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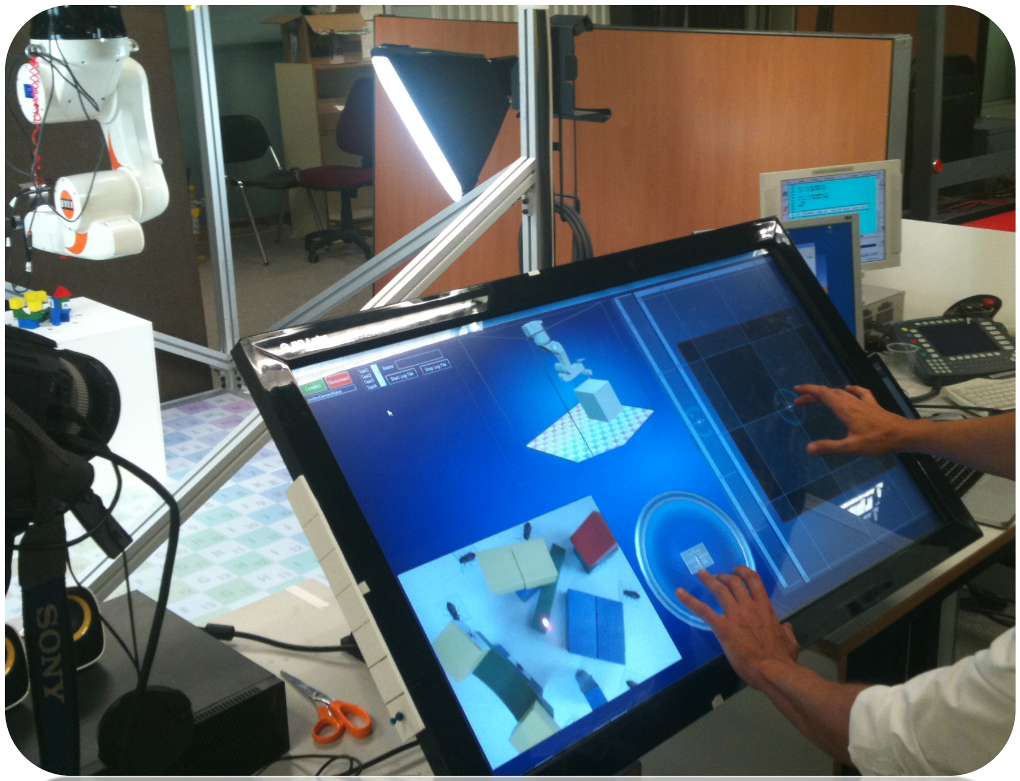

Implementing Multi-Touch Screen for Real-time Control of a Robotic cell At Universidad Politécnica de Valencia

Master of Science Thesis

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Göteborg, Sweden, 2010

THESIS FOR MASTER'S DEGREE IN PRODUCTION ENGINEERING

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Cover:
The cover shows a picture from the demonstrator built in the IDF laboratory, Polytechnic University of Valencia, Spain

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Abstract

Today Multi-touch technology are being developed to fit many different applications on the consumer market, but it is still something new and quite unknown in the industrial sector. The technology has expanded a lot during the latest years and compared to other control devices, such as a mouse or a keyboard, it has the ability to allow more intuitivism to be implemented.

The objective of this thesis is to make use of a Multi-touch screen to create an intuitive interface for industrial robot controlling. An operator shall be able to understand it with as little training as possible. A camera shall be mounted on the tip of the robot arm and the robot shall be completely controlled by inputs (touches, motions and gestures) made on the Multi-touch screen. One example of application can be to use it for inspection purposes by integrating the video stream from the camera in the user interface.

The thesis was performed at the Department of Design and Manufacturing (Instituto de Diseño y Fabricación) at the Polytechnic University of Valencia (Universidad Politécnica de Valencia) in Spain. The thesis is a part of a larger project with the goal to make a working demonstrator. Included in the thesis work was also an evaluation of the whole concept, which was done by performing a series of different usability tests. This test was done on a group of 20 people with different ages, sexes and backgrounds.

The results of the usability tests showed that the use of Multi-touch technology for controlling industrial robots could increase the intuitivism of the user interface compared to conventional controls. This conclusion is drawn from the fact that all users were able to complete the first usability test without any instructions, regardless of their background. The test also showed that using this technology could significantly decrease the learning period for an operator, even without experience of robot controlling or multi-touch technology.

Keywords: Multi-touch, industrial robots, human machine interface, intuitivism, real-time control, usability

Acknowledgement

This has been a research line performed at IDF department at the UPV University in Valencia, Spain in cooperation with Department of Product and Production development at Chalmers University of Technology, Gothenburg, Sweden.

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We also would like to express our appreciation to our supervisor Per Nyqvist, and examiner Rolf Berlin at Chalmers University of Technology who have helped and supported us throuhgout the project.

Abbreviations

KRL	KUKA Robot Language
UI	User Interface
HMI	Human Machine Interface
XML	Extensible Markup Language
RSI	Robot Sensor Interface
HD	High Definition
TCP/IP	Transmission Control Protocol/Internet protocol; Communication protocol for networks
UDP/IP	User Datagram Protocol used for network communication
C#	C – sharp, Object-oriented programmation language, a part of the .NET platform
End effector	The "tool" placed on the end of the robot arm. For example Grip-tool or camera
Syntax	Principles and rules for constructing sentences in natural languages. Normally a simplified description of a program
LAN	Local Area Network

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1. Introduction

Today Multi-touch technology is being implemented to fit many different applications. A lot of research is being done as the technology is being developed. Since the touch technology allows more intuitivism to be implemented than with normal control devices, such as a mouse or keyboard, it is an interesting area that has expanded a lot during the latest years.

Real-time control of industrial robots is today usually done using a so called teach-pendant (see explanation under the section ”Industrial robots”), with single motions in directions or axis, or multiple direction movement using a mouse. Regarding the programming there is often a need of experienced programmers to be able to move the robot in the desired way. The available tools for helping programmers are mostly simulators developed normally by the same company as the robot manufacturer, which require special training and a learning period before one can start using the software for its purpose.

The following text describes the purpose of the thesis, the background, the hardware and software prerequisites, methodology, system development process and the empirical study. From these the results of the thesis are discussed and conclusions are drawn.

1.1 Purpose and objective

This section discusses the purpose and the objective of this thesis.

1.1.1Purpose

The purpose of the project is to investigate the possibilities with a Multi-touch screen when controlling an industrial robot, especially when used for inspection purposes like quality control with a camera mounted on the robot arm. This is done by transforming the motions and gestures of fingers made on the screen into motions of the robot.

1.1.2 Objective

The objective of the project was to develop a real-time connection between a Human-Machine interface (HMI), running on a commercial Multi-touch screen, using PQ Labs’ overlay on an industrial full HD 42-inch LG monitor, and an industrial KUKA-robot. The interface on the Multi-touch screen should be easy to handle and display real time information about what is happening in the cell such as the position of the robot arm in space and tool position. The outcome of the project shall be a demonstrator that is going to be tested and later investigate its possibilities and limitations. The Multi-touch screen shall be evaluated and tested to see whether it is a good platform for this type of control.

The robot shall be able to follow a trajectory drawn on the Multi-touch screen in both online and offline modes. This means that the system must be fail-safe and not allow any collisions or movement that could cause failures. The interface on the Multi-touch screen needs to have a design that is easy to understand and has clear warning signals. Latency and safety issues must be considered. In order to guarantee an accurate control on real-time operations, it is necessary to retrieve real-time feedback from the robot cell to the Multi-touch user interface.

1.2 Background

Multi-touch applications is still something new and quite unknown in the industrial sector. The technology became available to the consumer market when the first version of the Iphone entered the market in 2007[1], and it was a real breakthrough for the technology. It set new standards when it came to how to handle and control an electronic device. After that, many other manufacturers realized that they also needed to utilize Multi-touch technology in order to stay competitive. Several gestures started to spread among different plattforms such as the two-finger spread motion for zooming and the one finger drag motion used for panning. On the field of robotics, there are at the moment few examples of Multi-touch applications. One interesting application can be controlling industrial robots used in production systems.

1.2.1 Project background

The "Instituto de Diseño y Fabricación" (refered to as "IDF") at the Universidad Politécnica de Valencia in Spain holds a new research line about Multi-touch control for industrial applications. The department has recently invested in a 42-inch Multi-touch overlay from PQ labs, a US-based company specialized in touch-technology. In order to use this overlay they also purchased a 42-inch industrial full HD monitor from LG. Since the department has a KUKA KR 5 sixx R650 industrial robot, the research has been aimed towards the combination of these two technologies. The controlling of robots via a Multi-touch screen is a relatively new application of use, so the benefits of using it may not be fully explored. The Multi-touch interface enables several inputs to be done simultaneously, which can make it to a powerful tool when controlling complex systems. Since the screen used in this project is relatively large (42 inch) it allows a collaborative UI (user interface) so that more than one people can be working on it at the same time.

1.3 Theory

Studies have been carried out on how the communication methods work and which was the best suited method for this application. When it was decided which type of communication method to use, the theory was to learn more about that specific method and its advantages, so that it could be exploited as much as possible for this specific purpose. Since the thesis has been a part of a larger project (see section ”Delimitations”), a lot of decisions has been taken through discussions with all group members. Regarding the communication, the KUKA robots understand a language that is called KUKA Robot Language (KRL) and at the end all signals needs to be transformed into this, so that the robot interpret the code and thus perform the corresponding motions.

1.4 Delimitations

The devices to work with were one Multi-touch screen controlling one industrial KUKA robot model KR 5 sixx R650. The tool to work with was primarily a camera used for inspection of products. This thesis was a part of a larger project, which includes programming of the Multi-touch screen controls and graphic design as well as the communication between the Multi-touch screen and the robot. The focus of this project was to establish and make sure that the communication between the robot and the computer with the Multi-touch screen runs smoothly. Specifically this means taking the signals from the Multi-touch screen and transfering it into real motions of the robot. This means that programming of the robot controller itself was needed.

The actual programming of the screen was not included in this part of the project, but a good understanding was necessary to retrieve a deeper knowledge of the communication in the human-machine interface. However this thesis work had a great influence of the graphic design since investigating the Multi-touch screen's usability is a part of the thesis.

The thesis had to be carried out and finished within the set timeframe, that had a due date the 30th of June 2010.

2. Theoretical background

This section describes the theoretical background, first in general and then more detailed about this specific project.

2.1 Industrial robots

It has to be clearly stated that there is a difference between robots in general and industrial robots. When talking about robots in general, that includes all types of robots which can have special purposes, humanoids (robots that are constructed to act as a human), cleaning robots, etc. However this report focus is on robots used within the industry.

By ISO definition an industrial robot is an automatically controlled, reprogrammable multipurpose manipulator that can be programmed in three axes or more [2]. The expression ”field of robotics” is often used and that includes everything related to the robots, normally when used in industrial appplications typically for production. Robots can be adapted and used for a lot of different tasks. Typical applications for industrial robots can be welding, assembly, painting, inspection etc, performed at a high speed and and with high precision.

Normally the robot is connected through a controller to a laptop, or desktop computer in which the programming takes place. Almost all industrial robots come with a so called tech-pendant which can be used in order to move and control the robot. In other words the robot can be taught to go to specific points in space and then perform the trajectory that it has been taught.

2.1.1 History

The first real robot patents were applied by George Devol in 1954 [3] Two years later the first robot was produced by a company called Unimation, founded by George Devol and Joseph F. Engelberger. In these first machines the angles of each joints were stored during a teaching phase and could then later by replayed. The accuracy was very high 1/10000 of an inch. Worth to notice is that the most important measure in robotics is *not* accuracy, but repeatability. This is due to the fact that normally the robots are taught to do one task over and over again.

The first 6-axis robot was invented in 1969 by Victor Scheinman at Stanford University, named "the Stanford arm" and could substitute the motions of an arm [3]. The Stanford arm made it possible to make arbitrary paths in space and also permit the robot to perform more complicated tasks, such as welding and assembly.

In Europe the industrial robots took off around 1973 when both KUKA and ABB entered the market and launched their first models. Both came with six electro-mechanically driven axes.

In the late 1970's the consumer market started showing interest and several American based companies entered the market. The real robotics boom came in 1984 when Unimation was sold to Westinghouse Electric Corporation. Few Japanese companies managed to survive, and today the major companies are Adept Technology, Stäubli-Unimation, the Swedish-Swiss company ABB Asea Brown Boveri and the German company KUKA Robotics.

2.2 Human Machine interface

An interface is a point of interactions between two systems or work groups, hence the Human machine interface (referred as HMI from here) is the interaction point between the human (in this case the user) and the machine. The machine can be all kinds of electronic devices that are controlled by the human user. A lot of research has been done over the years on how to make the HMI as easy and self explainatory as possible. A keyword when designing Human-Machine interfaces is transparency, which means that they should be as self-explanatory as possible. It should be easy to learn how to use it, with as little training as possible, and it should also be difficult to do something wrong.

In this project knowledge achieved by studying previous experiments have been applied when designed the HMI, see further explanation under the section "Methodology".

2.3 Multi-touch technology

Multi-touch is an extension (enhancement) of the touch technology, which allows the user to point or make gestures, normally with a stylus (small pen) or directly with the finger, on different objects on a screen with one contact area. The definition of Multi-touch is that you can use three or more contact areas when interacting with the device [4]. The use of Multi-touch technology opens up many possibilities for researching new ways of controlling complex systems in a more natural and intuitive way, allowing collaborative scenarios (two or more people controlling a robot), which can be difficult with conventional controls (like joystick or mouse). The Multi-touch screen's degrees of freedom when it comes to the graphic design of the interface allows customization the interface for a specific user or situation since it has the possibility to have many different interfaces on the same screen. Since the screen has the ability to handle many different inputs simultaneously it could be a really powerful tool when controlling complex systems such as the motions of an industrial robot, which has been the main objective with this thesis work.

The touch technology has in the latest years revolutionized many electronic devices with analogue input, especially when Apple introduced the Iphone to the market in 2007. Since you can point directly on the screen, on the object you want to affect, there is a great possibility to get a Multi-touch interface very intuitive. This can result in a short learning period for the end-user if the design of the interface is carefully prepared by the designer (see the section below about interface design).

2.3.1 History

When looking at interface design for computers in a historical perspective, the first designers only had a keyboard and lines of text to deal with. Then came the mouse which made it possible to implement more easy-to-use applications. In the recent years technology with Multi-touch has been developed a lot on both the software and the hardware. First it was a really expensive and bulky technology only available for a few. The real breakthrough that made the technology available to the consumer market (large-scale) was when the Iphone was released in 2007. This changed the paradigm on how a user interface (UI) should be designed and how to navigate through menus etc.[5]

Most people are probably not aware of the fact that the history of touch-sensitive control actually pre-dates the age of the PC [6]. The Iphone that some might think of as the first real Multi-touch device was actually the result of many years advancements within the field of touch devices and definitely not the first product [1]. The first single-touch none pressure sensitive screens were developed as early as the late 1960's and by 1971 researchers had discovered a number of different techniques for touch screens. Figure 1 shows the terminal, a 16x16 array, to the PLATO IV computer assisted education system, released in 1972, which is one of the first touch systems to be generally known. Similar systems like the PLATO IV are infact used today in cashpoints, ticketing machines, medical instrumentation etc. [1]

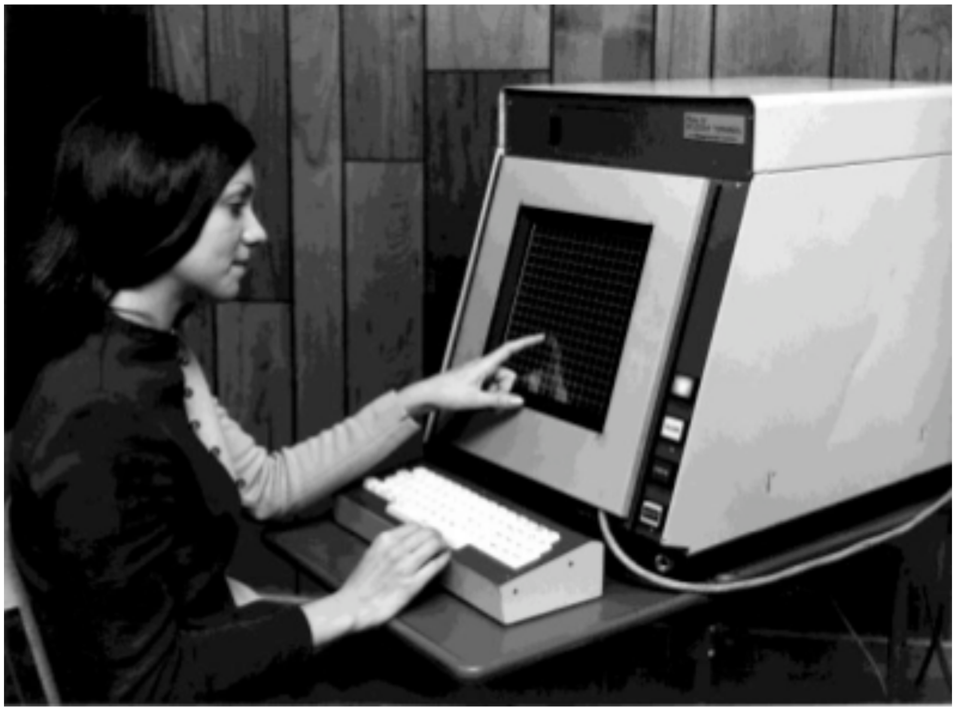


Figure 1: The Plato IV terminal with its touch-sensitive screen [1].

The University of Toronto's Input Reasearch Group developed the first human-input Multi-touch technology that dates back to 1982 (Macintosh released its first computer in 1984) and the now so common and well known pinch gesture (see table 1, in section 5.1.2, for description) dates back to 1983 [6].
This first system was not like todays Multi-touch screens where you click on the actual object, but a pad with a frosted glass that had a camera behind it. The camera detected the fingers pressed on the screen as black dots on an otherwise white background [6]. The system was also said to be somewhat pressure sensitive since the size of the dot depended on how hard the person was pressing on the glass. The system was used for simple image processing like drawing

etc. Already when this interface was created, the use of a projector together with a camera was discussed, much like a lot of Multi-touch systems use today, like for example the Microsoft Surface table-top touch platform (see more under "Different technologies").

