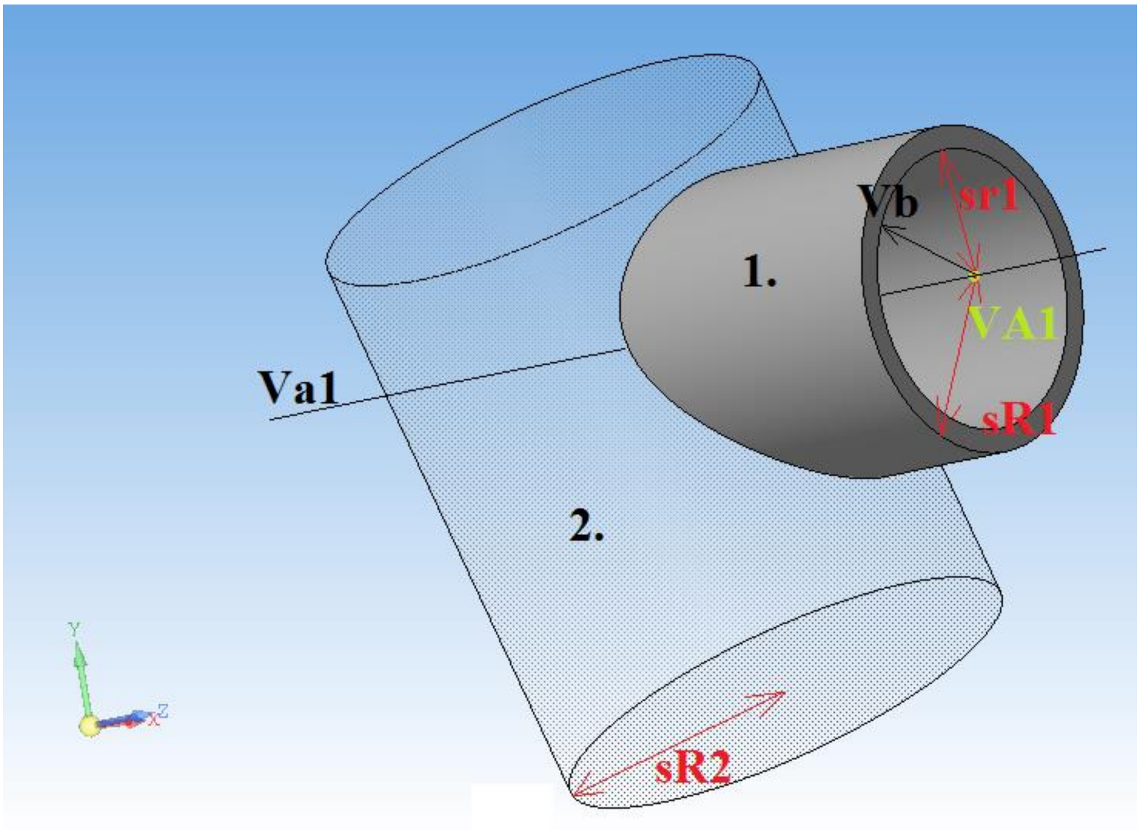

Figure 10. A visualisation of a joint.

To be able to choose where to start cutting from vector **Vb** is used.

Parameter **sa** represents the angle under which first tube will be welded to the second tube.

Parameter **sd** and **sc** represent the distance between VA1 and the axis of the second tube and the offset of two axes respectively – standard deviation.

