


Zagazig University, Faculty of Engineering,
Mechatronics Program

ZuKa

Deployment of industrial KUKA robot in CNC machining and visual servoing through Kinect interfacing on ROS

Graduation project for the degree Bachelor of Science (B.Sc.) submitted to Mechatronics Program, Faculty of Engineering, Zagazig University, Egypt

by

Ahmed Emam
Ahmed Saeed
Donna Mustafa
Dua'a Samir
Hoda Mahmoud
Reeham Mohamed

Supervisors

Asoc. Prof. Dr.
Ahmed Hamdy Hassanien
Mechanical Engineering Dept.

Asst. Prof. Dr.Ing.
Mohammed Nour A. Ahmed
Computer and Systems Engineering Dept.

Faculty of Engineering, Zagazig University, Zagazig, Egypt

July, 2017

Graduation Project Report submitted to
Zagazig University, faculty of Engineering, Mechatronics Program, Zagazig, Egypt
in partial fulfillment of the requirements for the degree
Bachelor of Science in Engineering (**B.Sc.**)
©2017

Date of Presentation
16. July 2017

Project Team Memebers

Ahmed Emam	Ahmed Saeed
Donna Mustafa	Dua'a Samir
Hoda Mahmoud	Reeham Mohamed

Supervisors

Asoc. Prof. Dr. **Ahmed Hamdy Hassanien**
Mechanical Engineering Department,
Faculty of Engineering, Zagazig University, Egypt
Asst. Prof. Dr.Ing. **Mohammed Nour A. Ahmed**
Computer and Systems Engineering Department,
Faculty of Engineering, Zagazig University, Egypt

Defense Commete

Prof. Dr. **Nabil H. Mostafa** ..... signature
Mechanical Engineering Dept., Faculty of Engineering, Zagazig University

Asoc. Prof. Dr. **Mohamed Talat** ..... signature
Electric Power Engineering Dept., Faculty of Engineering, Zagazig University

Asst. Prof. Dr.Ing. **Mohammed Nour A. Ahmed** ..... signature
Computer and Systems Engineering Dept., Faculty of Engineering, Zagazig University

Asoc. Prof. Dr. **Ahmed Hamdy Hassanien** ..... signature
Mechanical Engineering Dept., Faculty of Engineering, Zagazig University

Revision SVN.198.50.20170713

In memory of **Ahmed Emam**

Abstract

The first industrial revolution marked the transition to new manufacturing processes in eighteenth century, which is arguably similar to the transition introduced by the use of robotic manipulators in different industrial aspects in the late twentieth century. This project is motivated by the major developments in the industrial sector thanks to robots, especially in machining processes. Robots offer more flexibility, cost reduction and higher level of details, all of which are essential characteristics to any successful industry. Although these characteristics can be obtained by conventional CNC machines, however, the level and rate of production differ on larger scales, in favor of the robots.

The main problem can be summarized in Four points; accuracy, ease of use, flexibility and safety, and the solution to these problems defines the scope of our project. As for accuracy, it is obtained by implementing the robot itself, which offers multiple-axes movement, enabling the possibility for higher level of details than the conventional CNC machines. Ease of use is demonstrated in the user-friendly robot interface that enables the implementation of projects easily and without the need to multiple machines or tasks to deliver the final results. Flexibility is provided through the multiple programmable interfaces that offer multiple methods of control; Inline programming through KUKA's smartPAD, offline programming through converting G-codes from CAD files into KRL and ROS. Safety is increased in the work space of the robot by introducing a vision based safety system that reduces the robot's operating speed when someone enters this work space.

The results of the aforementioned methods and applications are diverse, offering milling in multiple dimensions and thus widening the scope of final products. In addition to introducing further control methods, which opens up new doors towards further developments and applications that were not applicable earlier.

Acknowledgements

We would like to express our deepest appreciation to all those who provided us the possibility to complete this project, most importantly, our deepest gratitude goes to KUKA AG, as without their Robots, our project would have never seen the light .

A special gratitude goes to our final year project supervisors, Prof. Ahmed Hamdy and prof. Mohamed Nour Abdelgawad, whose contributions in stimulating suggestions and encouragement, helped us to coordinate our project, especially in writing this report.

Furthermore I would also like to acknowledge with much appreciation the crucial role of the staff of Zagazig university's Mechanical Engineering department, who gave the permission to use all required equipment and the necessary materials to complete our project. We appreciate the guidance given by the supervisors as well as the panels especially in our project presentation that has improved our presentation skills thanks to their comment and advices.

This work was partially funded by Zagazig University. We would like to thank the funders. They had no role in study design, data collection and analysis, decision to publish, or preparation of this work.

Contents

List of Figures

List of Tables

List of Algorithms

"There is nothing more difficult to take in hand, more perilous to conduct or more uncertain in its success than to take the lead in the introduction of a new order of things."

— Niccolo Machiavelli, (Italian writer and statesman, Florentine patriot, author of 'The Prince', 1469-1527)

Chapter 1
Introduction

Industrial robots are reshaping the present and future of most, and very soon all, industrial aspects. They are currently used in a broad spectrum of industries, some of which include car parts assembly as in BMW and Mercedes factories, industrial automation as in Yaskawa factories, metal industries that include welding and machining processes and many others. While there is a controversial part in replacing humans with robots in factories, it, nevertheless, offers more accuracy and higher production rate with more space for development. The growth of the Global Industrial Robotics Market is driven by many factors, of which the need to reduce manufacturing cost in industries is one of the main drivers. Industrial robotics aids companies in reducing the cost due to product failure and product wastage.

Some of the pioneering companies in the Industrial robotics market are ABB Ltd., Fanuc Corp., Yaskawa Electric Corp., Apex Automation and Robotics, Mistubishi Electric Corp. and KUKA AG. We had the opportunity to work with the latter, KUKA AG, on the implementation of our project (*ZuKa: Deployment of the industrial KUKA robotic manipulator in CNC machining and visual servoing through Kinect interfacing on ROS*). Over the course of our final year, this project helped increase our knowledge, not only on the main topic, milling and visual servoing, but also on the KUKA platform itself, which is considered an advanced platform widely used in today's industries.

The milling process witnessed vast development since the early milling machines, known as mills, followed by CNC milling machines and all the way to milling robots. The latter, represented in KUKA robots in our project, can be compared to CNC machines in terms of introducing a computer-based control method, however, milling robots offers more advantages than the conventional CNC machines. One of these advantages is flexibility, because as the needs of manufacturing evolve; robots are proving to be nimble adjusters.

In addition to robots' ability to perform several tasks; by adding the desired end effector

Figure 1.1.: KUKA KR6 R900 sixx robotic manipulator

and designing the corresponding programming tool, they offer more variations of one task offered by a conventional machine. To verify this we can compare CNC milling machines and milling robots. CNC machines offer two-dimensional milling operations, moving either horizontally or vertically with fixed workpiece, resulting in a defined scope of products and processes. Milling robots on the other hand, are able to perform milling in up to five axes, providing rotation and movement in multiple directions. This flexibility can further be improved by providing a movable workpiece fixation, increasing the motion axes to nine.

Milling robots offer ease of use through programming, flexibility, speed, precision, cost reduction, repeatability and some of these robots even offer different mounting choices, as they could be mounted on ceilings and walls not just floors. All of this contributed to the current status of milling operations; in terms of final finishing, level of details obtained, rate of production and future possibilities for development.

The project is inspired by the aforementioned development in the industrial sector. The scope of the project can be summarized in the following three points; firstly,

the commissioning and operation of the KUKA KR6 R900 sixx robotic manipulator, which included the installation of the related software and creating a network that facilitates communications with the robot. In addition to software commissioning, hands-on experience with the KUKA robot language (KRL) platform was achieved through learning the basic and advanced forms of KRL, which later helped in the development of software tools that facilitates the main objective of the project; the milling process.

Secondly, the design and manufacturing of a base to support the robot during heavy duty operation, this included performing mathematical calculations based on the robot's weight and forces to obtain the optimal dimensions and weight for the base, besides performing CAD studies on the manipulator's body to support the results of the mathematical analysis.

Finally, the development of various software tools to achieve the purposes of remotely controlling the robot and milling. These tools include an Inkscape extension for converting 2D G-code to KRL, directly using sketches from Inkscape, an independent toolkit for converting 3 axis G-code to KRL. In addition to Python tools; one Python class for reading and writing system variables, and a Python library for controlling the arm motions from pc. The development also included editing openni_tracker for publishing uncalibrated person's depth and creating ROS nodes for safety operation distance and visual servoing (hand guiding) for the robot.

Initially, the project scope was limited to the milling process in addition to minor ideas in the smart development of the workspace, however, over the course of the semester we encountered many problems that required extended research in all the previously mentioned aspects, which eventually led to broadening the scope of the project to include these development tools, both relevant and irrelevant to milling.

1.1. Project Contributions

The results of the project studies and implementation include, but not limited to;

- The manufacturing of the robot's base, with mathematically calculated data endorsed by CAD studies, contributing in a stable, secure and robust base that can support the weight of the robot and tolerate the forces resulting from the robot's motion without major failure or errors.
- The attachment and operation of a pneumatic gripper, leading to the development and implementation of software tools for drawing and palletizing.
- The development of different software tools to obtain the appropriate KRL codes used in the milling process.
- The development of a safety system in the robot's workspace, similar to KUKA AG's own Collision detection, which stops thee robot from moving when it hits a

solid surface. However, being more efficient and safe, in terms that it does not require actual contact or collision but significantly reduced the operation speed of the robot when someone enters a defined perimeter of the robot's workspace. This is achieved using a Microsoft Kinect device for obtaining visual input of the workspace.

The results of the work exceeded both the preset expectations and goals for the project, resulting in a wide variety of applications and an extension in our own knowledge base, which is the most important achievement.

1.2. References

1. http://www.mmsonline.com/articles/a-new-milling-101-what-milling-is-then-and-now-plus-a-glossary-of-milling-terms
2. http://www.sickinsight-online.com/safety-and-more-sick-provides-protection-and-navigation-data-for-kukas-kmr-iiwa/
3. http://medicaldesign.com/contract-manufacturing/modern-cnc-machining-prescription-product-development
4. http://articles.sae.org/11272/
5. https://en.wikipedia.org/wiki/Multiaxis_machining
6. https://en.wikipedia.org/wiki/Milling_(machining)

"It is impossible for us, who live in the latter ages of the world, to make observations in criticism, morality, or in any art or science, which have not been touched upon by others. We have little else left us but to represent the common sense of mankind in more strong, more beautiful, or more uncommon lights."

— Joseph Addison, (English essayist, poet, and politician, 1672–1719), Spectator, No. 253

Chapter 2
CAD Analysis Approach

For the purpose of our study, SolidWorks was used as a CAD software, as it contains solid modelling, Motion studies, Simulation PhotoView 360, e-drawing and many other features that were used to obtain a complete CAD model for KR6 r900 sixx KUKA arm. In Simulation and Analysis, you can test your designed product in real environment.In simulation process the model can be tested against parameters like static and dynamic response, fluid dynamic, heat transfer. It also supports thermal, fatigue, structural and motion analysis.
In our project, SolidWorks is used to obtain a CAD model for KR6 r900 sixx and to perform a motion analysis study on the model. In addition to designing a base to fix the robot arm, perform a stress analysis and creating an animation video of the model's motion.

2.0.1. Complete CAD model

2.0.1.1. Searching for a suitable model

All CAD models for KR6 r900 sixx on KUKA website or GrabCAD were step imported parts which are treated as a one body where joints can't rotate therefore, motion study can't be performed because it was impossible to add motors at the robot joints. The solution for this issue was obtained by converting step parts into assembly, which is done through several steps:

- Open the .stp file part in SOLIDWORKS. Select the file type to be .stp
- Click the OPTIONS tab, select Import multiple bodies as parts and click OK.
- Then click Open.

SolidWorks will create an assembly and create an individual part file for each multibody (Part1,Part2,Part3 etc.)

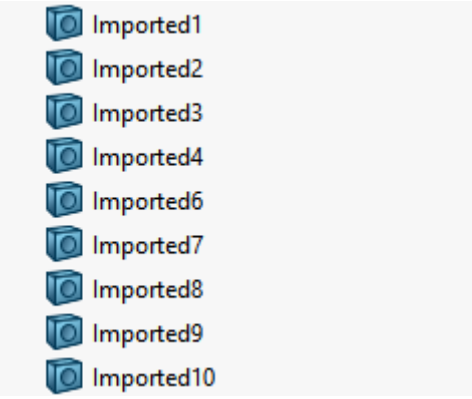


Figure 2.1.: Step parts

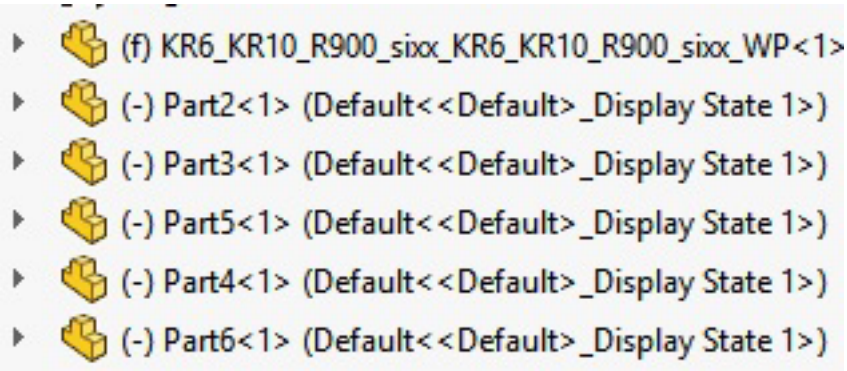


Figure 2.2.: SolidWorks parts

2.0.1.2. Modifications on CAD model

Material and weights The robot material wasn't specified and the model was a whole body, and the total mass for the robot was 33.74 Kg, which was not accurate, because the actual mass of the robot, according to the KR6 R900 sixx dimensions manual, must be approximately equal to 52Kg. This is achieved by making the model hollow, using the shell feature and adding to joins point masses similar to the real motors with mass approximate equal to motors masses.

Spindle In order to have a complete model for our graduation project, a router spindle and its holder were sketched to complete the existing KUKA model.

Figure 2.3.: KUKA motors

2.0.2. Motion studies

Motion studies are graphical simulations of motion for assembly models. They simulate and animate the prescribed motion for a model. SolidWorks offer three different types of motion study, Animation, Basic Motion and Motion Analysis. They also offer mate controller that show, save the positions of assembly components at various mate values and degrees of freedom and create simple animations between those positions.

Animation can be used to animate the motion of assembly. If you simply wish to create some nice visuals for presentation or marketing without consideration of mass and gravity effects, then animation is for you.

Basic Motion is an extra layer of complexity that takes into consideration the effects of mass, motors, springs, contact, and gravity on assemblies.

Motion Analysis is the top tier of motion study provides accurately simulation and analyze the motion of an assembly while incorporating the effects of Motion Study

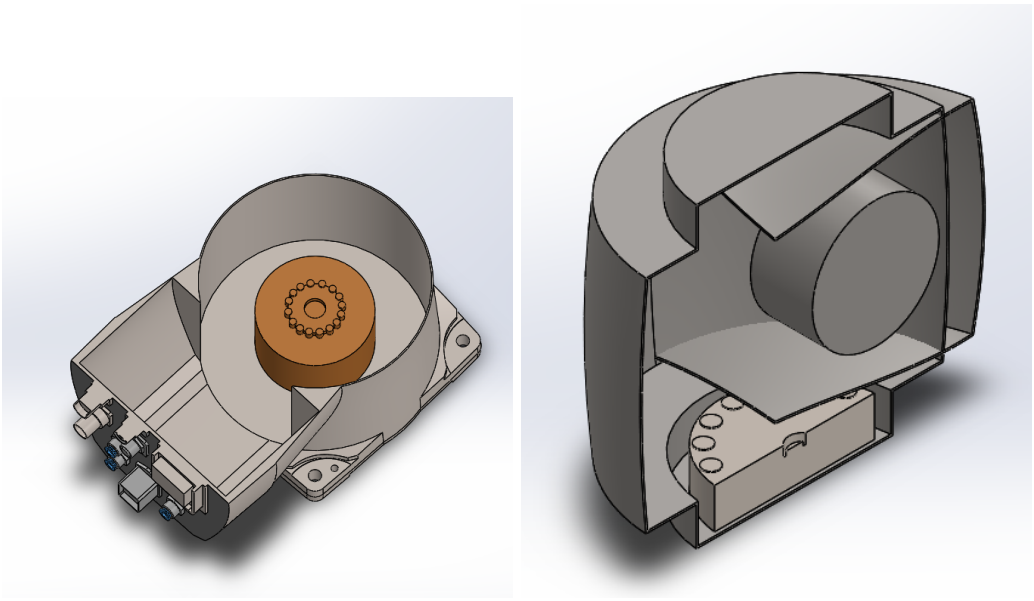


Figure 2.4.: Motors 1,2 and 3 , 4,5 and 6 models

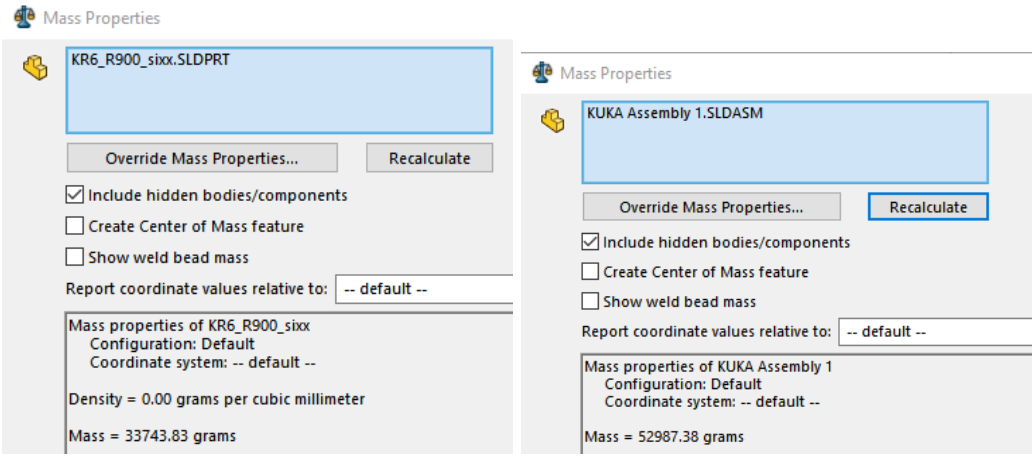


Figure 2.5.: The model mass: Old mass and final mass

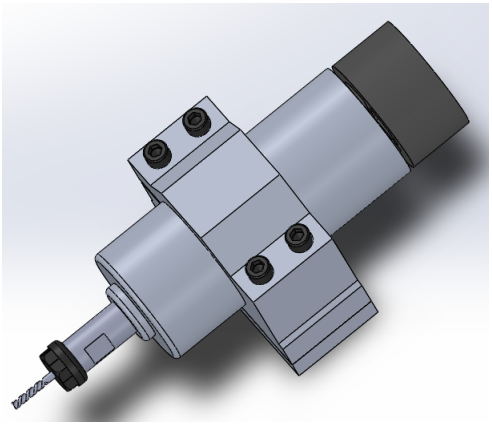


Figure 2.6.: Spindle model

elements (including forces, springs, dampers, and friction). Motion Analysis can also be used to plot simulation results for further analysis.

Therefore, Motion Analysis is used to simulate the model, generating results and plots of the simulation and Animation is used to make a video for motion.

2.0.2.1. Animation study

Animation study is done to make an animation video of the moving parts with the use of limit mates. Limit angle mate is an advanced mate type that is performed by selecting two planes which rotate with respect to each other giving the desired range to mate and input a maximum and minimum value for the angle to specify the desired range of motion. Another advantage of limit angle is that it prevent collision between the moving parts.

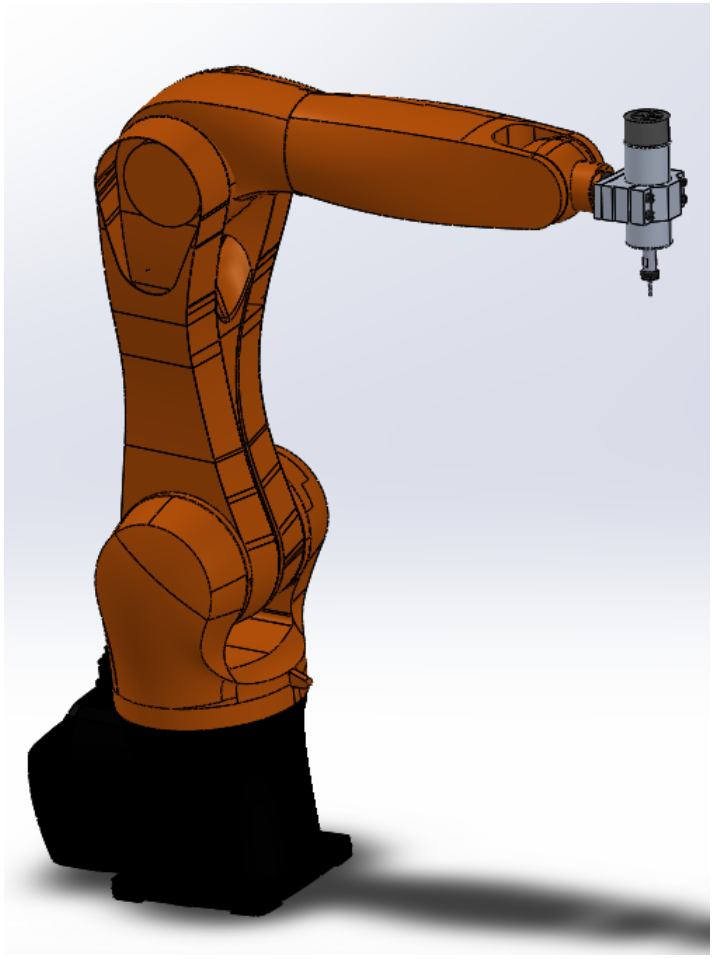


Figure 2.7.: Final CAD model

2.0.2.2. Motion analysis

On implementing motion analysis by adding a motor at the required location to start simulating the robot, a problem arose; the model exploded on running the simulation where some of the parts were separated from each other. This happened because of redundancy constrains. For Motion Analysis studies, having redundant mates is the equivalent of over-defining the model.

Axis	Range of motion, software-limited	Speed with rated payload
1	+/-170°	360 °/s
2	+45° to -190°	300 °/s
3	+156° to -120°	360 °/s
4	+/-185°	381 °/s
5	+/-120°	388 °/s
6	+/-350°	615 °/s

Figure 2.8.: Axes range of motion

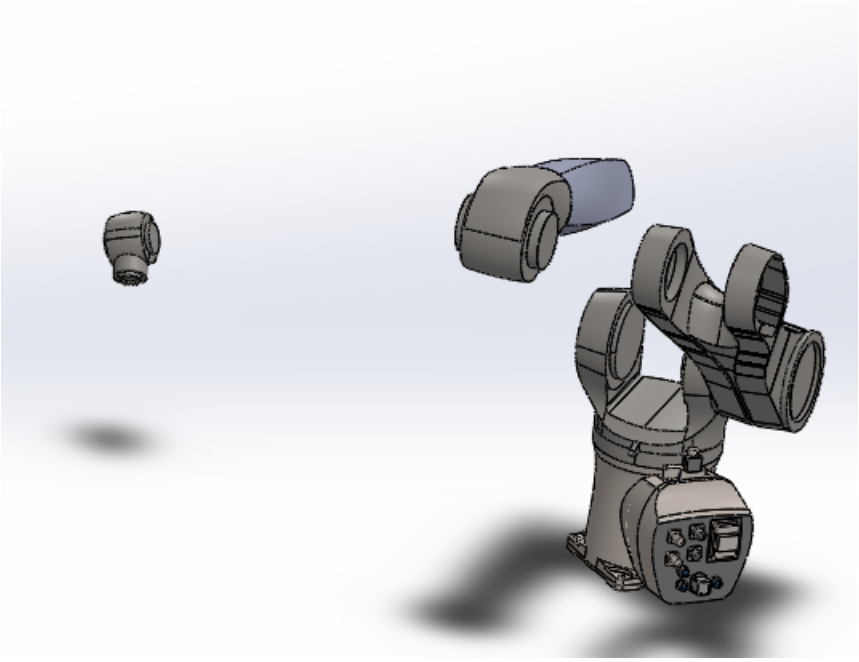


Figure 2.9.: Redundancy constraint problem

This issue was solved by using mechanical mates of hinge type instead of standard mates. Hinge mate limits the movement between two components to one rotational degree of freedom. It has the same effect as adding a concentric mate plus a coincident mate and also limit the angular movement between the two components by adding limit angles. Reducing the negative effect of redundant mates on analysis.

Now motors can be added to the model to perform any motion and results as motor torque, velocity, acceleration and force are generated.