The first real Multi-touch screen was developed during 1984 by Bell Labs and the first system to use capacitance sensing system was developed during 1985 by the Input Research Group at the University of Toronto [6].

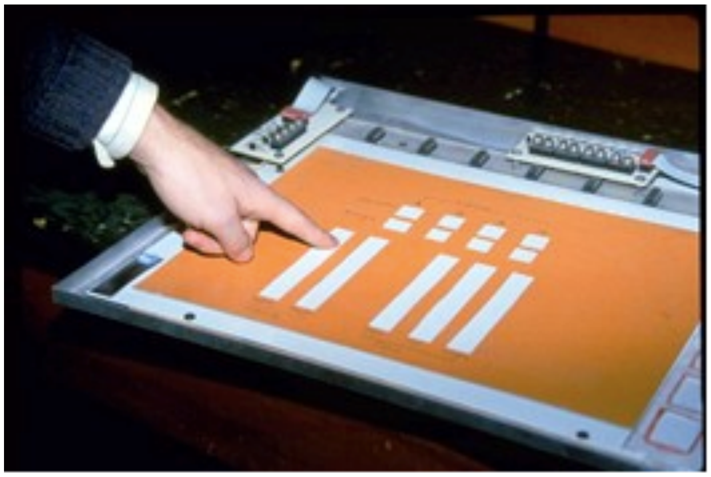


Figure 2: The first multi-touch system to use capitance was a tablet developed at the University of Toronto in 1985 [6].

Today, many Multi-touch manufacturer use some kind of capacitance system, since it allows a slimmer design than the bulky optical system, which requires projectors and sensors (see next section), and because it eventually allowed a transparent capacitance sensing screen to be placed in front of a regular LCD or LED screen. The optical system is still widely used though primarily beacuse it is a lot cheaper and easier to build for large applicaton where space is not limited.

2.3.2 Different technologies

This section will present the basics for the two most common Multi-touch technologies of today; optical sensing systems and capacitance sensing systems. Optical sensing systems use a projection of the screen onto a surface with sensors detecting where on the screen you are touching. A capacitance sensing system carry an electrical charge and can sense where on the screen the charge gets interupted (like the Iphone) [7]. The technology to use depends mostly on the size of the screen (also how much space that is available) and the type of interface the application shall have. The principal data processing though, is the same for both technologies. The input signals, created by fingers or other objects touching the screen, gets processed by a software that recognizes whether it is a just a touch, multi-touch or some kind of gesture and then translates the signals and excecutes the corresponding commands.

Touch tables and touch walls are examples of optical sensing systems and they usually use projectors that sends images through an acrylic or glass that faces the viewer. When the screen is touched by fingers or other objects, the light gets scattered and the reflection is sent back to sensors or cameras that reads the change and send it to the software, see figure 3 and 4. The software interprets the change and, depending on the reading, takes the appropriate action [8]. In order to create the reflection, LEDs are used to send light bouncing through the acrylic sheet or glass.

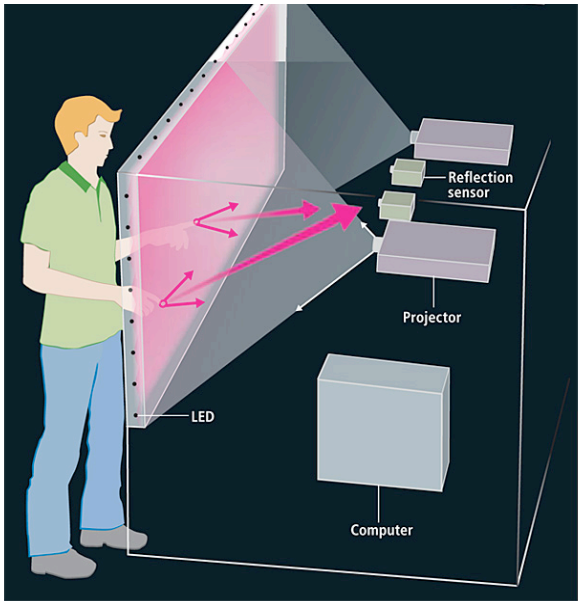


Figure 3: Principal function of a touch wall [8]. A touch table works in a similar manner.

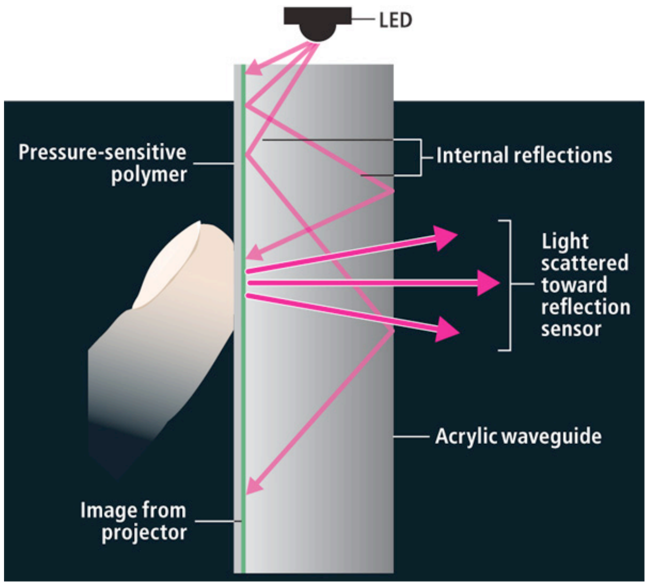

LED
Pressure-sensitive polymer
Internal reflections
Light scattered toward reflection sensor
Acrylic waveguide
Image from projector

Figure 4: When a Multi-touch system using optical sensors is touched by a finger or object the light created by the led gets scattered and sent toward a reflection sensor [8].

A touch sensitive overlay on a screen and a built in touch panel are examples of capacitance sensing systems. The main technologies are mutual capacitance or self-capacitance [9]. The difference is that the mutual capacitance system has two separate layers for the electrodes, one carrying the small current, and the other is the sensing circuit that measures on which node on the electrodes that the current gets interrupted by a touching object. The self-capacitance system on the other hand, has electrodes that can measure the capacitance change caused by an object directly. [9]

2.4 Robot Control

In this chapter it will be explained the common practice in industrial robot control. First section, programming, explains how to make the robot perform a task by writing a robot code that are read by the robot controller computer. Further down in the section "Programming of KUKA robots" it will be explained more specific about how the controlling is done with KUKA robots and how the robot language code works. Then it will be explained more about what type of controlling method that was used in this project, and what type of tools that were used for that under the sections "Real-time control" and "KUKA Ethernet RSI XML".

2.4.1 Conventional control

The common practice for industrial robot control is either to move the robot manually with the robot’s teach pendent, or with a program written in the robot’s language, in this case KUKA Robot Language (KRL), that is run on the robot controller. Either the program has been written directly in the specific robot language or the programmer has used some kind of post processor in combination with CAD/CAM software.

The programming of industrial robot can be divided into two categories, online-, and offline programming. Offline programming means that the robot code is created offline with no connection to the physical robot. The generated program is later transferred to the robot and executed in the real environment. Normally a verification of the code is made in some sort of simulation software before transferring the program. Online programming includes programming when the software is directly connected to the physical robot. This can be done with a teach pendant (See the section about Industrial robots) used for moving the robot to certain positions where they are stored, and then a trajectory is created between the stored points. The process when adjusting a position in space is commonly referred to as "jogging" or "inching" the robot.
Most industrial robots have a similiar programming structure, telling them how to act. You define points in space and then how the robot is supposed to reach the specific points, normally called P1, P2, P3 etc. An example of a program syntax is shown below in figure 5.

```
Move to P1 (a general safe position)
Move to P2 (an approach to P3)
Move to P3 (a position to pick the object)
Close gripper
Move to P4 (an approach to P5)
Move to P5 (a position to place the object)
Open gripper
Move to P1 and finish
```

Figure 5: Example of short robot program syntax.

Many industrial robot manufacturers offer a simulation software package for their robots which eases the programming and at the same time makes it possible to perform offline programming. The benefits from using offline programming are many; it prevents costly damages to happen in the real world, it can save money since you dont have to interrupt the production while programming, it speeds up for example ramp-up time when switching to production of a new models etc [10].

2.4.2 Programming of KUKA robots (KRL)

For programming of a KUKA robot, a specific language called KRL (KUKA Robot Language) is used. The structure of the code is similar to most other robot languages; Points are specified in space and commands are used to express how the robot are suppose to reach these points, see example under section "General programming". When programming in KRL, a .SRC-file is created containing the real program code that will be read by the robot controller and a .DAT file containing the declaration of variables, and other prerequisites that are read and stated automatically before executing the .SRC-file. The name of the two files shall always be the same to be identified as the same program by the robot controller. A small example of the contents in a .SRC-file is shown in figure 6.

```
DEF FR_VERS ( )
;------- Declaration section -------
EXT BAS (BAS_COMMAND :IN,REAL :IN )
DECL AXIS HOME ;Variable HOME of type AXIS
;----------- Initialization ----------
BAS (#INITMOV,0 ) ;Initialization of velocities,
;accelerations, $BASE, $TOOL, etc.
HOME={AXIS: A1 0,A2 -90,A3 90,A4 0,A5 0,A6 0}
;----------- Main section ----------
PTP HOME ;BCO run
; Motion relative to the $BASE coordinate system
PTP {POS: X 540,Y 630,Z 1500,A 0,B 90,C 0}
PTP HOME
END
```

Figure 6: An example of KRL-code [11].

The declaration and initialization part can also be located in the .DAT file, but are here showed in the same program to more clearly explain the different steps. The PTP HOME in the main section makes the robot perform a point-to-point motion to the defined home position, which is defined in the initialization part. The first instruction to the robot is normally called a BCO-run (Block Coincidence), which makes the robot go to a predefined point in space. This is done in order to set the correspondence between the current real robot position and the programmed position. The next line makes the robot go to the specified point, which in this case is defined directly in the same row as a point in the base coordinate system specified by six values. The six values are; X, Y, Z that defines the point in a 3D-space and A (rotation around Z-axis), B (rotation around Y-axis) and C (rotation around X-axis) that defines the tool orientation [11].

2.4.3 Real-time control

Normally industrial robots are programmed to perform a single task, for example welding the same part over and over throughout the day; hence it is not controlled in real-time. However, real-time control can be used for tasks that are none-repeatable and require the user to alter the robot’s movement from time to time. Example of this can be inspection with a camera, place a gripper as the end-effector in order to be able to pick up and move different objects etc.

2.4.4 KUKA.Ethernet RSI XML

The KUKA.Ethernet RSI XML software package is required to control the robot externally in real time. The term external system is often mentioned and refers to the computer(s) that are connected to the robot controller (in this case the computer that holds the server that the robot controller is communicating with).
The KUKA.Ethernet RSI XML is an add-on technology package with the following functions [12]:

- Cyclical data transmission from the robot controller to an external system in the interpolation cycle of 12ms (e.g. position data, axis angles, operating mode, etc.)
- Cyclical data transmission from an external system to the robot controller in the interpolation cycle of 12ms (e.g. sensor data)
- Influencing the robot in the interpolation cycle of 12ms
- Direct intervention in the path planning of the robot

The characteristics of the package are the following:

- Reloadable RSI-object for communication with an external system, in conformity with KUKA.RobotSensorInterface (RSI)

- Communications module with access to standard Ethernet
- Freely definable inputs and outputs of the communication object
- Data exchange timeout monitoring
- Expandable data frame that is sent to the external system. The data frame consists of a fixed section that is always sent and a freely definable section.

The KUKA.Ethernet RSI XML enables the robot controller to communicate with the external system via a real-time-capable point-to-point network link. The exchanged data is transmitted via the Ethernet TCP/IP or UDP/IP protocol as XML strings. For this thesis the Ethernet TCP/IP was used since it makes a more secure communication with response from the destination to the host, while the UDP/IP lacks this response.

Programming of the KUKA.Ethernet RSI XML package is based on creating and linking RSI-objects. RSI-objects are small pieces of pre-programmed code that can be executed and has additional functionalities than the normal KRL-code. To be able to communicate externally through Ethernet, a specific standard object (ST_ETHERNET or ST_COROB) needs to be created. The code line for creating for example the ST_ETHERNET is typically:

```
err=ST_ETHERNET (A,B,config_file.xml)
```

Where,

err is a type of string used by the RSI XML (called RSIERR) containing the error code produced when creating the object (normally #RSIOK when it works),

A is an integer value that contains the specific RSI-object ID so that it is possible to locate and refer to,

B is an integer value for the container to which you want the RSI-object to belong in order to create a group of different objects containing to the same container,

config_file.xml is a configuration file located in the INIT folder (path C:/KRC/ROBOTER/INIT) on the robot controller that specifies what should be sent and received by the robot controller.

The content of this file will be explained further down.

ST_ETHERNET and ST_COROB are objects that can be influenced by external signals, and also send data back to the external system in form of XML files, containing different tags with data. The data can be for example information about the robot's actual axis positions, Cartesian actual positions etc. This data shall sent to the server and back within each interpolation cycle of 12 ms. ST_ETHERNET has the same functionality as ST_COROB but with additional functionalities; one of these object always need to be created and correctly linked in the KRL code in order to establish communication with the external system. In this project, the communication object ST_ETHERNET was used. When one of these objects is created and linked correctly, the robot controller connects to the external system as a client.

There are a lot of different types of RSI-objects and depending on what you want to do, you have to create and link the correct objects to each other. Besides the standard Ethernet card, an additional card (3COM) was needed, to be able to handle the speed of the transferred data [12].

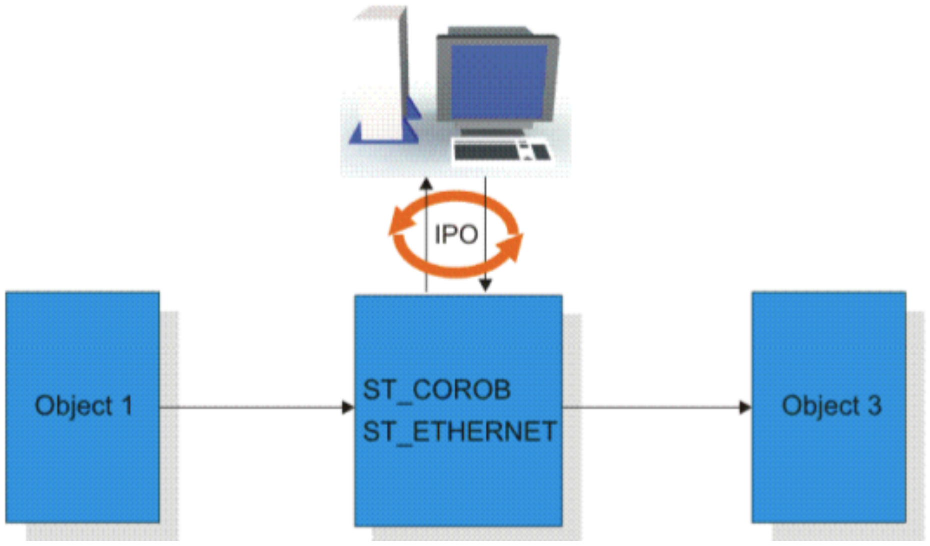


Figure 7: Functional principle of data exchange [12].

The robot controller initiates the cyclical data exchange with a KRC data packet and transfers further KRC data packets to the external system in the interpolation cycle of 12 ms. This communication cycle is called a IPO-cycle (Input Process Output) and can be seen in figure 7 above. The external system must respond to the KRC data packets with a data packet of its own.

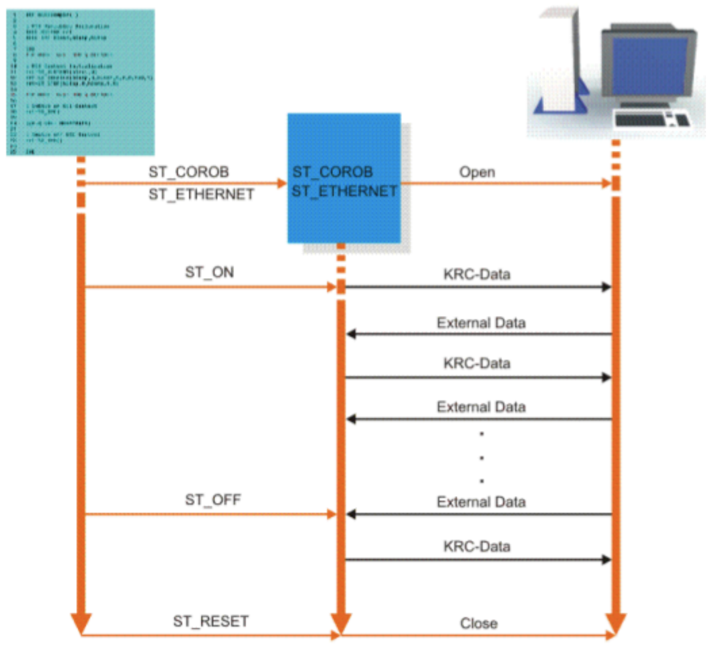


Figure 8: Data exchange sequence [12].

To be able to influence the robot, one needs to initiate an RSI-object for the movements. There are mainly two objects used for this. First an object called ST_AXISCORR(A,B) for specific movements in axis A1 to A6, where A is the specific ID of the created object, and B is the container that the object belongs to. The second object is called ST_PATHCORR(A,B) for movements in Cartesian coordinates, where A, B are the same as for the ST_AXISCORR object. A coordinate system is also needed (normally BASE, TCP, WORLD) as a reference for the movements. This is done by creating a RSI-object called ST_ON1(A,B) where the parameter A is a string containing the coordinate system that is supposed to be used (expressed as #BASE, #TCP or #WORLD) and B is an integer value, 0 if the correction values sent to the robot shall be absolute or 1 if they shall be relative. A schematic picture of the data exchange sequence with the different RSI-objects is shown in figure 8 above. When the robot is delivered from the factory, the BASE coordinate system is the same as the WORLD and both are located in the base of the robot by default. BASE is normally moved to the base of the work piece on which the robot is working. The differences between the different coordinate systems can be seen in figure 9 below. NOTE: For the robot used in this thesis, all three systems; WORLD CS, ROBOT CS and BASE CS have the same origin located on the base of the robot.