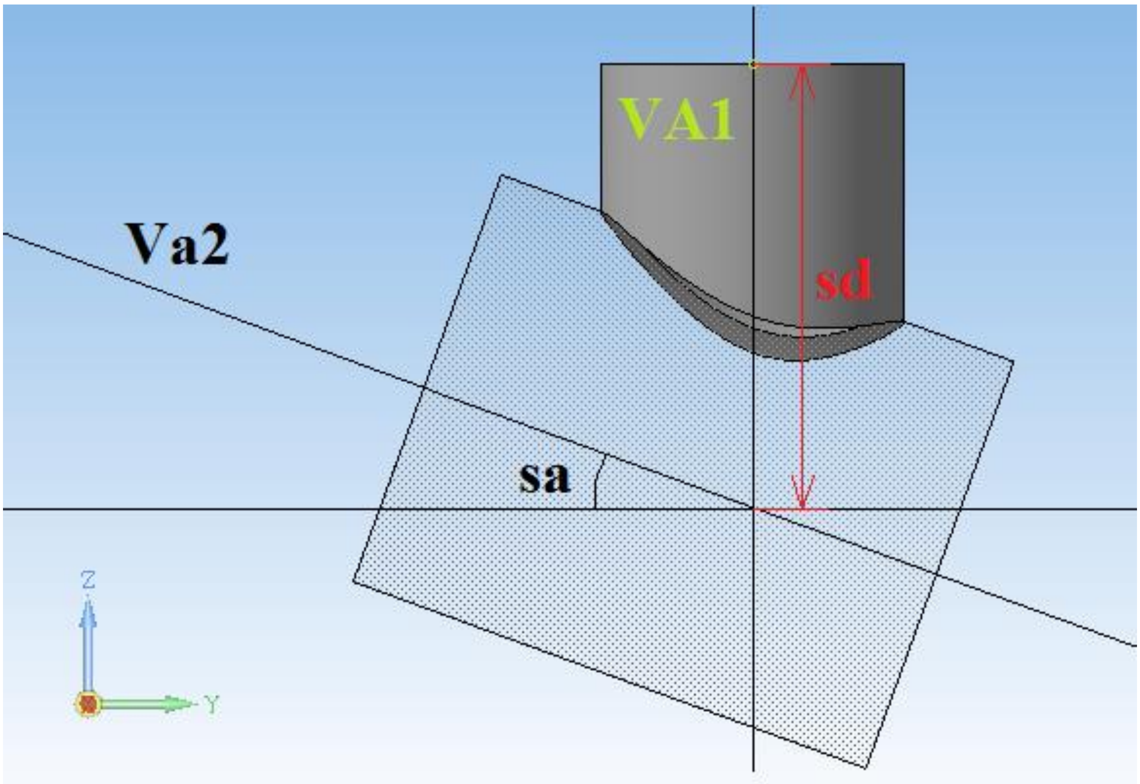

Figure 11. Side view with angle and distance shown.

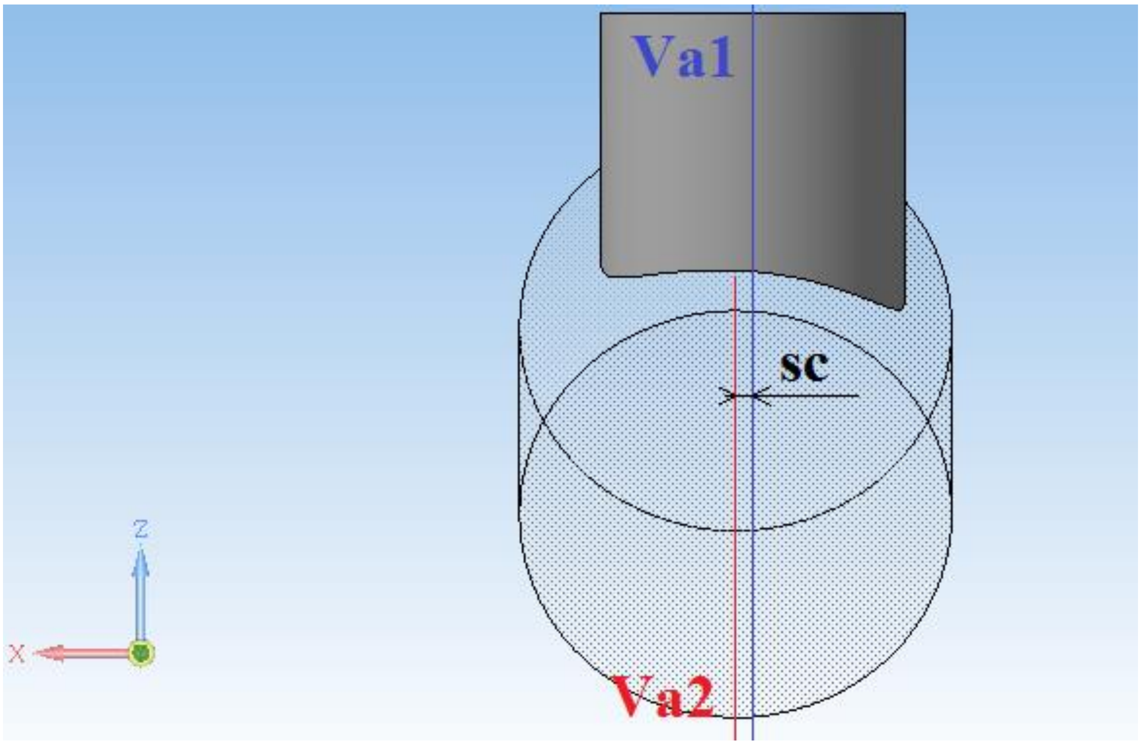

Figure 12. Front view with standard deviation shown.

For later welding process it's important that cross-sectional area of intersection – cross-area – is constant. Cross-area is calculated using three points. First one is intersection of inner radius of the first tube with outer radius of the second tube. Second point is intersection of outer radius plus enforcement **se** of the first tube with outer radius of the second tube. Third point should be calculated using area, it should be located on outer radius of the first tube. The area **S** is formed by these three points, but only between first and second points is not a line, but a curve formed by outer wall of the second tube (dS is filled area between line and curve, it's introduced and explained below).