Results of motion analysis study] By assigning a motor to simulate the motion of axis and plotting the results to achieve this motion we found:

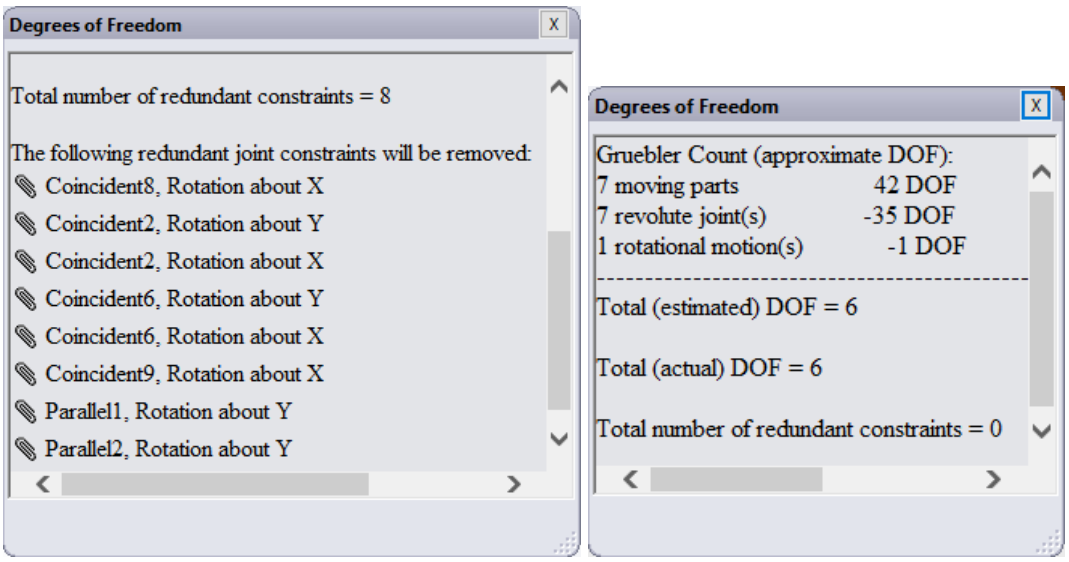


Figure 2.10.: present of redundancy constrains and Zero redundant constraints

- Results of motor torque for axis 1 to move 100 degrees in 4 seconds:

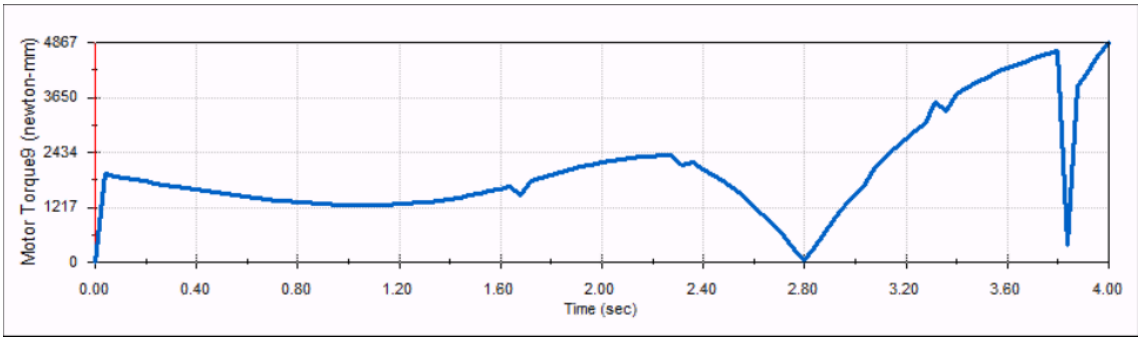


Figure 2.11.: Motor 1 torque

Knowing that the actual motor torque for axis 1 is 4.5 N.m so the motion analysis result is approximate to actual torque.

Motor torque vary with time because of the motion of the links beyond the motor which has an effect on the torque by changing the loads carried by the motor.

- Motor 2 torque to move 60 degrees in 2 seconds:

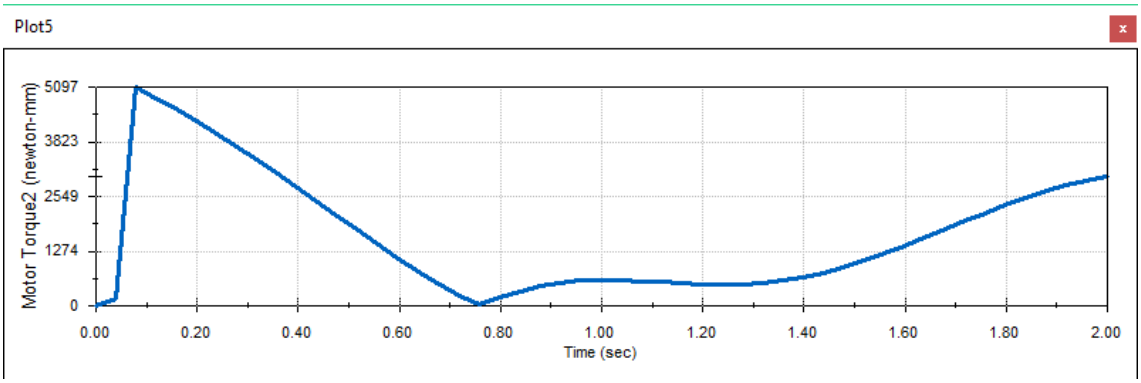


Figure 2.12.: Motor 2 torque

Where the actual motor torque is 4 N.m

- Motor torque for axis 3 to move 75 degrees in 1.8 seconds:

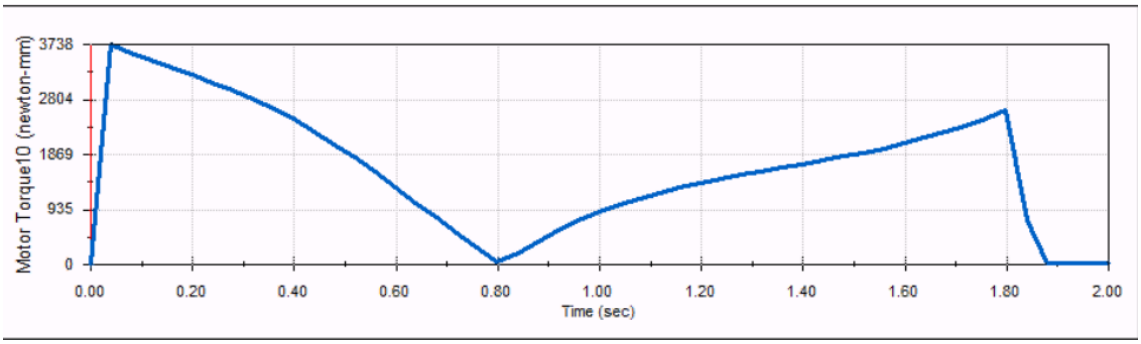


Figure 2.13.: Motor 3 torque

Knowing that the actual motor torque for axis 3 is 3.5 N.m so the motion analysis result is approximate to actual torque.

Trace path Motion analysis results and plots have a trace path option that can trace the path of a point in the assembly. The selected point is end mill vertex to create the curve feature that represent the motion of the links. By assigning a data point motors to the joints whose data is imported from excel spreadsheet of file type .csv containing two columns, first represent time in seconds while other is degrees of rotation. The generated curve of adding this data to joints 1-5 is an arc shape.

	A	B
1	0	0
2	1	10
3	2	20
4	3	30
5	4	40
6	5	50
7	6	60
8	7	70
9	8	80
10	9	90

Figure 2.14.: Used data point

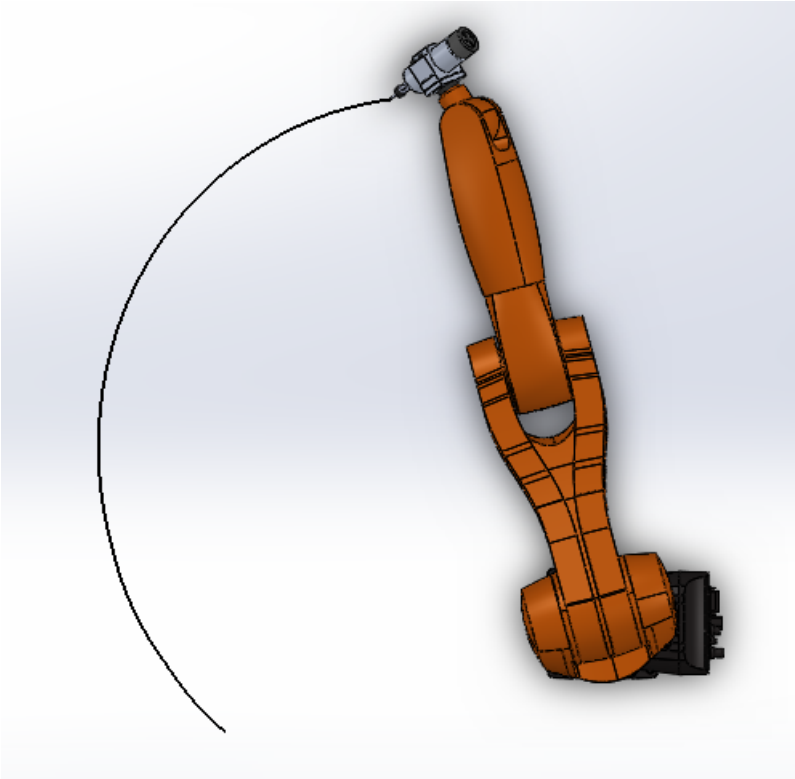


Figure 2.15.: Created curve

2.1. Refrences

- `http://www.engineersrule.com/motion-studies-and-how-to-do-them`
- SolidWorks help
- SolidWorks forums

- Specification manual
- Dimensions manual
- https://robotics.stackexchange.com/questions/10256/dynamic-torque-simulation-for

Chapter 3
Base Settings and CAD analysis

3.1. Mathematical and CAD analysis

A solid, strong base was required for a robust and free of vibrations motion of the robot. After discussing different base settings, a simple design that consists of a cylindrical body, that will support the robot, with upper and lower flanges, was chosen.

Base Structure The base body is mainly constructed of:

1. Two lower flanges:
   - 1st flange is screwed to the ground and held strongly by the concrete layer beneath it.
   - 2nd flange connects the cylindrical body of the base to the previously mentioned flange.
2. The cylindrical body that supports the robot. It's mounted on the 2nd lower flange to stand still while the robot is operated at full speed.
3. The upper flange which holds the robot and is welded to the cylinder.
4. Ribs: there are four upper and lower ribs evenly distributed on the upper and lower flanges, that helps to support the loads exerted on the cylinder.

Figure 3.1.: Base Structure

3.1.1. Design of Base Based On Strength

Base Calculations This section discusses the process of calculating the following:

1. Cylinder
   - Inner and outer diameters of the hollow cylinder.
   - The height of the cylinder.
2. Flanges
   - Dimensions (length x width) of the 3 flanges
   - The exact locations of the holes through which the bolts will be screwed
   - Thickness of the flanges
3. Bolts
   - Diameters of all bolts used in the installation and mounting of the base.
4. Ribs
   - Dimensions of the triangular ribs (height x width x thickness)

3.1.1.1. The inner and outer diameters of the cylinder

Since the cylindrical body of the base undergoes different axial and torsional loads, it can be considered as a shaft.

Determining the cylinder diameters First attempt was to design the cylinder using the predefined mechanical properties of the commercial materials available in the market, to get the inner and outer diameters. After several weeks of research and calculation, the results were within the range of 10^{-2} to 10^{-3} mm, which is very small compared to the expected geometry of the cylinder, leaving us to pursue another manner of designing, based on the strength of material.

Design based on strength Second design attempt aimed to use the inner and outer diameters of the cylinders available in the market, to check whether the resulting shear stress would exceed the maximum allowable shear the material can withstand or not. The ASME code for this method is:

$$\tau_{allowable} = \frac{16}{\pi d_o^3 (1-k^4)} \sqrt{(k_b M_b + \frac{F_a d_o (1+k^2)}{8})^2 + (k_t M_t)^2} \tag{3.1}$$

where:

- Maximum shear stress the material undergoes upon action of axial and torsional loads: τ_{all}
- Combined shock and fatigue factors: $k_b = k_t = 1:2$ *For safety purposes, the value of k_b and k_t constants is considered 2 in the calculations performed.*
- Bending Moment: $M_b = F_h H$
- Cylinder height: H
- Horizontal shear force acting on the base: F_h
- Torsional Moment: M_t
- Axial force (tension/compression) acting on the base: F_a
- Ratio of the inner to outer diameter: $k = \frac{d_i}{d_o}$
- Maximum Allowable shear stress of a predefined specifications of a material, without keyways:

$$\tau_{all} = 0.3\sigma_y$$

$$\tau_{all} = 0.18\sigma_u$$

  These values shall be reduced by 25% in the presence of keyways
- Maximum allowable shear stress of commercial steel, without keyways:

$$\tau_{all} = 55MPa$$

The key is a machine element, that connects a rotating machine element to the shaft. It's mainly used to prevent relative rotation between the two parts. A keyway is a slot in the shaft and the machine's rotating element, in which the key is seated. In our case, there are no keyways used, because the base is built to be held stationary.

Using the following values of loads acting on the foundation mentioned in the KR AGILUS specification manual:

Using steel A37 with the following specifications:

- Yield Strength: $\sigma_y = 235MPa$
- Ultimate Tensile Strength: $\sigma_u = 360MPa$

The max allowable shear stress is:

$$\tau_{all} = 0.3(235) = 70.5MPa$$

$$\tau_{all} = 0.18(360) = 64.8MPa$$

The following table shows the different values of diameters available in market, along with the corresponding resulting shear stress:

Thus, by comparing the previous values of resulting shear stress to the minimum value of the maximum allowable shear stress the material can withstand, 64.8 MPa, we find that any of the alternatives would be suitable for manufacturing the cylinder.

Bolts' diameters

- Lower flange

To get the diameters of the used bolts, we need to calculate the tension forces acting on them first.

$$M_b = 2F_1 r_1 + 2F_2 r_2 = HF_h \tag{3.2}$$

$$\frac{F_1}{r_1} = \frac{F_2}{r_2}$$

$$F_1 = F_2 \frac{r_1}{r_2}$$

Substituting F_1 in equation (1.2), we get:

$$HF_h = 2F_2\left(\frac{r_1^2}{r_2} + r_2\right) \tag{3.3}$$

Where r_1 and r_2 are the distances from one edge of the flange to the first pair of bolts, and the second pair respectively, as shown in figure below.

Figure 3.2.: values of r_1 and r_2

Notes:

- The values of dimensions of the flanges and distances r_1 and r_2 are defined based on the assumption that the bolts used in the lower flange is 10 mm, until reasonable results are obtained using try and error.
- All dimensions mentioned in this chapter are measured in mm.

If the diameter of bolts holding the lower flange is 10 mm, and the area of the flanges is (250x250) mm^2, then the values of r_1, r_2 are 15 mm and 235 mm respectively, as

shown in the figure below.
Substituting the values of M_b, r_1, and r_2, we get:

$$F_2 = 2308.89N$$

Repeating the previous steps by substituting F_2 with F_2, we get:

$$F_1 = 147.376N$$

For safety purposes, the design of the bolts will be based on the larger tension force, F_2. After obtaining the tensile forces on the bolts, the tensile strength (σ_t) should be calculated to check for safety:

$$\sigma_t = \frac{F_t}{\frac{\pi}{4}d^2} \tag{3.4}$$

For 10 mm bolts diameter, and the previously calculated tensile force, we get:

$$\sigma_t = \frac{2308.89}{\frac{\pi}{4}(0.01)^2} = 29.398MPa$$

Taking in consideration a factor of safety, and checking for the maximum tensile strength the material can undergo before failing:

$$\sigma_t = \frac{\sigma_y}{F.S.} = \frac{235}{3} = 78.33MPa$$

The resulting tensile stress is less than the maximum allowable tensile stress, hence, the previous design is safe.
It was previously mentioned that we used commercial materials available in the market. The manufactured steel sheets are of thickness 15 mm, calculations need to be made to check for safety according the maximum shear and bearing stresses.
The horizontal shear force exerted on the base will be acting on the bolts as well, however, it is negligibly small because it's mostly eliminated by the existence of friction between the two steel flanges it holds. Moreover, the moment resulting from tightening the bolts produces an axial force eliminating the axial load acting on the base.

Figure 3.3.: Forces acting on bolts. Black arrows: F_{tr} , purple: F_a, green: F_h

$$F_{total} = \sqrt{(\frac{F_h}{4})^2 + (F_{tr})^2 + 2F_{tr}F_h cos\theta} \tag{3.5}$$

$$F_{tr} = \frac{M_t}{4R} \tag{3.6}$$

Where R,which is the radius of perimeter, has a value of 176.78 mm as shown in figure below.

Figure 3.4.: value of R

$$F_{tr} = \frac{880}{4(0.1768)}$$

$$F_{total} = \sqrt{(\frac{1362}{4})^2 + (\frac{880}{4(0.1768)})^2 + (2\frac{1362(880)}{4(4)0.1768}cos45)} = 1504.5N$$

Checking for safety in terms of the bearing stress:

$$\sigma_{br} = \frac{F_{total}}{d_b t} = \frac{1504.5}{0.01(0.015)} = 10.03MPa \tag{3.7}$$

By comparison to the maximum allowable bearing stress, we find that both of the predetermined bolt diameter (10 mm), and the flanges thickness are verified to be safe and suitable, as following:

$$\sigma_{br} = 1.2\frac{\sigma_y}{F.S.} = \frac{1.2(235)}{3} = 94MPa \tag{3.8}$$

Checking on the maximum shear stress exerted on the bolts by the combined forces, we get:

$$\tau = \frac{F_{total}}{\frac{\pi}{4}(d_b)^2} = \frac{1504.5}{\frac{\pi}{4}(0.01)^2} = 19.156MPa \tag{3.9}$$

Comparing it to the maximum shear stress the bolts can stand which is 64.8 MPa since it's made of the steel-37 as well, we can conclude that this is a safe design in terms of the bolts diameters, flanges dimensions, and cylinder diameters.

3.1.1.2. Upper Flange

The upper flange holds the robot base motor, using the bolts provided with the robot. The flange was designed to have an area of (230x230) mm^2, with the locations of 4 bolts holding the robot taken from its base.

3.1.1.3. Ribs

The ribs are made of the same sheet of which the flanges are made of, with a thickness of the ribs is 10 mm.
There isn't an exact way of calculating the height and width of the triangular ribs. After discussing the matter with several machine design doctors, we concluded that the ribs' width should cover the length from the cylinder surface to the edge of flange, resulting in a width of 55 mm, while the height is 100 mm.

3.1.2. Base Manufacturing & Installation

3.1.2.1. Manufacturing

Several materials can be used to manufacture the body of the base, such as AISI 1010 & AISI 1010 carbon steel, SAE 304 stainless steel, etc., all of which the mechanical properties are predefined. However, the available material in the market was steel 37, which has the following mechanical specifications:

- Yield Strength: $\sigma_y = 235MPa$
- Ultimate Tensile Strength: $\sigma_u = 360MPa$

The calculations performed on this material are proven to be safe and suitable to our designed base geometry.

The squared, upper and lower flanges are made of a 15mm thick steel-37 sheet, and holes were drilled in the designated locations shown in the sketches below. The flanges are then welded to the cylindrical body of the base. It's worth mentioning that the dimensions of the manufactured base are larger than those calculated, this is due to different manufacturing and safety purposes, the final dimensions manufactured are illustrated below.

Figure 3.5.: Final dimensions manufactured base

For the ribs to be welded, the base needs to be cleaned of any accumulated rust, it is then taken to undergo different machining steps, using a lathe machine. Next, it is painted in black to match the robot colors.
Figure1.4 illustrates different stages of manufacturing.

Figure 3.6.: Manufacturing and Machining of the base

3.1.2.2. Installation

The following steps clarifies the process of installing the robot base:

1. The exact location of the base is chosen according to the safe operating range of the robot, mentioned in the KR AGILUS six specification manual.
2. Remove the ceramic plate. The number of plates removed depends on the area of the base and the ceramic plate itself, in our case, only one plate was removed.
3. Scrape the sand and cement layers beneath the ceramic until you reach the concrete, it can be recognized when a layer of gravels appears.

4. Drill the holes, in which the dowel rods will be placed, in the predesigned positions in the concrete. For this design, seven holes were drilled, however, the number of dowels depends on the design.
5. Make a mixture of sand, gravels, cement and anabond adhesive agent to mold a new concrete layer, and keep mixing until it's consistent.
6. Pour in the concrete mixture on top of the pre-existent one, while the dowels are placed, and wait for 2 days to ensure that it's completely solidified.
7. Remove the dowels and start screwing the bolts.
8. Start mounting the first flange. Use a bubble level to check if it lies in a perfectly horizontal position, if not, you must scrape the newly molded concrete layer until it's even.
   Note: Even out the newly molded concrete once it dries, this would help you to avoid such issues in further steps.
9. Mount the base, then move the robot carefully until it's placed on it in the right orientation.

Figure1.5 illustrates different stages of the previously explained installation process.

Figure 3.7.: Base Installation

3.1.2.3. CAD Analysis Performed on Base

For the purpose of our study, SolidWorks was used as a CAD software, as it contains solid modeling, motion studies, Simulation PhotoView 360, e-drawing and many other features that were used to obtain a complete CAD model for KR6 r900 sixx KUKA arm. SolidWorks simulation is used to make a stress and strain analysis on designed base model to have a verification on the calculated dimensions of the base before starting fabricating it. Static study is used to perform this analysis as we use maximum loads acting on foundation base

Material properties The mechanical properties of the material used to fabricate the base

Load and fixture It represent the fixed flange and the reaction force act on it in x,y and z axes.The used forces and torque acting on the foundation to perform the analysis.

Mesh information calculating size of selected element and tolerance between them to find the total number of elements and nodes to apply the analysis on it.

Study results stresses on the base due to the acting loads.The maximum stress is 10.34 N/m^2 at node 546 and the minimum stress is 6.8 N/m^2 at node 5564. Strain on the base due to the acting loads.The maximum strain is 7.56 at element 3828 and the minimum strain is 6.58 at element 3189. Displacement of the base due to this forces is 2.7mm maximum.

3.2. 2.4 CAD Analysis Approach

In Simulation and Analysis, you can test your designed product in real environment.In simulation process the model can be tested against parameters like static and dynamic response, fluid dynamic, heat transfer. It also supports thermal, fatigue, structural and motion analysis.
In our project, SolidWorks is used to obtain a CAD model for KR6 r900 sixx and to perform a motion analysis study on the model. In addition to designing a base to fix the robot arm, perform a stress analysis and creating an animation video of the model's motion.

3.2.1. Complete CAD Model

3.2.1.1. Searching for a suitable model

All CAD models for KR6 r900 sixx on KUKA website or GrabCAD were step imported parts which are treated as a one body where joints can't rotate therefore, motion study can't be performed because it was impossible to add motors at the robot joints. The solution for this issue was obtained by converting step parts into assembly, which is done through several steps:

- Open the .stp file part in SOLIDWORKS. Select the file type to be .stp
- Click the OPTIONS tab, select Import multiple bodies as parts and click OK.
- Then click Open.

SolidWorks will create an assembly and create an individual part file for each multibody (Part1,Part2,Part3 etc.)

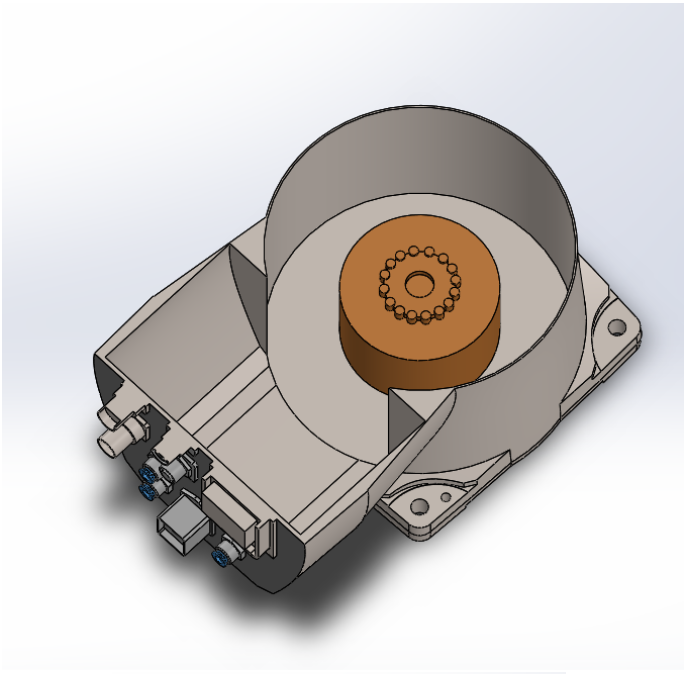
Figure 3.8.: Step parts

Figure 3.9.: SolidWorks parts

3.2.1.2. Modifications on CAD model

Material and weights The robot material wasn't specified and the model was a whole body, and the total mass for the robot was 33.74 Kg, which was not accurate, because the actual mass of the robot, according to the KR6 R900 sixx dimensions manual, must be approximately equal to 52Kg. This is achieved by making the model hollow, using the shell feature and adding to joins point masses similar to the real motors with mass approximate equal to motors masses.

Figure 3.10.: KUKA motors



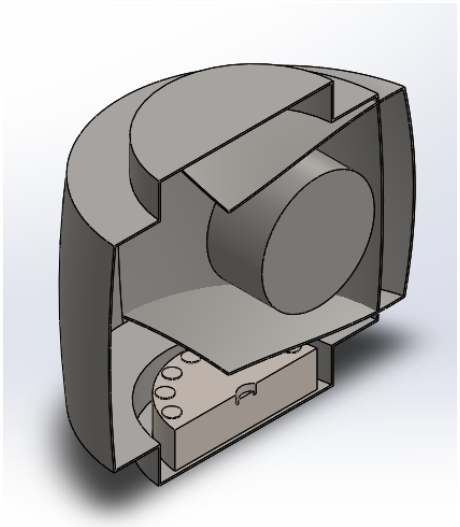


Figure 3.11.: Motors model: Motors 1,2 and 3 model and Motors 4,5 and 6 model

Figure 3.12.: The model mass: Old mass and final mass

Spindle In order to have a complete model for our graduation project, a router spindle and its holder were sketched to complete the existing KUKA model.

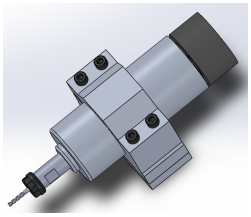


Figure 3.13.: Spindle model

Figure 3.14.: Final CAD model

3.2.2. Motion studies

Motion studies are graphical simulations of motion for assembly models. They simulate and animate the prescribed motion for a model. SolidWorks offer three different types of motion study, Animation, Basic Motion and Motion Analysis. They also offer mate controller that show, save the positions of assembly components at various mate values and degrees of freedom and create simple animations between those positions.