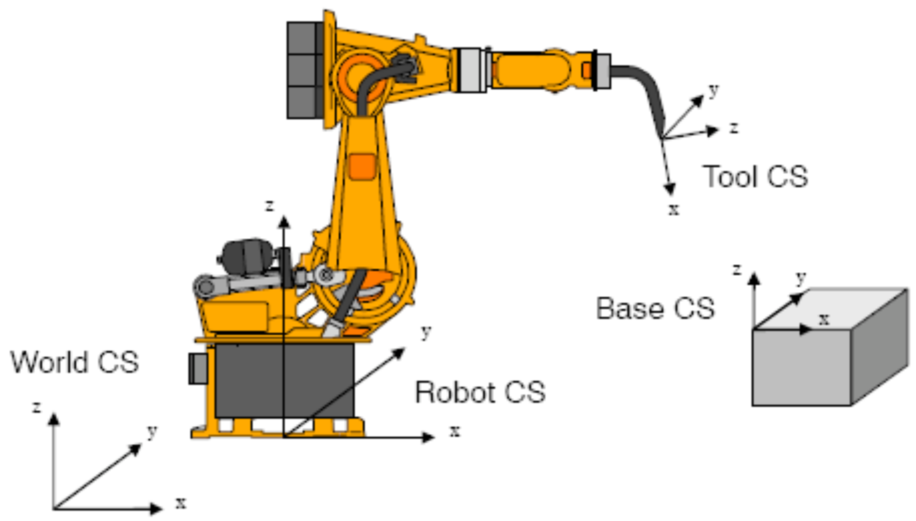


Figure 9: The different coordinate systems [11].

Though it was discovered that when starting the WORLD coordinate system, the origin where set on where the robot were standing when starting the system. This only applies for the communication *to* the robot controller, so that the starting position shall always be set as 0 before starting to move the robot. The response sent back to the external system was in real coordinates with the WORLD coordinate system starting at its standard position on the base of the robot.

When the robot controller communicates with the external system it interchanges XML Strings. The content in the XML strings for the demo program provided by KUKA, is decided and defined in a file called ERX_config.xml (the configuration file, mentioned above), which is located in the robot controller, inside the INIT folder. A typical example of the content in this file is shown in figure 10 below.

```
 <ROOT>
 <CONFIG>
   <IP_NUMBER>192.0.1.2</IP_NUMBER>
   <PORT>6008</PORT>
   <PROTOCOL>TCP</PROTOCOL>
   <SENTYPE>ImFree</SENTYPE>
   <PROTCOLLENGTH>Off</PROTCOLLENGTH>
   <ONLYSEND>FALSE</ONLYSEND>
 </CONFIG>
 <SEND>
   <ELEMENTS>
     <ELEMENT TAG="DEF_RIst" TYPE="DOUBLE" INDX="INTERNAL" UNIT="0" />
     <ELEMENT TAG="DEF_RSol" TYPE="DOUBLE" INDX="INTERNAL" UNIT="0" />
     <ELEMENT TAG="DEF_AIPos" TYPE="DOUBLE" INDX="INTERNAL" UNIT="0" />
     <ELEMENT TAG="DEF_ASPos" TYPE="DOUBLE" INDX="INTERNAL" UNIT="0" />
   </ELEMENTS>
 </SEND>
 <RECEIVE>
   <ELEMENTS>
     <ELEMENT TAG="DEF_EStr" TYPE="STRING" INDX="INTERNAL" UNIT="0" />
     <ELEMENT TAG="RKorr.X" TYPE="DOUBLE" INDX="1" UNIT="1" HOLDON="1" />
     <ELEMENT TAG="RKorr.Y" TYPE="DOUBLE" INDX="2" UNIT="1" HOLDON="1" />
     <ELEMENT TAG="RKorr.Z" TYPE="DOUBLE" INDX="3" UNIT="1" HOLDON="1" />
     <ELEMENT TAG="RKorr.A" TYPE="DOUBLE" INDX="4" UNIT="0" HOLDON="1" />
     <ELEMENT TAG="RKorr.B" TYPE="DOUBLE" INDX="5" UNIT="0" HOLDON="1" />
     <ELEMENT TAG="RKorr.C" TYPE="DOUBLE" INDX="6" UNIT="0" HOLDON="1" />
   </ELEMENTS>
 </RECEIVE>
</ROOT>
```

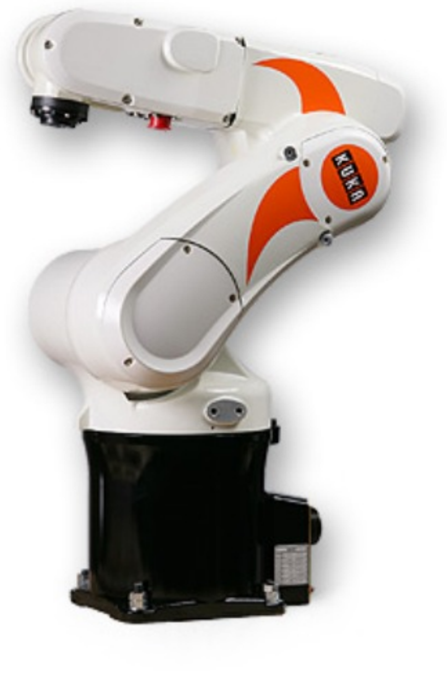
Figure 10: The structure of ERXconfig.xml.

As can be seen in figure 10 above, the IP address and port to which the robot controller will connect, when establishing the connection, are set in this file. The sub tags under <SEND> are what the robot controller sends to the external system. The most important tags for sending to the external system for this project are the tags called DEF_RIst, which is the real position of the robot's end-effector, and DEF_RSol that is the set position received from the external system. The DEF_AIPos and DEF_ASPos are real axis position and set axis position respectively. Under the tag RECEIVE is described what the robot controller expects to receive from the external system. In this case only corrections in six values (X, Y, Z, A, B and C) are included, tagged as RKorr. The meanings of these six values are described above under the section "programming of KUKA robots".

3. Hardware and software prerequisites

3.1 Robot

The robot used in this project is a KUKA KR 5 sixx R650 together with a KUKA KR C2 sr controller. This compact robot is a light-weight, fast and reliable robot for its size. Since this robot is able to be mounted on the ceiling it was beneficial for our project. A ceiling mounted robot is suitable for inspection purposes since you can get the best overview and can also go around objects in an easier way without touching them.



Robot specifications
(Source: KUKA webpage, www.Kuka.com):

Model:	KR 5 sixx R650
Payload:	5kg
Max. reach:	650mm
Speed:	375 ° /s
Controller:	KR C2sr
Number of axes:	6
Repeatability:	<±0,02 mm
Weight:	28 kg
Mounting positions:	Floor, ceiling
Speed max.:	8,2 m/s

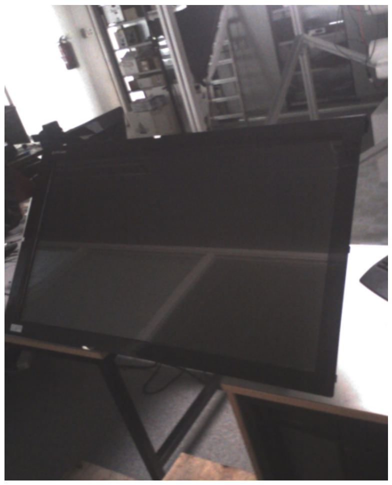
Figure 11: KUKA KR 5 sixx R650 robot with its specifications [13].

3.2 Robot controller

The robot controller used in this project is a KR C2 sr controller. The KR C2 sr uses an embedded version of Windows XP as operating system. This means that the operating system is a special version of Windows XP built to be run in parallel with KUKA's own controller application.

3.2 Screen

The Multi-touch screen used in this thesis is a Multi-touch overlay for a 42-inch monitor, called G3 Basic (Figure 12). The overlay is produced by a company called PQ Labs situated in Silicon Valley, USA. The company is a provider of Multi-touch solutions, developing both hardware and software in the field of broadcast, digital signage, defense, geo-intelligence, product presentation and interactive education etc.:



Specifications:

- 6 touch points
- 42" screen size
- 3mm tempered glass
- No touch activation force required
- 7-12ms touch response time
- Powered by USB

Figure 12: PQ Labs G3 Multi-touch overlay and LG 42" full HD screen [14].

3.3 External computers

Since the applications that were run in this project need a lot of resources to work the way it is intended, computers with a relatively high performance with today's standards were necessary. The whole system consists of three computers (including the robot controller computer); one running the interface, one running the server and the last one is the robot controller. The computer running the server (see explanation under system development) was a quad processor (4 cores) of 2,73GHz with 4GB RAM. This computer was needed since almost all CPU could be dedicated only for the communication (response to the controller was needed every 12 ms) which we found to be stable with this solution. The computer running the interface also needed to perform well since a smooth communication with the server was desired. For this purpose a computer with a dual core processor of 2,7GHz, and 4 GB of RAM was used.

3.4 Software

In this project a lot of different softwares have been used. Since the focus of this Master thesis is on the robot communication, only a short description will be presented of what softwares that were used for programming the interface. The first version of the interface was programmed in Flash with ActionScript3 (AS3) built in Adobe flex 4 together with Unity 3D. The second version was built using Windows Presentation Foundation (WPF), specifically Microsoft Visual Studio 2010, running on windows 7. The language used for second version was XAML for UI components and C-sharp for the logic. The reason why it was transferred to C-sharp was that the new Visual Studio with built-in support for Multi-touch interfaces came out during the work with the project.

4 Methodology

In this section the experimental methodology that was used during the project is described. The methodology is divided into the parts Initiation, Setup, Establishment of communication, Interface design and Concept evaluation.

4.1 Initiation

A comprehensive literature study was initially carried out in order to document the different domains of shared control, human-machine interface and real-time control. In this study basic knowledge in the following was also included:

- How to program the Multi-touch screen using Adobe Flash Builder (for the visual touch controls and video feeds) and Microsoft Visual Studio 2010 in combination.
- The specific robot used in the project, namely a KUKA KR 5 sixx R650 robot.
- Ways to remotely control the robot with an external device using direct connection through serial port, Ethernet, OPC (OLE for Process Control) etc.

4.2 Setup

A demonstrator was developed in order to illustrate and study some vital functions of the system setup. The safety solution was limited in the demonstrator, which means that extra arrangements for personal and machine safety were integrated so that all necessary precautions were taken when operating the demonstrator robot.

The two different areas of the project was commenced in parallel and will from here on be referred to as "Interface" and "Robot control" respectively. These two parts of the project were later coupled together.

4.3 Establishment of communication

To establish the communication some different options were studied. There were for example communication via a OPC-server, communication via serial port and ethernet communication via XML-strings. Since this project's objective was to control the robot in real time, a fast and responsive way of communication was needed. The fastest way of communicating was the ethernet communication with XML-strings that had a communication interpolation cycle of 12 ms, which should be more than enough for this project. To get this to work, the KUKA RSI XML 1.2 (described above in the section “Theoretical background”) was used. Also an extra ethernet card allowing high speed data interaction was needed in the controller computer to be able to establish the communication. In the case of this thesis, at first a demo program developed by KUKA was run on the robot controller, together with KUKA:s demo server in order to establish and test the communication with an external system.

4.4 Interface design

When designing the interface, data based on how people act is needed to be able to make it as user friendly and intuitive as poossible. In this project a study of the documentation of previous human experiments with Multi-touch screens was made in order to collect as much knowledge as possible. Then this knowledge was applied in the interface design and common commands and gestures were used for controlling the different objects. For example the study revealed that the two-finger spread motion to zoom and the single finger drag for panning had been proved to be very intuitive in previous studies. A sketch of how the interface were supposed to look like when finished was made after meetings and discussions of what could be the best way of designing the interface. It was not necessary to follow paradigm on how a UI should be designed, so new inventions were also discussed.

4.5 Concept evaluation

The method used to evaluate the developed concept and the built demonstrator has been to perform usability tests. User tests were chosen as evaluation method because it gives a good picture of the intuitivism of the screen from the users point of view. After the tests were performed the results were collected, analyzed and conclusions were drawn, see "conclusion" section".

5. System development process

The project is divided into 3 main parts:

- Interface Development
- Robot Controller Programming (KRL)
- Communication

These parts will be explained under the following sub-sections.

5.1 Interface Development

This project has aimed to get the user interface (UI) as intuitive as possible. A lot of research has been done about previous experiments and knowledge achieved from those, to see which design could be most suitable for this specific project. Mostly the research was focused on shared control and design of human-machine interfaces (HMI). The appearence of the interface and the function was discussed and evaluated before deciding the final concept of UI to use.

Through discussion, with the members of the group who were responsible for the programming of the Multi-touch screen, different possibilities of how to design the first beta-version of the interface were investigated. It was agreed initially that the most important part of the project was not to find the absolute best way to design the interface, but rather see what was possible to do and whether it was possible to establish a good communication. The development of the interface layout when it comes to intuitivism and user friendliness was initially of second nature, depending on success of the communication part of the project. What was of greater importance however, was what sort of data packages that had to be sent to the controller and via which ports.

The first step in building of the interface was to be able to move the robot in the X-Y-plane with a simple 2D interface, see figure 13. When that was solved, the project moved on to developing the interface further and implementing control of the other robot movements, such as the Z-direction, tool orientation and individual rotation of the robots A1-joint (First joint counting from the base of the robot). This programming was done in flash language using flash builder at a mini-MAC that was connected to the Multi-touch screen.

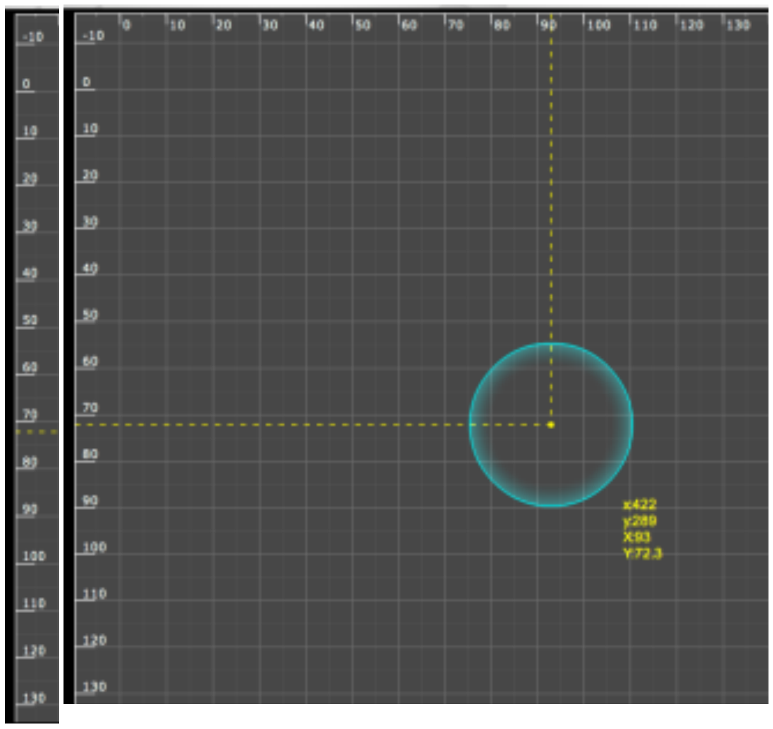


Figure 13: XY and Z controls in the first version of the interface.

Then a conceptual sketch showing how the layout of the interface was created. This can be seen in figure 14. This concept was never fully tested since the recording area was left for later implementation.

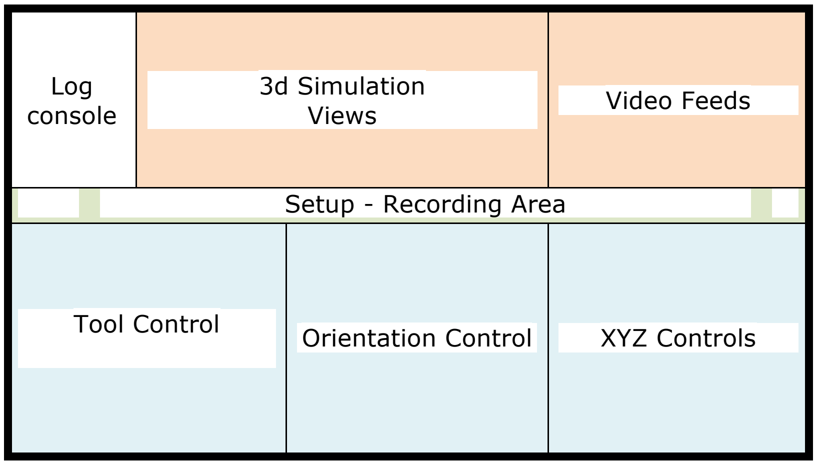


Figure 14: Conceptual sketch of the first version of the interface that never was created.

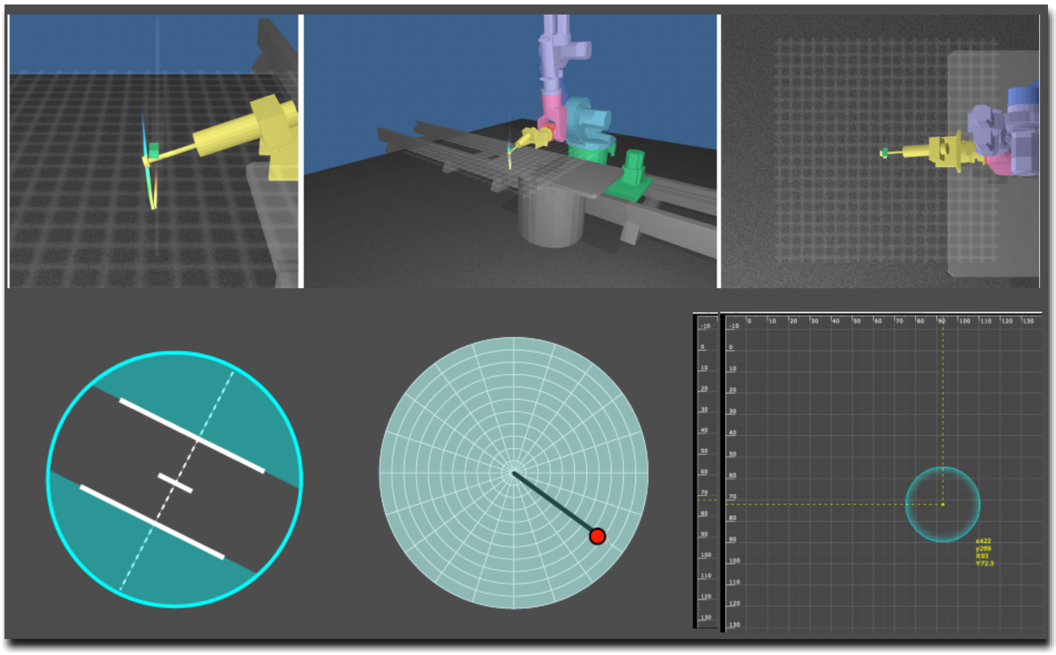


Figure 15: Photo of the first version of the interface.