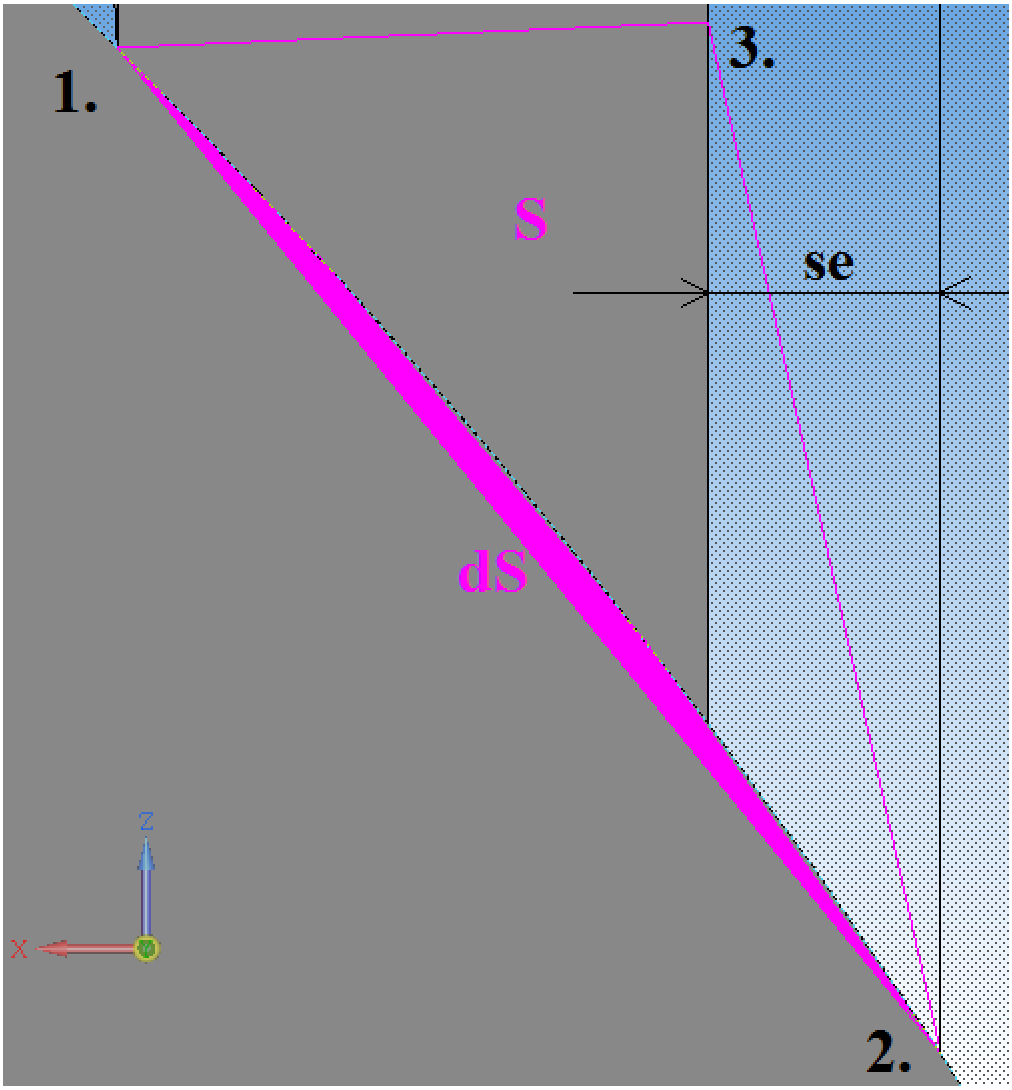

Figure 13. Cross-area with se and S shown.

Since robot's cutter can't go 360 degrees around tube without stopping, positioner holding the tube will rotate while cutter changes its' angle. Since tube's axis and positioner's axis in most of cases are not equal positioner's center point and normal vector are needed - **VS** and **Vs** respectively.

