UNIVERSITI TEKNIKAL MALAYSIA MELAKA

SIMULATION AND STUDY ON PUMA ROBOT CONFIGURATION WITH WORKSPACE

Thesis submitted in accordance with the requirement of the National Technical
University College of Malaysia for Degree of Bachelor of Engineering
(Honours) Manufacturing (Robotic and Automation)

By

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Faculty of Manufacturing Engineering
April 2007

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APPROVAL

This thesis submitted to the senate of KUTKM and has been accepted as fulfillment of the requirement for the degree of Bachelor of Manufacturing Engineering (Honours) (Robotic and Automation). The members of the supervisory committee are as follows:

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ABSTRACT

Programmable Universal Machine for Assembly (PUMA) Robot study is one of the robotics fields stems and the robot itself is categorized in industrial robot types. PUMA Robot is widely used in industrial field, especially in manufacturing field; and also usually appeared in universities research laboratories. In this project, a mathematical approach is applied towards designing a PUMA Robot configuration. The Denavit-Hartenberg algorithm and Arm Parameters must be determined to create and simulate PUMA robot by using Workspace software. In studying the configuration of the PUMA Robot, Forward Kinematics Solution is calculated to obtain the internal computation in Workspace database about the position and orientation of the robot. In designing a robot for industrial application, it is important to know the workspace volume of the robot and how the robot would moves during the process happened. This case can be observed by simulating the robot configuration and movement. Therefore, Workspace 5.04 Software is being used to designing and simulating the robot. A study of PUMA Robot configuration and Workspace is related and essential to achieve the aims and objectives of this project.

ABSTRAK

Kajian tentang Robot *Programmable Universal Machine for Assembly* (PUMA) adalah tergolong dalam salah satu bidang kajian robotic, dan Robot PUMA itu sendiri telah dikategorikan sebagai jenis robot industri. Robot PUMA telah digunakan secara meluas di dalam bidang industri, terutamanya, industri pembuatan. Robot PUMA juga boleh ditemui di kebanyakan makmal-makmal penyelidikan di universiti yang berkenaan dengan robotik. Di dalam projek kajian ini, satu teori matematik telah diaplikasikan di dalam merekabentuk satu konfigurasi Robot PUMA. Kaedah algoritma *Denavit-Hartenberg* (D-H) dan *Arm Parameters* mestilah ditentukan dahulu untuk merekabentuk Robot PUMA dan membuat simulasi dengan menggunakan *Workspace Software*. Dalam kajian konfigurasi Robot PUMA ini, *Forward Kinematics Solution* dihitungkan supaya pangkalan data dalaman *Workspace* tentang komputasi posisi dan orientasi sesebuah robot boleh diperolehi. *Workspace* 5.0.4 digunakan untuk merekabentuk Robot PUMA dan membuat simulasi tentang pergerakan konfigurasi robot tersebut.

DEDICATION

For my families, lecturers, friends, and Vic Scheiman.

ACKNOWLEDGEMENTS

Appreciations are expressed to those who have given generous contributions within the period of this thesis development to fulfill the requirement of the Degree of Bachelor of Engineering (Honors) Manufacturing (Robotic and Automation) program.

Here, I would like to express my deepest appreciation to my supervisor, Mr. Shariman Bin Abdullah, also acts as chief of department of robotic and automation of faculty of manufacturing engineering in University of Technical Malaysia Malacca.

His constant guidance, patience and support during my thesis writing are invaluable to me. Furthermore, guides and helps from him on how to make this thesis a more effective reference are followed with my sincere gratitude.

Finally, I would like to thank to all lecturers, technicians and colleagues who has involved directly or indirectly in my thesis.

Mohd Aizat binti Ahmad Tarmizi
April 2007

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LIST OF ABBREVIATIONS, SYMBOLS, SPECIALIZED NOMENCLATURE

a	-	Link Length
$\mathbf{a}$	-	Approach vectors
A	-	Homogenous Transformation
ACIS	-	Alan, Charles, Ian's System
AFR	-	Association Francaise de Robotique
c_{23}	-	$cos\ (\theta_2 + \theta_3)$
s_{23}	-	$sin\ (\theta_2 + \theta_3)$
CAD	-	Computer Aided Design
CNC	-	Computer Numerical Control
d	-	Joint Distance
DH	-	Denavit-Hartenberg
DOF	-	Degree of Freedom
GM	-	General Motor
GP	-	Geometry Points
H	-	Kinematics Matrices
JIRA	-	Japan Industrial Robot Association
kg	-	Kilogram
$\mathbf{n}$	-	Normal vectors
O	-	Origin point
P	-	Prismatic
$\boldsymbol{P}$	-	Position vectors
PPP	-	Prismatic/Prismatic/Prismatic
PUMA	-	Programmable Universal Machine for Assembly
R	-	Rotational
R	-	Rotational Matrices
RIA	-	USA Robotic Industrial Association
RPP	-	Rotational/Prismatic/Prismatic
RRP	-	Rotational/Rotational/Prismatic
RRR	-	Rotational/Rotational/Rotational