One important thing when designing the UI was how to interpret the tool orientation. Two different concepts or a combination of the two were considered for the solution of the tool orientation control. The first concept was a ball, which could be rotated in all three axes simultaneously using one finger touch and movements; this can be seen in figure 15 above. The second was a ball, which could be rotated in only two directions (B and C) with one-finger touch. For the second concept, the rotation of A (around the Z-axis) was done by a different module other than the ball. The theory behind this solution is that the user might find it more intuitive and easier to control the A rotation separately since controlling all three rotations with the same module might be considered as to complex. Early tests with the first concept proved that it was hard to move the first ball back to its original position after moving it around for a bit, something that was easier with the second concept. On the other hand the second concept needed two modules and the first only one, which might seem to add a bit more complexity to the interface.

These two concepts or rather a combination of the two was then decided to use as the final version of the tool orientation, which is described further down in this section.

The HMI that was created in this project has the aim to move a robot in a 3D-space from a 2D-interface. The problem was to get it as intuitive as possible with controllers and commands from the 2D-space that should be transferred into 3D-motions. In other words, movements in the 3rd direction must be substituted by some kind of motion or gesture that is easy to understand and as self-explanatory as possible.

After testing the interface built in Flash, figure 15, it was realized that after some use it started lagging and was not as smooth as wanted. Therefore experiments were made on controls made in Visual Studio 2010 in programming language C#, and it seemed to be smoother for this kind of purpose. Hence a translation of the code from flash to C# was made. Also experiments were made with other layout of the controls since it was discovered by tests that the controls could be improved from the first version. The first conceptual sketch of the second version of the interface can be seen in figure 16 and figure 17 below:

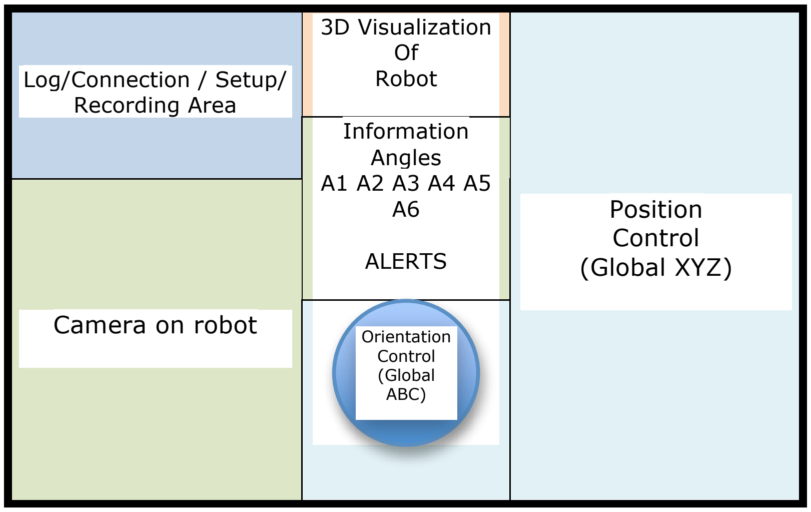
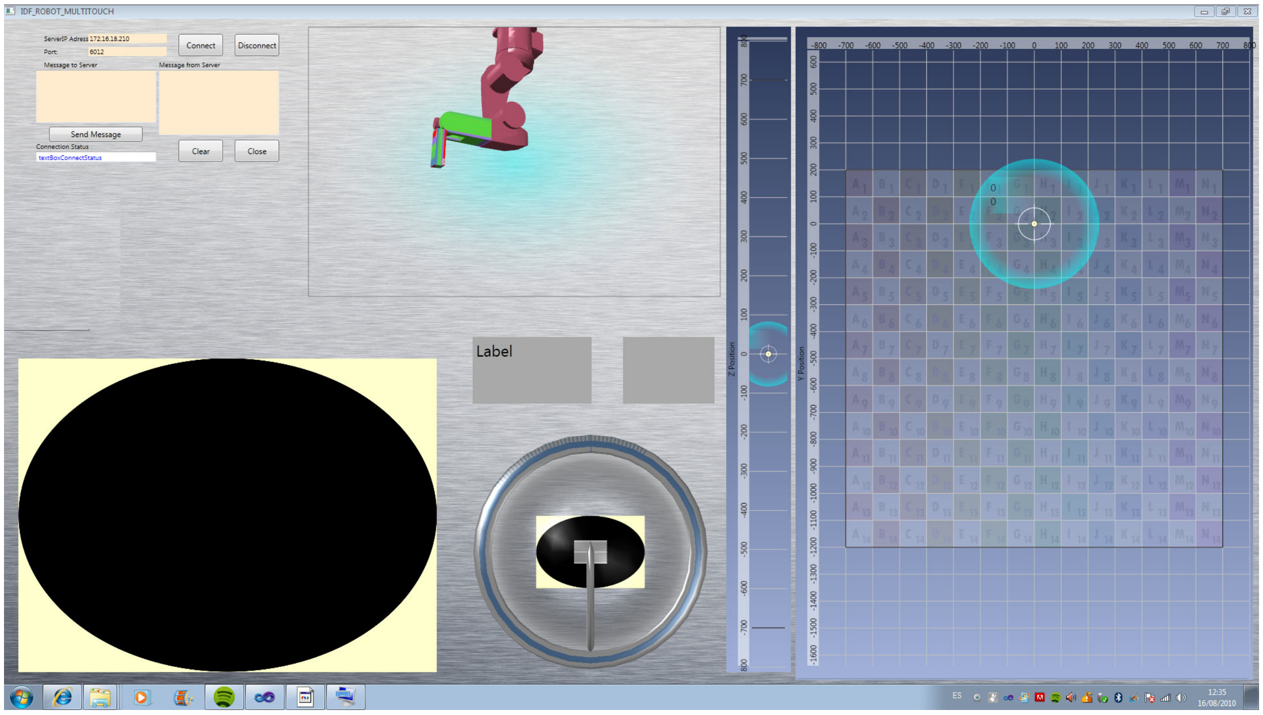

Log/Connection / Setup/ Recording Area
3D Visualization Of Robot
Information Angles A1 A2 A3 A4 A5 A6
ALERTS
Position Control (Global XYZ)
Camera on robot
Orientation Control (Global ABC)

Figure 16: Conceptual sketch of the second version of the interface.



ServerIP Adress 172.16.18.210
Port: 6012
textBoxConnectStatus

Figure 17: Photo of the second version of the interface.

After more discussion and testing, the final version of the interface for this project was decided and a conceptual sketch from the interface is shown in figure 18 below:

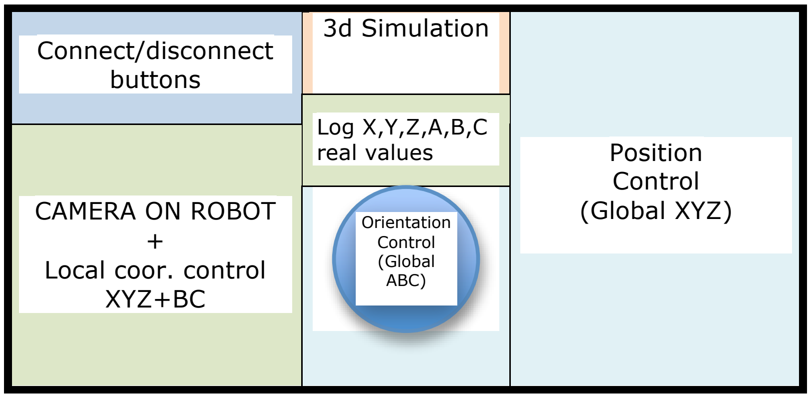

Connect/disconnect buttons
3d Simulation
Log X,Y,Z,A,B,C real values
Position Control (Global XYZ)
CAMERA ON ROBOT + Local coor. control XYZ+BC
Orientation Control (Global ABC)

Figure 18: Conceptual sketch of the third and final version of the interface.

As can be seen, the ability to move the robot in the A1 axis separately was never used. This was due to the fact that the meaning was to get it as simple as possible, especially for the user tests.

A screenshot is shown in figure 19 below:

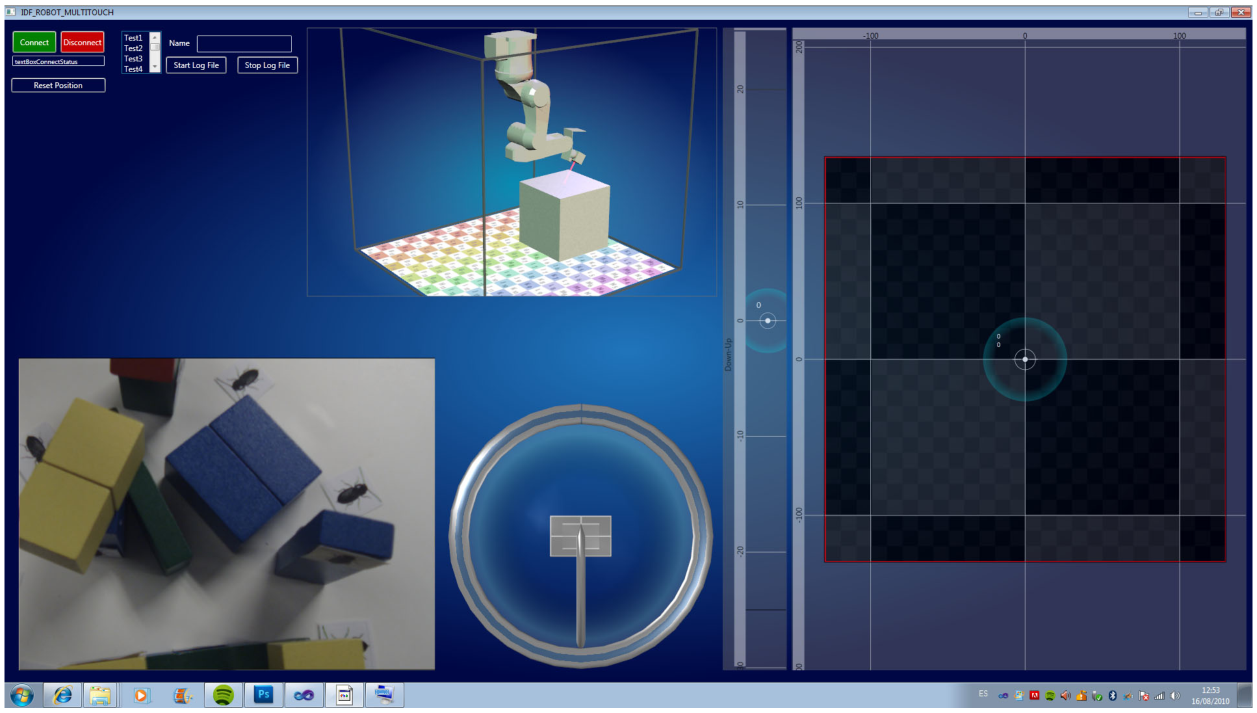


Figure 19: The third and final version of the interface.

The interface now consists of one area for movements in XY, one slider for movements in Z, one "video control" for movements in local coordinates, one ball for orientation of the tool maintaining the same point in space and a graphical visualization of the robot position based on the real feedback from the robot. Besides that, an area with the real values of X, Y, Z, A, B and C are shown in the middle of the screen, and connect/disconnect buttons in the upper left corner.

The controlling with respect to the local coordinate system is placed as an overlay control over a video stream coming from the camera mounted on the tool tip. The idea was that controlling it in this way should be intuitive since it can directly be seen what is being controlled. To control the camera locally in the plane, one finger is used to "snap" the background and then dragging to move it in the desired direction. To go forward and backward (direction of the lens) a pinch motion is used (see section "proposed gestures").

At the end it was decided that all movements on the interface should be translated into X, Y, Z and A, B and C coordinates respectively. Therefore to do the movements in local coordinates, these are translated into the global coordinates before sending them to the robot. This is done by checking the orientation of the camera and then calculating the projection in each axis, before sending the target coordinates.

As mentioned above, to control something in 3D- from a 2D-interface is complex, so one direction needs to be interpreted and translated to a motion in some way. To be more self-explanatory, a redesigning of the 3D-ball (orientation of the camera) was done. At the beginning it was just a 3D-ball controlled by one finger in all directions. When tested it was realized that it must be better to have one finger controlling rotation around X and Y (B and C respectively) so that the ball can "snap" to the finger that is touching. This results in a more precise controlling of the orientation. The last direction A (rotation around Z) is then separated and controlled by a two-finger rotation on the same controller. In previous tests [15] most users chose two fingers for rotation. For an explanation of all gestures used in this project, see section "Proposed gestures" further down.

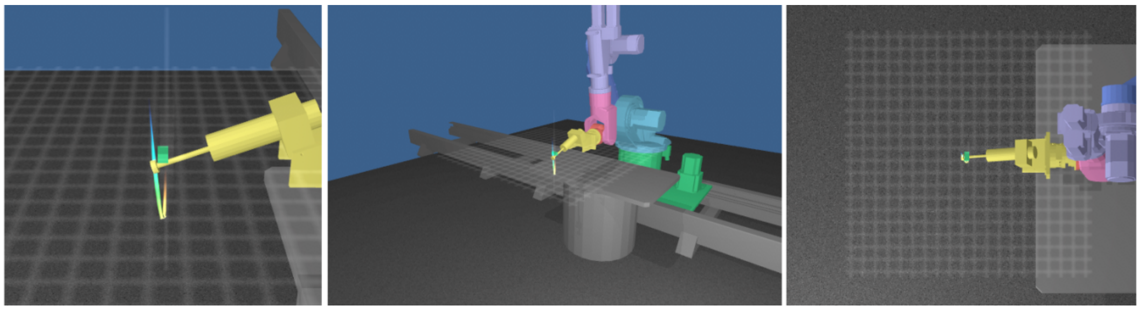
The intention has been to make the controls that are natural for the user. The grid control includes both the XY-control and the Z-control, and work in the same manner. When touching the blue ball with one finger and moving it, it snaps to the finger and the robot follows your finger. The white dot in the center of the blue ball is the real position of the robot so when moving it, one can directly see the latency of the commands according to the robot's actual position.
The final step to evaluate the interface was to perform a usability test of the interface with a small test group containing people with different backgrounds, age and sex, see section "Usability tests".

5.1.1 Layout

Main components with pictures from the first version of the UI are described here

Main visualization area

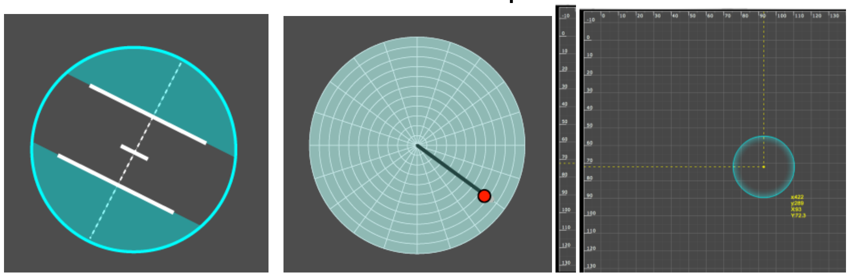
3D Simulation views



Video feeds from a webcam located close to the robot.

Main control area.

Multi-touch controls compiled with Flex



Y/XZ Position, Orientation and Tool Controls

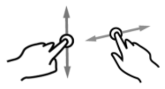
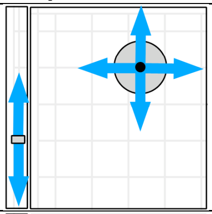
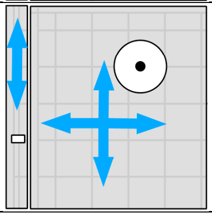
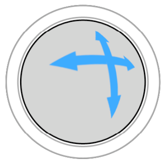
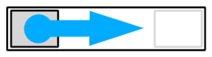
Log console. A simple white space to show log-data. Show the data sent and received

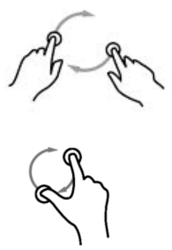
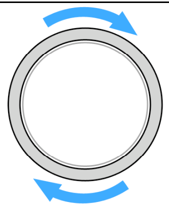
Figure 20: Different areas on the Multi touch screen's interface.

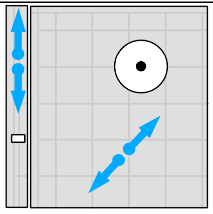
5.1.2 Proposed gestures

Gestures do not have a global meaning; each Multi-touch device (like the Iphone) associates different gestures to fixed actions, simple or complex ones. In most cases the same gesture is reused in different contexts to perform specific functions, which also has been done in this project. (Otherwise many different gestures are needed, which make it complex and hard to remember) Table 1 shows a list of gestures and the contextual meaning on the UI.

Table 1: Proposed gestures for robot control.

Gesture		**Graphics**	**Context**	**Meaning**
DRAG			Control Area **Position Handlers: xy + z**	**Move** XY and/or Z positions of the end-effector (1 or 2 hands)
			Control Area **Grid**	**Move** the Grid to reframe the Control Area
			Orientation Control Area **Rotation Handler (B+C)**	**Move TrackBall to Orientate** the end-effector.
			Simulation View Area **3D Perspective Camera**	**Orbit** (Tilt/roll) around the targeted robot on the 3d view.
			Setup Area Buttons **Buttons**	**Switch on/off** safe slider buttons. (Not implemented in the demonstrator)

Gesture		**Graphics**	**Context**	**Meaning**
ROTATE			Orientation Control Area **Rotation Handler (A)**	**Rotate** the tool of the robot arm. (1 or 2 hands)

Gesture		Graphics	Context	Meaning
PINCH SCALE ZOOM	 		Position Control Area **Position Grid**	**Zoom in/out** the Grid to change the scale of the coordinates system on the Control Area and the 3d views. (1 or 2 hands)
			Position Control Area **Tool Handler**	**Open/close** the tool if it is a claw

5.2 Robot Controller Programming

The different ways of controlling the robot in real time were investigated (since this is not a common practice for controlling an industrial robot) in parallel with research about Multi-touch screens and research in the different domains of shared control, human-machine interface and real-time control.