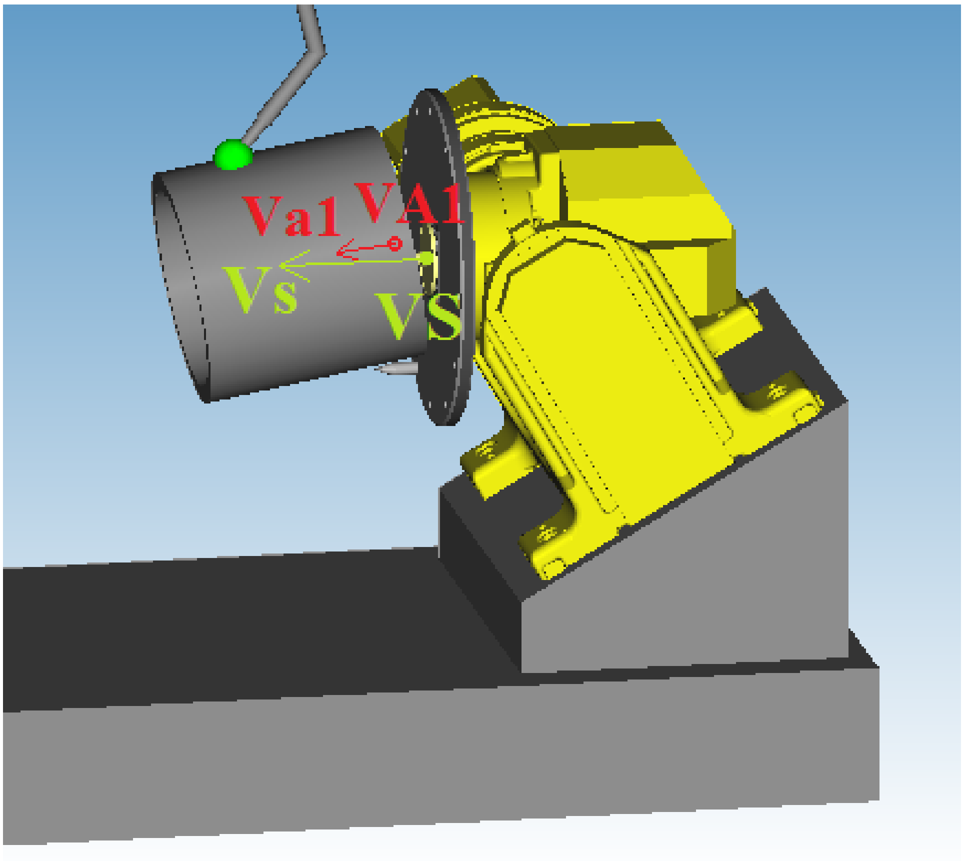

Figure 14. Positioner with VS and Vs shown.

A couple of programs' inside parameters are introduced later.

5.2 Project structure

Project consist of 3 KAREL programs A_Calc_Ax.kl, A_ROT.kl and A_SyncServ.kl, 3 Python programs Utils.py, tubesCollision.py and SocketPart.py and 4 FANUC robots' control programs A1_P1P2P3, A2_P1P2P3, AP_P1P2P3 and A_MAIN. To start the process of trajectory calculation and profile cutting both A_MAIN and tubesCollision.py should be started.

Firstly, A_MAIN uses A1_P1P2P3, A2_P1P2P3 and AP_P1P2P3 to get coordinates of positioners' joints at different angles. Using these coordinates and A_Calc_Ax.kl and A_ROT.kl it calculates relative position and axles of tube and positioners' joints. Then A_MAIN starts A_SyncServ.kl in parallel thread and tubesCollision.py starts SocketPart.py which connect with each other using TCP. After connecting A_SyncServ.kl sends Va1, VA1, Vs, VS to SocketPart.py. After receiving the data tubesCollision.py calculates the trajectory of a cut and writes it into text file. Then

SocketPart.py sends coordinates to A_SyncServ.kl and A_MAIN manipulates the robot so it cuts the tube in desired profile.

5.3 Trajectory calculations

Figures are used for visualization purposes, 3D model was used during development only to verify the results of different steps of calculations. Calculation of searched trajectory is a multi-step task and requires different algorithms.

In calculations:

$$u(V) = \frac{V}{abs(V)} \text{ (u means unit vector)}$$
$$abs(V) = \sqrt{V.x^2 + V.y^2 + V.z^2}$$

Since axis of the second tube is not an input parameter, it should be calculated:

$$uVc = u\big(u(Vb) \times u(Va1)\big)$$
$$VA2 = VA1 + sd * u(Va1) + sc * uVc$$
$$qc = Quaternion\left(\cos\frac{sa}{2}, uVc * \sin\frac{sa}{2}\right)$$
$$qcr = Quaternion\left(\cos\frac{sa}{2}, -uVc * \sin\frac{sa}{2}\right)$$
$$uVa2 = qc * (u(Va1) \times uVc) * qcr$$

A trajectory of a place where two tubes intersect with each other needs to be calculated. The trajectory is an intersection of inner radius of the first tube and outer radius of the second tube (p means projection):

$$uVa1p = uVa2 \times u(Va1) \times uVa2$$
$$Vr1 = u(Va1) \times uVc * sr1$$
$$Vr1p = uVa2 \times Vr1 \times uVa2$$
$$Vr1pp = u(uVa1p) \times Vr1p \times u(uVa1p)$$
$$VR2 = (Vr1pp - uVc * sc) - \left(u(uVa1p) * \sqrt{sR2^2 - abs(uVc * sc - Vr1pp)^2}\right)$$
$$ka1 = \frac{abs(VR2 - Vr1p - uVa2 \times (VA1 - VA2) \times uVa2)}{abs(uVa1p)}$$
$$P = VA1 + uVa1 * ka1 + Vr1$$

Now P is just one dot on intersection of two tubes. To find trajectory vector Vr1 needs to be rotated on a small angle **sRot** using the same algorithm. Repeating it until full circle is done.