Animation can be used to animate the motion of assembly. If you simply wish to create some nice visuals for presentation or marketing without consideration of mass and gravity effects, then animation is for you.
Basic Motion is an extra layer of complexity that takes into consideration the effects of mass, motors, springs, contact, and gravity on assemblies.

Motion Analysis is the top tier of motion study provides accurately simulation and analyze the motion of an assembly while incorporating the effects of Motion Study elements (including forces, springs, dampers, and friction). Motion Analysis can also be used to plot simulation results for further analysis.

Therefore, Motion Analysis is used to simulate the model, generating results and plots of the simulation and Animation is used to make a video for motion.

3.2.2.1. Animation study

Animation study is done to make an animation video of the moving parts with the use of limit mates. Limit angle mate is an advanced mate type that is performed by selecting two planes which rotate with respect to each other giving the desired range to mate and input a maximum and minimum value for the angle to specify the desired range of motion. Another advantage of limit angle is that it prevent collision between the moving parts.

Figure 3.15.: Axes range of motion

3.2.2.2. Motion analysis

On implementing motion analysis by adding a motor at the required location to start simulating the robot, a problem arose; the model exploded on running the simulation where some of the parts were separated from each other. This happened because of redundancy constrains. For Motion Analysis studies, having redundant mates is the equivalent of over-defining the model.

Figure 3.16.: Redundancy constraint problem

This issue was solved by using mechanical mates of hinge type instead of standard mates. Hinge mate limits the movement between two components to one rotational degree of freedom. It has the same effect as adding a concentric mate plus a coincident mate and also limit the angular movement between the two components by adding limit angles. Reducing the negative effect of redundant mates on analysis.

Figure 3.17.: Presence of redundancy constrains

Figure 3.18.: Zero redundant constraints

Now motors can be added to the model to perform any motion and results as motor torque, velocity, acceleration and force are generated.

Results of motion analysis study] By assigning a motor to simulate the motion of axis and plotting the results to achieve this motion we found:

1. Results of motor torque for axis 1 to move 100 degrees in 4 seconds:

Figure 3.19.: Motor 1 torque

Knowing that the actual motor torque for axis 1 is 4.5 N.m so the motion analysis result is approximate to actual torque.
Motor torque vary with time because of the motion of the links beyond the motor which has an effect on the torque by changing the loads carried by the motor.

2. Motor 2 torque to move 60 degrees in 2 seconds:

Figure 3.20.: Motor 2 torque

Where the actual motor torque is 4 N.m

3. Motor torque for axis 3 to move 75 degrees in 1.8 seconds:

Figure 3.21.: Motor 3 torque

Knowing that the actual motor torque for axis 3 is 3.5 N.m so the motion analysis result is approximate to actual torque.

Trace path Motion analysis results and plots have a trace path option that can trace the path of a point in the assembly. The selected point is end mill vertex to create the curve feature that represent the motion of the links. By assigning a data point motors to the joints whose data is imported from excel spreadsheet of file type .csv containing two columns, first represent time in seconds while other is degrees of rotation. The generated curve of adding this data to joints 1-5 is an arc shape.

Figure 3.22.: Used data point

Figure 3.23.: Created curve

"A computer would deserve to be called intelligent if it could deceive a human into believing that it was human."

— Alan Turing, (British pioneering computer scientist, cryptanalyst,···, and philosopher, 1912–1954)

Chapter 4
Robotic Operating System (ROS)

Recently, robotics community witnesses excessive progress. In Spite of this progress, It still undergo complexity and significant challenges to the software developers; One of the main reasons for this issue is handling the wide variation in tasks and environments of robot systems by an individual. ROS -Robot Operating System- is the flexible framework that makes robot software developing is more robust and accessible by robotics community. The official description of ROS is:

> "ROS is an open-source, meta-operating system for your robot. It provides the services you would expect from an operating system, including hardware abstraction, low-level device control, implementation of commonly-used functionality, message-passing between processes, and package management. It also provides tools and libraries for obtaining, building, writing, and running code across multiple computers."

4.1. Modularity

The core of successive software algorithm is the ability to reuse in different projects without reimplementing. Modularity is an important Software principle. It divides complex systems into manageable and simpler modules ROS adds value to the most robotics projects and applications because of it Modularity, so you can use ROS as much as you desire and still implement your own parts.

4.2. Distributed Nature

Communication between multiple process is the key to powerful system. ROS provides an integration point that able to manage hardware, drives, development tools, useful

libraries, simulators and much more. A ROS distribution is a set of ROS software packages that can be downloaded to your computer.

4.3. Road Map to ROS development

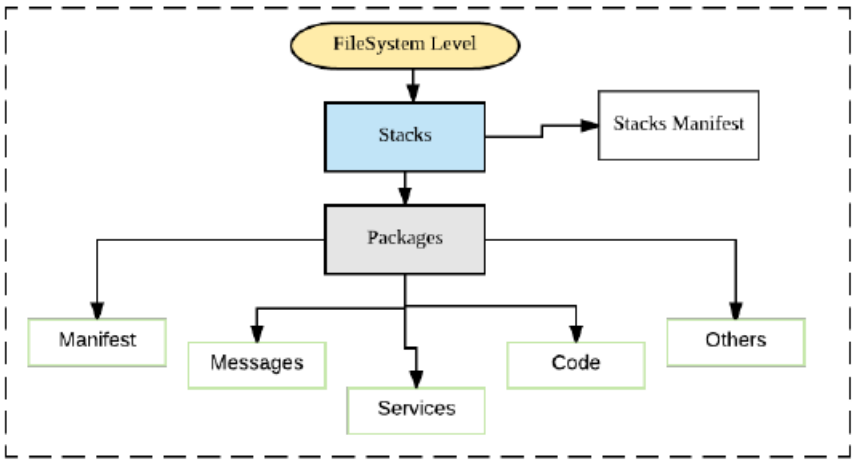
4.3.1. Filesystem Level

The filesystem level explains how ROS files are organized on the hard disk.ROS program is divided into folders, and these Folders has some files that describe their functionality

label description

Packages A package might contain ROS nodes, a ROS-independent library, a dataset, configuration files, a third-party piece of software, or anything else that logically constitutes a useful module.

Figure 4.1.: Filesystem level representation



ROS Package tools To create, modify, or work with packages, ROS gives us some tools for assistance

Command	Function
`rospack`	This command is used to get information or find packages in the system
`roscreate-pkg`	creating new package with your own dependencies
`rosmake`	This command is used to compile package
`rosdep`	This command installs system dependencies of a package
`rxdeps`	This command is used if you want to see the package dependencies as a graph

Table 4.1.: ROS Package commands

Stacks Packages in ROS are organized into ROS stacks.the main goal of stacks is to ease the process of sharing codes.

Messages Nodes communicate with each other by publishing messages to topics. A message is a simple data structure, comprising typed fields. Standard primitive types (integer, floating point, boolean, etc.)

Services ROS uses simplified service description language for describing ROS service types. This builds directly upon the ROS msg format to enable request/response communication between nodes. Service descriptions are stored in .srv files.

4.3.2. Computaional Graph Level

The basic Computation Graph concepts of ROS are: nodes, Master, Parameter Server, messages, services, topics, and bags, all of which provide data to the Graph in different ways.

- Nodes: Nodes are processes where computation is done. A system better has many nodes to control different functions. Nodes are written with ROS client library; roscpp, or rospy.
- Master: ROS Master is the part that facilitates all the communication between nodes.You should allow the master to continue running for the entire time that you're using ROS.
- Parameter Server: The Parameter Server gives us the possibility to have data stored using keys in a central location.
- Messages: The Parameter Server gives us the possibility to have data stored using keys in a central location.
- Topics: Messages are organized into topics. Nodes that need to listen to certain messages will **subscribe** to the topics that it is interested in, or if the node wants to share it is information, the node will **publish**to an appropriate topic.

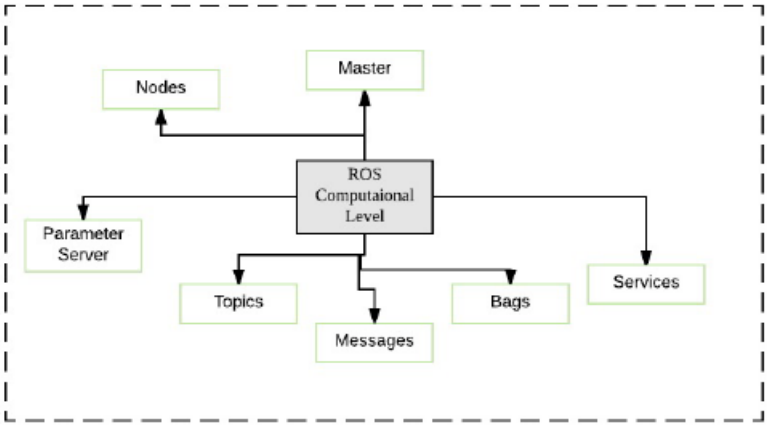


Figure 4.2.: Filesystem level representation

4.3.3. Community Level

The third level is the Community level where you can find useful resources and interact with different developers to exchange knowledge, algorithms, and softwares. The official description of ROS Community level resources:

- *Distributions: ROS Distributions are collections of versioned stacks that you can install. Distributions play a similar role to Linux distributions: they make it easier to install a collection of software, and they also maintain consistent versions across a set of software.*
- *Repositories: ROS relies on a federated network of code repositories, where different institutions can develop and release their own robot software components.*
- *The ROS Wiki: The ROS community Wiki is the main forum for documenting information about ROS. Anyone can sign up for an account and contribute their own documentation, provide corrections or updates, write tutorials, and more.*
- *Bug Ticket System: Please see Tickets for information about file tickets.*
- *Mailing Lists: The ros-users mailing list is the primary communication channel about new updates to ROS, as well as a forum to ask questions about ROS software.*
- *ROS Answers: A Q and A site for answering your ROS-related questions.*
- *Blog: The Willow Garage Blog provides regular updates, including photos and videos.*

ROS tutorials `wiki.ros.org/ROS/Tutorials`

Figure 4.3.: Kinect Xbox 360 with RGB Camera, Depth Camera, and Microphone array

4.4. Using Sensors with ROS: Kinect

4.4.1. Operation and Inferring body position

The process of inferring body position done by two main stages: analyzing a speckle pattern of infrared laser light to produce depth map; then transforms depth image to body part image from motion capture system and finally transforms the body part image into a skeleton.

Figure 4.4.: Speckle Pattern

4.4.2. OpenNI: Natural Interaction

The term natural interaction refers to people communicating with devices through their human senses, such as audio, and vision. The most obvious applications uses this technology are: face/ voice recognition; body motion tracking; and control room electronics using hand gesture

Abstract Layered View The three layered view of OpenNI :

- **Top**: Represents the software that implements natural interaction applications on top of OpenNI.
- **Middle**: Represents OpenNI, providing communication interfaces that interact with both the sensors and the middleware components, that analyze the data from the sensor..
- **Bottom**: Shows the hardware devices that capture the visual and audio elements of the scene.

4.4.3. Skeleton Tracking: User segmentation

Skeleton tracker generate data of the users who exist in the scene; these data includes location of the skeletal joints, and ability to track skeleton position.

There are some consideration for accurate skeleton tracking:

- User considered to be lost if the user is not visible in the scene within 10 seconds
- Users get ID “user 1,2,...”. However the ID is recycled.
- Ideal distance for tracking around 2.5 m
- User should not wear very loose clothing, for better result.

Calibration To start tracking body, the user should do calibration position “psi pose” as shown in figure.

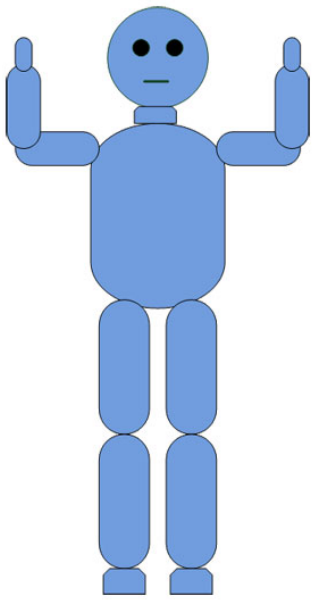


Figure 4.5.: PSI pose

Limitations:

- User should not be sitting
- Most of the user body should be invisible
- User should be located 1 m away from kinect

Skeleton tracker output Skeleton tracker return the position, and quaternion of the joint.

Joint Transformation Joint positions and orientations are given in the real world coordinate system. The origin of the system is at the sensor. The positive direction of X-axis is to the right of origin “, The positive direction of Y-axis is up, and The positive direction of Z-axis is in the direction of increasing depth. The coordinate frame is shown in the figure above.

Keep in mind that representation of the skeleton in Rviz supposed to be in Mirror mode which indicates that the LEFT side labeled in Rviz window is actually your RIGHT side. Joint positions are measured in units of m and orientations are in radians.

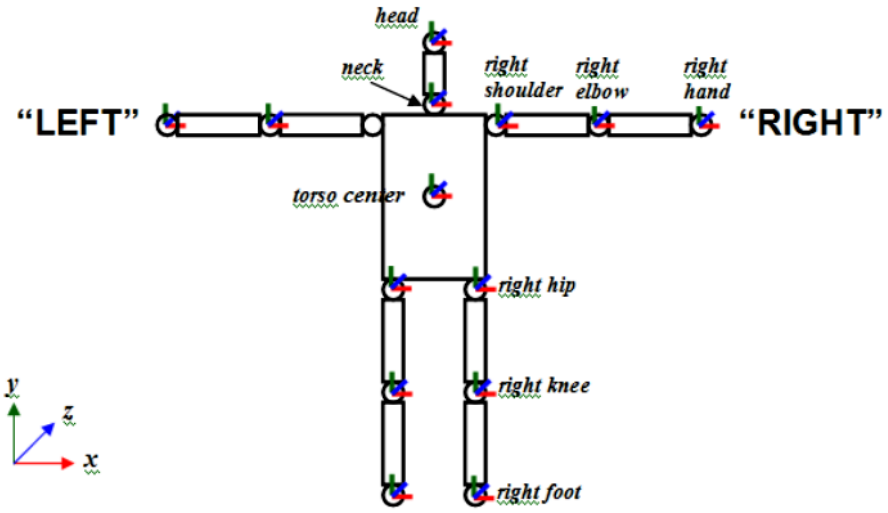


Figure 4.6.: Skeleton joints Coordinate

4.4.4. Kinect Driver

Openni launch Package This package contains launch files for using OpenNI-compliant devices such as the Microsoft Kinect in ROS. from the device driver into point clouds, disparity images, and other products suitable for processing and visualization.

to open Kinect device and transform raw data to convenient data, run this command:

```
$ roslaunch openni_launch openni.lanuch
```

Openni tracker Package openni_tracker broadcasts the OpenNI skeleton frames using tf. this package allows you to track a person's skeleton using a Kinect. It also gives you the positions, relative to the camera frame run this command:

```
$ rosrun openni_tracker penni_tracker
```

Stand in front of the Kinect. If the terminal window where you ran openni_tracker, you should see output like this:

```
    [INFO]: New User 1
    [INFO]: Calibration started for user 1

    [INFO]: Calibration complete, start tracking user
```

4.4.5. 3D Visualizing

As discussed in the previous sections, Kinect produced 3D data in form of point clouds.For this reason ROS has invented tool to visualize this type of data. these tools enable you to develop robotic system faster by visualizing your data and evaluate the quality of result for validation.

Visualizing 3D data using rviz With roscore running, we only have to execute the following code to start rviz:

```
$ rosrun rviz rviz
```

This command will open rviz interfac

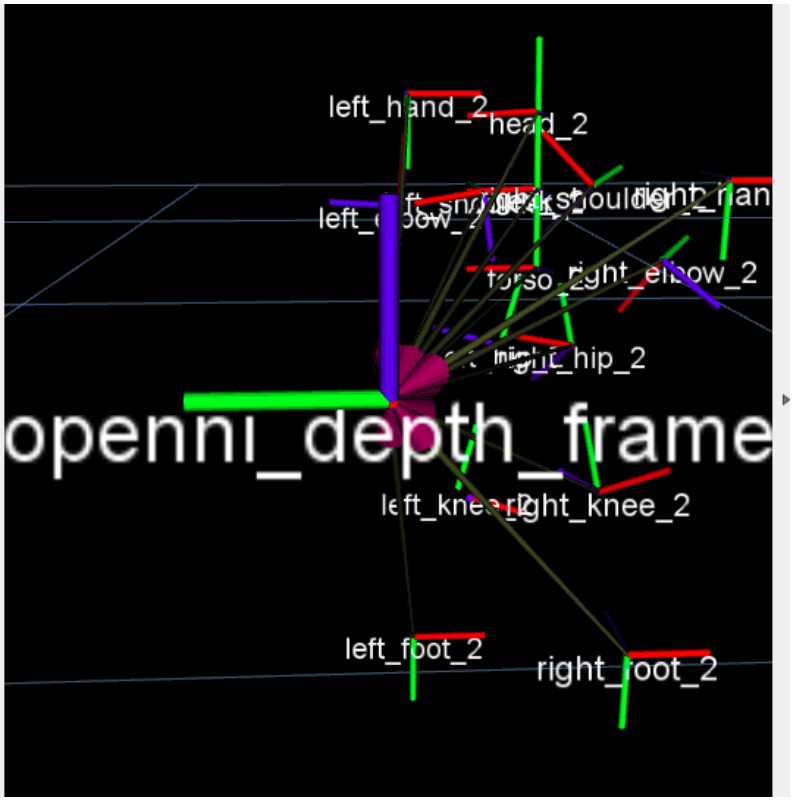


Figure 4.7.: Visualizing skeleton joints using Rviz

"Be sure you put your feet in the right place, then stand firm."

— Abraham Lincoln, (American 16th President, 1809–1865)

Chapter 5
Robot Programming

5.1. Cartesian–Axis Specific Coordinate System

5.1.1. Coordinate systems in conjunction with robots

The following Cartesian coordinate systems are defined in the robot controller:

WORLDCoordinate System Fixed, rectangular coordinate system whose origin is located at the base of the robot. It is the root coordinate system for the ROBROOT and BASE coordinate systems. By default, the WORLD coordinate system is located at the robot base.

ROBROOT Coordinate System Fixed, rectangular coordinate system whose origin is located at the base of the robot. It is the root coordinate system for the ROBROOT and BASE coordinate systems. By default, the WORLD coordinate system is located at the robot base.

BASE Coordinate System Fixed, rectangular coordinate system whose origin is located at the base of the robot. It is the root coordinate system for the ROBROOT and BASE coordinate systems. By default, the WORLD coordinate system is located at the robot base.

TOOL Coordinate System a Cartesian coordinate system which is located at the tool center by default, the origin of the TOOL coordinate system is located at the flange center point. The TOOL coordinate system is offset to the tool center point by the user

5.2. KUKA Robot Language (KRL) Quick Guide

KRC 4 controller uses KRL KUKA programming language.

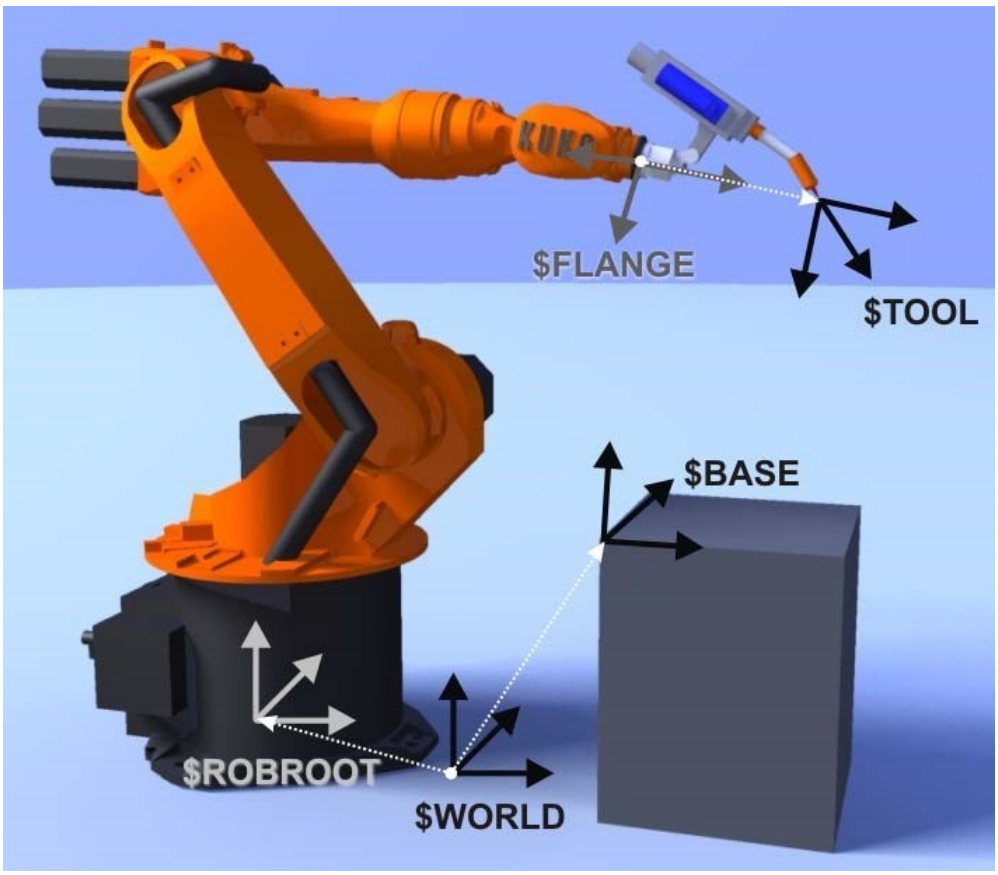


Figure 5.1.: KUKA robot coordinate systems

5.2.1. Variables and Declarations

All system variables start with $ sign, mind not starting any "user-defined" name with this sign to avoid syntax errors.

Names in KRL

- Can have a maximum length of 24 characters
- Can consist of letters(A - Z), numbers(0 - 9) and the special characters '$'.
- Must not begin with a number.
- Must not be a keyword.

Declaration and initialization of variables

- Variables (simple and complex) must be declared in the SRC file before the INI line and initialized after the INI line
- Variables can optionally also be declared and initialized in a local or global data list.
- Every variable is linked to specific data type.

- The data type must be declared before use.
- The keyword for the declaration is DECL. It can be omitted in case of the four simple data type
  - In order to place syntax before the INI line, the DEF line must be activated:
    Open file >Edit >View >DEF line

```
DEF programName()
    DECL data type user defined variable
    ;declaration section of  variables
    INI
    ;Initialization section of user defined variables.
    ...
    ;Instruction Section
    ...
END
```

Simple Data types

Data Type	Keyword	Meaning	Range	Example
Integer	INT	integer number	$-2^31 \ldots 2^31-1$	2
Real	REAL	floating point number	$\pm 1.1E-38 \cdots \pm 3.4E+38$	4.23
Boolean	BOOL	logic state	TRUE, FALSE	TRUE
Character	CHAR	character	ASCII character	C

Table 5.1.: KRL Data Types

Structure Types

- AXIS: A1 to A6 are angle values (rotational axes) or translation values (translational axes)

Axis: A1 .., A2 .., A3 .., A4, A5 .., A6 ..

- FRAME: X, Y, and Z are space coordinates, while A, B, and C are the orientation of the coordinate system.

FRAME: X .., Y .., Z .., A .., B .., C ..

- POS and E6POS: S (Status) and T (Turn) define axis positions unambiguously

POS: X .., Y .., Z .., A .., B .., C .., S ..., T

5.3. Motion Programming

5.3.1. Motion Types

The robot can move in various motion types. Paths are created according to the operation of each axis. Thus, the robot can be controlled to create either linear or circular path.

5.3.1.1. Axis-specific motion

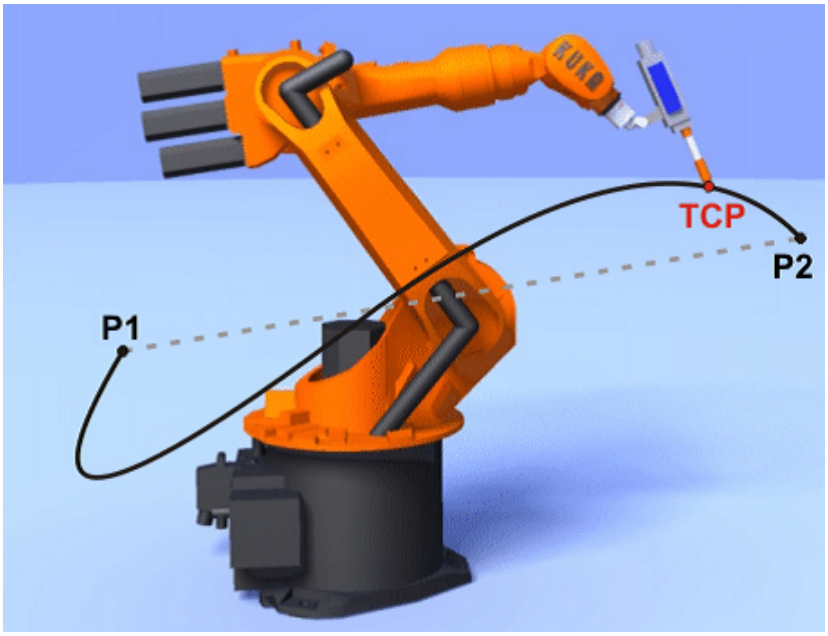
The robot guides the TCP along the fastest path to the end point. The fastest path is generally not the shortest path and is thus not a straight line. The first motion in the program must be PTP as status and turns are only evaluated here. The coordinates of the end point are absolute.

characteristics

- smooth motion

- Robot can move from start to end singularity free. As long as both the starting and ending points are in the working envelope, the robot will get to the end point without collision or sudden movement.
- Control is much simpler than continuous path control.