In order to establish the communication via Ethernet, the add-on software package called KUKA Ethernet RSI XML 1.2 (described above in the section “Theoretical background”) was required. Hence, this software together with latest KUKA robot simulator software, SimPro v.2.1, and KUKA’s virtual controller, OfficeLite v.5.4, was ordered from KUKA. When SimPro and OfficeLite are run in parallel this can be used as a virtual setup of the real robot and its controller. The purpose is that it should work and behave as similar as possible to the reality.

SimPro was used in the early stages of the project in order to test the functionality of the Ethernet RSI.XML in a virtual environment first, in order to learn how to use it before commencing the testing with the real robot. The Ethernet RSI XML package came together with demo programs from KUKA as example of how the package could be used. While waiting for the software packages to arrive, the documentation of the software was studied.

In order to get everything to work, licenses needed to be ordered separately after receiving the software. When that was done, experiments started on how to control the robot real-time in the virtual world. This was done by first installing all software on the same computer, then importing a virtual model of the robot in SimPro and then trying to connect SimPro with the virtual controller in OfficeLite. When that connection was stable, it was possible to move the robot manually through the virtual teach pendant in OfficeLite. Then the sample program for KUKA Ethernet RSI XML was run, together with the sample server provided in the Ethernet RSI XML package. At first a lot of problems were experienced, such as unstable communication, problems with moving the robot in all directions, problems with exceeding allowed speeds in the joints that caused the robot communication to break etc. All these problems and the causes are explained in table 2 below.

Table 2: Encountered problems that caused the communication to break.

Problems	**Solutions**
• Speed exceeded in several joints, especially joint A4	• Changing the system variable $CP_VEL, from #CONSTANT to #VAR_ALL
• Too high forces on robot axis.	• Changing the system variable $CP_VEL, from #CONSTANT to #VAR_ALL
• Work envelope exceeded	• Limit the workspace by using RSI-object ST_SETPARAM
• Software limit switch reached, all joints	• Limit the workspace by using RSI-object ST_SETPARAM • Set a new starting position, that are outside risk of singularity
• Communication randomly was interrupted	• Moving the server to a more powerful computer, able to response within the IPO cycle of 12ms

Once the programming of the demo programs was understood and a stable communication with the virtual robot was established, the project moved on to trying to control the real robot. As mentioned before the real robot required a special 3COM card to be installed on the controller computer in order to connect via Ethernet to an external computer. This was not required on the computer running the virtual controller and the simulator since it had the same IP address and communicated internally. So this had to be ordered as well and was later installed by a technician from KUKA. The reason why it was not sent from the beginning was that this technology is so new that very little information on how to use it was to be found and the person that received the order of the XML package at KUKA was not aware of that it was needed. Once the card was installed and tested together with the RSI XML demo program and the sample server provided by KUKA, the connection could finally be established.

A MATLAB toolbox was also studied for inverse kinematics to use for a 3D simulation of the robot. Inverse kinematics can be simplified as: given the real position of the end-effector, it calculates the joint angles that are needed to reach this point. It was later realized that this was not required, since full feedback is received from the robot in form of all angles and real positions of each joint, according to the coordinate system that is used for reference (in this case WORLD coordinate system).

During the first tests, KUKA's own demo-server was used for communication with the robot controller. It was almost directly discovered that joint A4 in the robot had too much speed in many movements, so that software switches built-in in the robot controller interrupted the robot communication. In order to get the real time control to work with KUKA's own server in a satisfying way, the values of an RSI-object called SETPARAM needed to be altered to prevent the software limit switches to be activated and hence stop the communication. SETPARAM sets the upper and lower limits of each moving axis and rotation angles, hence creating the work envelope. The work envelope is the area where the robot is allowed to move within. The communication remains stable even if these limits are reached and only causes the robot to stand still, until a value within the set limits are received. Worth noticing is that to be able to not exceed any limits of the orientation of the tool, the A, B and C values needed to be set to 20 degrees of movement in all directions. The limits set for X, Y and Z were -130 – 130, -130 – 130, -25 – 20 in mm respectively. The speed of the A4 joint were also exceeded at various occasions and that was eventually solved by changing a system parameter, $CP_VEL, from #CONSTANT to #VAR_ALL. The effect of this is that when the robot controller receives a command that will cause any of the axes to move too fast, it will slow down the movement to avoid any movement that will cause interruption (failure). The software limit switches are only preset limits set to avoid any hardware damages.

When starting the coordinate system with the parameter ST1_ON (A,B), one can also decide if the values received by the robot controller should be incremental from the start position or absolute values, also referring to the start position of the robot. After discussing with the other group members it was decided to use the base coordinate with absolute values instead of incremental values, since the staring position always remains the origin for the movements.

When using the interface it was realized that the robot would have much larger work envelope if the single joints could be moved separately. First this was implemented for Joint A1, since this would make the whole robot turn. After testing the demonstrator, it was realized that when moving this joint, the whole coordinate system moves in accordance with the movements in A1. The control for the A1-joint was disabled during the usability tests due to that the fact that it would have been one more control for the users to learn. The goal was to perform the test with a simple but still fully working interface.

In order to make the tool orientation rotate around the lens of the PS3-camera, mounted on the tool tip of the robot, the Tool Center Point (TCP) had to be moved. The TCP has its own coordinate system and by default the origin is located at the tip of the robot, shown in figure 21 below. This transformation of the TCP, were made directly in the program by first measuring the real displacement of the PS3-camera lens from the default origin (compare Tool CS in figure 9 and figure 21). The coordinates of the lens were then introduced in the KRL code of the robot controller.

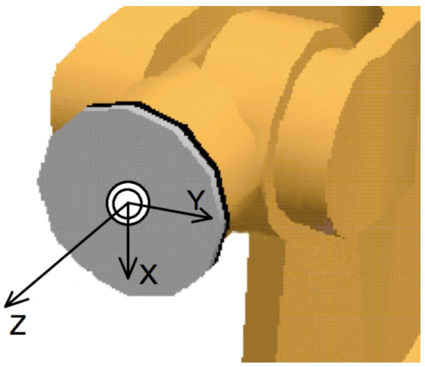


Figure 21: Default Tool CS [11].

When running the robot using the Multi-touch screen, it was discovered that sometimes the robot made a very fast rotation of the A4-joint and sometimes tried to rotate the A4-joint too much (thus triggering the software limit switches), causing the communication to break. This phenomena is caused by something that is called singularity. Singularity occurs when two of the robot's axis are lined up, causing the robot to have an infinite number of possible solutions to reach the target position. For example, if axis 4 and 6 are lined up, see figure 22, and the robot's target position requires a roll of 20 degrees, the robot could use an infinite number of combinations to satisfy that roll value: (30 deg, -10 deg), (50 deg, -30 deg), (0 deg, 20 deg) etc. This results in high speeds and unpredictable movements of the axes in between. The singularity problem was solved by changing the system variable $CP_VEL, from #CONSTANT to #VAR_ALL (limits the speed by slow down the end-effector movement in order to not exceed any axis angle velocity), and by changing the home position (start position, in this case) to a safer location. Also the problem with the software limit switches was solved, as shown in table 2 above, by using the ST_SETPARAM object to limit the motions.

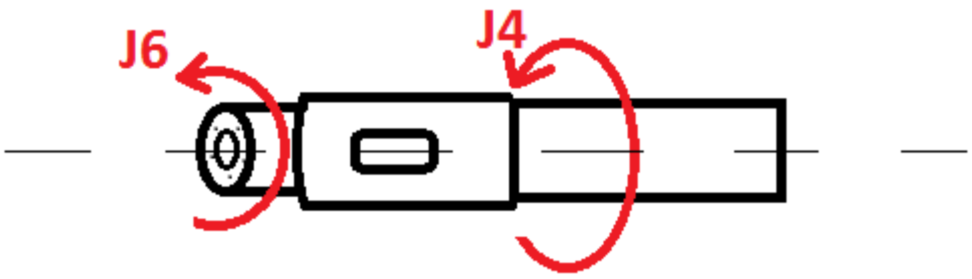


Figure 22: Singularity occurs when two joints are lined up, in this case joint 4 and 6.

5.3 Communication

The communication between the interface and the robot goes via Ethernet from the robot controller to an external computer(running only a small efficient server with two two-way communication) and then to the interface. The purpose of the server is to maintain a stable and fast communication to the robot controller. It should just take the data and send it to the other end, both interface to controller and controller to interface.

After development of the interface it was discovered that it was not possible to have a stable communication with the robot controller if the server was integrated and run on the same computer. The reason for this was that when the robot controller runs the program used for Ethernet communication and has created the RSI-object ST_ETHERNET (described above in section "KUKA.Ethernet RSI XML") it expects communication within each interpolation cycle of 12ms. If answer is not recieved whitin this time, the communication will be interrupted, and a restart is needed. Therefore it was decided to develop a small server that required minimum resources. This server was placed on a separate computer in order to maintain a stable communication to the robot controller. The connection was physically established using Ethernet cables connected to a hub, creating a LAN (Local Area Network). Fixed IP needed to be set on all computers in the network since the robot controller connects to the preset IP, defined in the ERX_conifig.xml (described above, in section "Theoretical background"). The addresses used were for the controller 172.16.18.200, for the server 172.16.18.210, and for the interface 172.16.18.100. Different ports were also defined in order to use different ports for communication server to robot controller (6008) and server to interface (6012)

The purpose of the server is just to forward all communication in both ways, only that the communication between the interface and the server does not need as fast communication as the one between the server and robot controller. A schematic picture of the communicaton is displayed in figure 22 on the next page.

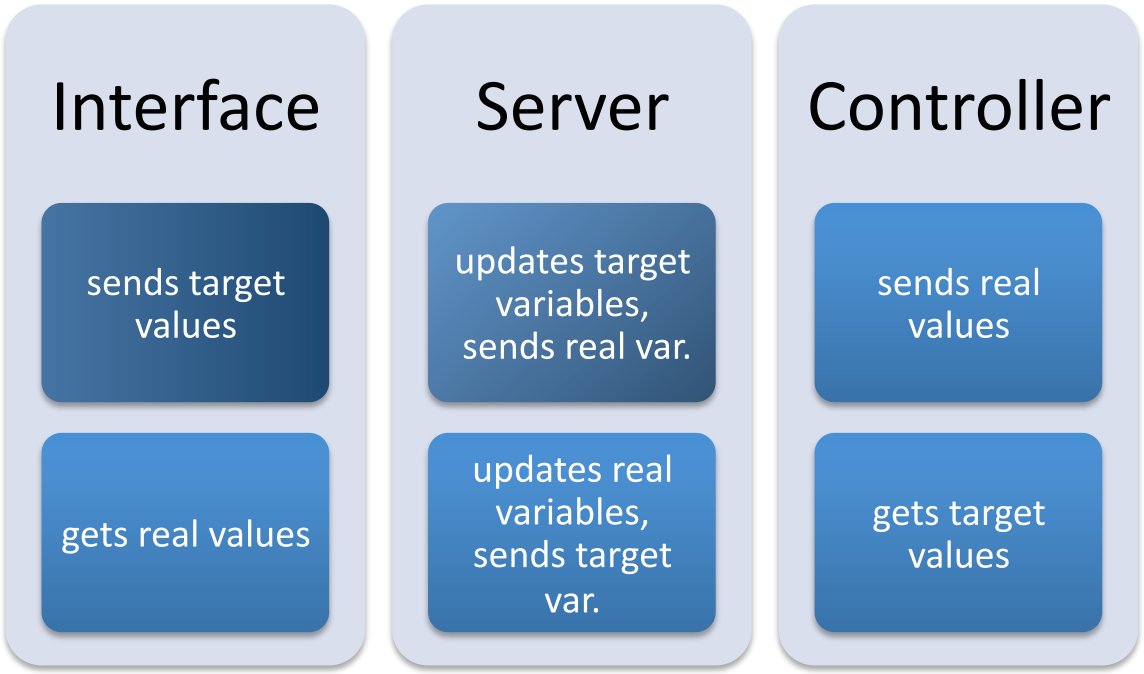


Figure 22: Schematic picture of the communication.

6. Empirical study

In order to evaluate how this concept worked and the usability of the interface, a diverse test group was needed. The people used for the test were randomly picked and had various backgrounds. It is important to notice is that most of the users in this study were academics.

6.1 Usability tests

The tests consisted of 7 different tasks. The main purpose of each test was to use a laser pointer that was placed on the end-effector in order to point, and follow different points or trajectories. First the test persons had to answer questions about age, sex, education, computer experience, earlier experience with touch/Multi-touch and robots. Also a list was made to see whether the user had a technical- or a non-technical background.

In order to test whether the interface had a good usability, or "intuitivism", a number of different tests were performed. It is important to note that due to time limits this thesis does not include research and utilization of all the available tools for measuring the intuitivism. The usability tests are just an initial step to see the possibilities that could lie within the use of Multi-touch interfaces when controlling a robot.

In total 7 tests were performed on a group of 20 people. The people had different backgrounds in respect to education, country and sex. The tests were performed with the think aloud protocol [15] and were recorded with a video camera. This protocol means that the users are asked to say what they are thinking in every moment. In addition to this the user touches and gestures on the Multi-touch screen were also logged in log files in order to analyze the usage of the screen, mostly to see how the controls were used and which control the user preferred.

After the tests, the persons were given a small form to fill in, in order to give their opinion of what was good, what could be better etc. This was also taken into account when analyzing the results.

The instructions for the usability tests and pictures of the mazes are shown in appendix A.

7. Results

After the test was performed the logs were analyzed and the most interesting data were extracted and put in a database using Microsoft Access. From there, different formulas could be introduced in order to plot the most interesting data. The following graphs show the results of the usability tests. The first test mission was to use whatever control (without instruction) to follow a trajectory that was drawn on a paper sheet with the laser pointer. This test was mainly to see how self-explanatory the interface was.

Tests 2, 3 and 4 were to follow the same trajectory using only one control (X-Y-control, orientation and last the local coordinate control, placed over the video stream from the camera). In these test instructions were given on how to use the different controls. Test 5 was to follow a longer trajectory that was outside the limits for the X-Y control, so that to complete it correctly it was necessary to use the orientation control to tilt the camera. Test 6 was to follow a thinner trajectory, with the purpose that the users should use the zooming function in the grid control to increase the accuracy of the control. Test 7 was a 3D space with hidden pictures of different kinds of bugs, and the point was to use the different controls in order to point out the two hidden butterflies.

Below is the distribution of the usage in percentage of each control for each test, shown in figure 23.

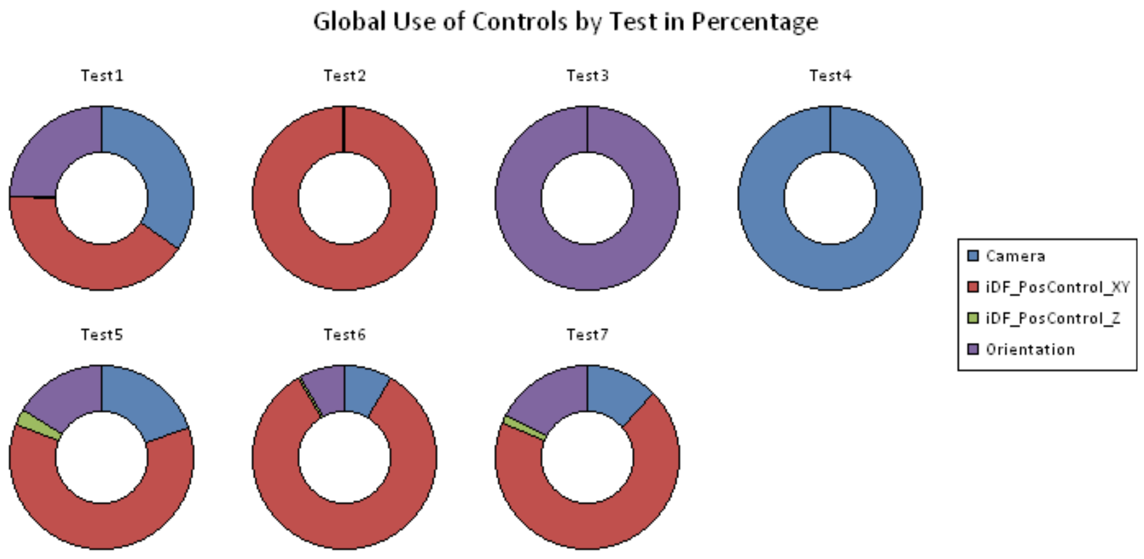


Figure 23: Global use of controls by test in percentage.

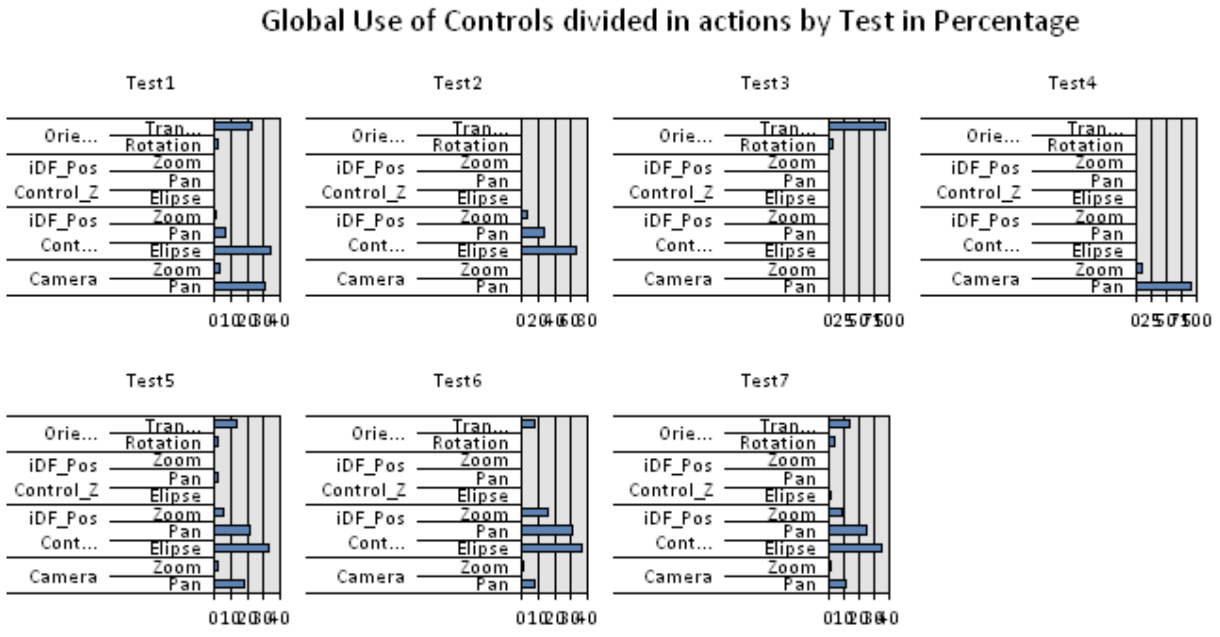


Figure 24: Global use of control divided in gestures by test in percentage.