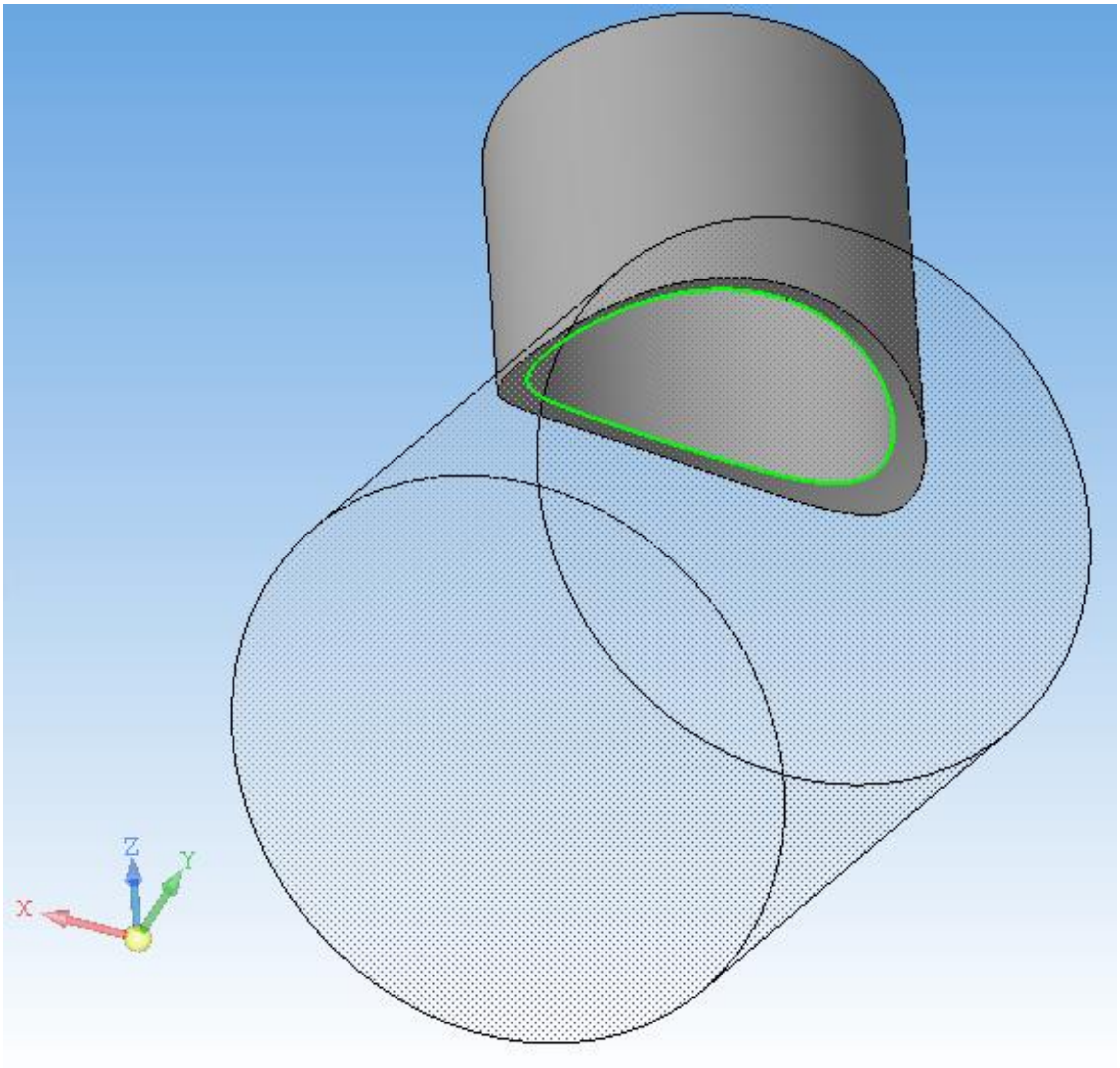

Figure 1. Initial intersection trajectory.

Then using the same algorithm (changing only sr1 to (sR1 + se) in equation 9) with a larger radius the trajectory of enforcement is calculated. The radius used is outer radius of the first tube plus enforcement which is an input parameter.