RRS	-	Realistic Robot Simulation
R.U.R	-	Rossum's Universal Robots
T	-	Translation
T	-	Transformation Matrices
Trans	-	Translation
VBA	-	Visual Basic for Application
s	-	Seconds
$\boldsymbol{s}$	-	Sliding vector
x	-	Axis-x
y	-	Axis-y
z	-	Axis-z
α	-	Link Twist Angle
θ	-	Joint Angle
°	-	Degree of Rotation

CHAPTER 1

INTRODUCTION

1.1 Background of the Project

This final project is entitled "**Simulation and Study on PUMA Robot Configuration with Workspace**". According to the title, the project is a study of robotics literature generally and focusing on PUMA robot studies. The PUMA robot model is studied thoroughly so that it can be created and simulated by using Workspace 5.04 software. The use of Workspace 5.04 is essential in completing this project.

1.2 Introduction to Robotics

Hardware or machines that independently work has affected and fascinate humankind since the beginnings of the recorded history. Imaginations and dreams of a humanlike robot or a flying vehicle or a machine perform various tasks has been depicted into arts performances or drawings and has been realized by the invention of machineries and vehicles.

Even though dreams or imaginations could not be exactly realized in reality, and the industrial robots today may not look the least bit like a human being, but that fascinated dream has inspired a lot of invention existed today to make human life easier and led to human civilization. To sum up, machines or hardware that can replace human beings as regards to physical work and decision making are categorized as robots and their study as robotics.

Robotics is the art, knowledge base, and the know-how of designing, applying, and using robots in human endeavors. In general, robotics is a study of robots field, which is an important field among other modern technologies and has been categorized as a sub-genre in science field. Understanding of robotics field needs deeply basic knowledge of mechanical, electric and electronic engineering; industry; computer-science; and mathematic. One of the outcomes in robotics study is the invention of PUMA robot, which has been marked in history as the significant development in technology evolution.

1.3 Problem statement

Programmable Universal Machine for Assembly (PUMA) Robot study is one of the robotics fields stems and the robot itself is categorized in industrial robot types. PUMA Robot is widely used in industrial field, especially in light weight manufacturing field e.g. assembly line and welding; and also usually appeared in universities research laboratories.

The purpose of PUMA robot is to solving the light weight problems in a manufacturing line. The application of PUMA robot could save cost of labor and lead time of manufacturing. It also could implement repetitive and dangerous tasks regarding manufacturing fields.

In creating a system of automated manufacturing, it is important to analyze the workspace volume and the robot movements and configurations during the implementation of the manufacturing process. This analysis study consideration would estimate the effects and consequences of the process. Simulation is one of the analysis approaches.

In this project, several areas have been analyzed as a prerequisite in creating and simulating a robot. PUMA robot configuration designs and simulation has to do mainly with mathematical approaches and the utilization of the software related.

A mathematical approach is applied towards designing a PUMA Robot configuration solution. Forward kinematics of the robot configuration must be determined first before create and simulate PUMA robot by using Workspace software. As solving problems of analyzing and observing the movement and configuration of the working robot, robot simulation is being done by using simulation software.

Therefore, Workspace 5.04 Software is used to designing and simulating the robot. A thorough study of PUMA Robot configuration and Workspace utilization is essential to achieve the aims and objectives of this project.

1.4 Aims, Objectives and Scopes of the Project

1.4.1 Aims

The aim of this project is to simulate the PUMA Robot by using the Workspace Software, hence getting know the configuration of the robot. This is being implemented by studying how to design and simulate PUMA Robot by using the Workspace 5.04 Software.

1.4.2 Objectives

The objectives that have to be achieved by the completion of this project are:

1. Design and create a PUMA robot.
2. Simulate the designed PUMA robot by using Workspace software.
3. Relate the calculated kinematics with the configuration of the PUMA Robot.