Figure 24 above shows the percentage of use of each control divided into the different actions that could be performed on the different controls. For the orientation control, the available actions were one-finger *translation*, or two-finger *rotation*. For the Z and X-Y position control respectively, it was two-finger *zoom* (for the grid resolution), one-finger *pan* (to move the grid) and one-finger movement of the blue ball, *ellipse* (for movements of the robot). For the local coordinate control, it was the two-finger *zoom* (making the robot go in the direction of the lens) and the one-finger *pan* (to “snap” the background to the finger, making the robot go the opposite direction of the finger movement).

8. Discussion

Multi-touch interfaces are today developed to fit a lot of different applications. Since the technology has not been available for the consumer market for so long, most likely it has not yet reached its full potential.

The usability tests were performed in order to evaluate this specific concept, using the demonstrator that was made. The goal is that a normal person with little or none experience of robots should be able to control and handle the robot.

Interesting information that the usability tests revealed was the difference in use, comparing test 1 and test 5. Before the controls were explained (test1) the use of the camera control and the grid control (XY-control) were almost identical. After the controls had been explained (test 5), more or less the double amount of time was spent with the grid control. This shows that when the user has got every control explained, it is more likely that they chose the grid-control to use when performing actions that require relatively high accuracy, like following a drawn trajectory. Even more time was spent on the grid control in test 6, where the objective was to follow a thinner trajectory.

It is important to note that more extensive usability tests would be needed to see wether the Multi-touch is preferable compared to other possible robot controls, like a joystick, mouse or wheel etc. It would have been interesting to compare with a state of the art joystick control for example, which was not possible within this thesis due to time limits. The result of such a comparison will most likely conclude that it depends on the application which one that is to prefer. One thing that is for sure though is that the research in the possibilities of how to use Multi-touch for robot control has only begun and this thesis is just a part of this.

From the interviews that were performed after the tests it was revealed that a lot of persons were very positive to the usage of the Multi-touch screen for this purpose. After all controls were explained, most users found it relatively easy to use the interface as it was supposed to be used. A lot of people commented on the fact that the robot movements were limited, and the orientation control was limited to +-20 degrees angle in all three rotation-directions. They meant that it would have been easier to complete the different missions if there were no limits, stopping them from doing free motions in space.

Furthermore some people had comments regarding the position and layout of the interface. For example it would have been better to have the video stream in a more central location, since this was more or less the only feedback from the robot controller that was used by the test persons. The visualization of the robot was shown and explained but hardly used. Maybe this would have been more utilized if the user not had been able to see the real robot while controlling it.

Since the design and layout was chosen by the developers and *not* chosen by the users, it is not necessarily that the users would have chosen this concept if there were several options available. Another thing that is implemented in other multi-touch devices but not this case is inertia (for example that an object with speed continues after releasing the finger). This was not implemented in this project, since the movements had to be exact, and this concept was not considered to be safe when controlling a robot.

Furthermore the multi-touch function was only used in “zooming”-function of the grid and the rotation of the orientation control. As can be seen in figure 25 in the results section, the relative time spent on using these functions was very low, in all of the tests. In future experiments, one possibility could be to take more use of the real multi-touch features so that its potential can be fully exploited.

9. Conclusions

For robot control, Multi-touch is very useful since it can make complex controlling more lucid and easier to use than with conventional handling objects, such as mouse or keybord. The interviews with the test persons revealed that most people found the interface relatively *easy* to understand and used it the way it was intended.

Moreover there are a lot of changes that can be made to improve and make this concept even better. Examples from what was realized from the usability tests were mostly:

- Ability to increase the sensitiveness (resolution) of the orientation control, in order to be able to do more accurate motions.
- More central located video stream.
- Increased workspace of the robot.
- Increase the structure holding the robot in place, since it was trembling a bit making the tests harder to perform successfully.
- Ability to customize the interface to fit different user needs (i.e drag and drop controls)

Multi-touch is definitely something that is going to be more used in the future, probably both within the robotics, but also in other applications, since it can ease the usage and decrease the learning period to almost none, if combined with a user-friendly interface. This can save a lot of time and money when companies choose to invest in this kind of technology.

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Appendix A - Instructions for usability tests

You are now going to be requested to perform seven different tests. We will record your attempts with cameras. It is very important for us that you remember to think aloud at all time while performing the tests. After the tests are finished we are going to give you a short interview.

1st

Here you can see a Multi-touch screen, with which you can control the industrial robot inside the robotic cell in front of you. As you can see, the robot has a laser and an USB-camera mounted on it. We will not give you any instruction at this point about how to use the interface. Please, do this first test, feel free to try to control it in whatever way you think is possible and remember to think aloud!
MISSION: Try to make the laser follow the black trajectory printed on the sheet located on the top of the box inside the robotic cell.

2nd

Before starting the 2nd test we will now show you how the grid controls, located to the right on the interface, works. Please, touch the blue ball with one finger and move the camera forward, backward, left and right. Now, put two fingers on the grid and do a pinch motion to zoom in and out. Try to zoom in to the maximum, and touch the grid with one finger to pan the grid. On the left there is a control with the same functionalities to move the camera move up- and down.
MISSION: Please, use *only* these controls to follow the trajectory on top of the box.

3rd

Now we will show you how to use the camera orbit controls, which are located in the lower center of the screen. Touch the sphere with one finger to tilt the camera up, down, left and right. The red alert means that you have reached a limit. Touch the sphere with two fingers and rotate to rotate the camera.
MISSION: Please, use *only* these controls to follow the trajectory on top of the box.

4th

Now we will show you how to control the video controls, located in the lower left of the screen. Touch the video with one finger and drag, to move the camera accordingly. Do a two-finger pinch motion to move the camera forward and backward.
MISSION: Please, use *only* these controls to follow the trajectory on top of the box.

5th and 6th

Now a new labyrinth is placed on the box. Feel free to try to control the robot in whatever way you think is possible. Remember to think aloud!
MISSION: Use whichever controls you want to follow the trajectories on the two following sheets.

7th

We have now blocked your view over the robot so you have to rely on the interface for feedback on where it is. One thing that may help you is the simulation showed in the top center of the screen. You can rotate it by touching with one finger and drag.

MISSION: Tell us how many butterflies there are on the sheet and point the laser on them.

Appendix A – Instructions for usability tests

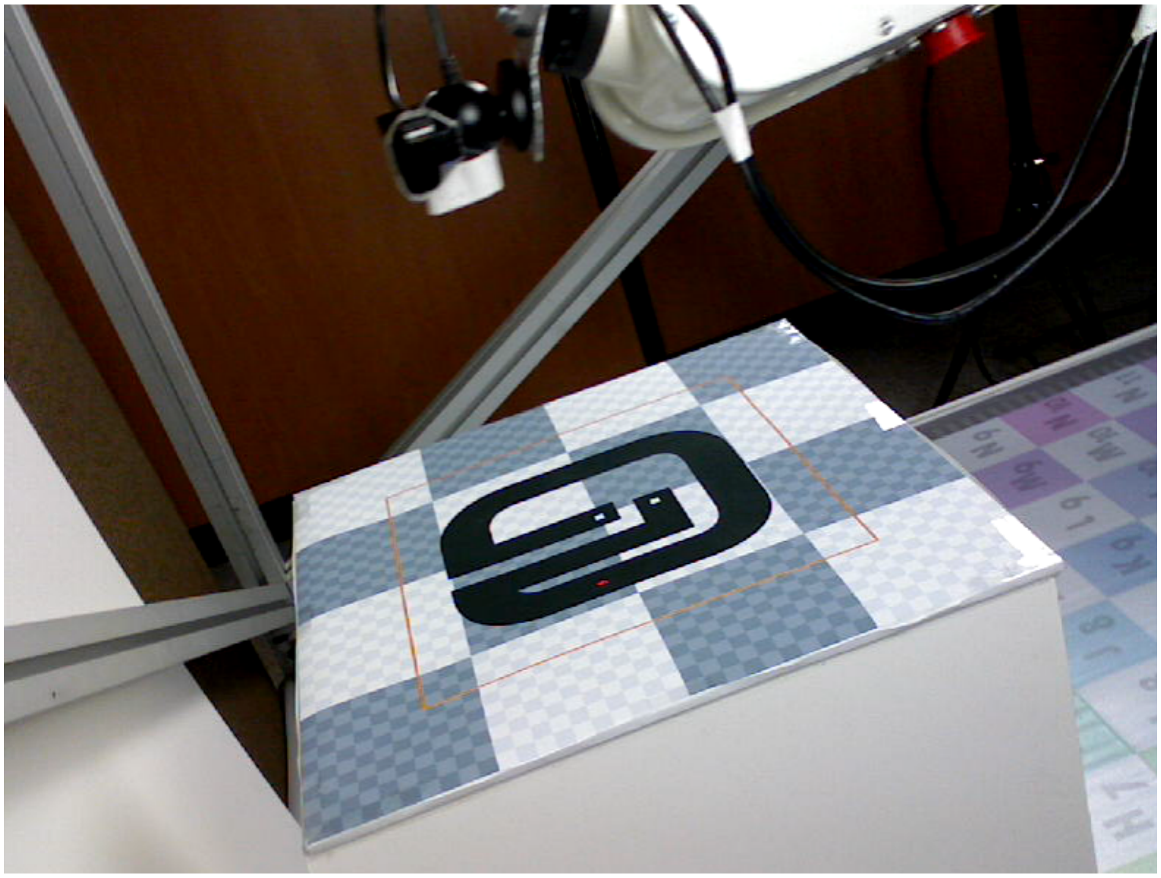
Figure 1: The maze used for test 1-4.

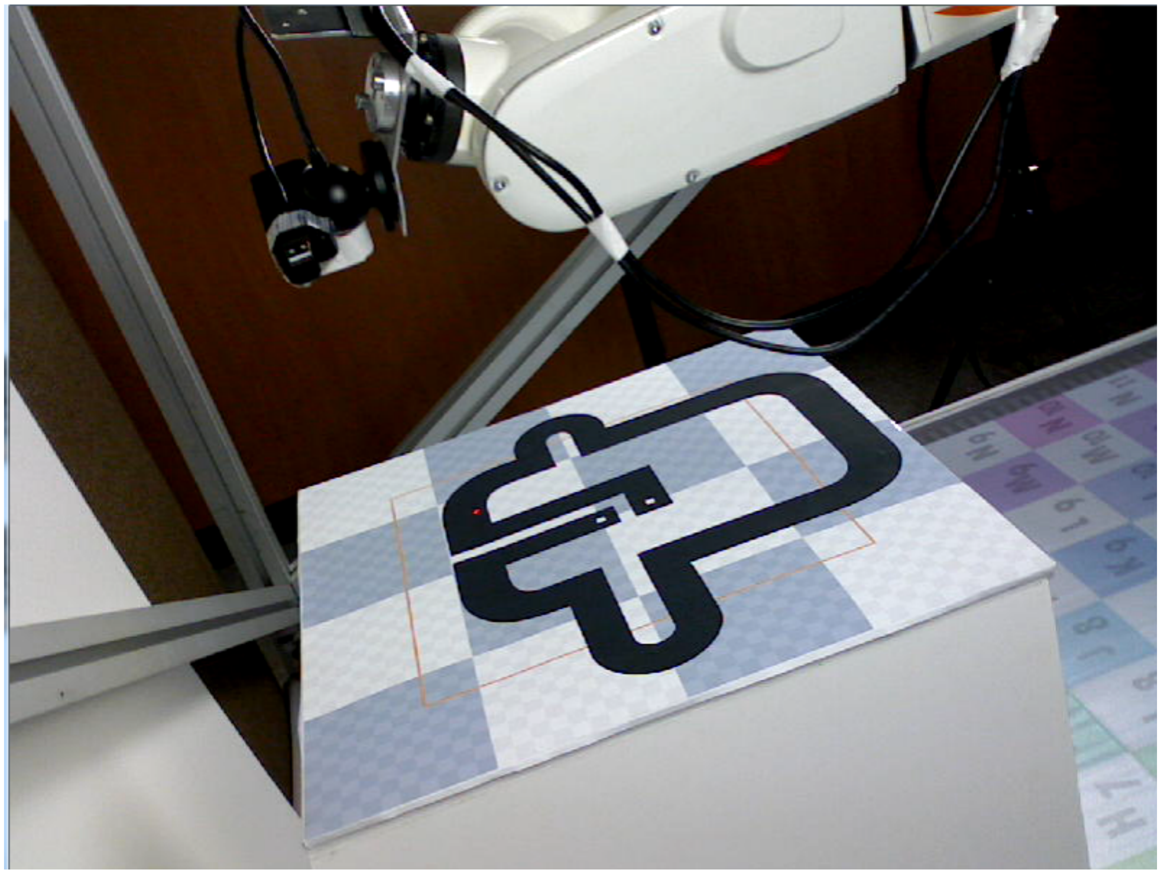
Figure 2: Maze used for test 5.

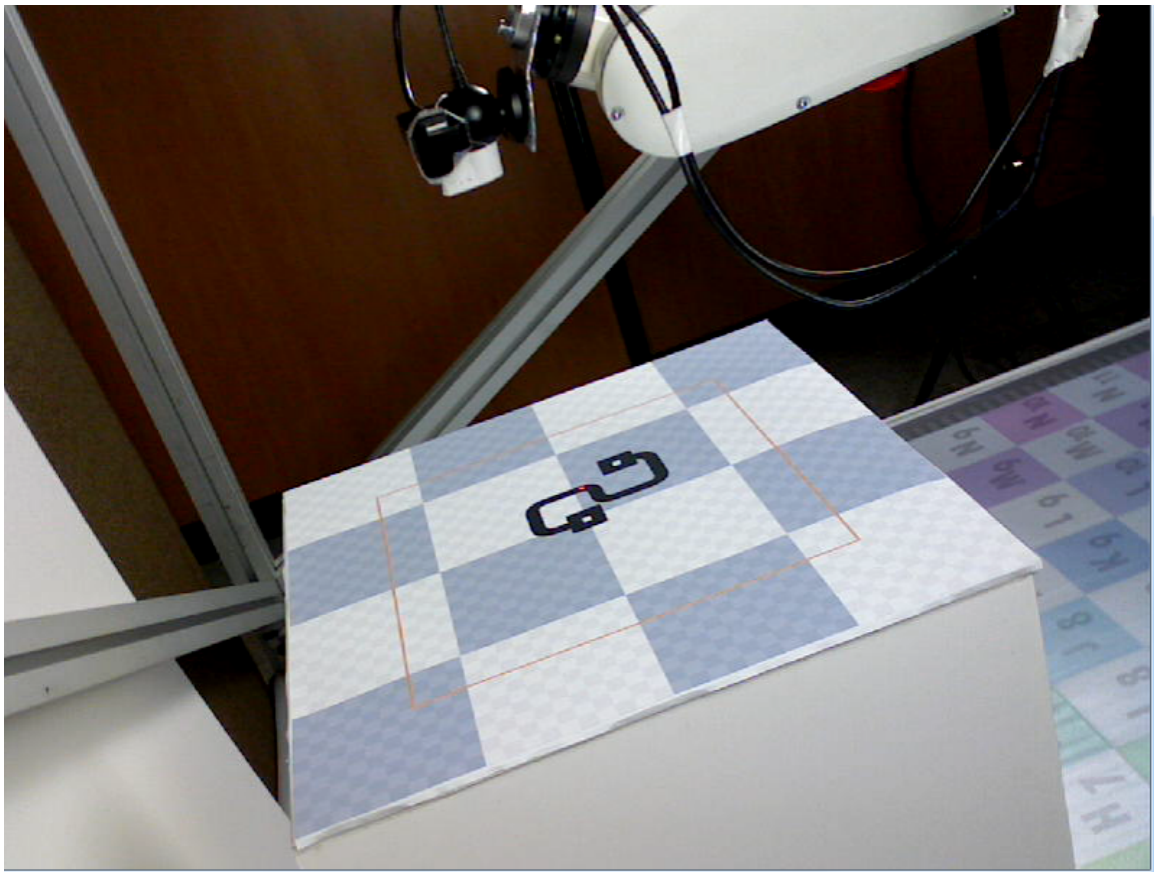
Figure 3: Maze used for test 6.

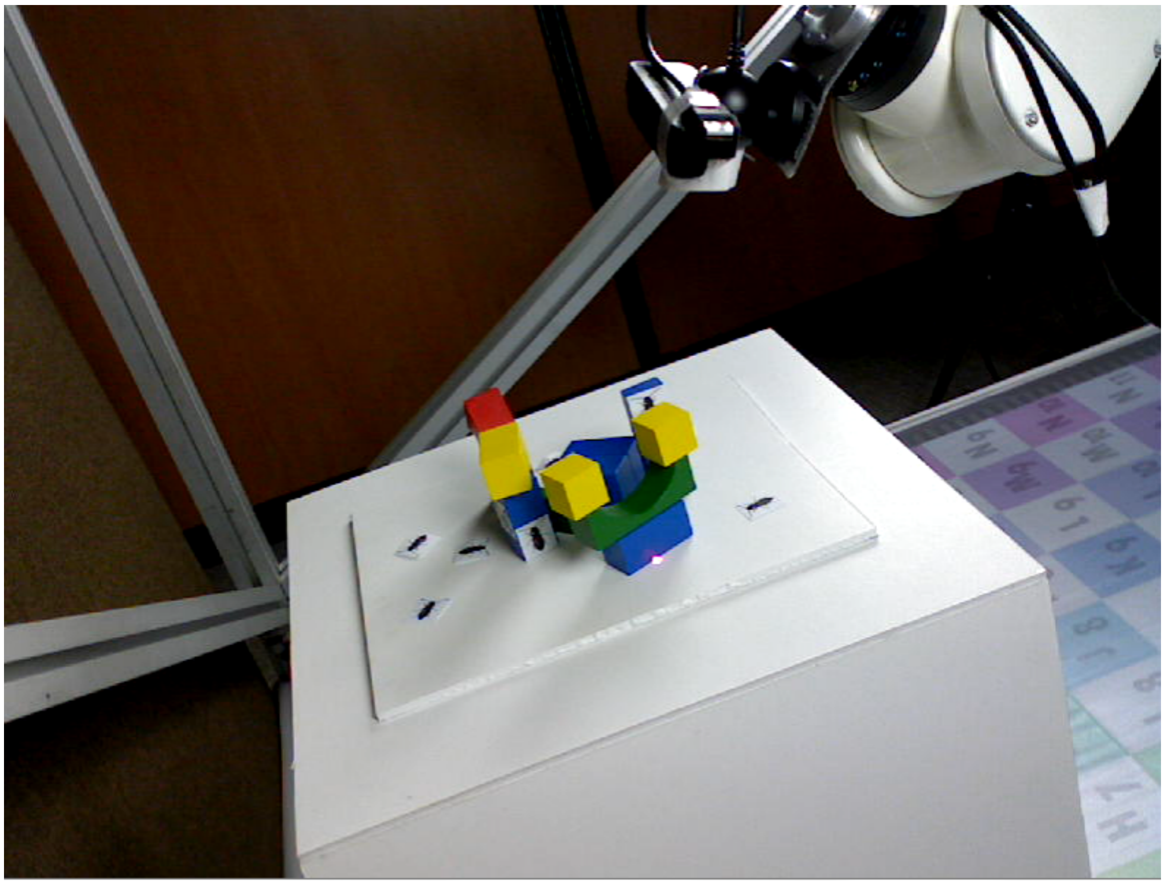
Figure 4: 3D-environment used for test 7.