Figure 5.2.: PTP Motion

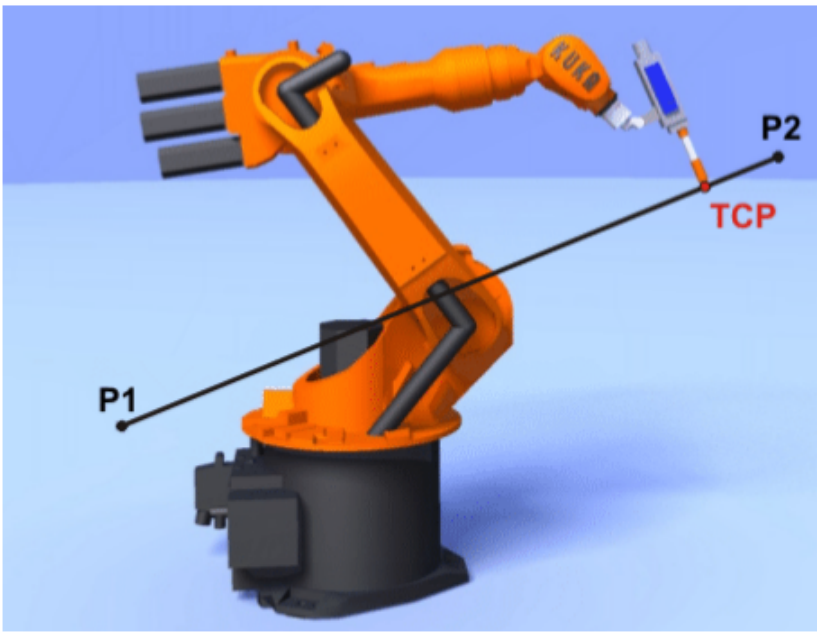


5.3.1.2. CP motion

LIN Motion Motion at a defined velocity and acceleration along a straight line. This motion requires the programmer to "teach" one point. The robot uses the point defined in the previous move as the start point and the point defined in the current command as the end point and interpolates a straight line in between the two points.

CIRC Motion Motion at a defined velocity and acceleration along a circular path or a portion of a circular path. This motion requires the programmer to "teach" two points, the mid-point and the end point. Using the start point of the robot (defined as the end point in the previous motion command) the robot interpolates a circular path through the mid-point and to the end point.

Figure 5.3.: LIN Motion



5.3.2. Approximate Positioning

Approximate positioning of motion means that the next programmed point will not be exactly reached. This can help to shorten cycle times

5.3.2.1. PTP-PTP approximate positioning

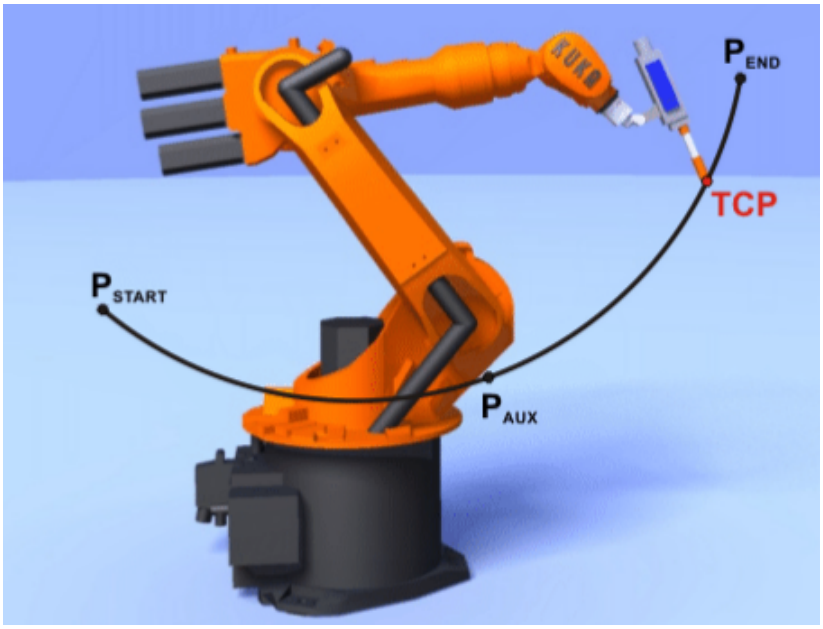
For the purposes of PTP approximate positioning,the controller calculates the distances the axes are to move in the approximate positioning range, and plans velocity profiles for each axis which ensure tangential transition from the individual instructions to the approximate positioning contour.

System Variable, $APO.CPTP enables the start of approximate positioning to be specified as a percentage of these maximum values. The approximate positioning of a point is displayed in the PTP command by adding the key word C_PTP:

```
$ APO.CPTP = 80
PTP HOME C_PTP
```

The greater this value the, the more path is rounded.

Figure 5.4.: CIRC Motion



Status and Turns The position of x,y,z and orientation A,B,C values of TCP are not sufficient to define the robot position ,as different axis positioning are possible for the same TCP . Status and turns serve to define the position that can be achieved with different axis positions.

5.3.3. User Programming

Inline forms are available in the KSS for frequently used instruction. They simplify programming and facilitates user interface with controller without the need of knowing detail information about KUKA programming Language

5.3.4. Expert Programming

In the Expert interface, can achieve advanced programming using the KRL programming language and perform complex application programs including subprograms, interrupt programming, loops, and program branches.

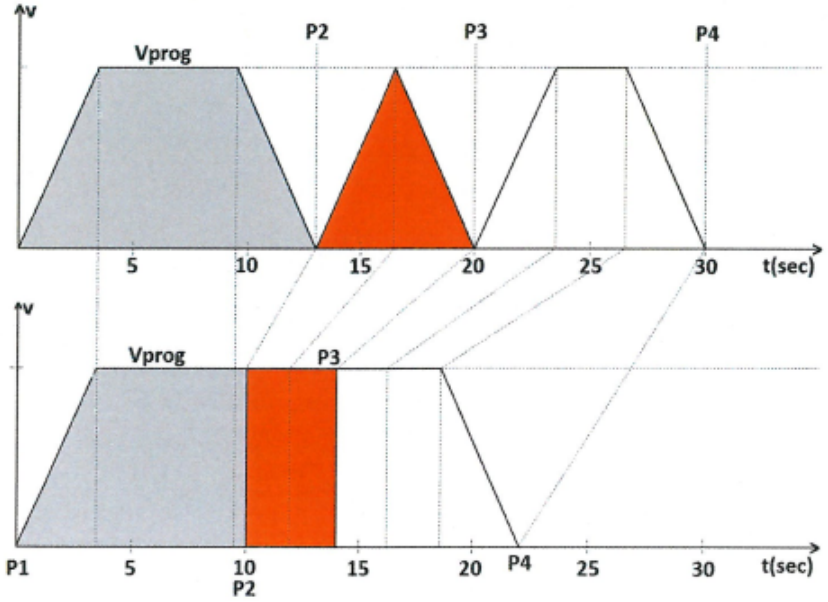


Figure 5.5.: Speed Profile: a) If all points approached exactly and b)In case of approximate positioning of the points

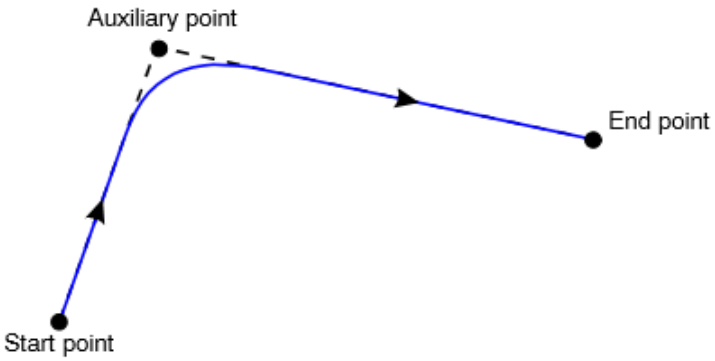


Figure 5.6.: Approximate positioning of an auxiliary points

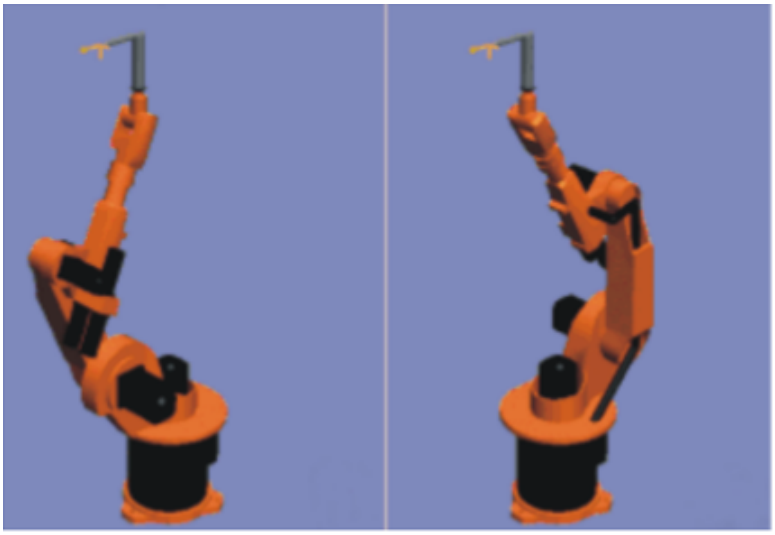


Figure 5.7.: Same TCP, different axis position

Chapter 6
KUKA conditioning

6.1. Robot Mastering

The Mastering operation calibrates the relationship between the position sensor, attached to each axis motor, and each axis angle defined for each robot. Mastering axes enables the definition of geometric parameters used to describe the analytic parameters of a robot's geometric model. This helps in increasing the accuracy of the robot and correcting for discrepancies between design parameters and actual values.

Mastering the robot is performed by moving the each axis into a defined mechanical position, which is known as the "Mechanical zero position". The zero position, which is defined by a reference notch, is an assignment to the axis drive angle. Whenever the robot moves from the mechanical zero position, its deflection represents the change in corresponding axis angle (0 increments for 0 degrees).

To locate the mechanical zero position of a robot axis precisely, the axes must be aligned to their pre–mastering position. The protective cap of the gauge cartridge is then removed and a dial gauge, or the supplied EMD, is fitted to it.

Note: The robot must be mastered in the same temperature conditions (either always cold or at operating temperature) to avoid inaccuracies.

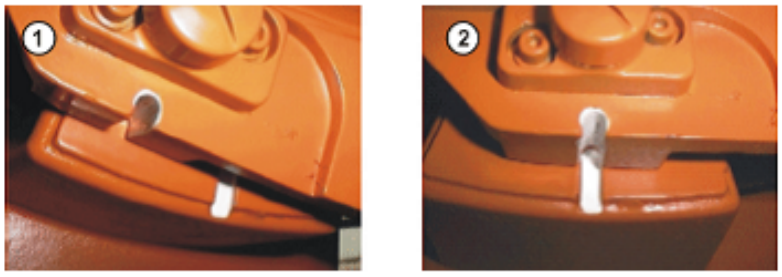


Figure 6.1.: Moving an axis to pre-mastering position

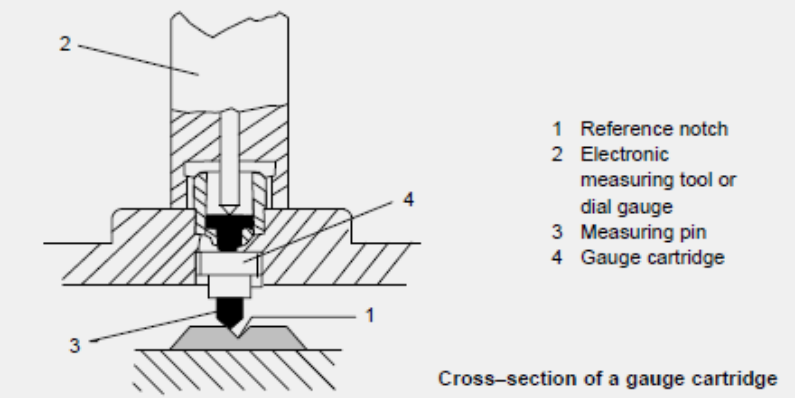


Figure 6.2.: Moving an axis to pre-mastering position

On passing over the reference notch, the gauge pin reaches its lowest point, the mechanical zero position is reached. The electronic measuring tool sends an electronic signal to the controller.

Mastering can be performed through several methods; for older Robot versions it is performed using EMT, as for the KUKA AGILUS, mastering is done using one of these methods; EMD, dial gauge or MEMD. For our purpose, we used the MEMD supplied with the robot. The mastering positions are similar, but not identical, for all robots. Exact positions may vary between individual robots or single robot type.

6.1.1. Mastering using MEMD

Unlike Dial gauge mastering, which requires moving the robot manually to the mastering position, MEMD mastering offers automatic movement, done by the robot, to reach the mastering position. Mastering is per-

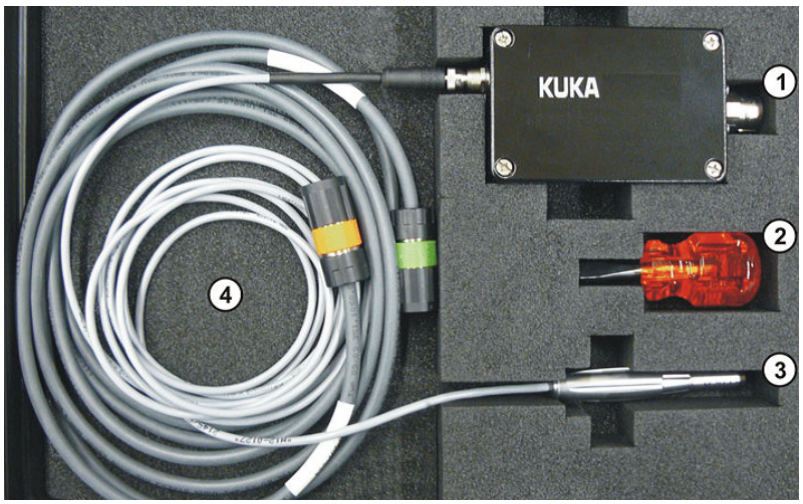


Figure 6.3.: MEMD kit: 1. MEMD box, 2. Screwdriver, 3. MEMD, and 4. Cables.

formed first without a load then repeated using a load. The MEMD mastering tools are shown in the below picture.

Types of mastering

1. First mastering (without a load).
2. Tech offset (with a load and with saving the difference from first mastering being saved).
3. Master load with offset is based on saving an offset value that can be used to calculate first mastering in case it was lost (used when required, carried out with a load for which an offset has already been taught. This type is used to check first mastering or to restore it in case it was lost).

Precondition

- There is no load on the robot; i.e. there is no tool, workpiece or supplementary load mounted.
- A1 to A5 are in the pre-mastering position.
- No program is selected.
- Operating mode T1

Procedure

1. In the main menu, select Start-up > Master > EMD > With load correction > First mastering. A window opens. All axes to be mastered are displayed. The axis with the lowest number is highlighted.
2. Remove the cover from connection X32.
3. Connect the EtherCAT cable to X32 and to the MEMD box.
4. Remove the protective cap of the gauge cartridge on the axis highlighted in the window.
5. Screw the MEMD onto the gauge cartridge.
6. Press Master.
7. Press an enabling switch and the Start key.
8. When the MEMD has passed through the reference notch, the mastering position is calculated. The robot stops automatically. The values are saved. The axis is no longer displayed in the window.
9. Remove the MEMD from the gauge cartridge and replace the protective cap.
10. Repeat steps 4 to 8

Mastering of A6

1. Move A6 to the mastering position. A6 has very fine marks in the metal. Align these marks exactly with one another.
2. In the main menu, select Start-up > Master > Reference.
3. The option window Reference mastering is opened. A6 is displayed and is selected.
4. Press Master. A6 is mastered and removed from the option window.
5. Close the window.
6. Disconnect the EtherCAT cable from X32 and the MEMD box.

Note

For more information about the remaining mastering types (teach offset and mastering load with offset) and other mastering methods (using dial gauge and EMD), please refer to section: “5.9 Mastering” in the provided manual “07-KSS_82_Software programming_en”

6.2. Robot Calibration

Robot calibration is defined as identifying certain parameters in the robot’s kinematic structure, as an example; identifying relative position of robot links. Robot calibration can be performed through various methods, two of which are using a predefined and built-in calibration programs, or external methods (hardware and/or software) as RoboDK or advintec TCP. Calibration process differs in complexity from one method to another.

Calibration can be divided into three levels, depending on the type of modeled errors. The first of which models the differences between the actual and reported joint displacement values. This is also known as mastering. The second level, kinematic calibration, is related to the geometry of the robot and performing full geometric calibration, including angle offsets and joint lengths. The third level, non-kinematic calibration, models errors such as stiffness and friction.

Calibration offers higher positioning accuracy for offline programmed robots. Accuracy means that the real position of the robot end effector corresponds better to the actual position calculated from the robot’s mathematical model. In the case of offline programming, pose accuracy is considered an important performance criteria.

The calibration method used in out project is the first; using a predefined and built-in calibration program, which can be performed through different procedures in the KUKA platform, varying for tool and base calibration. For base calibration, these procedures are 3-point method, indirect method and Numeric input, and for tool calibration the procedures are

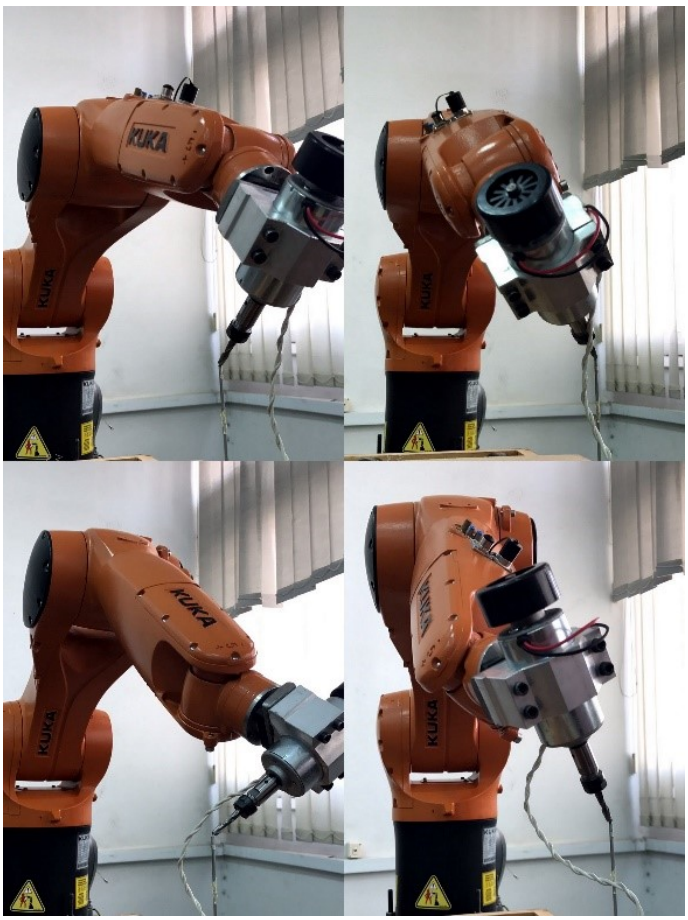


Figure 6.4.: calibration

XYZ 4-point method and XYZ reference method, both for TCP, ABC 2-point method and Numeric input. For the purpose of our project, the applied calibration procedures for both tool and base calibration were XYZ 4-point method and 3-point method respectively.

6.2.1. Tool calibration using XYZ 4-point procedure

The TCP of the tool to be calibrated is moved to a reference point from four different directions. The reference point can be freely selected. The robot controller calculates the TCP from the different flange positions. These four directions must be sufficiently different from one another (similar to the positions shown in the provided pictures).

Precondition

- A previously calibrated tool is mounted on the mounting flange.
- Operating mode T1

Preparation Calculate the TCP data of the calibrated tool:

1. In the main menu, select Start-up > Calibrate > Tool > XYZ Reference.
2. Enter the number of the calibrated tool.
3. The tool data are displayed. Note the X, Y and Z values.
4. Close the window.

Procedure

1. In the main menu, select Start-up > Calibrate > Tool > XYZ Reference.
2. Assign a number and a name for the new tool. Confirm with Next.
3. Enter the TCP data of the calibrated tool. Confirm with Next.
4. Move the TCP to a reference point. Press Calibrate. Answer the request for confirmation with Yes.
5. Move the tool away and remove it. Mount the new tool.
6. Move the TCP of the new tool to the reference point. Press Calibrate. Answer the request for confirmation with Yes.
7. Enter the payload data. (This step can be skipped if the payload data are entered separately instead.) (>>> 5.12.3 "Entering payload data" Page 138)
8. Confirm with Next.
9. If required, coordinates and orientation of the calibrated points can be displayed in increments and degrees (relative to the FLANGE coordinate system).
10. For this, press Meas. points. Then return to the previous view by pressing Back.

11. Either: press Save and then close the window via the Close icon. Or: press ABC 2-point or ABC World. The previous data are automatically saved and a window is opened in which the orientation of the TOOL coordinate system can be defined.

6.2.2. Base calibration using 3-point method

During base calibration, the user assigns a Cartesian coordinate system (BASE coordinate system) to a work surface or the workpiece. The BASE coordinate system has its origin at a user-defined point. In 3-point calibration, the robot moves to the origin and 2 further points of the new base. These 3 points define the new base.

Advantages of base calibration

1. The TCP can be jogged along the edges of the work surface or workpiece.
2. Points can be taught relative to the base. If it is necessary to offset the base, e.g. because the work surface has been offset, the points move with it and do not need to be retaught.

Precondition

- A previously calibrated tool is mounted on the mounting flange.
- Operating mode T1

Procedure

1. In the main menu, select Start-up > Calibrate > Base > ABC 3-point.
2. Assign a number and a name for the base. Confirm with Next.
3. Enter the number of the mounted tool. Confirm with Next.
4. Move the TCP to the origin of the new base. Press Calibrate. Answer the request for confirmation with Yes.
5. Move the TCP to a point on the positive X-axis of the new base. Press Calibrate. Answer the request for confirmation with Yes.

6. Move the TCP to a point in the XY plane with a positive Y value. Press Calibrate. Answer the request for confirmation with Yes.
7. If required, coordinates and orientation of the calibrated points can be displayed in increments and degrees (relative to the FLANGE coordinate system). For this, press Meas. points. Then return to the previous view by pressing Back.
8. Press Save.

Note

For more information about tool and base calibration, please refer to section “5.11 Calibration” in the provided manual “07-KSS_82_Software programming_en”.

6.3. WorkVisual and LAN connection

The WorkVisual software package is the engineering environment for KR C4 controlled robotic cells. It offers the following functionalities:

- Configuring and connecting field buses
- Programming robots offline
- Configuring machine data
- Configuring machine data
- Editing the safety configuration
- Transferring projects to the robot controller
- Loading projects from the robot controller
- Comparing a project with another project and accepting differences where necessary
- Managing long texts
- Managing option packages
- Diagnostic functionality
- Online display of system information about the robot controller

- Configuring traces, starting recordings, evaluating traces (with the oscilloscope)

Hardware requirements: Minimum requirements

- PC with Pentium IV processor, min. 1500 MHz
- 512 MB RAM
- DirectX8-compatible graphics card with a resolution of 1024x768 pixels

Recommended specifications

- PC with Pentium IV processor and 2500 MHz
- 1 GB RAM
- DirectX8-compatible graphics card with a resolution of 1280x1024 pixels

Software requirements:

- Windows 7 (Both the 32-bit version and the 64-bit version can be used).
- Or: Windows XP (32-bit version, with at least Service Pack 3, the 64-bit version cannot be used).

If the following software are not already installed on the PC, the installation wizard automatically starts their installation before preceding with the WorkVisual installation.

- .NET Framework 2.0, 3.0 and 3.5
- SQL Server Compact 3.5
- Visual C++ Runtime Libraries
- WinPcap

6.3.1. WorkVisual Installation

1. Start the program setup.exe.

2. If the following components are not yet installed on the PC, an installation wizard opens:
   - NET Framework 2.0, 3.0 and 3.5 Follow the instructions in the installation wizard. .NET Framework is installed.
3. If the following component is not yet installed on the PC, an installation wizard opens:
   - SQL Server Compact 3.5 Follow the instructions in the installation wizard. SQL Server Compact 3.5 is installed.
4. If the following components are not yet installed on the PC, an installation wizard opens:
   - Visual C++ Runtime Libraries
   - WinPcap Follow the instructions in the installation wizard. Visual C++ Runtime Libraries and/or WinPcap is installed.
5. The WorkVisual [...] Setup window opens. Click on Next.
6. Accept the license agreement and click on Next.
7. Click on the desired installation type.
8. Click on Install. WorkVisual is installed.
9. Once installation is completed, click on Finish to close the installation wizard.

Note

For more information about installation, uninstallation and GUI of the WorkVisual software, please refer to Manual "KST_WorkVisual_en".

6.3.2. LAN connection

In order to start file sharing process and to be able to use all functions of WorkVisual, a PC-Controller connection must be established. There are several ways to connect the KRC4 and KUKA-PC, one of which is setting up a local network for the connection of between several devices. This

can be done by either setting static IPs for the connected devices and connecting them physically using a specified Ethernet cable, or by using a network router and assign dynamic IPs starting from a specified value, with specified number of connected devices.

To obtain and/or change IP values for the PC

1. Open "Network and sharing center"
2. Choose "Change adapter settings"
3. Right click "Ethernet connections"
4. Choose "Internet protocol version 4 (TCP/IPv4)"
5. Choose "Properties"
6. Next you either set static IPs or choose dynamic IPs to be set, in our case by the router.

Note

The following address ranges are used by default by the robot controller for internal purposes. IP addresses from this range must not therefore be assigned by the user.

- 192.168.0.0···192.168.0.255
- 172.16.0.0···172.16.255.255
- 172.17.0.0···172.17.255.255

LAN Configuration steps

1. Connect the PC and the KRC4 to the router using regular Ethernet cables.
2. Access the router configuration page using the given data on the back of the router. (the router used in our case is TP-LINK, with username and password both being admin)
3. In the Interface setup change the LAN settings to your preferred values

4. It is preferred to set the starting IP address similar to that of the KRC4 (172.31.147) to avoid conflicts. Network gateway value is (172.31.1.1) and subnet mask (255.255.0.0), all other settings shall remain unchanged.