1.4.3 Scopes

The scope of this project is involving generally about the PUMA Robot study and the application of the Workspace 5.04 Software.

1. Study on PUMA Robot.
2. Design the Denavit-Hartenberg Algorithm for the PUMA Robot and use these parameters to create, simulate, and analyze the configuration of PUMA Robot.
3. Design, create and simulate PUMA Robot by using Workspace Software.

1.5 Chapters Description

In Chapter 1, an introduction is presented, where the background of the project, problem statement, and aims, objectives, and scopes of the project are stated. Chapter 2 deals with the literature review and general study about the scope of the project. Chapter 3 represents how the project will be carried out. Chapter 4 shows the result with a brief explanation. Chapter 5 represents the discussion about the result and the study. Chapter 6 stated the conclusion and recommendations.

1.6 Gantt Chart

Table 1 Gantt Chart PSM 1.

CONTENTS	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15	W16
Project Selection	■								SEMESTER BREAK							
Information research		■	■	■	■	■	■	■								
Write a literature review					■	■	■	■		■	■	■				
Brainstorming and Designing Robot				■	■	■	■	■		■	■	■				
Robot Kinematics Calculation										■	■					
Study on Workspace 5.04 Software					■	■	■	■		■	■	■	■	■	■	■
Gathering all information and sources					■	■	■	■		■	■	■				
Draft report preparation										■	■	■	■			
Final draft report preparation													■	■		
Presentation and report submission															■	■

Table 2 Gantt Chart PSM 2.

CONTENTS	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15	W16
Re-Sketch and design PUMA Robot	■	■							SEMESTER BREAK							
Re-calculate Robot Kinematics	■	■														
Create PUMA Robot in Workspace			■	■	■											
Simulate PUMA Robot in Workspace				■	■	■	■	■								
Study the Robot Configuration					■	■	■	■		■						
Gathering all information and sources							■	■		■	■	■				
Draft report preparation										■	■	■	■			
Final draft report preparation													■	■		
Presentation and report submission															■	■

4. Name joint PUMALINK1 in the joint dialog is selected. The value for the position - x, y, and z; and orientation - roll, pitch, and yaw is entered into the Position field for PUMALINK1, by using the data obtained in Table 4.
5. When the values for PUMALINK1 have been entered, Apply button is left clicked on to confirm the values. The following dialog will then appear "Changing the position of this joint will permanently change the kinematics of the robot. Do you wish to continue." Click "Yes".
6. Steps 3 – 6 are repeated for LINK1LINK2, LINK2LINK3, LINK3LINK4, LINK4LINK5, LINK5LINK6, FLANGE and WORLD, referring to Table 4.
7. Properties tab is selected from the Robot main menu. Under the Kinematics tab, the tick box named Show Internal Kinematics is left-clicked on. OK button is left-clicked on to confirm and exit.