Appendix A – Instructions for usability tests

Appendix B – Tables of the collected data from log files

Total mean percentage of use		
Mission	**Control**	**Percentage**
Test1	Camera	34,2071029102185
Test1	iDF_PosControl_XY	40,9588339949832
Test1	iDF_PosControl_Z	0,215055827973797
Test1	Orientation	24,6190072668244
Test2	iDF_PosControl_XY	99,6901537488586
Test2	iDF_PosControl_Z	0,309846251141375
Test3	Orientation	100
Test4	Camera	100
Test5	Camera	19,6683583002466
Test5	iDF_PosControl_XY	61,2331348187504
Test5	iDF_PosControl_Z	2,72853269150522
Test5	Orientation	16,3699741894978
Test6	Camera	8,17517702265131
Test6	iDF_PosControl_XY	83,4734872865737
Test6	iDF_PosControl_Z	0,435307561538511
Test6	Orientation	7,91602812923651
Test7	Camera	12,406933218874
Test7	iDF_PosControl_XY	68,5772233539666
Test7	iDF_PosControl_Z	1,5939756962578
Test7	Orientation	17,4218677309016

Total mean percentage of use divided by action			
Mission	**Control**	**Action**	**Percentage**
Test1	Camera	Pan	31,2462213214951
Test1	Camera	Zoom	2,96088158872345
Test1	iDF_PosControl_XY	Elipse	33,7321328558272
Test1	iDF_PosControl_XY	Pan	6,46175040019018
Test1	iDF_PosControl_XY	Zoom	0,76495073896585
Test1	iDF_PosControl_Z	Elipse	0,123633466260736
Test1	iDF_PosControl_Z	Pan	0,079604559087578
Test1	iDF_PosControl_Z	Zoom	1,18178026254827E-02
Test1	Orientation	Rotation	2,05413641187154
Test1	Orientation	Translation	22,5648708549529
Test2	iDF_PosControl_XY	Elipse	65,2488946684412
Test2	iDF_PosControl_XY	Pan	28,2470235568751

Appendix B – Tables of the collected data from log

Total mean percentage of use divided by action

Mission	Control	Action	Percentage
Test2	iDF_PosControl_XY	Zoom	6,19423552354235
Test2	iDF_PosControl_Z	Elipse	0,309846251141375
Test3	Orientation	Rotation	7,42451991516356
Test3	Orientation	Translation	92,5754800848364
Test4	Camera	Pan	89,12476166779
Test4	Camera	Zoom	10,8752379833222
Test5	Camera	Pan	17,8679163807719
Test5	Camera	Zoom	1,80044191947469
Test5	iDF_PosControl_XY	Elipse	33,4909390232709
Test5	iDF_PosControl_XY	Pan	21,56161008874
Test5	iDF_PosControl_XY	Zoom	6,18058570673954
Test5	iDF_PosControl_Z	Elipse	0,453199742555866
Test5	iDF_PosControl_Z	Pan	2,27533294894935
Test5	Orientation	Rotation	2,26652164235404
Test5	Orientation	Translation	14,1034525471437
Test6	Camera	Pan	7,43654247968302
Test6	Camera	Zoom	0,738634542968288
Test6	iDF_PosControl_XY	Elipse	36,4868214887463
Test6	iDF_PosControl_XY	Pan	30,7999096846242
Test6	iDF_PosControl_XY	Zoom	16,1867561132031
Test6	iDF_PosControl_Z	Elipse	0,435307561538511
Test6	Orientation	Rotation	6,31212835546742E-02
Test6	Orientation	Translation	7,85290684568184
Test7	Camera	Pan	10,8132916428543
Test7	Camera	Zoom	1,59364157601976
Test7	iDF_PosControl_XY	Elipse	35,1787624745325
Test7	iDF_PosControl_XY	Pan	25,1149731975724
Test7	iDF_PosControl_XY	Zoom	8,28348768186174
Test7	iDF_PosControl_Z	Elipse	1,54260429718658
Test7	iDF_PosControl_Z	Pan	4,82929797420555E-02
Test7	iDF_PosControl_Z	Zoom	3,07841932916919E-03
Test7	Orientation	Rotation	3,64771628011909
Test7	Orientation	Translation	13,7741514507825

Appendix B – Tables of the collected data from log

Appendix C – User manual for Robotic cell at IDF

2010-06-28

User manual

Real-time robot communication for the KUKA robot KR 5 sixx R650 with a KUKA KR C2 sr controller

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Appendix C – User manual for robotic cell at IDF

Table of Contents

Appendix C – User manual for robotic cell at IDF

1. Introduction

This user manual is created in order to ease the use of KUKA's real time control package called KUKA.Ethernet RSI XML. These instructions are for the KR C2 sr robot controller together with the KR 5 sixx R650 robot at the Instituto Diseño y Fabricación in Valencia, Spain. For more information about the variables and functions mentioned in this document, see the references.

Below are the instructions to install and run KUKA.Ethernet RSI XML with the demo programs Demo_1, for the RSI object ST_ETHERNET, which comes with the package, without any modifications. For modifications, see the chapter "Modifications".

A special KUKA network card (brand 3COM) is needed to make the communication to work. This is due to the speed of data that is required. The card is designed for KUKA only and can only be ordered via their support.

2. Installation and running of Demo programs

The first step is to install the 3COM card in the robot controller, since the real-time control will not be possible otherwise [1]. The same would have been applied for a KR C2 ed 05 robot controller but not for a KR C2 or a KR C3 robot controller where you can use the Ethernet connection on the Robots multi-function card (if the card is of the model MFC2 or MFC3). In order to install the network card and to retrieve the correct model and brand, the KUKA support has to be contacted. A certified technician from KUKA must install the network card due to warranty issues.

2.1 Installation

The second step is to install the software package including the demo programs and data files on the robot controller, following the installation procedure for the Demo_1.src in the software manual KUKA.Ethernet RSI XML 1.2 [1].

The third step is, in order to run the demo program that comes with the package, to install the server program on an external computer. After that, make sure that the firewalls, anti-virus software and similar software are turned off on the external computer, disable the wireless and make sure that the only Ethernet connection that exist is the one going between the computer and the robot controllers 3COM Ethernet card.

2.2 Setup Connection

When the computer and the robot controller are connected with an Ethernet cable, go to the settings of the active Ethernet connection on the external computer. In the TCP/IP settings (lpv4) choose a fixed IP address and write a new address manually (for example 172.16.18.210).

Now, locate the file ERXconfig.xml on the robot controller, open it with notepad and write the IP address that you just created in the field after "<IP_NUMBER>" (default port shall be 6008 on the row below). Save and close the file.

Change the IP address of the network card on the robot controller in a similar matter as on the external computer. A smart way of choosing IP would be to have the same IP as the external computer except for the last three digits (for example 172.16.18.210 and 172.16.18.110 respectively).
Note: Do not use the IP address range 192.0.1.x since this will create a system error in the KUKA software and will make it impossible to boot the robot controller [1]. This range is used by other parts of the system and will therefore cause a conflict.

2.3 Establish Connection

Open the server program on the external computer, choose TCP/IP and ST_Ethernet and click on "Listen". The port shall be set on the default value (1).

When the server program is listening, open the "demo_1.src" on the robot controller and run it. NOTE: The operation mode of the robot controller must be set to AUT (automatic). A special key is required to change the modes.

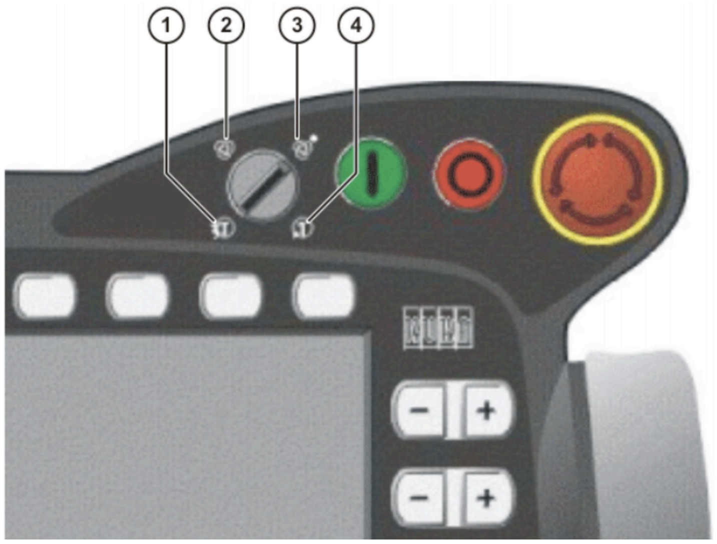


Figure 1: The operation mode switch [2]

As you can see in figure 1, the operation mode switch has four modes which are 1: T2 (manual high velocity), 2: AUT (automatic), 3: AUT EXT (automatic external), 4: T1 (manual reduced velocity). For description of the different modes, see the manual for the robot controller [2].
Now the program should stop on "ST_SKIPSENS" and the message "ERX Message! Free config!" should be visible in the message console of the robot controller. This means that it should now be possible to move the robot, using the buttons in the server program. The first time the connection is made, the program in the robot controller might need to be restarted a few times before it works.

NOTE: The default allowed movements of the robots are set to ±5 millimeter [3], after that you will get the message that the maximum range is reached (for example "Xmin is reached") and you will have to move the robot the other way to continue moving it. See chapter 3.1 for instructions in how to change the range of the robot.

2.4 Troubleshooting if experiencing connection problems:

In the start menu in windows, choose "run" and then type CMD to open the command console. Type "ping IP", where "IP" shall be the IP address of the computer that shall be connected. If no response, make sure that all cables are connected correctly and that they are not broken, that anti-virus software and firewalls are turned off on both computers and that no other applications are blocking the communication.

3. Modifications

This section describes possible modifications to the demo program.

3.1 How to change the allowed range of the robot with the server:

In the code of the demo_1.src program, after creating the ST_PATHCORR, type in:

```
err=ST_SETPARAM(PATHCORR,S,L)
```

Where,
PATHCORR is the name of the object,
S is the corresponding object parameter of the axis that is to be changed [3] and
L shall be the new limit value.

The values for X, Y and Z are translation in millimeters and the values for A, B and C is rotation in degrees around Z, Y and X respectively.
NOTE: If the values are not changed, they will be set to their default values.

The corresponding object parameters (S) are [3]:
1 (REAL): Lower bound of correction in X, Default: -5
2 (REAL): Lower bound of correction in Y, Default: -5
3 (REAL): Lower bound of correction in Z, Default: -5
4 (REAL): Lower bound of correction in A, Default: -5
5 (REAL): Lower bound of correction in B, Default: -5
6 (REAL): Lower bound of correction in C, Default: -5
7 (REAL): Upper bound of correction in X, Default: 5
8 (REAL): Upper bound of correction in Y, Default: 5
9 (REAL): Upper bound of correction in Z, Default: 5
10 (REAL): Upper bound of correction in A, Default: 5
11 (REAL): Upper bound of correction in B, Default: 5
12 (REAL): Upper bound of correction in C, Default: 5

The first 6 parameters are the lower limits of X, Y, Z, A, B and C respectively, and the upper limits are the parameters 7 to 12, following the same order.

For example, to set the maximum allowed movement in negative X-direction to 300 millimeter for the object hPath, the corresponding code will be:

```
err=ST_SETPARAM(hPath,1,-300)
```

For positive x-direction direction, the corresponding code will be:

```
err=ST_SETPARAM(hPath,7,300)
```

The same procedure is applied for the RSI object ST_AXISCORR, if this object is used instead of the ST_PATHCORR object (see chapter 8 for more info on how to use the ST_AXISCORR). The corresponding object parameters for ST_AXISCORR are [3]:

1 INTEG (INT): Integration mode
-> 0: Absolut
-> 1: Relativ (Default)
2 (REAL): Lower bound of correction A1, Default: -5
3 (REAL): Lower bound of correction A2, Default: -5
4 (REAL): Lower bound of correction A3, Default: -5
5 (REAL): Lower bound of correction A4, Default: -5
6 (REAL): Lower bound of correction A5, Default: -5
7 (REAL): Lower bound of correction A6, Default: -5
8 (REAL): Lower bound of correction E1, Default: -5
9 (REAL): Lower bound of correction E2, Default: -5
10 (REAL): Lower bound of correction E3, Default: -5
11 (REAL): Lower bound of correction E4, Default: -5
12 (REAL): Lower bound of correction E5, Default: -5
13 (REAL): Lower bound of correction E6, Default: -5
14 (REAL): Upper bound of correction A1, Default: 5
15 (REAL): Upper bound of correction A2, Default: 5
16 (REAL): Upper bound of correction A3, Default: 5
17 (REAL): Upper bound of correction A4, Default: 5
18 (REAL): Upper bound of correction A5, Default: 5
19 (REAL): Upper bound of correction A6, Default: 5
20 (REAL): Upper bound of correction E1, Default: 5
21 (REAL): Upper bound of correction E2, Default: 5
22 (REAL): Upper bound of correction E3, Default: 5
23 (REAL): Upper bound of correction E4, Default: 5
24 (REAL): Upper bound of correction E5, Default: 5
25 (REAL): Upper bound of correction E6, Default: 5

NOTE: Axis E1 to E6 is the parameters for an external system, if one exists. How to use an external system will not be covered in this document.

The units for parameter 2 to 25 are the rotation of the specific axis in degrees. The difference is that the first parameter in ST_AXISCORR, sets the integration mode to absolute or relative. If the parameter is set to absolute, the correction value received by the robot controller will be interpreted as the number of degrees from the robots home position. If the set to relative the value will be interpreted as the number of degrees relative the current position of the robot, no matter its previous position.

3.2 How to change the coordinate system

To start the RSI execution the following line must be executed:

```
err = ST_ON1(TSYS:IN,INTEG:IN)
```

When the RSI execution is started, all RSI objects are executed in calling order every sensor cycle [1]. The object parameters for ST_ON1 defines the correction processing for the RSI object ST_PATHCORR and they are the following [3]:

IN TSYS (TECHSYS): Correction coordinate system
-> #BASE
-> #TCP
-> #TTS
-> #WORLD
IN INTEG (INT): Integration mode
-> 0: Absolute
-> 1: Relative

The in-data parameter TSYS defines which correction coordinate system that ST_PATHCORR shall use, which are #BASE, #TCP, #TTS or #WORLD (see figure 2). #TTS can only be used for welding or adhesive applications and will not be explained here, for more information, see the Expert Programming Manual from KUKA [4].

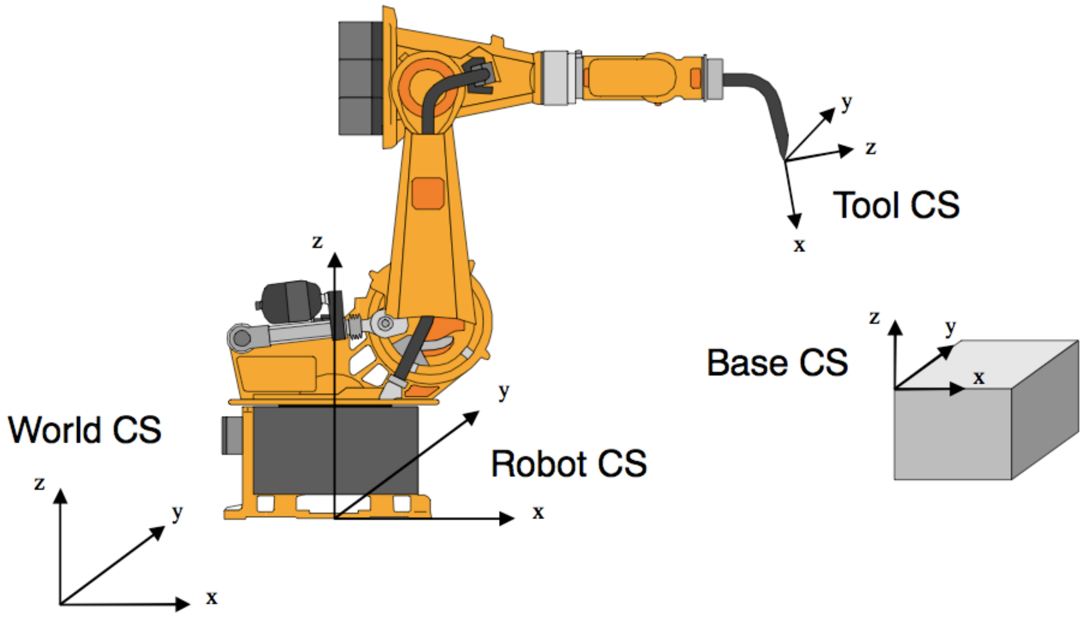


Figure 2: The robots different coordinate systems. [4]

Note that the Robot CS (Robot coordinate system) cannot be used together with KUKA Ethernet RSI XML [3]. Base CS and Tool CS are free for the user to define but not the World CS, which is write-protected [4]. By default the origin of Robot CS, Base CS (sometimes referred to as Workpiece coordinate system) and the World CS are the same, with their origin located at the base of the robot (like the Robot CS in figure 2). The Tool CS is by default located on the flange of the robot with the Z-axis being identical to axis A6 and pointing out from the flange, see figure 3 [4].