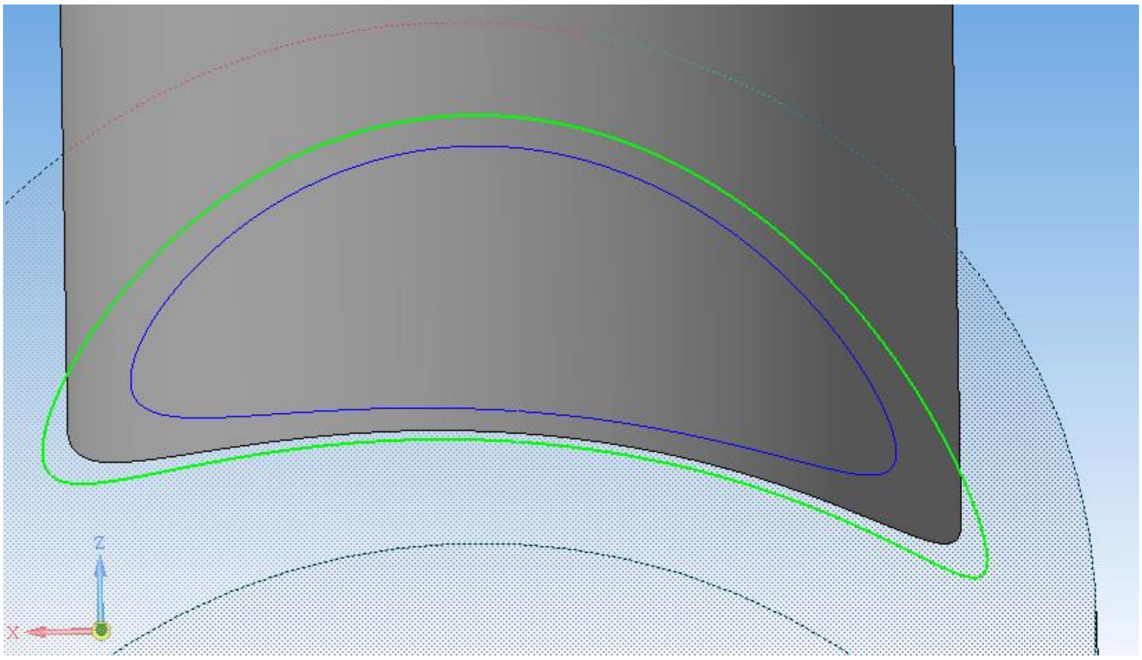

Figure 2. Enforcement trajectory.

When cutting a tube for future welding there should be enough space for a welding machine. Purpose of this project is to automate cutting process in a way that all next steps of tube welding can be automated as well. Because of that area of a triangle between three points must be constant so amount of metal applied in welding process will be constant as well. Since at the bottom of a triangle there is not a line, but a curve integrational function had to be used.

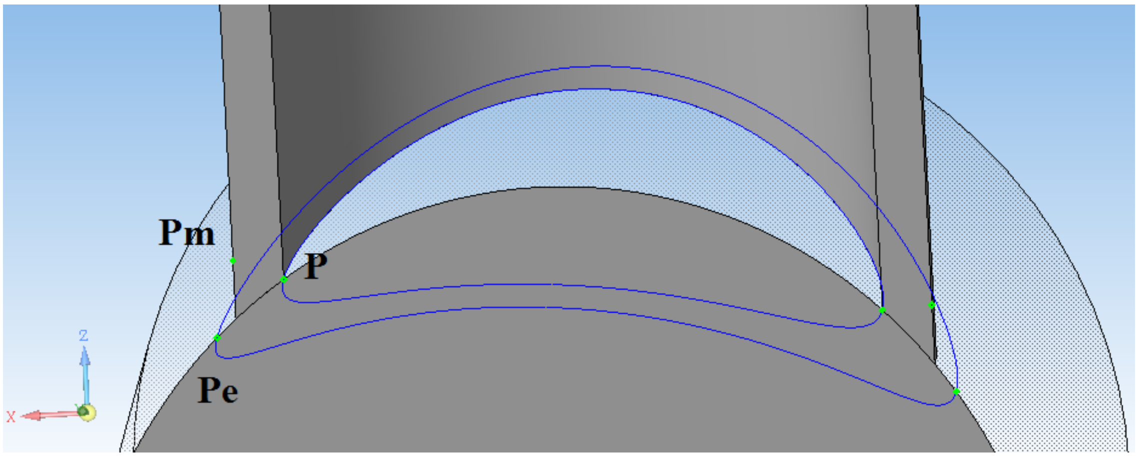

Figure 3. Cross-area with dots creating triangle.

The integration function involves some programming elements as well. PList is a list of dots which mark the trajectory of the curve between P and Pe. dS is space between the line and the curve between P and Pe. Trapezoid rule is used for approximating the integral:

$$VP = P - Pe$$

$$H = u(VP) \times (PList[0] - P) \times u(VP)$$

$$dVP = abs\big((PList[0] - P) * u(VP)\big)$$

$$dS = \frac{abs(H) * dVP}{2}$$

for dPi in range(1, len(PList)):

$$dVP = abs\big((PList[dPi] - PList[dPi - 1]) * u(VP)\big)$$

$$H2 = u(VP) \times (PList[dPi] - P) \times u(VP)$$

$$dS{+}{=} \frac{abs(H) + abs(H2)}{2} * dVP$$

$$H = H2$$

There is the end of the for loop.

$$dVP = abs\big((Pe - PList[-1]) * H\big)$$

$$dS{+}{=} \frac{abs(H) * dVP}{2}$$

Now having cross-area dS position of dot Pm can be calculated:

$$Pl1 = \frac{u(Pe - P) * (sR1 - sr1)}{abs\big(uVa1 \times u(Pe - P)\big)} + P$$

$$m = \frac{2 * (S + dS)}{abs\Big((P - Pl1) \times \big(-u(Va1)\big)\Big) + abs\big(-u(Va1) \times (Pe - Pl1)\big)}$$

$$Pm = Pl1 - m * u(Va1)$$

From these dots new trajectory can be found around the first tube.