Figure 6.5.: Network Configuration

5. After changing these values, the IP address used to access the router settings will change from (192.168.1.1) to the set gateway value (172.31.1.1) but with the same user name and password.

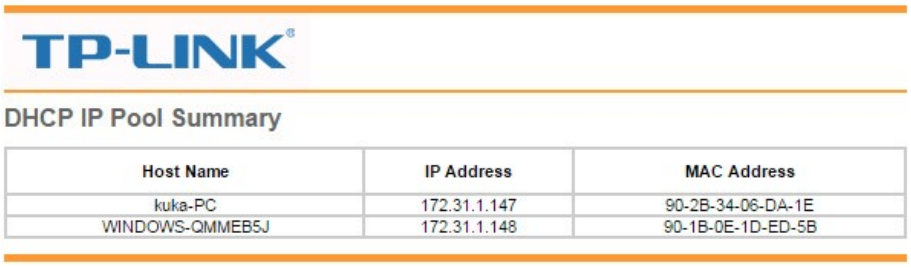


Figure 6.6.: Network Configuration: IP address

6. The connection is now established and can be verified by checking the router LEDs

6.4. Installation of KUKA.Sim Pro

KUKA.Sim Pro is used for the complete offline programming of KUKA robots. This product allows the analysis of cycle times and the generation of robot programs. It also enables a real-time connection to the virtual KUKA robot controller (KUKA.OfficeLite). KUKA.Sim Pro is additionally used for building parametric components and defining kinematic systems, which can also be used in KUKA.Sim Layout and KUKA.Sim Tech. KUKA.OfficeLite is included in the KUKA.Sim Pro package. CAD importers are available as an option. This requires a purchasable license for each import interface.

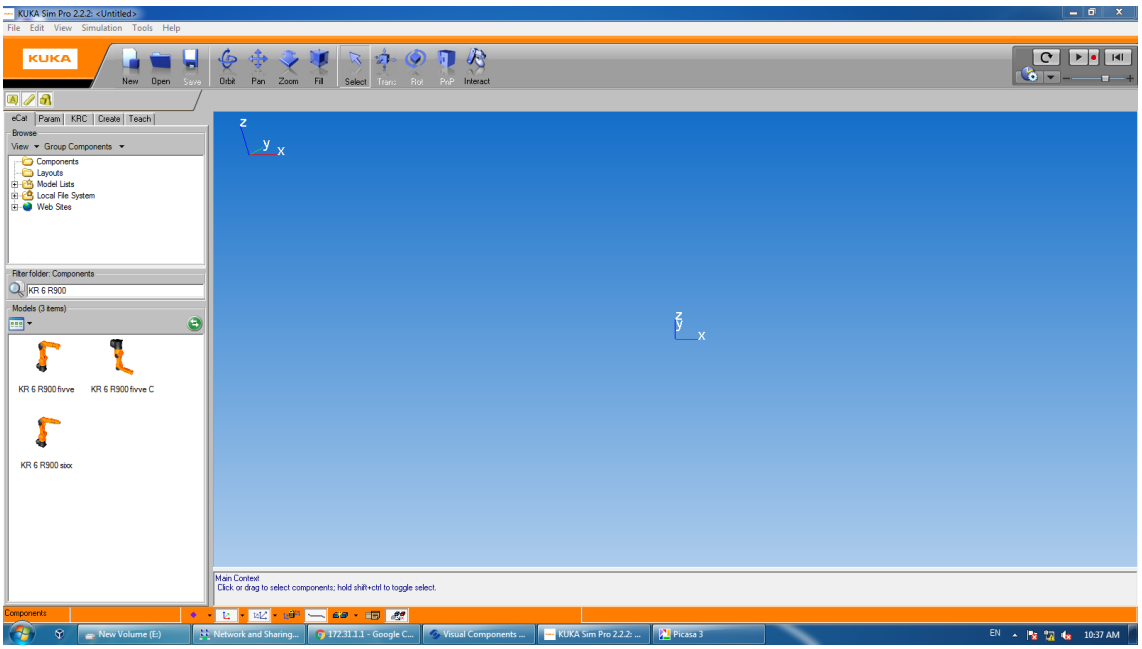


Figure 6.7.: simpro

Requirements

- The minimum requirements for the computer are a 2 GHz CPU and 2 GB RAM, and an OpenGL-capable graphics card with at least 512 MB RAM and a resolution of 1024 x 768 pixels or a similarly specified notebook.
- Supported operating systems are WIN XP - 32-bit or WIN 7 - 32/64-bit.

6.4.1. Installation

1. Start the setup file ".exe"
2. Read the agreement and activate the check box "I accept ..."
3. Select "Install" to start installation.
4. Select "Install" to complete installation

Installing the component library

After installation of the KUKA.Sim software product, the component library is installed with the following program: SetupKUKASimLibrary_2.2.0_Buildx.exe The procedure is very similar to the installation of the software products. Simply follow the instructions given. The KUKA.Sim component library contains over 1,000 typical layout components (robots, grippers, fences, etc.), various demo layouts and tutorials for KUKA.Sim. Although the KUKA.Sim products still work without the component library installed, it is strongly recommended that the component library is installed in order to be able to create layouts quickly and easily.

6.4.2. License types

There are different types of licensing for the KUKA software. License types are determined and verified in accordance with the purchase

made from KUKA Roboter GmbH. The software licensing concerning the KUKA arm at Zagazig university is an educational bundle license. The serial number for the license is found in the booklet of the KUKA.Sim Pro CD. Information about different licensing bundles are obtained by contacting KUKA Roboter GmbH by email **simulation@kuka-roboter.de.** Further details about the steps of obtaining the serial key, for different commercial bundles, are found on page 13 of (KUKA.Sim 2.2- Installation-en) manual.

Note

The serial number associated with this purchase is: **K5P22-N174H-AW7KY-9**

Stand-alone License The license is on the PC on which KUKA.Sim is used. The license key is then valid for this PC only. It can also be transferred to a different PC, but cannot be used on a two different PCs at the same time, or when either of the two PCs is off.

Network License Network licenses provide a flexible way of using KUKA.Sim on more than one PC. When a license is requested by a PC, this license is then allocated to this PC. When KUKA.Sim is closed, the license becomes available again and can be accessed by other PCs. A license server is required to manage the network licenses. When KUKA.Sim Pro is started, the computer's identity (IP address, please refer to **LAN connection** in manual Section "WorkVisual & LAN connection") is required occasionally, however, KUKA.Sim Pro needs to check with the local license server to make sure that KUKA.Sim Pro and server are on the same PC, which is required in the network license configuration.

Requesting a license file manually

1. Start the installation of KUKA.Sim Pro
2. Enter the license key
3. Select "Activate manually" and save the request file

4. Go to the Visual components customer portal and use the given email and password, mentioned in the previous section, to login.
5. On the website, choose Manual Licensing, upload the request file and confirm.

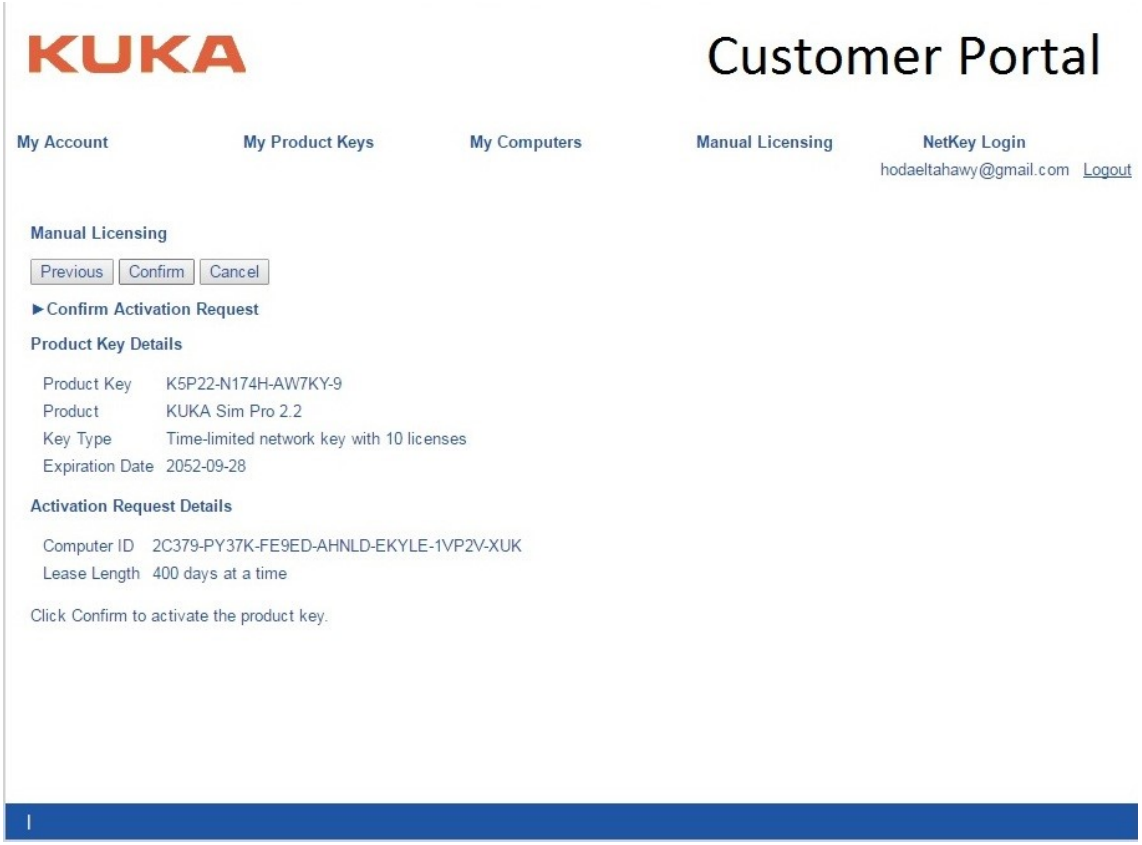


Figure 6.8.: Requesting a license file manually

6. The license should be activated.
7. Download the license (.dat) file and click Finish. Please complete the installation steps of the license server before proceeding with the next steps.
8. The license (.dat) file should be loaded into the license server, not the KUKA.Sim Pro interface, in order to complete the activation process.

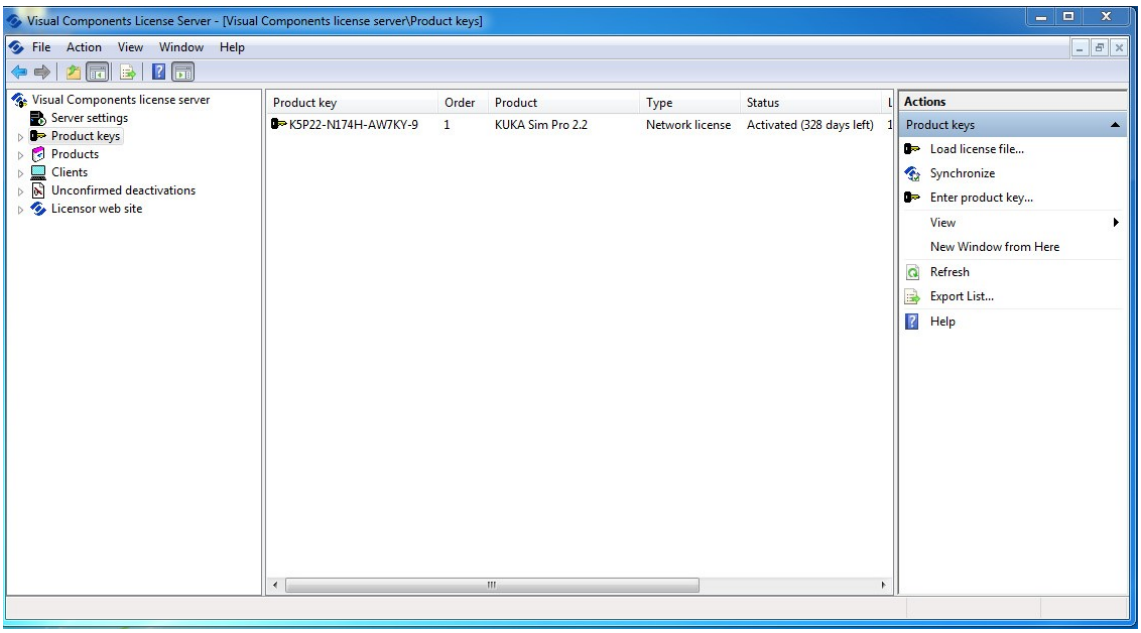


Figure 6.9.: Requesting a license file manually

9. After this process is completed, the network server interface should appear as follows

Installing the license server

Requirements "Microsoft Management Console" (MMC) must be installed on the license server. The software can be downloaded from the Microsoft website. In addition, ".NET framework 3.5" or higher should be installed.

Installation

1. The license server is started via "Start > Programs > Visual Components > Visual Components License Server > Visual Components License Server Manager".
2. Choose "Server settings" from the left panel, make sure that the license server is started, if not, click Start to activate it. The port number value is 5093.

3. On the left-hand side, select “Product keys” in order to enter the license key.
    - The right-hand side changes and “Enter product key...” is offered. Click on this.
    - A window is opened in the center, in which the license key can be entered.
    - If manual licensing is being performed using a license file, this license file must be loaded with “Load license file...”.
4. Enter the license key and confirm with OK.

For network licensing, an account linked with the purchase is created on the Visual Components website (`http://www.visualcomponents.com`). In the specified customer portal (`https://portal.visualcomponents.net/website/Login.aspx`), sign in with the email `hodaeltahawy@gmail.com` and password quails@123 . In the “My Products keys” tab, you will find the product key for KUKA.Sim Pro on the KUKA-PC device, at the Mechatronics lab. The license is already activated and will only require renewal after a period of 400 days starting 3-12-2016, which is on 7-1-2018.

6.5. End-effector installation

6.5.1. Pneumatic gripper

The KUKA AGILUS offers numerous options for different end-effectors installations. One of the most common end effectors is a gripper, whether it be vacuum, pneumatic, hydraulic or servo-electric grippers. We are concerned with pneumatic grippers, which operate using air pressure. When air pressure is applied on the pistons, the gripper closes. When the pressure is released the gripper opens. The only way to manage the force in the gripper is to manage the air pressure in the air intake (or valve). The gripper used in our study is the SOMMER automatic GP 404 NC-C We also had the opportunity to work with one of KUKA Roboter's Application software; Gripper&SpotTech. These are ready-made software packages created for different industrial applications. Optional features can be installed on the controller easily and quickly and can also be tailored to the specific production environment.

These software include, and not limited to, KUKA.ArcTech, which enables implementation and programming of applications for arc welding and plasma cutting, KUKA.ConveyorTech, which automatically adapts the actions of the robot to the motion of an assembly line or conveyor belt and KUKA.CNC, which links the CNC and robot directly to each other. As a result, they can be operated like a conventional CNC controller.

Pneumatic grippers can be used in many applications, some of which include assembly purposes, Labs automation, and on mobile robots.

This software package offers numerous advantages, including:

- 16 freely configurable grippers
- 16 freely configurable grippers
- Gripper conditions statically and dynamically monitored
- Unlimited user-defined gripper icons
- Unlimited user-defined gripper icons
- Graphical user interface with indicator lamps, a status display and online adaptation

- Adaptation via WorkVisual 4.0 and on the smartPAD for production-relevant elements

6.5.1.1. Gripper connection

The gripper is connected to the air supply through the Air 1 port located on link 3 (The port is shown in the following picture). This port is connected internally to Air 1 port on the back of the robot arm, which in turn is connected with the air compressor.

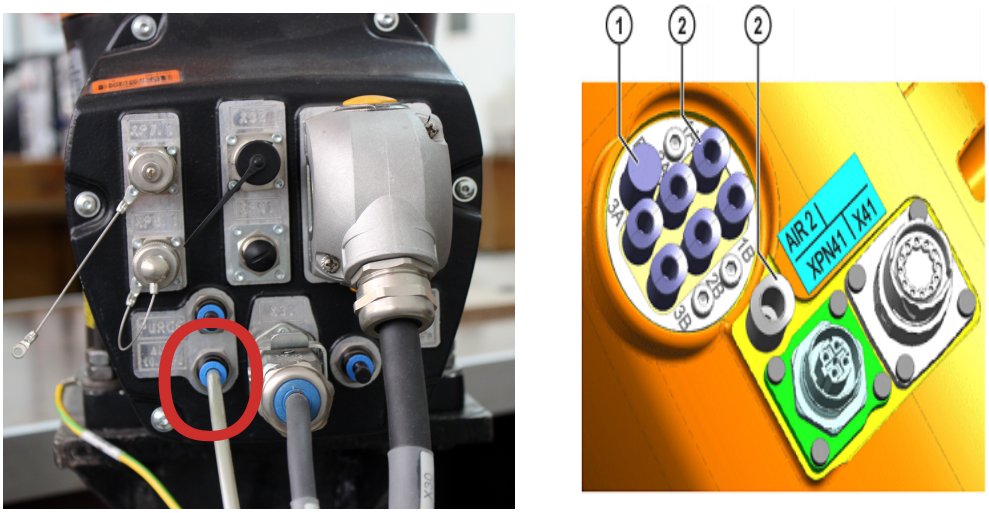


Figure 6.10.: Grippers

In order for these ports to be operative, the connection between the ports and the controller must be activated, this is performed using mapping. Mapping can be simply described as the process of creating a link or a connection between ports on the robot arm and inner components in the controller in order to use them in control purposes, in our case operating the gripper. Mapping is performed through WorkVisual through the steps mentioned below.

1. get current project from robot using workvisual
2. save it as different file name
3. activate project in work visual (by double clicking on Controller<kss version>)

4. open I/O mapping
5. leave left pane on KRC (those are I/Os that robot programs can access), and click on inputs
6. move right pane to Fieldbus (those are physical I/O), then highlight EM8905 module (this is I/O card inside agilus arm)
7. map inputs of EM8905 to robot inputs of your choice
8. repeat steps 5.6.7 for outputs
9. on the robot login as Expert or higher (Expert will work in this case since we did not modify safety configuration)
10. deploy modified project to robot and activate it (on robot). You should have something like on image below.

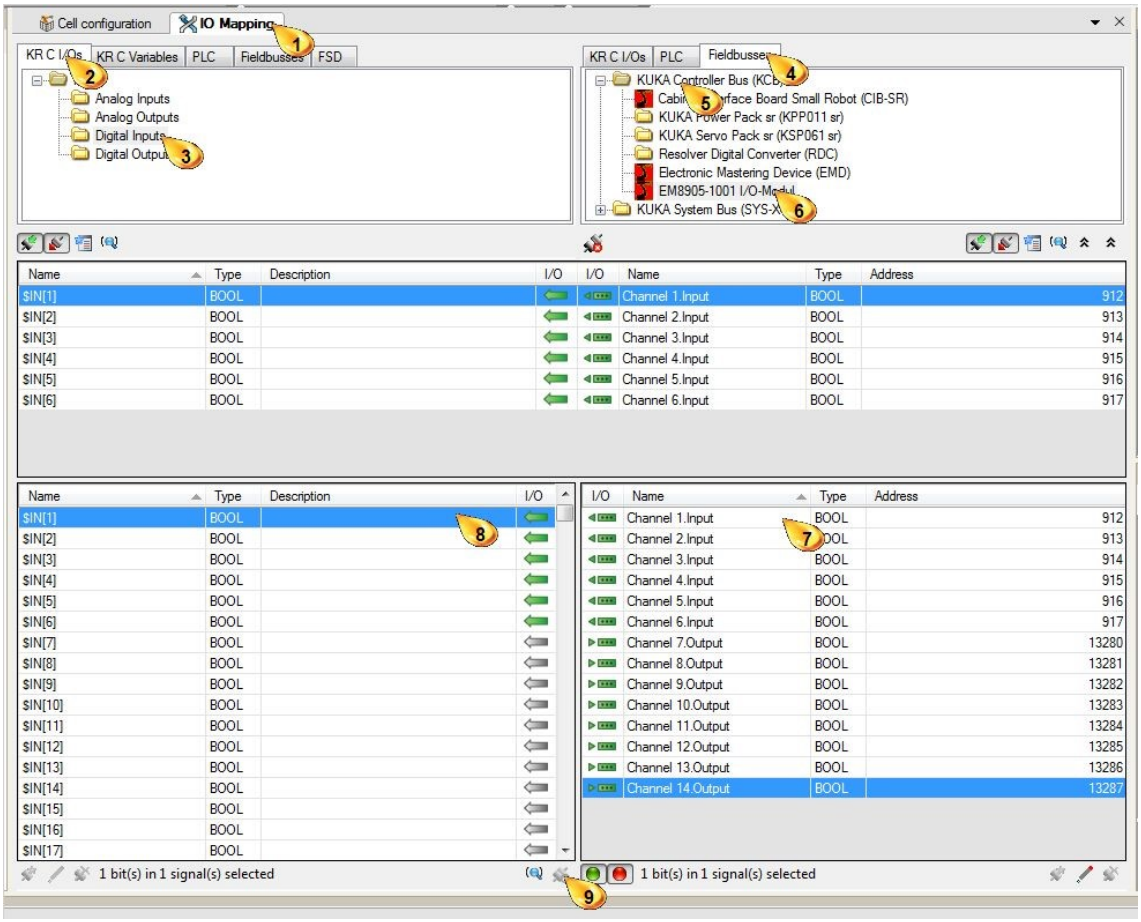
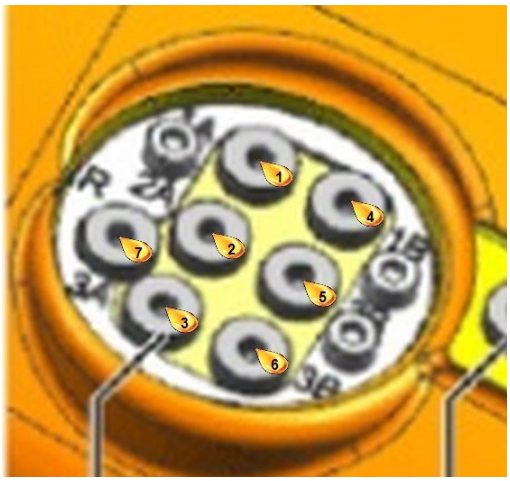


Figure 6.11.: Gripper configuration

Six valves are mapped to ports:

1. 1A
2. 2A
3. 3A
4. 1B
5. 2B
6. 3B
7. R (relief/exhaust)



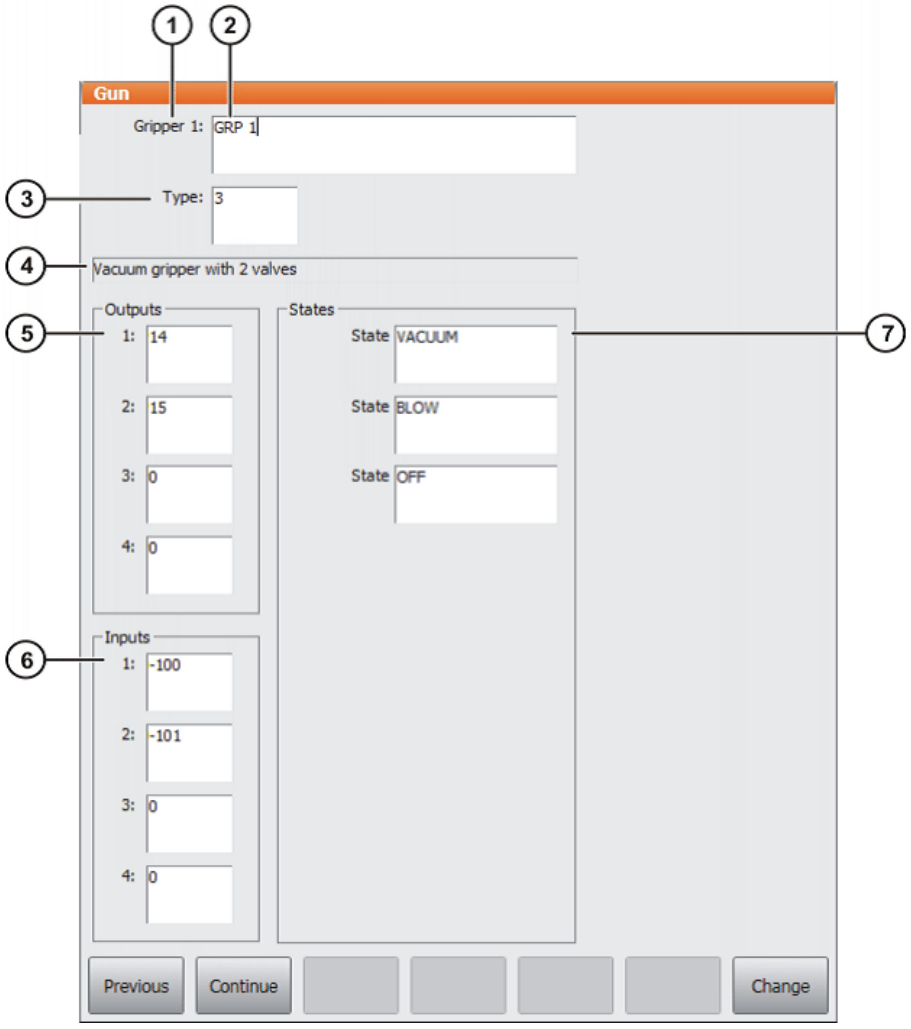


Figure 6.12.: Configuring predefined grippers

Configuring predefined grippers

Gripper settings can be changed using smart pad. In the main menu, select Configure > I/O > Gripper. A window opens (shown in figure), inside it you'll find a list of the predefined grippers, select the desired gripper number with Next or Previous.

You can change number of grippers)1), Name of gripper (2), Type of gripper (3), designation of gripper type (4), Assignment of the output numbers (5), Assignment of the input numbers (6) and Switching states (7).

The third cell, designated for the type of gripper is explained in the following section, Predefined gripper types.