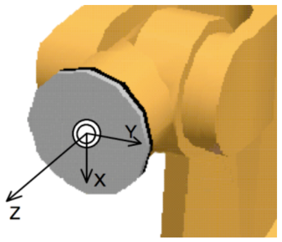


Figure 3: Default Tool CS [4]

INTEG defines the integration mode [3] that defines how the robot controller unit shall interpret the coordinates sent to it. There are two different integration modes, the first being relative, which means that the new coordinates sent to the robot controller are always calculated from the actual position of the robot, no matter its previous coordinates. This means that each new position will have the coordinates:

[X=0,Y=0,Z=0,A=0,B=0,C=0]

Note that the absolute coordinates always use the start position as origin. This means that no matter the robot's previous position, the robot will go back to its start position if the following coordinates are sent to the robot controller:

[X=0,Y=0,Z=0,A=0,B=0,C=0]

3.3 How to control the axis angles instead of the Cartesian coordinates

To add the control of the axis A1, A2, A3, A4, A5 and A6 to the system, modifications must be made in both the program running on the robot controller and the server.

3.3.1 Modifications on the program on the robot controller

To control the robot axes manually, it is necessary to use the AXISCORR [3]. In order to do so, one needs to extend the demo_1.src program.

First an ST_AXISCORR RSI object needs to be created. This is done in the code of the demo_1.src after the creation of ST_PATHCORR and in the same manner. Below is the code for creating a ST_PATHCORR object named hPath and a ST_AXISCORR object named hAxis.

```
;FOLD RSI-Objects to link out of ST_Ethernet
; link RKorr to correction on path
err = ST_PATHCORR(hPath,0)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
; link AKorr to movement of axis
err = ST_AXISCORR(hAxis,0)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
```

When the object is created, the object parameters (lower and upper limit of motions of each axis, see rsiCommands.chm[3]) can be set:

```
err = ST_SETPARAM(hAxis,1,0)
err = ST_SETPARAM(hAxis,2,-170)
err = ST_SETPARAM(hAxis,14,170)
err = ST_SETPARAM(hAxis,3,-170)
err = ST_SETPARAM(hAxis,15,170)
err = ST_SETPARAM(hAxis,4,-170)
err = ST_SETPARAM(hAxis,16,170)
err = ST_SETPARAM(hAxis,5,-170)
err = ST_SETPARAM(hAxis,17,170)
err = ST_SETPARAM(hAxis,6,-170)
err = ST_SETPARAM(hAxis,18,170)
err = ST_SETPARAM(hAxis,7,-170)
err = ST_SETPARAM(hAxis,19,170)
```

After that, the outputs of the RSI object ST_ETHERNET named hEthernet, which is created earlier in the code (how this is done will not be explained here, see KUKA.Ethernet RSI XML [1]), must be linked to the inputs of the RSI object hAxis. The corresponding tag in the XML string must also be defined [1]. The resulting code will be (outputs 1-6 of hEthernet is already linked to the inputs of hPath):

```
err = ST_NEWLINK_OUT(hEthernet,7,hAxis,1,"AKorr.A1")
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_NEWLINK_OUT(hEthernet,8,hAxis,2,"AKorr.A2")
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_NEWLINK_OUT(hEthernet,9,hAxis,3,"AKorr.A3")
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_NEWLINK_OUT(hEthernet,10,hAxis,4,"AKorr.A4")
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_NEWLINK_OUT(hEthernet,11,hAxis,5,"AKorr.A5")
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_NEWLINK_OUT(hEthernet,12,hAxis,6,"AKorr.A6")
IF (err <> #RSIOK) THEN
  HALT
```

```
ENDIF
```

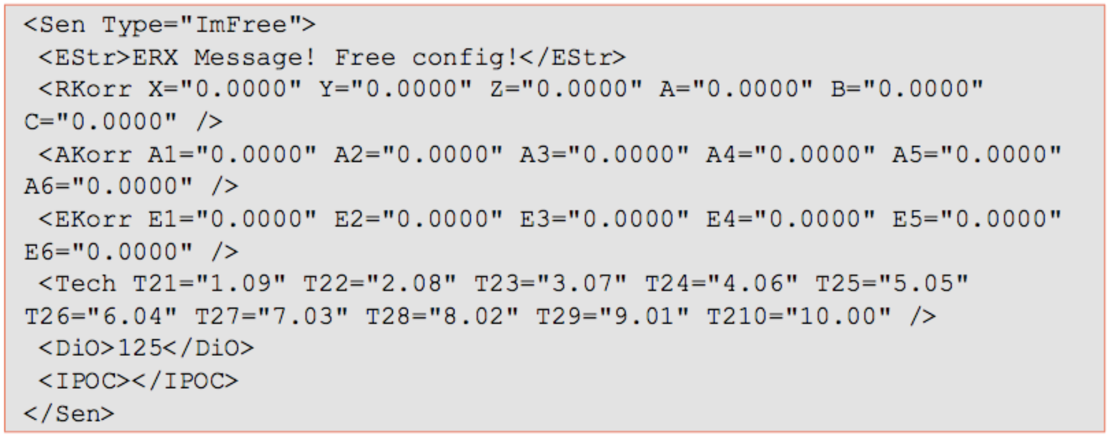
Last thing that has to be done is to map the outputs of hEthernet to the system variables $SEN_PREA[7…12]. The data received by the robot controller will be saved in these variables [1][5].

```
err = ST_MAP2SEN_PREA(hmap,0,hEthernet,7,7)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_MAP2SEN_PREA(hmap,0,hEthernet,8,8)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_MAP2SEN_PREA(hmap,0,hEthernet,9,9)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_MAP2SEN_PREA(hmap,0,hEthernet,10,10)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_MAP2SEN_PREA(hmap,0,hEthernet,11,11)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_MAP2SEN_PREA(hmap,0,hEthernet,12,12)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
```

3.3.2 Modifications on the server

The XML string received by the robot controller from the server contains the target values for the robot. Exactly how these values are updated by from the inputs on the interface and sent to the robot controller will not be explained here but the principal function will. For detailed description see the document explaining the software of the interface and the server.

Figure 4 shows the XML string received by the robot controller and includes all the target values for the robot. Basically what the server does is that it finds the location of these target values, erases them and replaces them with new ones before it sends them to the robot controller. The server does this for the Cartesian coordinates which means that it replaces the values on the line that starts with “<RKorr” and ends with “/>”. To add the functionality of controlling the each axis separately, the target axis values need to be found, erased and replaced. These values are found on the line that starts with “<AKorr” and ends with “/>”.



```
<Sen Type="ImFree">
 <EStr>ERX Message! Free config!</EStr>
 <RKorr X="0.0000" Y="0.0000" Z="0.0000" A="0.0000" B="0.0000"
C="0.0000" />
 <AKorr A1="0.0000" A2="0.0000" A3="0.0000" A4="0.0000" A5="0.0000"
A6="0.0000" />
 <EKorr E1="0.0000" E2="0.0000" E3="0.0000" E4="0.0000" E5="0.0000"
E6="0.0000" />
 <Tech T21="1.09" T22="2.08" T23="3.07" T24="4.06" T25="5.05"
T26="6.04" T27="7.03" T28="8.02" T29="9.01" T210="10.00" />
 <DiO>125</DiO>
 <IPOC></IPOC>
</Sen>
```

Figure 4: Structure of XML string received by the robot controller [1]

3.4 How to not exceed maximum allowed speed in the joints

All robot axes have a certain maximum speed that they can operate at. By default it moves at 100 percent of its maximum speed. A problem can arise when operating in cartesian coordinates, since the motion is translated to certain axis speed by the robot. When the robot is moving at 100 percent to follow a certain trajectory and has to rotate an axis in order to maintain the same trajectory speed, it may exceed the maximum allowed speed in an axis, causing the robot communication to break. An error message will be displayed, saying that the maximum axis velocity has been exceeded, and the robot stops.
This problem occurs mostly for the axis A4, when axes A4 and A6 arelined up. In other words when the robot is getting close to singularity.

To avoid this problem there is a system variable called $CP_VEL_TYPE [5] located in the file Steu\Mada\$custom.dat on the robot controller. The default value of this variable is #CONSTANT which means that there is no reduction of the speeds. If this value is changed to #VAR_ALL this will make the robot slow down whenever a maximum speed limit is reached, and not break the communication. This means that the limits can never be exceeded, resulting in that the communication will not break due to this [5].

4. How to run IDF_RSI_XML.src together with the IDF RobotServer and the Multi-touch Interface

The steps are similar to those for the Demo programs from KUKA, with the exception that the Interface is also connected via Ethernet and running on a different external computer than the server. To connect this there has to exist a LAN connection, for example via an Ethernet HUB, instead of direct connections as for the Demo_1 program. It will have the same setup for the TCP/IP on the computer running the interface but the address shall be different of course, for example 172.16.18.100.

The first step is to start the server program and click “Conectar”. Then the program IDF_RSI_XML.src needs to be started on the robot controller and executed. These two steps might need to be repeated the first time before a stable connection is established.
The last step is to run the interface software and then click connect.

Appendix C – User manual for robotic cell at IDF

References

1. KUKA Robot Group: Communication, *KUKA.Ethernet RSI XML 1.2: for KUKA system software 5.4, 5.5, 7.0* (25.02.2008), Version: KST Ethernet RSI XML 1.2 V2 en
2. KUKA Roboter GmbH, *Controller, KR C2 sr; Operating Instructions* (18.09.2009); Version: BA KR C2 sr V5 en
3. KUKA Roboter GmbH, *rsiCommands.chm*, file included in the software package KUKA.Ethernet RSI XML 1.2, located in /Ethernet RSI-XML V1.2.0_Build1/V__12ERX_0001_1/RSI/DOC/rsiCommands.chm
4. KUKA Roboter GmbH, *Software; KRC2/KRC3; Expert Programming; KUKA System Software (KSS); Release 5.3* (26.09.2003), Version 00
5. KUKA Roboter GmbH, *Software; KR C…; System Variables; KUKA System Software (KSS)* (05.06.2005), Version: 00

Appendix D - Complete code for IDF_RSI_XML.src

```
&ACCESS RVP
&REL 58
&PARAM TEMPLATE = C:\KRC\Roboter\Template\vorgabe
&PARAM EDITMASK = *
DEF IDF_RSI_XML( )
; ================================================
; EXAMPLE OF: ST_ETHERNET
; Type: RSI Object
; ================================================
;FOLD Overview notes
; ================================================
;  NAME
;    KUKA.Ethernet.RSIXML
;  COPYRIGHT
;    KUKA Robter GmbH
; ================================================
;ENDFOLD
;FOLD INI
  ;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

;Moving the TCP origin to the tip of the camera
$TOOL = {X -102,Y 0,Z 15,A 0,B -110,C 0}
  ;ENDFOLD (USER INI)
;ENDFOLD (INI)

HALT
; The current position will be used as SAK movement!
;PTP $POS_ACT

;Setting the home position of the robot to desired position
HOME = {AXIS: A1 0,A2 -109,A3 106,A4 0,A5 33,A6 0}
PTP HOME
```

```
; Create RSI Object ST_Ethernet, read object configuration .../INIT/ERXConfig.xml
err = ST_ETHERNET(hEthernet,0,"ERXconfig.xml")
IF (err <> #RSIOK) THEN
  HALT
ENDIF
; err = ST_SETPARAM(hEthernet,eERXmaxLatePackages,1) ; after "value" to late packages the
robot stopps
; err = ST_SETPARAM(hEthernet,eERXmaxLateInPercent,10) ; RSIWARNING if the limit
reached
; err = ST_SETPARAM(hEthernet,eERXmaxFieldOfView,1000) ;reset every 'value' statistics.
err = ST_SETPARAM(hEthernet, eERXFastCycle, 0) ; FALSE: Time to answer 11ms / TRUE: Fast
cycle: answer <2ms necessary!
; err = ST_SETPARAM(hEthernet, eERXerrorFlag, 1) ; $FLAG[1] will be set in case off errors

;FOLD RSI-Objects to link in ST_Ethernet
; read $IN[1-16]
err = ST_DIGIN(hDin,0,1,2,0)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_NEWLINK_IN(hDin,1,hEthernet,1,"DiL")
IF (err <> #RSIOK) THEN
  HALT
ENDIF

; read $OUT[1-3]
err = ST_DIGOUT(hDout1,0,1,0,0)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_DIGOUT(hDout2,0,2,0,0)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_DIGOUT(hDout3,0,3,0,0)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_NEWLINK_IN(hDout1,1,hEthernet,2,"Digout.o1")
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_NEWLINK_IN(hDout2,1,hEthernet,3,"Digout.o2")
IF (err <> #RSIOK) THEN
  HALT
ENDIF
```

```
err = ST_NEWLINK_IN(hDout3,1,hEthernet,4,"Digout.o3")
IF (err <> #RSIOK) THEN
  HALT
ENDIF

; make sine signal
UNIT_RSI = 3601
err = ST_SOURCE(hsource,0,UNIT_RSI)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_SETPARAM(hsource,1,1)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_SETPARAM(hsource,3,50)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_NEWLINK_IN(hsource,1,hEthernet,5,"ST_Source")
IF (err <> #RSIOK) THEN
  HALT
ENDIF
;ENDFOLD

;FOLD RSI-Objects to link out of ST_Ethernet
; Creating RSI object ST_PATHCORR named hPath
err = ST_PATHCORR(hPath,0)
IF (err <> #RSIOK) THEN
  HALT
ENDIF

; Creating RSI object ST_AXISCORR named hAxis
err = ST_AXISCORR(hAxis,0)
IF (err <> #RSIOK) THEN
  HALT
ENDIF

;Defining the allowed movements in X, Y, Z, A, B and C
err = ST_SETPARAM(hPath,1,-130)
err = ST_SETPARAM(hPath,2,-130)
err = ST_SETPARAM(hPath,3,-25)
err = ST_SETPARAM(hPath,4,-20)
err = ST_SETPARAM(hPath,5,-20)
err = ST_SETPARAM(hPath,6,-20)
err = ST_SETPARAM(hPath,7,130)
err = ST_SETPARAM(hPath,8,130)
err = ST_SETPARAM(hPath,9,20)
err = ST_SETPARAM(hPath,10,20)
err = ST_SETPARAM(hPath,11,20)
err = ST_SETPARAM(hPath,12,20)

;Defining integration mode and allowed rotations of axes
err = ST_SETPARAM(hAxis,1,0)
err = ST_SETPARAM(hAxis,2,-170)
err = ST_SETPARAM(hAxis,14,170)
err = ST_SETPARAM(hAxis,3,-170)
err = ST_SETPARAM(hAxis,15,170)
err = ST_SETPARAM(hAxis,4,-170)
err = ST_SETPARAM(hAxis,16,170)
err = ST_SETPARAM(hAxis,5,-170)
err = ST_SETPARAM(hAxis,17,170)
err = ST_SETPARAM(hAxis,6,-170)
err = ST_SETPARAM(hAxis,18,170)
err = ST_SETPARAM(hAxis,7,-170)
err = ST_SETPARAM(hAxis,19,170)

;linking rKorr to correction on path and hAxis to rotation of axes
err = ST_NEWLINK_OUT(hEthernet,1,hPath,1,"RKorr.X")
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_NEWLINK_OUT(hEthernet,2,hPath,2,"RKorr.Y")
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_NEWLINK_OUT(hEthernet,3,hPath,3,"RKorr.Z")
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_NEWLINK_OUT(hEthernet,4,hPath,4,"RKorr.A")
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_NEWLINK_OUT(hEthernet,5,hPath,5,"RKorr.B")
IF (err <> #RSIOK) THEN
  HALT
ENDIF

err = ST_NEWLINK_OUT(hEthernet,6,hPath,6,"RKorr.C")
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_NEWLINK_OUT(hEthernet,7,hAxis,1,"AKorr.A1")
```

```
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_NEWLINK_OUT(hEthernet,8,hAxis,2,"AKorr.A2")
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_NEWLINK_OUT(hEthernet,9,hAxis,3,"AKorr.A3")
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_NEWLINK_OUT(hEthernet,10,hAxis,4,"AKorr.A4")
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_NEWLINK_OUT(hEthernet,11,hAxis,5,"AKorr.A5")
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_NEWLINK_OUT(hEthernet,12,hAxis,6,"AKorr.A6")
IF (err <> #RSIOK) THEN
  HALT
ENDIF

; DiO map to $OUT[8-24]
err = ST_MAP2DIGOUT(hMapDio,0,hEthernet,19,2,2)
IF (err <> #RSIOK) THEN
  HALT
ENDIF

; show RKorr on $SEN_PREA[1-6] and AKorr on $SEN_PREA[7-12]
err = ST_MAP2SEN_PREA(hmap,0,hEthernet,1,1)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_MAP2SEN_PREA(hmap,0,hEthernet,2,2)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_MAP2SEN_PREA(hmap,0,hEthernet,3,3)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_MAP2SEN_PREA(hmap,0,hEthernet,4,4)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
```

```
err = ST_MAP2SEN_PREA(hmap,0,hEthernet,5,5)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_MAP2SEN_PREA(hmap,0,hEthernet,6,6)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_MAP2SEN_PREA(hmap,0,hEthernet,7,7)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_MAP2SEN_PREA(hmap,0,hEthernet,8,8)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_MAP2SEN_PREA(hmap,0,hEthernet,9,9)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_MAP2SEN_PREA(hmap,0,hEthernet,10,10)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_MAP2SEN_PREA(hmap,0,hEthernet,11,11)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
err = ST_MAP2SEN_PREA(hmap,0,hEthernet,12,12)
IF (err <> #RSIOK) THEN
  HALT
ENDIF

; show DiO on $SEN_PINT[1]
err = ST_MAP2SEN_PINT(hmap,0,hEthernet,19,1)
IF (err <> #RSIOK) THEN
  HALT
ENDIF
;ENDFOLD

;Setting the coordinate system
err = ST_ON1(#BASE,0)
;err = ST_ON1(#TCP,0)
;err = ST_ON1(#WORLD,1)
```

```
IF (err <> #RSIOK) THEN
  HALT
ENDIF

; *=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=**=*=*=*=*=*=*=*=*=*=*
ST_SKIPSENS() ;Hold on - until RSI-Break reason occur
; *=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=**=*=*=*=*=*=*=*=*=*=*

PTP $POS_ACT

END
```