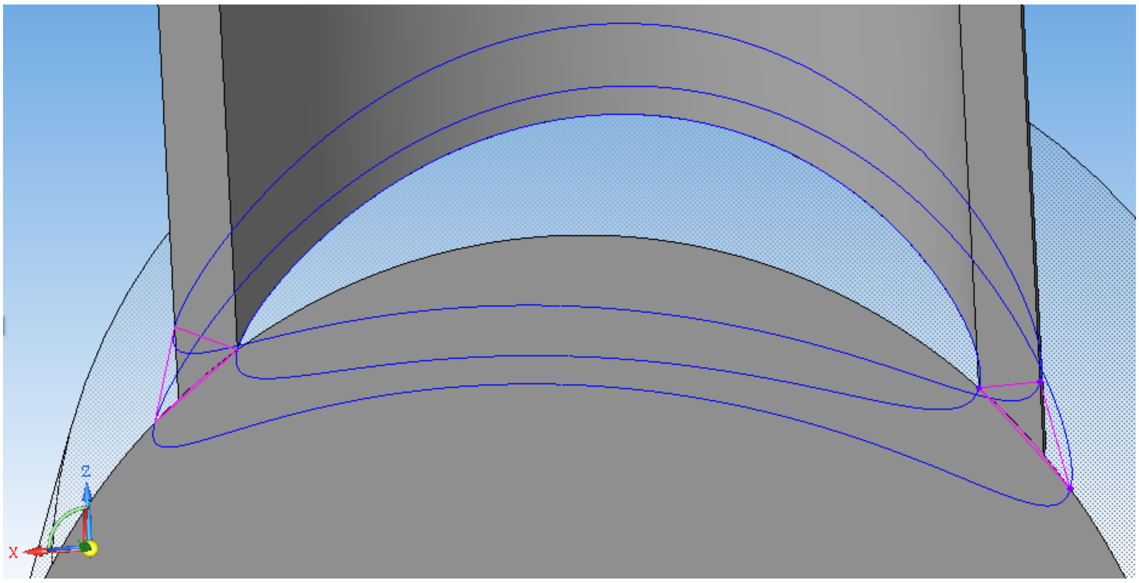

Figure 4. All three trajectories with constant cross-area between them.

Now all is needed are two trajectories on the first tube.

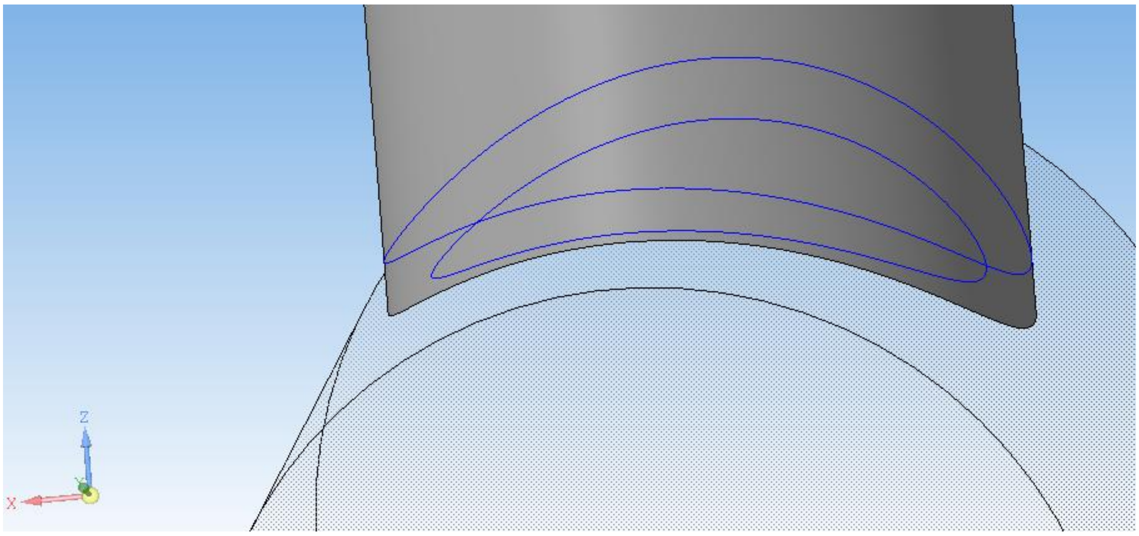

Figure 5. Two trajectories used in cutting trajectory and tool orientation calculation.