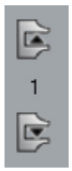
Predefined gripper types There are five predefined gripper types in Gripper&SpotTech. If these types are not sufficient, additional gripper functions can be programmed.

- Type 1: Single-element gripper, static, open/closed
- Type 2: With mid-position valve
- Type 3: Vacuum gripper with 2 valves
- Type 4: Vacuum gripper with 3 valves
- Type 5: Single-element gripper with pulse valves, open/close

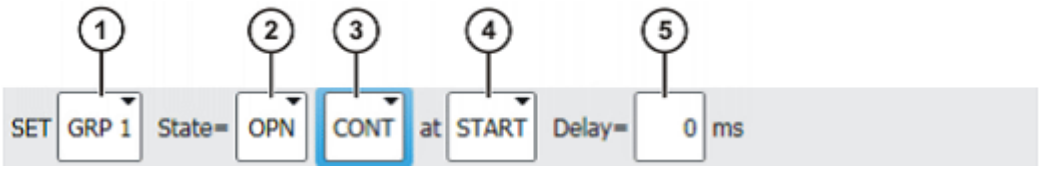
Note

More information about the specifications of each type and user specified grippers can be found in manual "KST_GripperSpotTech_32_en".

Gripper operation Manual gripper control can be performed using technology keys on smart pad. The settings for the technology keys are already set for this gripper and appear with the following icons on the smart pad screen, next to the assigned buttons.

Icon	Description
	Select gripper The number of the gripper is displayed. Pressing the upper key counts upwards. Pressing the lower key counts downwards.
	Toggle between the gripper states (e.g. open or close)

The gripper is opened or closed using these buttons, after pressing the enable buttons on the back of the smart pad. They can also controlled inside KRL programs in inline form through the following command



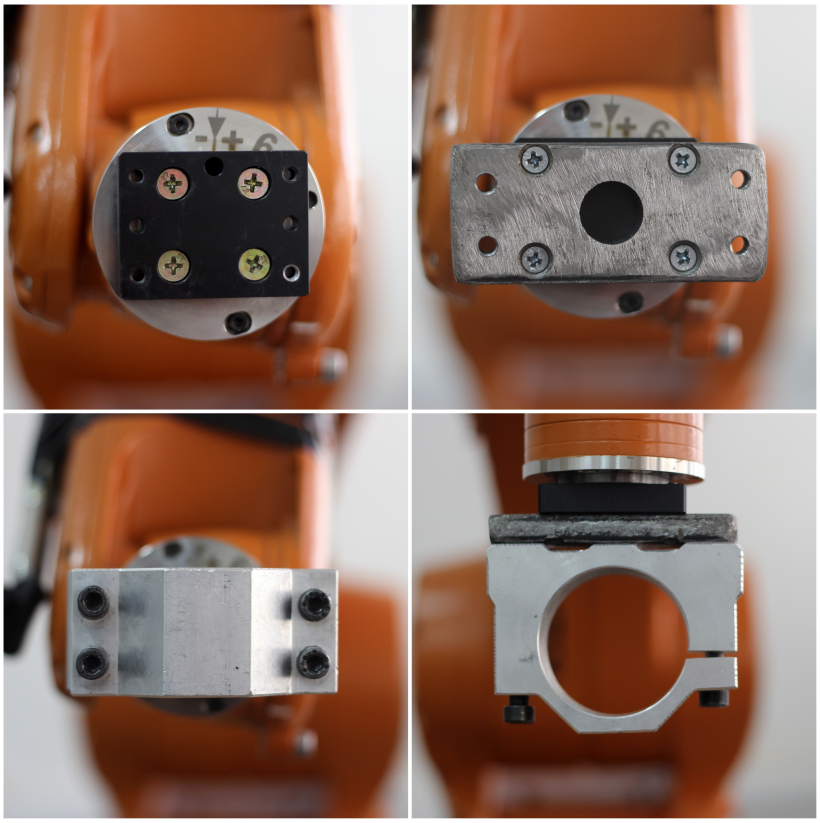
Where:

1. Choosing the desired gripper from a list of predefined grippers in settings
2. Set the state of the gripper, whether to open or close
3. CONT: Execution in the advance run
4. Box only available if CONT selected.
   - START: The gripper action is executed at the start point of the motion.
   - END: The gripper action is executed at the end point of the motion.
5. Box only available if CONT selected. Define a wait time (-200:200 ms), relative to the start or end point of the motion, for execution of the gripper action.
6. Box only available if [blank] selected. Data set with gripper parameters

6.5.2. Electric spindle

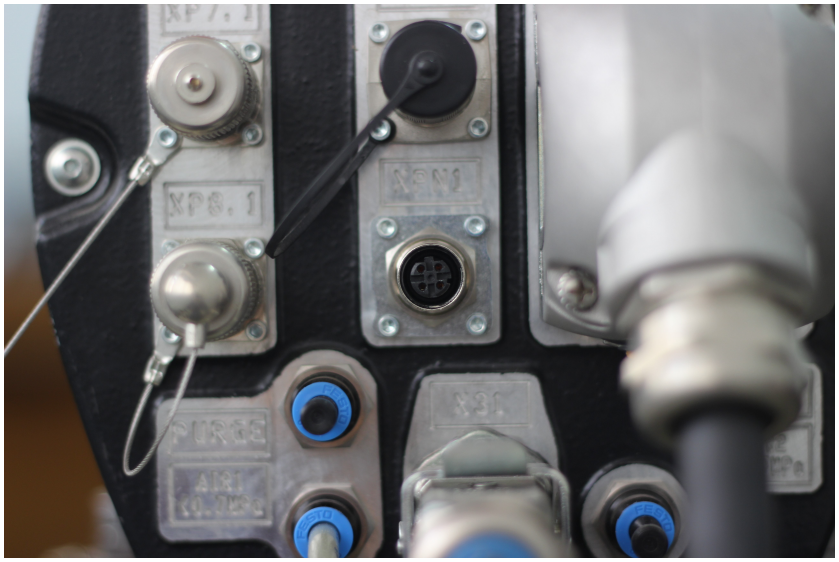
For the purpose of milling, a spindle was attached as an end effector to perform this process. The spindle used was a simple ON/OFF spindle, which required no control signals, so it merely needed to be attached to the end effector and to an external power supply.

Spindle attachment For the spindle to be attached to the sixth axis of the robot, a metal linkage was designed and manufactured to fit both the spindle and the mounting surface on the sixth axis. The first picture shows the mounting surface of the sixth axis of the robot. The second shows the metal linkage after being installed to the mounting surface. The Third and fourth pictures shows the spindle's metal holder.



Spindle connection The power supply of the spindle is connected to port XPN1 on the fourth axis, whose output is internally linked to a similar

port XPN1 on the back side of the robot. The port contains four openings or smaller ports; the positive wire is connected to the two right-hand side ports and the negative side to the left-hand side ports. The ports are shown in the picture below.



Spindle specifications The spindle used is an Air cooled spindle, with a 300W CNC Spindle Motor, supplied by a 220 voltage source, with adjustable speed through the attahced knob. The spindle must operate with full speed during the milling process. Further information about the spindle can be found in the resources in the references.

End mill used for machining The end mill used is a double blade 6 mm Carbide blade. A 6 mm collet was used to attach the end mill to the spindle. A collet is a subtype of chuck that forms a collar around an object to be held and exerts a strong clamping force on the object when it is tightened, usually by means of a tapered outer collar. Both the end mill and the collet can be changed for different milling purposes, as an example, a smaller end mill can be used to obtain a higher level of fine details that larger end mills can't offer, while larger end mills can be used to remove more material or perform faster in basic milling operations that does not require a high level of details.

"Look up at the stars and not down at your feet. Try to make sense of what you see, and wonder about what makes the universe exist. Be curious."

— Stephen Hawking, (British theoretical physicist, and cosmologist

Chapter 7
Safety

7.1. General

7.1.1. Terms used

- Work space: Space where the manipulator allowed to move.
- Danger zone: consist of workspace and stopping distance.
- Safety zone: Is outside the danger zone.
- KCP: KUKA control panel (teach pendant) has all operator control.
- Stop 0: Drivers are deactivated immediately and breaks are applied.
- Stop 1: Drivers are deactivated after 1s and breaks are applied.
- Axis range: Range of each axis, in degrees or millimeters, within which it may move.
- T1 Test mode: Manual Reduced Velocity (less than 250 mm/s)
- T2 Test mode: Manual High Velocity (more than 250 mm/s permissible)

7.1.2. Description of KUKA manipulator

components

- Manipulator
- smart PAD
- connecting cable from smart PAD to controller
- Controller
- Data connection cable
- Motors connecting cable

Axis

- In-line wrist (A4,A5,A6)
- Arm (A3)
- Link arm (A2)
- Rotational column (A1)

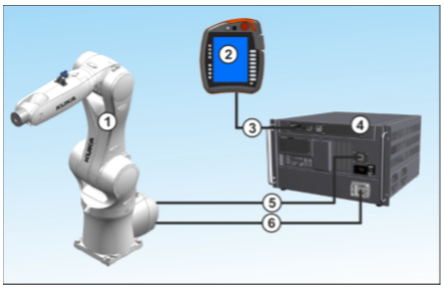


Figure 7.1.: Description of KUKA arm

7.2. Warnings and notes

These warnings are relevant to safety and must be observed.

Figure 7.2.: warning and notes

7.3. Workspace, safety and danger zone

Workspaces are to be restricted to the necessary minimum size it must be safeguarded using appropriate safeguards.The safeguard must be situated inside the safety zone. In the case of a stop, the manipulator and external axes are braked and come to a stop within the danger zone which consists of the workspace and the stopping distances of the manipulator.The maximum reach of the robot is 901mm

Work envelope[1]	Dimensions A	Dimensions B	Dimensions C	Dimensions D	Dimensions E	Dimensions F	Dimensions G	Dimensions H	Dimensions I	Dimensions J
KR 6 R900 sixx	1,276 mm	1,620 mm	901.5 mm	656 mm	245.5 mm	851.5 mm	420 mm	455 mm	400 mm	855 mm

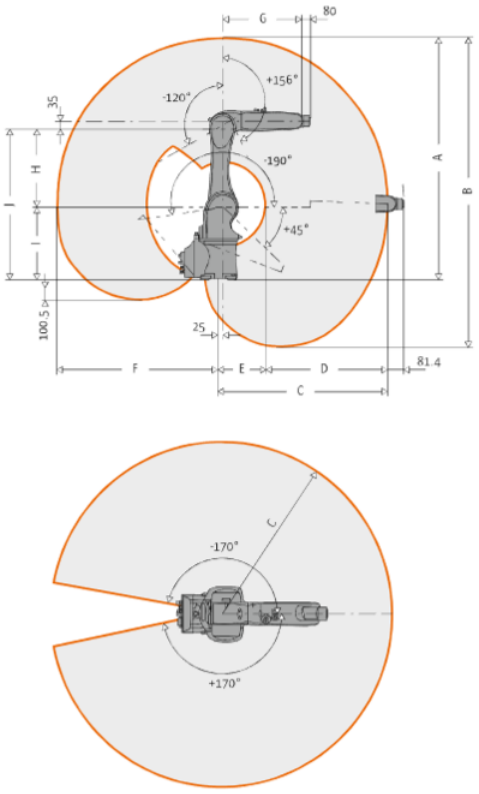


Figure 7.3.: Working space

7.4. Safety function

- Emergency stop is the device must be pressed in the event of a hazardous situation or emergency, The manipulator and any external

axes are stopped with a safety stop1.

- Enabling device of the industrial robot are the enabling switches on the KCP.There are 3 enabling switches installed on the KCP which have 3 positions
  - Not pressed
  - Center position
  - Panic position
- Jog mode is an additional protective equipment where the robot use operating modes T1 and T2 to execute the program.This means that it is necessary to hold down an enabling switch and the Start key in order to execute a program.
- operator safety is a signal used for interlocking physical safety gate in case of losing the signal during automating operation the manipulator will stop with stop 1.

7.5. Safe operating zone

Vision technology has become a critical component for many robot applications, enabling robots to be deployed into new areas. Over the years the technology has matured becoming very reliable, with higher performance and pricing has dropped dramatically. Giving robots eyes enables them to perform increasing complex operations in ways that dramatically improve their performance. For example, robots guided by vision can locate parts to be picked up, determine where to apply a weld, inspect parts that have been assembled, determine where to place a part. The possibilities are endless. The possibilities are not only limited to the industrial applications. For example, hand gestures can be used in teleoperation, navigation, or even to perform a surgery! [[[IEEE reference]]]. Computer vision libraries made it possible to detect human body and hence a safe operation zone can be provided. For more applications, you can have a look at this interesting IEEE article: `http://spectrum.ieee.org/automaton/robotics/diy/top-10-robotic-kinect-hacks`

7.6. State of the art

One of the most important piece of information that a normal camera misses is the depth of the image. The depth is important in recognizing the real world in a proper way. Researchers had found many solutions for this problem like the stereo camera installations, or even including depth sensors with the RGB camera itself, like in the Kinect. Kinect is a depth sensor which is able to return images like an ordinary camera, but instead of color, each pixel value represents the distance to the point. As such, the sensor can be seen as a range- or 3D-camera. For more technical details about Kinect, please refer to this website:

`https://ese.wustl.edu/ContentFiles/Research/UndergraduateResearch/CompletedProjects/WebPages/fl12/MattJohnson/kinect1.html`

Robotic grasping, object recognition, and human tracking became possible by interfacing Kinect camera to robots, especially robotic manipulators.

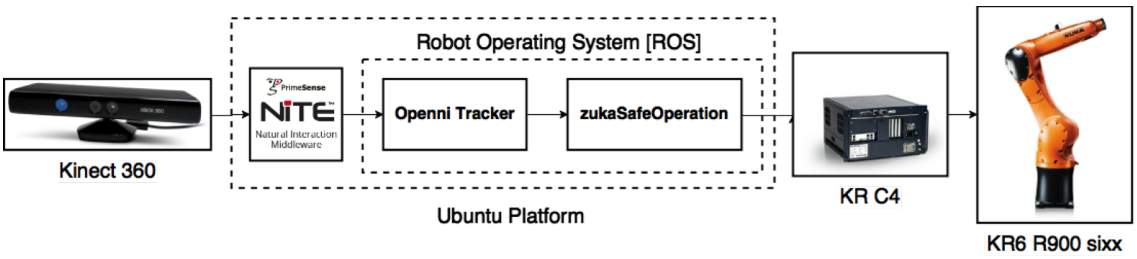


Figure 7.4.: Safe Operating Zone

7.7. What we have done

We have used the Kinect and Robot Operating System (ROS) platform to implement two vision dependent systems on the KUKA robot:

- Visual Servoing System, that makes the robot moves according to the tracked person's hand position.
- Safe Operating Zone, where the robot slows down to 10

7.8. Safe Operating Zone

Human safety is the main concern which prevents performing some tasks requiring physical interaction between human and robot. Therefore, the safety concept was previously based on eliminating contact between human and robots. Using vision system, we've made it possible for the robot to detect and recognize human body, and its distance to the fixed camera, hence a safe operating zone can be acquired by sending a signal to the robot to change its speed when a human is in the safety zone. This is done by sending the RGB and depth data from the Kinect to the NiTE library, which is a middleware that provides body and skeleton detection, then reading this data by a ROS node to calculate the instantaneous distance of each human's center of mass, and the signal is sent by another ROS node that listens to the stream of the least user distance.

7.9. How to Use

- Install kukavarproxy as explained before, and make sure that everything is ok
- Install ROS, NiTE, and openni_tracker as explained before
- Launch the roscore, but don't launch the openni_tracker node
- Copy the our modified openni_tracker.cpp file to your catkin openni_tracker package. Our node publish and extra topic called /closestUser-Distance which gives the least detected distance of any tracked user without the need of standing in the psi calibration position
- Copy the zukaSafeOperation package to your catkin workspace, and run catkin_make to build the node. Don't forget to change node mode to executable if it hasn't.
- Use: rosrun zukaSafeOperation zukaSafeOperation to launch the package
- The package requires a proper internet connection through kukaproxvar, and changes the robot speed to 10% of it's speed when a user is detected within a range of 2 meters.

How to edit the detection data and the speed limits: In the source code you'll find variables to define the range, and the limited speed. Change these variables to your desired ones

Where to download:

- Edited openni_tracker: `https://github.com/mnourgwad/zuka/tree/master/codes/openni_tracker`
- zukaSafeOperation: `https://github.com/mnourgwad/zuka/tree/master/codes/zukaSafeOperation`

"I think setting a goal, getting a visual image of what it is you want. You've got to see what it is you want to achieve before you can pursue it."
— Chuck Norris, (American martial artist, actor, film producer and screenwriter)

Chapter 8
Experiments Guide

8.1. Experiment 01:Motion Programming Inline Form

Aim of the experiment

- Text program execution
- understand PTP motion
- Get familiar with program creation and editing in "User" interface

Preconditions

- Knowledge of how to use Navigator.
- Knowledge of operating modes
- Theoretical knowledge in motion programming (PTP type)
- Tool and base coordinate system calibration

Introduction

User programming Inline forms are available in the KSS for frequently used instruction. They simplify programming and facilitates user interface with controller without the need of knowing detail information about KUKA programming Language

Explaining Program structure Program structure previews a simple KRL syntax. The DEF line indicates the name of the program; this can be hidden or displayed. Declaration section after DEF-line, where variables and their data types declared. INI - line contains the internal variables and parameters.Mind that PTP command motion is the first command in any KRL program to be fully defined. The "HOME" position is not a program specific. It is used as the first and last position. The HOME position is stored with following values in the robot controller:

Axis	A1	A2	A3	A4	A5	A6
Value	0	-90	90	0	0	0

procedure While in the user interface, make sure to choose the right directory KRC:R1ċlick "New." to create a new module. Press "Select." to execute the program automatically.

Setting the program Override Program override is the velocity of the robot during Program execution. This value is specified as a percentage of the programmed velocity. Realize that in T1 mode, the maximum velocity is 250 mm/s. To modify the program override, touch the POV/HOV status indicator and slide the bar to the required value.

Starting Program forward (manual) After selecting the program, and the operating mode. Hold the enabling switch down and wait until the status bar indicates "Drives ready".

8.2. Experiment 02:Motion programming Inline form

Aim of the experiment

1. Understand PTP motion
2. Get Familiar with program creation and editing in "User" interface.

Preconditions

1. Familiar with Experiment 01
2. Theoretical knowledge in motion programming (PTP type)

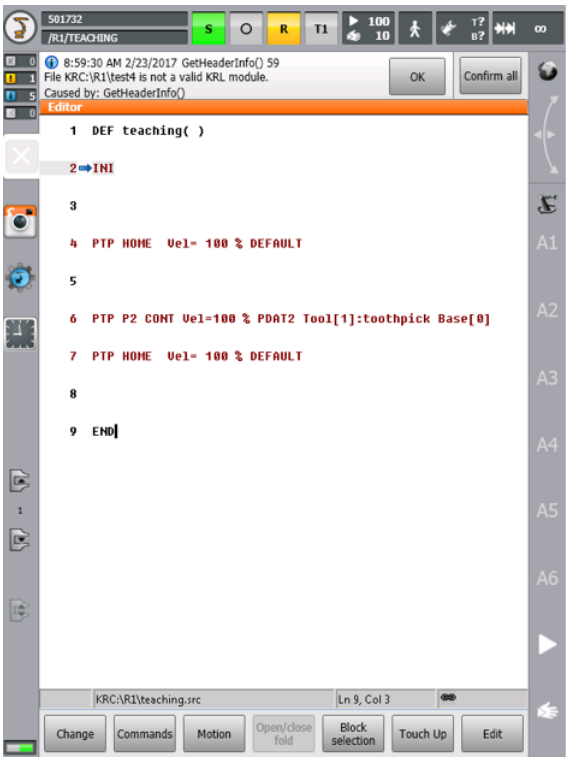
Introduction

Point to point motion type (PTP): Robot guide TCP from the current position along the fastest path to the end point specified. The first motion in the program must be PTP; Status and turns only defined in PTP command and ignored in CP motion.

"Teaching" program description: "Teaching" program is an application of online robot programming using teach pendant. The robot can move in PTP motion type to the point specified by the user. The end point assigning can be applied in the different operating modes, either axis-specific or Cartesian.

procedure While in the user interface, make sure to choose the right directory KRC:R1Ṡelect "New." to create a new module. Press "Select." to execute the program automatically. Add new motion command by pressing "Motion.". The inline form provides several settings. First, choose which kind of movement required; In this case, "PTP." is chosen. Next field specifies the position you want the robot to move. As a default, the first position is called "P1" and the index increments every time creating a new one. Names can be overwritten; in the program, the position called "P2."

Explaining Program structure: As stated in "Experiment 01", the program should start by "PTP HOME ... " and ends with the same command to ensure that all the information needed for the robot to move is fully defined. The next motion command is specified as PTP. Selecting "CONT." means that the end point is approximated this helps in executing next command early. In the last field, there is the name of motion data settings. It is created automatically so no need to change anything. After setting all parameters, Robot moved to the desired position. By pressing "touch up" button position is saved.



8.3. Experiment 03:Motion programming (Expert level)

Aim of the experiment

1. Understand and perform basic programs using KRL
2. Get Familiar with program creation and editing in "Expert" interface

Preconditions

1. Passing Experiment 02.
2. KRL basic knowledge.
3. Motion programming theoretical knowledge.
4. Tool and base coordinate system calibration

Introduction

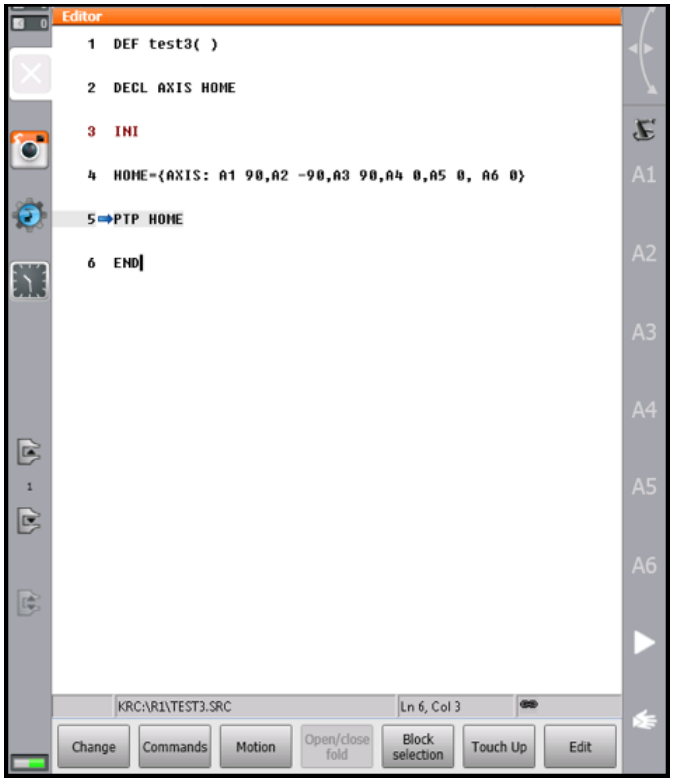
Expert group In the Expert interface, can achieve advanced programming using the KRL programming language and perform complex application programs including subprograms, interrupt programming, loops, and program branches.

"Test 3" Program Description: This program allows moving the robot to the HOME position using KRL commands. The program is similar to the one applied in "Experiment 01".

Procedure While in the Expert interface, make sure to choose the right directory KRC:R1Ċlick "New." to create a new module.

1. In the Declaration section, HOME declared as variable, Axis-specific data type > DECL AXIS HOME
2. In the initialization section, HOME assigned be the required values > HOME=AXIS: A1 90, A2 -90, A3 90, A4 0, A5 0, A6 0
3. The motion type selected is PTP > PTP HOME

User Manual provides the procedure for changing user group to Expert, in operation section > change user group.



8.4. Experiment 04:Motion programming (Expert level)LIN motion

Aim of the experiment

1. Understand and perform basic programs using KRL
2. Get Familiar with program creation and editing in "Expert" interface
3. Understand and implement LIN motion command

Preconditions

1. Familiar with Experiment 03
2. KRL basic knowledge.
3. Motion programming theoretical knowledge.
4. Tool and base coordinate system calibration.

Introduction

LIN motion In the case of linear motion, the KRC "KUKA Robot Controller" calculates a straight line from the current position (the last point programmed in the program) to the point specified by the motion command. Linear motion is programmed using the keywords LIN or LIN_REL in connection with the specification of the endpoint. LIN motion categorized as a continuous path.