The cutting line should be exactly between these two trajectories. Outer trajectory shows where cutting tool should be directed and inner trajectory determines at what angle the cut must be done. Parameter smm is the distance between cutting tool and outer trajectory. (tf means tool frame).

$$Ptf = Pm + u(Pm - P) * smm$$

When moving robot there is not only the point it needs to move to, but also rotation of its' coordinate axes. There are a couple of ways to represent this rotation. The first one, which can be easily found using vectors, are actual vectors of rotated coordinate system. In robot z-axis is the direction where tool is pointing. Y-axis and x-axis can be chosen freely, but they must be persistent not to rotate tool around. For y-axis tangent of trajectory is used.

$$Ztf = u(Pm - P)$$
$$Ytf = u\big(u(Pe - P) \times u(Pm - P)\big)$$
$$Xtf = Ytf \times Ztf$$

To describe the orientation of the tool frame FANUC robots are using Euler angles with z-y-x sequence – it means the first rotation is about the z-axis by the amount Θ_1, the second is about the y'-axis (which is the position of axis after first rotation) by the amount Θ_2 and the third rotation is about the x''-axis (which is the position of axis after two rotations) by the amount Θ_3.
For transformation of given coordinate system into Euler's angles [6] is used.

$$\Theta_1 = \mathrm{atan2}(\mathrm{Xtf.y}, \mathrm{Xtf.x})$$
$$\Theta_2 = atan2\left(-Xtf.z, \sqrt{1 - Xtf.z^2}\right)$$
$$\Theta_3 = atan2(Ytf.z, Ztf.z)$$

This coordinate system is good if tool frame is moving around tube, but since rotation of tube is done by the positioner and cutting tool only changes angle this coordinate system should be rotated backwards around positioner axis.

$$q_1 = \sin\left(\frac{\Theta_1}{2}\right) * \sin\left(\frac{\Theta_2}{2}\right) * \sin\left(\frac{\Theta_3}{2}\right) + \cos\left(\frac{\Theta_1}{2}\right) * \cos\left(\frac{\Theta_2}{2}\right) * \cos\left(\frac{\Theta_3}{2}\right)$$
$$\mathrm{q}_2 = -\sin\left(\frac{\Theta_1}{2}\right) * \sin\left(\frac{\Theta_2}{2}\right) * \cos\left(\frac{\Theta_3}{2}\right) + \cos\left(\frac{\Theta_1}{2}\right) * \cos\left(\frac{\Theta_2}{2}\right) * \sin\left(\frac{\Theta_3}{2}\right)$$
$$\mathrm{q}_3 = \sin\left(\frac{\Theta_1}{2}\right) * \cos\left(\frac{\Theta_2}{2}\right) * \sin\left(\frac{\Theta_3}{2}\right) + \cos\left(\frac{\Theta_1}{2}\right) * \sin\left(\frac{\Theta_2}{2}\right) * \cos\left(\frac{\Theta_3}{2}\right)$$
$$\mathrm{q}_4 = \sin\left(\frac{\Theta_1}{2}\right) * \cos\left(\frac{\Theta_2}{2}\right) * \cos\left(\frac{\Theta_3}{2}\right) - \cos\left(\frac{\Theta_1}{2}\right) * \sin\left(\frac{\Theta_2}{2}\right) * \sin\left(\frac{\Theta_3}{2}\right)$$
$$qpax = Quaternion\left(\cos\left(\frac{nowAt}{2}\right), \sin\left(\frac{nowAt}{2}\right) * u(Vs)\right)$$
$$qpaxr = Quaternion\left(\cos\left(\frac{nowAt}{2}\right), -\sin\left(\frac{nowAt}{2}\right) * u(Vs)\right)$$
$$Ptf' = qpax * (Ptf - VS) * qpaxr + VS$$

$$q = qpax * Quaternion(q1, q2, q3, q4)$$

Then again it should be converted to Euler's angles. Since in [6] Euler angles are calculated from matrix, quaternion must be mapped to the rotation matrix using method from [7].

$$\Theta_1' = atan2((2 * q.i * q.j + 2 * q.dot * q.k), 1 - 2 * q.j^2 - 2 * q.k^2$$
$$\Theta_2' = atan2((2 * q.i * q.dot - 2 * q.i * q.k), (\sqrt{1 - (2 * q.j * q.dot - 2 * q.i * q.k)^2}$$
$$\Theta_3' = atan2((2 * q.j * q.k + 2 * q.i * q.dot), (1 - 2 * q.i^2 - 2 * q.j^2))$$

6 Summary

The goal of this thesis was to create a program which can be used to automate the process of creating a profile of a tube to be welded to another tube. The trajectory to be traversed is a complex 3-dimensional curve. Research question was to calculate needed trajectory and send it to a robot to traverse it. Thesis' author was approached with this task by ASG Robotics OÜ.

The problem was solved using vector arithmetic, rotation quaternions, integrational functions and Euler's angles. The result of the solution is the working programs in Python and FANUC robot's programming language KAREL which work together solving the problem.

The result of this work is only a part of what should be done to actually start cutting profiles automatically. This thesis' result is a mathematical model which works in ideal world, in simulation. In reality, there are more challenges to be solved. One challenge comes from defining the position a tube in robot's coordinate system. Another one comes from deviation in shape and distortions in dimensions in tube itself like ovality, taper, surface roughness, content of alloying components, etc. And the final one comes from controlling speed of cutting and considering thermal expansion of the tube. All of this should be done to achieve the desired result, but this thesis made a core for a future system, it's a place to start. ASG Robotics in collaboration with TUT are planning to continue development of this system in next few years.

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