"test 10" Program Description The program moves the robot from current position to a point specified in the Cartesian way. The path generated is linear using the LIN motion type. The program is written in KRL using the Expert user.

```
BAS (#tool 01)
BAS (#base 01)
; Initialization of TOOL and BASE coordinate system
PTP HOME Vel=100 % PDAT1
; PTP motion (in line command) to the system variable "HOME"
$APO.CDIS = 20
$APO.CORI = 20
$APO.CVEL = 0.2
; System variables of end point approximations
PTP HOME
LIN{X 20, Y 0, Z 0, A 180, B 0, C 0} C_VEL
; LIN motion instruction with activation of velocity approximation
```

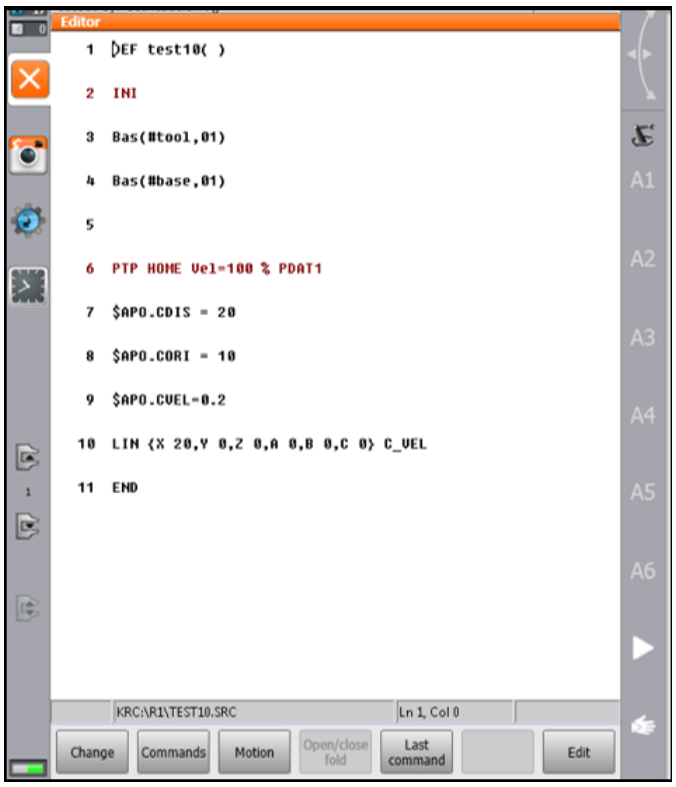
Procedure

1. While in the Expert interface, make sure to choose the right directory KRC:R1Ċlick "New." to create a new module.
2. In the initialization section, define the base and tool coordinate system for the robot.
   - BAS(#tool 01)
   - BAS(#base 01)

   Another way for initialization is to use system variables
   - $TOOL = TOOL_DATA[1]
   - $BASE = BASE_DATA[1]
3. Start to assign values to end point specifications: approximation distance, approximation orientation, and approximation velocity. These specifications can be adjusted using system variables: $APO.CDIS, $APO.CORI, and $APO.CVEL.
4. Add PTP command to HOME position. This is necessary in every program.
5. To generate the linear path, type LIN instruction and activate approximate positioning by inserting one of the keywords: C_DIS, C_ORI, and C_VEL. at the end of the command line.

Empirical Information In KRL program, the first motion instruction must declare a firm initial situation. Bear in mind to start any motion program with a PTP motion. PTP motion can be defined in Cartesian and axis-specific coordinates unlike CP motions (LIN and CIRC). HOME position is specified in axis-specific coordinate. In this program, the PTP motion written as inline form.

For further information about the system variables used in Experiment 04, check User Manual in KRL-guide section > System Variables .



8.5. Experiment 05:Motion programming (Expert level)PTP-POSE motion

Aim of the experiment

1. Understand and perform basic programs using KRL
2. Get Familiar with program creation and editing in "Expert" interface
3. Understand and implement PTP motion command in Cartesian coordinate
4. Understand "Status and turns" concept

Preconditions

1. Passing Experiment 04
2. KRL basic knowledge.
3. Motion programming theoretical knowledge.
4. Tool and base coordinate system calibration.

Introduction

Status and Turns Moving the robot into a point can produce different axis positions for the same TCP (tool center point). Referring to KRL -guide > structure type in the user manual, The entries “S” and “T”-status and turns- in a POS structure type are used to define an unambiguous position; For this reason, it is important to start any program instruction by defining the status and turn. Since "S" and "T" not taken into consideration in the CP- motion, the first line must be complete PTP structure. Status and Turn both require integer entries, which should be made in binary form.

"PTP" Program Description In this program, the first motion instruction is not the default HOME position- AXIS datatype variable – but instead

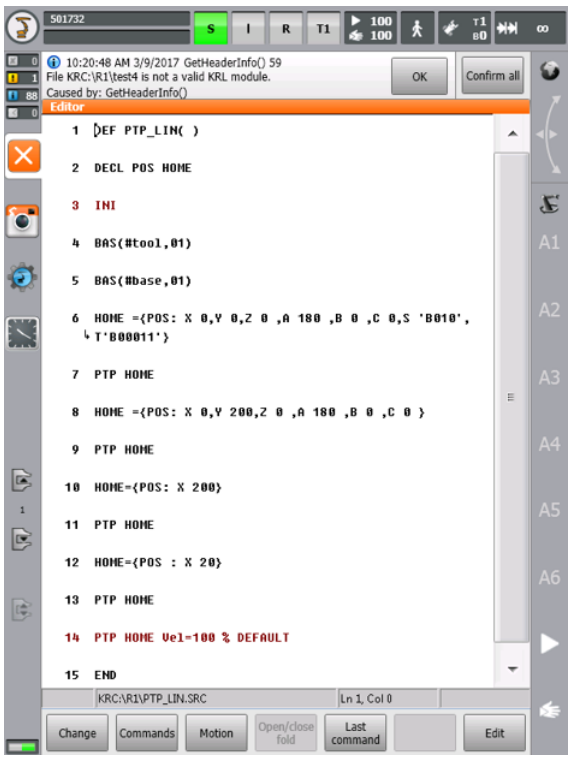
the statement is using complete PTP instruction of type POS. The program moves the robot to the point assigned to the HOME variable. The first motion is to the origin of base and tool system specified. Then the robot moves in linear and absolute shifts in X-axis and y –axis.

```
DECL POS HOME
; Declaration of HOME variable, POS structure data type.
BAS (#tool 01)
BAS (#base 01)
; Initialization of TOOL and BASE coordinate system
HOME = {POS: X 0, Y 0, Z 0, A 180, B 0, C 0, S 'B010', T 'B0011'}
PTP HOME
; PTP motion to the system variable "HOME"
HOME = {POS: X 0, Y 200, Z 0, A 180, B 0, C 0}
PTP HOME
HOME = {POS: X 200}
PTP HOME
HOME = {POS: X 20}
PTP HOME
END
```

Procedure

1. While in the Expert interface, make sure to choose the right directory KRC:R1Ċlick "New." to create a new module.
2. In the initialization section, define the base and tool coordinate system for the robot.
   - BAS(#tool 01)
   - BAS(#base 01)

   Another way for initialization is to use system variables
   - $TOOL = TOOL_DATA[1]
   - $BASE = BASE_DATA[1]
3. Write PTP motion of type POS.
4. Add PTP command to HOME position. This is necessary in every program.



8.6. Experiment 06:Motion programming (Expert level)Orientation Control

Aim of the experiment

1. Understand and perform basic programs using KRL
2. Get Familiar with program creation and editing in "Expert" interface
3. Understand and implement motion programming command in Cartesian coordinate with orientation control

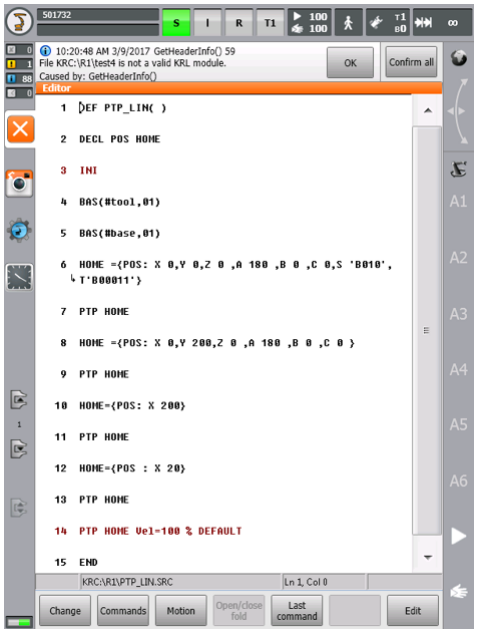
Preconditions

1. Familiar with Experiment 05
2. KRL basic knowledge.
3. Motion programming theoretical knowledge.
4. Tool and base coordinate system calibration.

Orientation Control Defining a point in space requires three translational values beside three rotational Specifications. A, B, C are the essential elements of KUKA KRL language. These values describe the orientations of tool in the base frame. KRL uses Euler angles (Z-Y-X) instead of fixed angles(X-Y-Z)

"CONE" Program Description In this program, the TCP changes orientation using for loop.

```
DECL POS HOME
; Declaration of HOME variable, POS structure data type.
BAS (#tool 01)
BAS (#base 01)
; Initialization of TOOL and BASE coordinate system
HOME = {POS: X 0, Y 0, Z 0, A 180, B 0, C 0, S 'B010', T 'B0011'}
PTP HOME
; PTP motion to the system variable "HOME"
HOME = {POS: X 0, Y 200, Z 0, A 180, B 0, C 0}
PTP HOME
HOME = {POS: X 200}
PTP HOME
HOME = {POS: X 20}
PTP HOME
END
```



8.7. Experiment 07:Gripper (Expert User)

Aim of the experiment

1. Understand and perform basic programs using KRL
2. Get Familiar with program creation and editing in "Expert" interface
3. Program gripper to toggle between open and close states in KRL

Preconditions

1. Install gripper to the robot
2. KRL basic knowledge.
3. Air line connection AIR1.
4. Tool and base coordinate system calibration.

8.8. Experiment 08: Gripper 2 (Expert User)

Aim of the experiment

1. Understand and perform programs using both Expert and Inline mode
2. Make Modifications to inline form instructions
3. Use Geometric Operator
4. Program gripper to toggle between open and close states in KRL

Precondition

1. Install gripper to the robot
2. KRL basic knowledge.
3. descriptionAir line connection AIR1.
4. Tool and base coordinate system calibration.

This experiment is a palletizing demo, where cubes are aligned with equal spaces. Only one cube position will be taught, and the robot will automatically calculate position offsets. This is done by the geometric operator (:), that adsds the offset variable to the first position. First, we need to define two variables:

- POS RR [offset postion]
- INT I [for loop counter]

The X axis of RR position will be set to I in the for loop, then the robot will move to anew point consisting of the original one and the offset.

```
DEF grip2( )
INT i
DECL POS RR
BAS (#INITMOV,0 )
RR= {X 0,Y 0,Z 0,A 0,B 0, C 0}
BAS(#VEL_CP,100)
FOR i =0 TO 200 STEP 100
FOLDs:
RR.X = i
PTP XP1:RR
ENDFOR
END
```

The true function of philosophy is to educate us in the principles of reasoning and not to put an end to further reasoning by the introduction of fixed conclusions.

— George Henry Lewes, (English philosopher and critic of literature, 1817–1878)

Chapter 9
Conclusions and Future Outlook

Chapter A
Appendices

A.1. Key terms

- Repeatability - variability in returning to the same previously taught position/configuration
- Accuracy - variability in moving to a target in space that has not been previously taught
- Tool speed - linear speed capability when tool moving along a curvilinear path
- Screw speed - rotational speed when tool is being rotated about an axis in space
- Joint interpolated motion - motion where joint taking longest time to make the joint change governs the motion and the other joints are slowed in proportion so that all joints accomplish their joint changes simultaneously with the slowest joint
- Joint limits - either the software or physical hardware limits which constrain the operating range of a joint on a robot. The software limits have a smaller range than the hardware limits.
- Joint speed limits - speed limit for robot joints, which limit how fast the links of a robot may translate or rotate.

- Point-to-point motion - characterized by starting and stopping between configurations or as the tool is moved between targets.
- Continuous path motion - characterized by blending of motion between configurations or targets, usually with the loss of path accuracy at the target transitions, as the robot moves between configurations/targets.
- Interpolation (kinematic) capabilities - robot usually capable of both forward and inverse kinematics. Both combine to give the robot the capability to move in joint space and in Cartesian space. We typically refer to the moves as joint, linear, or circular interpolation.
- Forward kinematics - specifying the joint values to accomplish a robot move to a new configuration in space. These may not be simple as it seems because secondary joints such as four-bar linkages, ball screws, etc. may be required to accomplish this motion.
- Inverse kinematics - solving a mathematical model of the robot kinematics to determine the necessary joint values to move the tool to a desired target (frame) in space. This is accomplished by frame representation whereby a triad (xyz axes) is attached to the tool on the robot and a target frame is attached to the part or operating point in the workcell. The inverse kinematics determine the joint values that align the tool triad with the target triad.
- I/O - input/output which consist of ON/OFF signal values, threshold values, or analog signal values which allow the control of or response to external devices/sensors as required to sequence workcell operations.
- Programming language - The language and logical constructs used to program the set of operational instructions used to control robot movement and interact with sensors and other cell devices.
- Multi-tasking - ability to process more than one program at a time or process I/O concurrently.
- Load capability - force and torque capability of the robot at its tool interface
- TCF - tool or terminal control frame

- TCP - tool/terminal control point
- Teach Pendant - Operator interface device used to teach/save robot
- configurations and program simple instructions.

A.2. Kinect specifications

Sensor:

- Colour and depth-sensing lenses
- Voice microphone array
- Tilt motor for sensor adjustment

Field of View:

- Horizontal field of view: 57 degrees
- Vertical field of view: 43 degrees
- Physical tilt range: 27 degrees
- Depth sensor range: 1.2m - 3.5m

Data Streams:

- 320x240 16-bit depth @ 30 frames/sec
- 640x480 32-bit colour @ 30 frames/sec
- 16-bit audio @ 16 kHz

Skeletal Tracking System:

- Tracks up to 6 people, including 2 active players
- Tracks 20 joints per active player

The interaction space is the area in front of the Kinect sensor where the infrared and color sensors have an sensor. If the lighting is not too bright and not too dim, and the objects being tracked are not too reflective skeletons. While a sensor is often placed in front of and at the level of a user's head, it can be placed in a w

The interaction space is defined by the field of view of the Kinect cameras, which is listed in Kinect for Wind To increase the possible interaction space, tilt the sensor using the built-in tilt motor. The tilt motor suppo greatly increases the possible interaction space in front of the sensor.

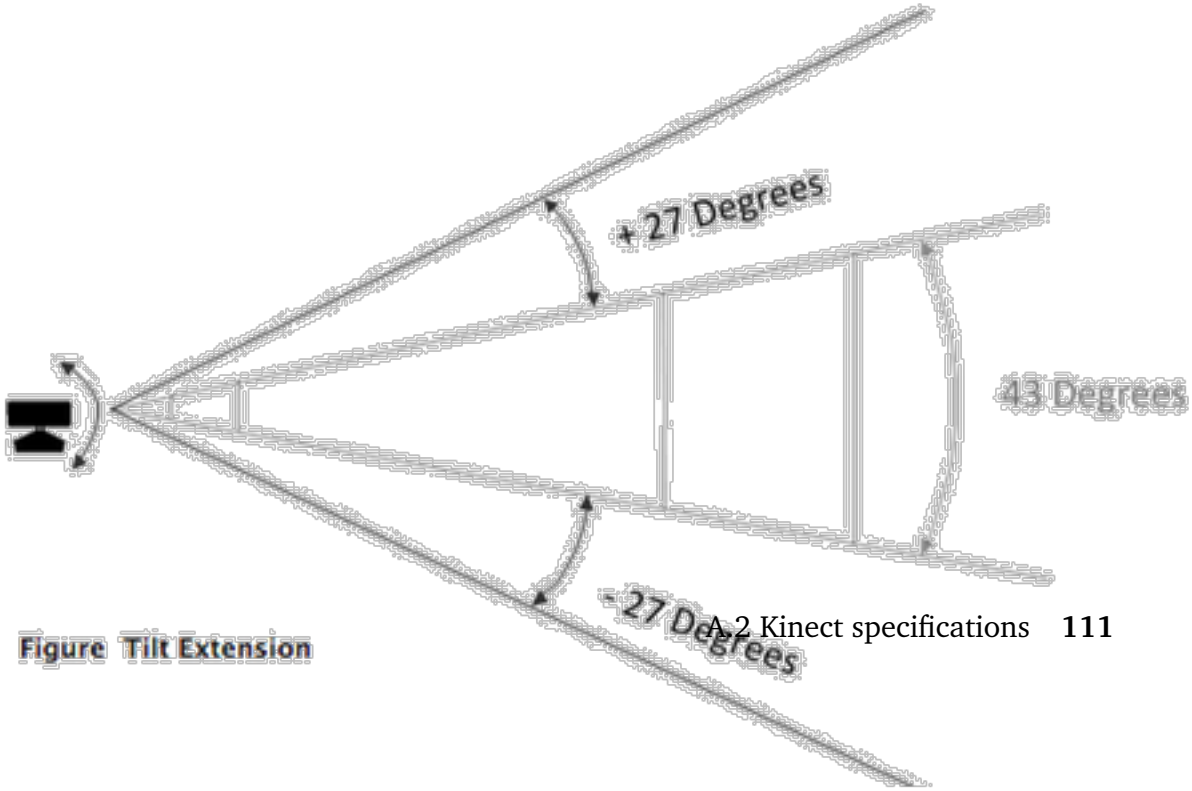


Figure Tilt Extension

Specifications for the Kinect

Kinect	Array Specifications
Viewing angle	43° vertical by 57° horizontal field of view
Vertical tilt range	±27°
Frame rate (depth and color stream)	30 frames per second (FPS)
Audio format	16-kHz, 24-bit mono pulse code modulation (PCM)
Audio input characteristics	A four-microphone array with 24-bit analog-to-digital converter (ADC) and Kinect-resident signal processing including acoustic echo cancellation and noise suppression
Accelerometer characteristics	A 2G/4G/8G accelerometer configured for the 2G range, with a 1° accuracy upper limit.

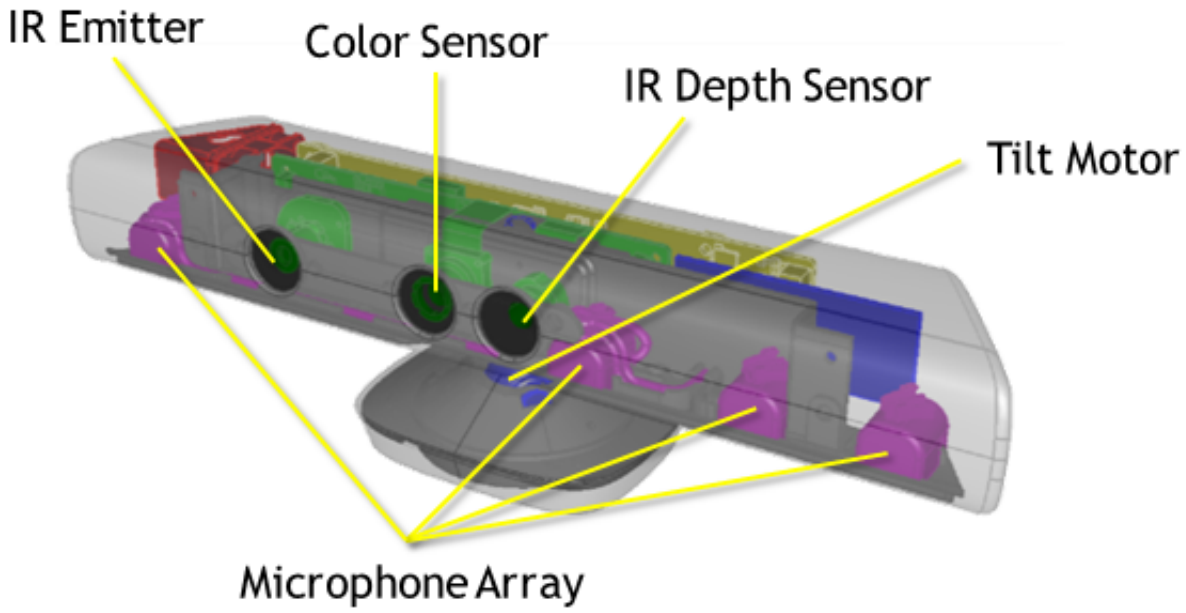


Table 6: Parameters of the robot shown in Fig. 3 [9].

A [mm]	B [mm]	C [mm]	D [mm]	E [mm]	F [mm]	G [mm]	H [mm]	I [mm]	J [mm]
1276	1620	901.5	656	245.5	851.5	420	455	400	855

Table 7: Parameters D-H for the robot KR 6 R900 sixx AGILUS.

i	α_i [rad]	d_i [mm]	a_i [mm]	θ_i [rad]
1	$-\pi/2$	$d_1 = I$	$a_1 = 25$	$q_1 = \pi/2$
2	0	0	$a_2 = H$	$q_2 = -\pi/2$
3	$\pi/2$	0	$a_3 = 35$	$q_3 = 0$
4	$-\pi/2$	$d_4 = -(G-1.4)$	0	$q_4 = 0$
5	$\pi/2$	0	0	$q_5 = 0$
6	π	$d_6 = -80$	0	$q_6 = 0$

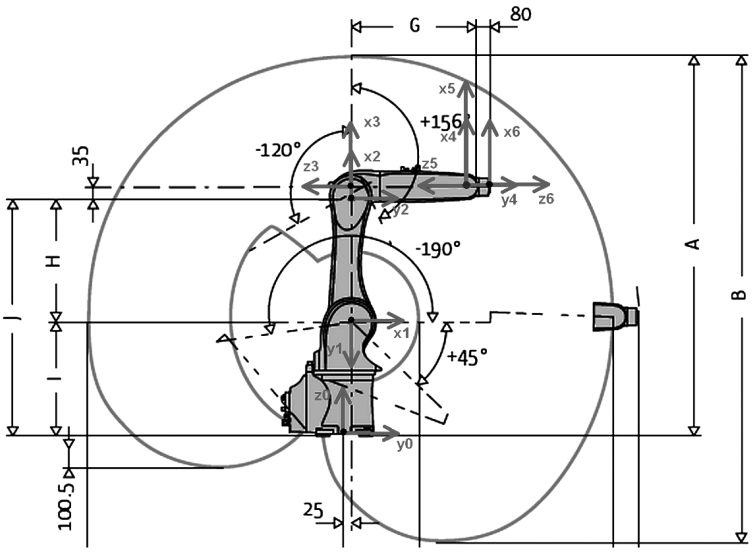
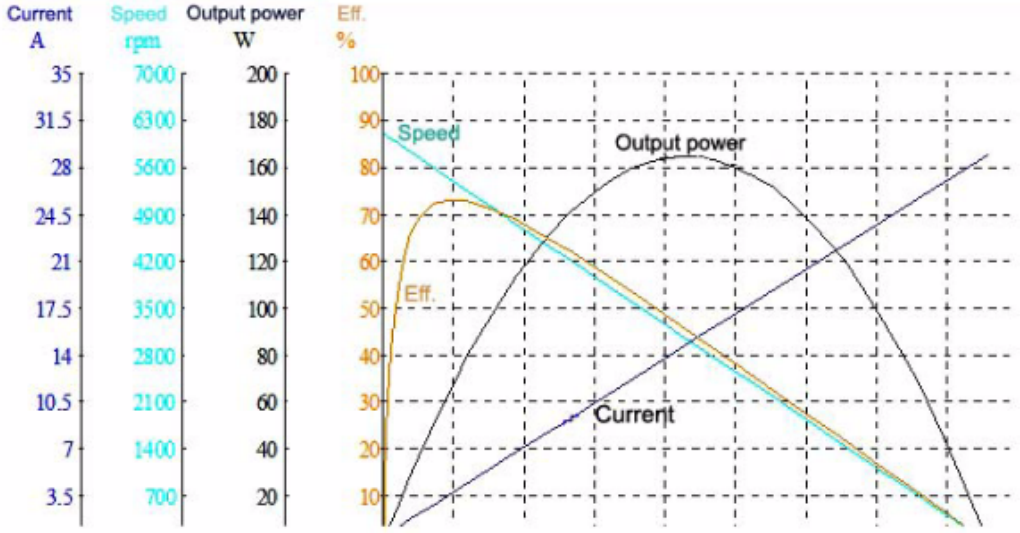


Figure 3: Dimensions of the robot KR 6 R900 sixx AGILUS [9] with marked coordinate systems.

1). 300W Spindle Test Sheet



Characteristic	Voltage	Current	Input power	Torque	Speed	Output power	Efficiency
	V	A	W	mN.m	rpm	W	%
No._Load	24.19	0.504	12.19	0.0	6109	0.000	0.0
Eff_Max	24.28	4.001	97.12	126.7	5359	71.09	73.2
Output power_Max	24.52	14.22	348.6	496.8	3168	164.8	47.3
Torque_Max	24.88	28.99	721.4	1032.2	0	0.000	0.0
End	24.88	28.99	721.4	1032.2	0	0.000	0.0

2. Spindle brush life-span(Max.): 1000 hours @ unload 48V

3. Shaft run-out: 0.02 ~0.05

A.3. Codes

A.3.1. KUKAVARPROXY.py

```
import socket                                                    #
   Used for TCP/IP communication
client = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
           # Initializing client connection

class KUKA(object):

def __init__(self, TCP_IP):
try:
client.connect((TCP_IP, 7000))                        # Open socket.
   kukavarproxy actively listens on TCP port 7000
except:
self.error_list(1)


def send (self, var, val, msgID):
"""
kukavarproxy message format is
msg ID in HEX                        2 bytes
msg length in HEX                    2 bytes
read (0) or write (1)                1 byte
variable name length in HEX          2 bytes
variable name in ASCII               # bytes
variable value length in HEX         2 bytes
variable value in ASCII              # bytes
"""
try:
msg = bytearray()
temp = bytearray()
if val != "":
val = str(val)
msg.append((len(val) & 0xff00) >> 8)             # MSB of variable
   value length
msg.append((len(val) & 0x00ff))                  # LSB of variable
   value length
msg.extend(map(ord, val))                        # Variable value in
    ASCII
temp.append(bool(val))                               # Read (0) or
   Write (1)
temp.append(((len(var)) & 0xff00) >> 8)              # MSB of
   variable name length
temp.append((len(var)) & 0x00ff)                     # LSB of
   variable name length
temp.extend(map(ord, var))                           # Variable name
    in ASCII
msg = temp + msg
```

```
del temp[:]
temp.append((msgID & 0xff00) >> 8)                    # MSB of
   message ID
temp.append(msgID & 0x00ff)                           # LSB of
   message ID
temp.append((len(msg) & 0xff00) >> 8)                 # MSB of
   message length
temp.append((len(msg) & 0x00ff))                      # LSB of
   message length
msg = temp + msg
except :
self.error_list(2)
try:
client.send(msg)
return  client.recv(1024)                             # Return
   response with buffer size of 1024 bytes
except :
self.error_list(1)


def __get_var(self, msg):
"""
kukavarproxy response format is
msg ID in HEX                         2 bytes
msg length in HEX                     2 bytes
read (0) or write (1)                 1 byte
variable value length in HEX          2 bytes
variable value in ASCII               # bytes
Not sure if the following bytes contain the client number, or they'
   re just check bytes. I'll check later.
"""
try:
# Python 2.x
lsb = (int (str(msg[5]).encode('hex'),16))
msb = (int (str(msg[6]).encode('hex'),16))
lenValue = (lsb <<8 | msb)
return msg [7: 7+lenValue]

"""
# Python 3.x
lsb = int( msg[5])
msb = int( msg[6])
lenValue = (lsb <<8 | msb)
return str(msg [7: 7+lenValue],'utf-8')
"""

except:
self.error_list(2)

def read (self, var, msgID=0):
try:
return self.__get_var(self.send(var,"",msgID))
```

```
except :
self.error_list(2)


def write (self, var, val, msgID=0):
try:
if val != (""): return self.__get_var(self.send(var,val,msgID))
else: raise self.error_list(3)
except :
self.error_list(2)


def disconnect (self):
client.close()                                          # CLose socket


def error_list (self, ID):
if ID == 1:
print ("Network Error (tcp_error)")
print ("    Check your KRC's IP address on the network, and make
   sure kukaproxyvar is running.")
self.disconnect()
raise SystemExit
elif ID == 2:
print ("Python Error.")
print ("    Check the code and uncomment the lines related to your
   python version.")
self.disconnect()
raise SystemExit
elif ID == 3:
print ("Error in write() statement.")
print ("    Variable value is not defined.")
```

A.3.2. KRLDRIVER.SRC

```
&ACCESS RVP
&REL 8
&PARAM EDITMASK = *
&PARAM TEMPLATE = C:\KRC\Roboter\Template\vorgabe
DEF KRLDRIVER( )
;FOLD INI;%{PE}
;FOLD BASISTECH INI
GLOBAL INTERRUPT DECL 3 WHEN $STOPMESS==TRUE DO IR_STOPM ( )
INTERRUPT ON 3
BAS (#INITMOV,0 )
;ENDFOLD (BASISTECH INI)
;FOLD SPOTTECH INI
USERSPOT(#INIT)
;ENDFOLD (SPOTTECH INI)
;FOLD GRIPPERTECH INI
USER_GRP(0,DUMMY,DUMMY,GDEFAULT)
;ENDFOLD (GRIPPERTECH INI)
;FOLD USER INI
;Make your modifications here

;ENDFOLD (USER INI)
;ENDFOLD (INI)
KRLD_COM=0
$ADVANCE=1
$PAL_MODE=FALSE
$OV_PRO=100
PTP {A1 0, A2 -90, A3 90, A4 0, A5 0, A6 0}
WHILE TRUE
SWITCH KRLD_COM
CASE 1
KRLD_COM=0
PTP KRLD_AXIS C_PTP

CASE 2
KRLD_COM=0
PTP KRLD_POS C_PTP

CASE 3
KRLD_COM=0
LIN KRLD_POS C_DIS

CASE 4
KRLD_COM=0
CIRC KRLD_POS_AUX, KRLD_POS

CASE 5
KRLD_COM=0
PTP_REL KRLD_AXIS C_PTP
```

```
CASE 6
KRLD_COM=0
PTP_REL KRLD_POS C_PTP

CASE 7
KRLD_COM=0
LIN_REL KRLD_POS C_DIS

CASE 8
KRLD_COM=0
WAIT SEC KRLD_SLEEP

CASE 9
KRLD_COM=0
$BASE=KRLD_BASE:KRLD_BASE_OFFSET

CASE 10
KRLD_COM=0
$TOOL=KRLD_TOOL

CASE 11
KRLD_COM=0
$APO.CPTP=KRLD_APO
$APO.CDIS=KRLD_APO

CASE 12
KRLD_COM=0
$VEL.CP=KRLD_VEL_CP

CASE 13
KRLD_COM=0
BAS(#VEL_PTP,KRLD_VEL_PTP)

CASE 14
KRLD_COM=0
$OUT[KRLD_IO]=KRLD_SIGNAL

CASE 15
KRLD_COM=0
$PAL_MODE= KRLD_SIGNAL
ENDSWITCH
ENDWHILE
END
```

A.3.3. KRLDRIVER.py

```
from kukavarproxy import *

robot = KUKA('172.31.1.147')

axes_limits = [ [-170,170],[-190,45],[-120,156],[-185,185],[
    -120,120],[-350,350]]
AXIS = 'a'
POS = 'p'
FALSE = 0
TRUE = 1

def INI(VEL_CP_VAL=3, VEL_AXIS_VAL=100, OV_PRO_VAL=10 ,APO_VAL=0):
VEL_CP(VEL_CP_VAL)
VEL_PTP(VEL_AXIS_VAL)
OV_PRO(OV_PRO_VAL)
APO(APO_VAL)
BASE(525,0,890,0,0,0)
TOOL(0,0,0,0,-90,0)
PTP(POS,0,0,0,0,0,0)

def PTP_HOME():
PTP(AXIS,0,-90,90,0,0,0)

def GRIPPER_OPEN():
OUT(1,TRUE)
OUT(1,FALSE)
OUT(4,TRUE)
OUT(4,FALSE)

def GRIPPER_CLOSE():
OUT(4,TRUE)
OUT(4,FALSE)
OUT(1,TRUE)
OUT(1,FALSE)

def OUT(ioPort, Signal):
while (int (robot.read("KRLD_COM"))): continue
robot.write("KRLD_IO",ioPort)
if Signal == True: robot.write("KRLD_SIGNAL","TRUE")
else: robot.write("KRLD_SIGNAL","FALSE")
robot.write("KRLD_COM",14)

def PAL_MODE(Signal):
while (int (robot.read("KRLD_COM"))): continue
if Signal == True: robot.write("KRLD_SIGNAL","TRUE")
else: robot.write("KRLD_SIGNAL","FALSE")
robot.write("KRLD_COM",15)

def PTP(interpolation, v1="",v2="",v3="",v4="",v5="",v6=""):
```

```
if v1 == v2 == v3 == v4 == v5 == v6 == "":
raise error(2)
return 0
if interpolation == AXIS:
axes = [v1,v2,v3,v4,v5,v5]
for index,axis in enumerate(axes):
pass
#if float(axis) <= axes_limits[index][0] or float(axis) >=
   axes_limits[index][1]: raise error(1,(index+1))
while (int (robot.read("KRLD_COM"))): continue
destination = format_axis(v1,v2,v3,v4,v5,v6)
robot.write("KRLD_AXIS", destination)
robot.write("KRLD_COM",1)
elif interpolation == POS:
while (int (robot.read("KRLD_COM"))): continue
destination = format_pos(v1,v2,v3,v4,v5,v6)
robot.write("KRLD_POS",destination)
robot.write("KRLD_COM",2)
else:
raise error(3)

def PTP_REL(interpolation, v1="",v2="",v3="",v4="",v5="",v6=""):
if v1 == v2 == v3 == v4 == v5 == v6 == "":
raise error(2)
return 0
if interpolation == AXIS:
while (int (robot.read("KRLD_COM"))): continue
destination = format_axis(v1,v2,v3,v4,v5,v6)
robot.write("KRLD_AXIS", destination)
robot.write("KRLD_COM",5)
elif interpolation == POS:
while (int (robot.read("KRLD_COM"))): continue
destination = format_pos(v1,v2,v3,v4,v5,v6)
robot.write("KRLD_POS",destination)
robot.write("KRLD_COM",6)
else:
raise error(3)

def LIN (x="",y="",z="",a="",b="",c=""):
if x == y == z == a == b == c == "": raise error(3)
while (int (robot.read("KRLD_COM"))): continue
destination = format_pos(x,y,z,a,b,c)
robot.write("KRLD_POS",destination)
robot.write("KRLD_COM",3)

def LIN_REL (x="",y="",z="",a="",b="",c=""):
if x == y == z == a == b == c == "": raise error(3)
while (int (robot.read("KRLD_COM"))): continue
destination = format_pos(x,y,z,a,b,c)
robot.write("KRLD_POS",destination)
robot.write("KRLD_COM",7)
```

```
def CIRC (x="",y="",z="",a="",b="",c="",xAux="",yAux="",zAux="",
    aAux="",bAux="",cAux=""):
if x == y == z == a == b == c == "": raise error(3)
if xAux == yAux == zAux == aAux == bAux == cAux == "": raise error
    (5)
while (int (robot.read("KRLD_COM"))): continue
destination = format_pos(x,y,z,a,b,c)
robot.write("KRLD_POS",destination)
auxilliary = format_pos(xAux,yAux,zAux,aAux,bAux,cAux)
robot.write("KRLD_POS",auxilliary)
robot.write("KRLD_COM",4)

def WAIT(time_sec):
while (int (robot.read("KRLD_COM"))): continue
robot.write("KRLD_SLEEP", abs(time_sec))
robot.write("KRLD_COM",8)

def BASE(x=0,y=0,z=0,a=0,b=0,c=0,offX=0,offY=0,offZ=0,offA=0,offB
    =0,offC=0,BASE_DATA=-1):
while (int (robot.read("KRLD_COM"))): continue
if BASE_DATA > 0:
base_frame = "BASE_DATA["  + str(BASE_DATA) + "]"
robot.write("KRLD_BASE", robot.read(base_frame))
else:
if x == y == z == a == b == c == "": raise error(3)
base_frame = format_pos(x,y,z,a,b,c)
robot.write("KRLD_BASE", base_frame)
offset_data = format_pos(offX,offY,offZ,offA,offB,offC)
robot.write("KRLD_BASE_OFFSET", offset_data)
robot.write("KRLD_COM",9)

def TOOL(x=0,y=0,z=0,a=0,b=0,c=0,TOOL_DATA=-1):
while (int (robot.read("KRLD_COM"))): continue
if TOOL_DATA > 0:
tool_frame = "TOOL_DATA["  + str(TOOL_DATA) + "]"
robot.write("KRLD_TOOL", robot.read(tool_frame))
else:
if x == y == z == a == b == c == "": raise error(3)
tool_frame = format_pos(x,y,z,a,b,c)
robot.write("KRLD_TOOL", tool_frame)
robot.write("KRLD_COM",10)

def APO(approximation_value):
while (int (robot.read("KRLD_COM"))): continue
robot.write("KRLD_APO", approximation_value )
robot.write("KRLD_COM",11)

def VEL_CP(velocity_value):
while (int (robot.read("KRLD_COM"))): continue
robot.write("KRLD_VEL_CP", velocity_value)
robot.write("KRLD_COM",12)
```

```
def VEL_PTP(velocity_value):
while (int (robot.read("KRLD_COM"))): continue
robot.write("KRLD_VEL_PTP", velocity_value)
robot.write("KRLD_COM",13)

def OV_PRO(percentage):
while (int (robot.read("KRLD_COM"))): continue
if percentage < 0 or percentage > 100: raise error(4)
robot.write("$OV_PRO", percentage)


def format_axis(A1, A2, A3, A4, A5, A6):
axes = [A1,A2,A3,A4,A5,A6]
axes_names = ["A1","A2","A3","A4","A5","A6"]
instruction = " "
for index,axis in enumerate(axes):
if axis != "":
if instruction[len(instruction)-1] != " ":      instruction += ", "
instruction += axes_names[index] + " " + str(axis)
return "{" + instruction + "}"

def format_pos(x, y, z, a, b, c):
coordinates = [x,y,z,a,b,c]
coordinates_names = ["X","Y","Z","A","B","C"]
instruction = " "
for index,coordinate in enumerate(coordinates):
if coordinate != "":
if instruction[len(instruction)-1] != " ":      instruction += ", "
instruction += coordinates_names[index] + " " + str(coordinate)
return "{" + instruction + "}"

def error(index, axis=9):
if index == 1: print("A" + str(axis)+ " limits violated.")
if index == 2: print("One parameter- at least- should be defined
   for motion.")
if index == 3: print("Interpolation type is wrongly defined.")
if index == 4: print("$OV_PRO values should be percentage.")
if index == 5: print("Incorrect base number.")
if index == 6: print("One auxilliary coordinate- at least- should
   be defined for CIRC motion.")
raise SystemExit
```

A.3.4. zukaHandGuiding.py

```
#!/usr/bin/env python
import rospy
import roslib
import tf
import time
from math import *
from krldriver import *

def main():
PAL_MODE(TRUE)
VEL_CP(3)
VEL_PTP(100)
OV_PRO(10)
APO(30)
BASE(750,0,770,0,0,0)
TOOL(0,0,0,0,-90,0)

rospy.init_node('ZUKA_Hand_Guiding', anonymous=True)
print("Node Initialized.")
listener = tf.TransformListener()
running = False
notificationSent = False
user = 1
gripState = False

xcalib = 0
ycalib = 0
zcalib = 0
wcalib = 0

xRobot = 0
yRobot = 0
zRobot = 0
wRobot = 0


while not rospy.is_shutdown():
readings = 0
xlist = []
ylist = []
zlist = []
wlist = []
zKick = []
yKick = []

while readings < 50:
try:
listener.waitForTransform("/torso_%d" %user,"/left_hand_%d" %user,
   rospy.Time(), rospy.Duration(1))
```

```
trans, rot = listener.lookupTransform("/torso_%d" %user, "/
    left_hand_%d" %user, rospy.Time())
xlist += [trans[0]*1000]
ylist += [trans[1]*1000]
zlist += [trans[2]*1000]

listener.waitForTransform("/openni_depth_frame", "/torso_%d" %user,
     rospy.Time(), rospy.Duration(1))
trans, rot = listener.lookupTransform("/openni_depth_frame", "/
    torso_%d" %user, rospy.Time())
if rot[3] > 0: wlist += [rot[3]*5*180.0/pi]
else : wlist += [rot[3]*4.2*180.0/pi]

listener.waitForTransform("/torso_%d" %user,"/right_hand_%d" %user,
     rospy.Time(), rospy.Duration(1))
trans, rot = listener.lookupTransform("/torso_%d" %user, "/
    right_hand_%d" %user, rospy.Time())
zKick += [trans[2]*1000]
yKick += [trans[1]*1000]
readings += 1
except (tf.LookupException, tf.ConnectivityException, tf.
    ExtrapolationException,tf.Exception) :
if rospy.is_shutdown(): return
user = user + 1
if user > 5 : user = 1
print "Trying user", user
notificationSent = False
running = False

x = int(sum(xlist))/len(xlist)
y = int(sum(ylist))/len(ylist)
z = int(sum(zlist))/len(zlist)
w = int(sum(wlist))/len(wlist)
zKick = int(sum(zKick))/len(zKick)
yKick = int(sum(yKick))/len(yKick)


# HERE GOES THE ALGORITHM
if (zKick) < (-350) and yKick > 100 and not running:
for i in range(5):
print ("Starting in %d" %(5-i))
time.sleep(1)
if rospy.is_shutdown(): return
wcalib = 0
running = True
print ("Tracking...")
continue

elif (zKick) < (-350) and yKick > 100 and running:
print ("Tracking has stopped")
running = False
notificationSent = False
```

```
time.sleep(2)
rospy.signal_shutdown("User Kick detected.")

elif (zKick) < (-150) and yKick < 0 and running:
if gripState == False:
GRIPPER_OPEN()
gripState = True
else:
GRIPPER_CLOSE()
gripState = False
time.sleep(.5)

elif running:
wRel = w - wcalib
yRel = y - ycalib
zRel = z - zcalib
if wcalib == 0:
wcalib = w
ycalib = y
zcalib = z
else:
# The code
if abs(wRel - wRobot) > 2:
wRobot = max(min(169, wRel), (-169))
#print wRobot , yRel, zRel
BASE(350,0,750,0,0,0,0,0,0,(-wRobot))
PTP(POS,-zRel,0,yRel,"",0,0)
#print yKick, zKick
time.sleep(.01)
else:
if not notificationSent:
print ("User %d is active. Waiting for the kick."% user)
notificationSent = True




if __name__ == "__main__":
main()
```

A.3.5. zukaSafeOperation

```
#!/usr/bin/env python
import os
import threading
import rospy
from std_msgs.msg import Float32
from kukavarproxy import *

zuka = KUKA('172.31.1.148')

safeRange = 1500
limitedSpeed = 0
fullSpeed = int (zuka.read("$OV_PRO"))


speedChanged = False

def openniTracker():
global speedChanged
while 1:
print" LOW SPEED"
speedChanged = True
zuka.write("$OV_PRO",limitedSpeed)
os.system("killall -9 openni_tracker")
print"Loading Openni Tracker ..."
os.system("rosrun openni_tracker openni_tracker")

def get_distance(distance):
global speedChanged
if distance.data < safeRange and not speedChanged:
print" LOW SPEED"
zuka.write("$OV_PRO",limitedSpeed)
speedChanged = True

if distance.data > safeRange and speedChanged:
print" FULL SPEED"
zuka.write("$OV_PRO",fullSpeed)
speedChanged = False

def main():
lol= rospy.Subscriber("/closestUser", Float32, get_distance)
rospy.init_node('zukaSafeOperation', anonymous=True)

t = threading.Thread(target = openniTracker,args = ())
t.start()

while not rospy.is_shutdown():
if lol.get_num_connections() == 0 :
lol.unregister()
lol= rospy.Subscriber("/closestUser", Float32, get_distance)
```

```
if \__name\__ == "\__main\__":
main()
```

References

1. http://www.mmsonline.com/articles/a-new-milling-101-what-milling-is-then-and-now-plus-a-glossary-of-milling-terms
2. http://www.mmsonline.com/articles/a-new-milling-101-what-milling-is-then-and-now-plus-a-glossary-of-milling-terms
3. http://www.sickinsight-online.com/safety-and-more-sick-provides-protection-and-navigation-data-for-kukas-kmr-iiwa/
4. http://medicaldesign.com/contract-manufacturing/modern-cnc-machining-prescription-product-development
5. http://articles.sae.org/11272/
6. https://en.wikipedia.org/wiki/Multiaxis_machining
7. https://en.wikipedia.org/wiki/Milling_(machining)
8. http://www.engineersrule.com/motion-studies-and-how-to-do-them/
9. http://help.solidworks.com/2017/English/SolidWorks/cworks/c_Study_Types.htm
10. SolidWorks forums
11. Dimensions manual
12. Specification manual
13. https://robotics.stackexchange.com/questions/10256/dynamic-torque-simulation-for-a-6-dof-robotic-arm

14. Handbook of Industrial Robotics, Volume 1, edited by Shimon Y. Nof.
15. KUKA manual “01-Mastering and unmastering”
16. KUKA manual “07-KSS_82_Software programming_en”
17. KUKA manual “KST_WorkVisual_en”
18. KUKA manual “KUKA.Sim_2.2_Installation_en”
19. KUKA manuals “KST_GripperSpotTech_32_en”
20. http://blog.robotiq.com/bid/72815/Top-5-Applications-for-Robotic-Electric-Grippers
21. https://www.kuka.com/en-de/products/robot-systems/software/application-software/kuka_gripper_spottech
22. https://www.robot-forum.com/robotforum/kuka-robot-forum/valves-and-inputs-on-the-wrist-krc4-agilus-kr6-r900-sixx-17168/
23. https://www.aliexpress.com/item/0-3kw-Air-cooled-spindle-ER11-chuck-CNC-300W-Spindle-Motor-Power-Supply-speed-governor-Clamp/326989
24. https://www.repetier.com/repetier-g-code-plugin-for-inskscape/
25. http://javakuka.com/xyzabc/
26. KST Expert Programming Manual KSS 5.2
27. INTRODUCING ROBOTICS: MAKING ROBOTS MOVE QUEENSLAND UNIVERSITY OF TECHNOLOGY
28. Robotics, Vision and Control: Fundamental Algorithms in MATLAB. Book by Peter Corke
29. Shigley’s Mechanical Engineering Design, Richard G. Budynas, J. Keith Nisbett, 10th edition, 2014.
30. KR AGILUS six with W & C variants Specifications.
31. http://wiki.ros.org/ROS/Introduction
32. A Gentle Introduction to ROS, Jason M. O’Kane
33. Learning ROS for Robotics Programming, Aaron Martinez ,Enrique Fernández.

34. OpenNI user Guide.
35. https://rosresearch.wordpress.com/2013/12/26/openni-nite-skeleton-tracking-algorithm-related-notes/
36. http://pr.cs.cornell.edu/humanactivities/data/NITE.pdf
37. http://wordpress.mrreid.org/2011/08/20/kinect-physics/
38. http://sourceforge.net/projects/openshowvar/
39. https://github.com/aauc-mechlab/jopenshowvar/
40. http://filipposanfilippo.inspitivity.com/publications/jopenshowvar-an-open-source-cross-platform-communication-interface-to-kuka-robots.pdf
41. https://www.robodk.com/forum/attachment.php?aid=4
42. http://answers.ros.org/question/30575/detecting-user-position-with-kinect-without-psi-pose/
43. KSS KUKA Robot Programming 1 Training -KSS8_v4.
44. KST-Expert_Programming_manual KSS 5.2.
45. Notes_ Bochum KUKA Programming.
46. KRL Quickguide Syntax 8x.
47. 07-KSS_82_Software programming.
48. KST_GripperSpotTech_32.
49. Spez_KR_AGILUS_sixx_CR.
50. http://javakuka.com/xyzabc
51. www.globalrobots.com

Bibliography

[Byrd and de Vries, 1990] Byrd, J. and de Vries, K. A. (1990). six-legged telerobot for nuclear applications development. *Int. J. Robot*, 9:43–52. []

[Cousins, 2011] Cousins, S. (2011). Exponential growth of ros [ros topics]. *IEEE Robotics Automation Magazine*, 18(1):19–20. []

[Digia, 2017] Digia (2017). Qt project. `http://qt-project.org`. []

[Ding et al., 2010] Ding, X., Rovetta, A., Zhu, J. M., and Wang, Z. (2010). Locomotion analysis of hexapod robot. *INTECH Open Access Publishe*. []

[Dynamics, 2015a] Dynamics, B. (2015a). Dedicated to the science and art of how things move, Boston dynamics. []

[Dynamics, 2015b] Dynamics, B. (2015b). *Boston Dynamics*. Boston dynamics. []

[Dürr et al., 2004] Dürr, V., Schmitz, J., and Cruse, H. (2004). "behaviour-based modeling of hexapod locomotion: linking biology and technical application". *Arthropod Structure & Development*, 33:237–250. []

[G.M.Nelson, 1997] G.M.Nelson, R. (1997). Design & simulation of a crockroach like-hexapod robot. In *the IEEE international conference on Robotics & automation*, New Mexico. IEEE. []

[Gurfinkel et al.,] Gurfinkel, V., Gurfinkel, E., Devjanin, E., Efremov, E., Zhicharev, D., Lensky, A., Schneider, A., and Shtilman, L. I. o. r. In six-legged walking model of vehicle with supervisory control; nauka press: Moscow, russia, 1982;. *p*, pages 98–147. []

[KanYoneda, 2007] KanYoneda (2007). Light weight quadruped with nine actuators. *journal of robotics & mechatronics*, 19(2). []

[Lewinger and MartinReekie, 2011] Lewinger, W. A. and MartinReekie, H. (2011). A hexapod robot modeled on the stick insect carausius-morosus. In *the 15th international conference on advanced robotics*, Tallinn. []

[Lewinger and Quinn, 2010] Lewinger, W. A. and Quinn, R. D. (2010). A hexapod walks over irregular terrain using a controller adapted from an insects nervous system. In *the IEEE/RSJ international conference on intelligent robots & systems (IROS)*, pages 18–22, Taiwan. IEEE/RSJ. []

[Manoiu-Olaru et al., 2011] Manoiu-Olaru, S., Nitulescu, M., and Stoian, V. (2011). Hexapod robot. mathematical support for modeling and control. In *System Theory, Control, and Computing (ICSTCC), 15th International Conference on*, pages 1–6. []

[McGhee, 1977] McGhee, R. (1977). Control of legged locomotion systems. *In Proceedings of the*, 18:205–215. []

[Mehdigholi&SaeedAkbarnejad, 2012] Mehdigholi&SaeedAkbarnejad, H. (2012). " optimization of watt's six-bar linkage to generate straight& parallel leg motion" in the journal of humanoids. *ISSN*, pages 1996–7209. []

[MohdDaud and KenzoNonami, 2012] MohdDaud and KenzoNonami (2012). Autonomous walking over obstacles by means of lrf for hexapod robot comet-iv. *robotics & Mechatronics*, 24(1). []

[Moore and Buehler, 2001] Moore, E. Z. and Buehler, M. (2001). Stable stair climbing in a simple hexapod robot. Technical report, DTIC Document. []

[Okhotsimski and Platonov, 1973] Okhotsimski, D. and Platonov, A. (1973). Control algorithm of the walking climbing over obstacles.

In *Proceedings of the 3rd International Joint Conference on Artificial Intelligence*, CA, USA, 20. Stanford. []

[Peternella and Salinari, 1973] Peternella, M. and Salinari, S. (1973). Simulation by digital computer of walking machine control system. In Genova, I., editor, *Proceedings of the 5th IFAC Symposium on Automatic Control in Space of the Conference*. []

[Saranlı, 2002] Saranlı, U. (2002). *Dynamic locomotion with a hexapod robot*. PhD thesis, The University of Michigan. []

[Schneider and Schmucker, 2006] Schneider, A. and Schmucker, U. (2006). Force sensing for multi-legged walking robots: Theory and experiments part 1: Overview and force sensing. In Intelligence, M. and Buchli, J., editors, *Mobile Robotics*, pages 125–174. Germany; Austria, ; Pro Literatur Verlag ARS. []

[Seljanko, 2011] Seljanko, F. (2011). "hexapod walking robot gait generation using genetic gravitational hybrid algorithm" in the 15th international conference on advanced robotics, estonia, june 20-23. 2011. []

[Tedeschi and Carbone, 2014] Tedeschi, F. and Carbone, G. (2014). Designissues for hexapod walking robots. *Robotics*, 3(2):181–206. []

[terrain hex-limbed extra-terrestrial explorer,] terrain hex-limbed extra-terrestrial explorer, N. A. 2009. []