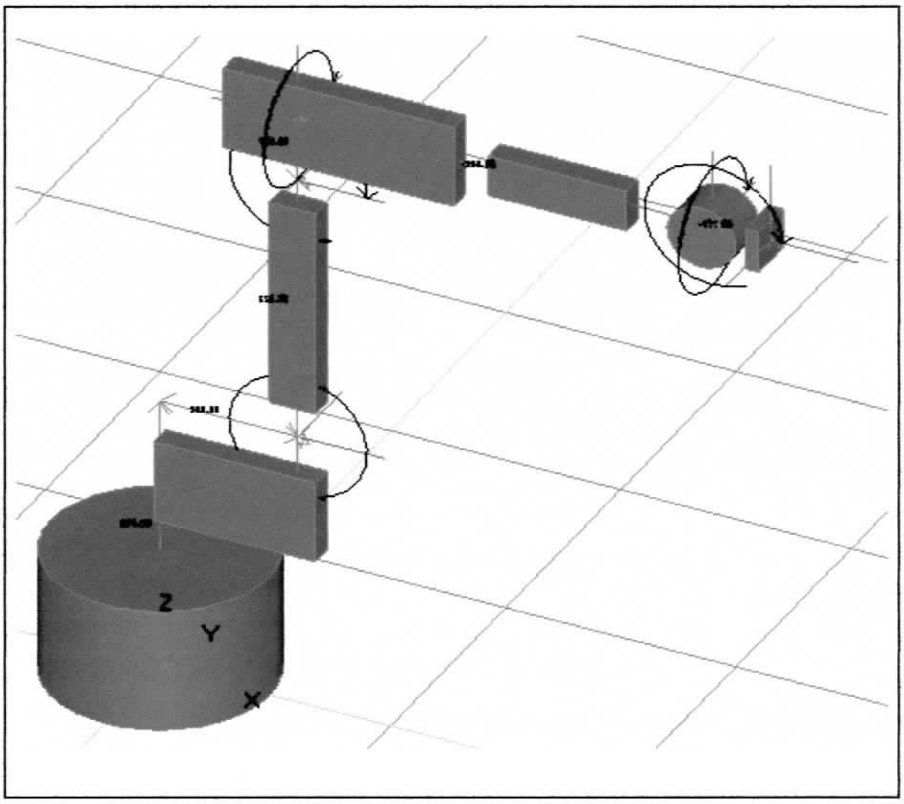
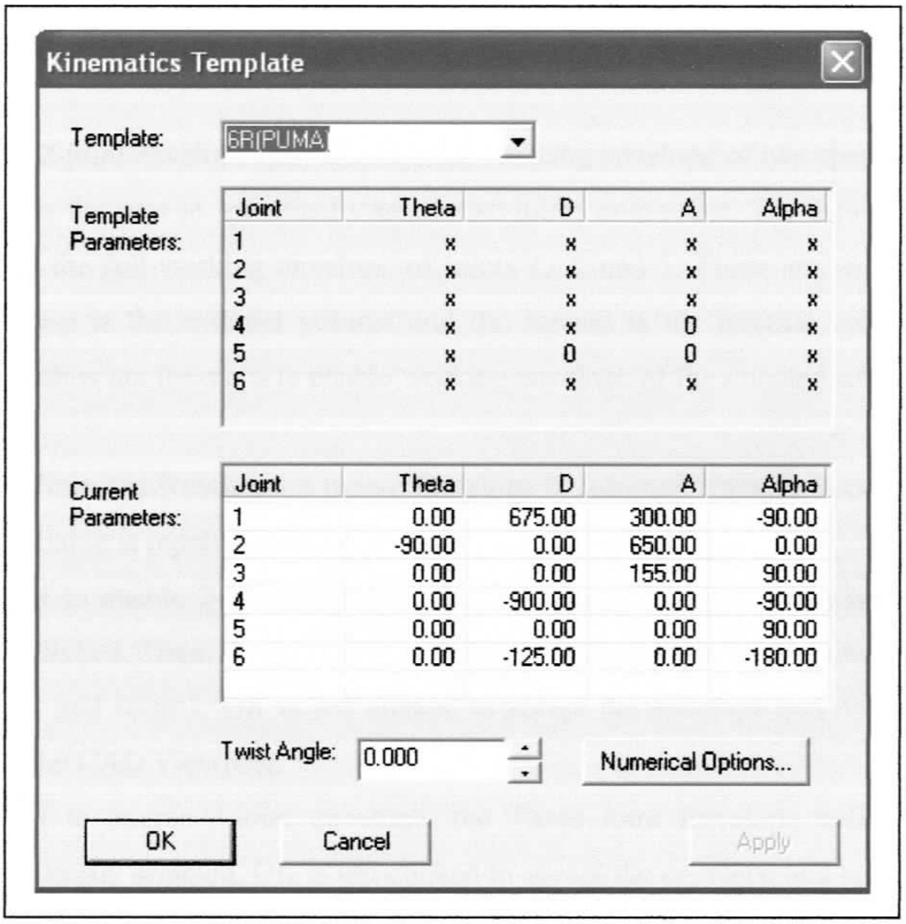


Figure 3.4-8 The Positions and Orientations of PUMA Robot.

3.4.4 Kinematics Modeling

1. From the Robot main menu, "Kinematics…" is left-clicked. A Floating dialog is activated, as shown in Figure 3.4-9 below.



Template: 6R(PUMA)

Template Parameters:

Joint	Theta	D	A	Alpha
1	x	x	x	x
2	x	x	x	x
3	x	x	x	x
4	x	x	0	x
5	x	0	0	x
6	x	x	x	x

Current Parameters:

Joint	Theta	D	A	Alpha
1	0.00	675.00	300.00	-90.00
2	-90.00	0.00	650.00	0.00
3	0.00	0.00	155.00	90.00
4	0.00	-900.00	0.00	-90.00
5	0.00	0.00	0.00	90.00
6	0.00	-125.00	0.00	-180.00

Twist Angle: 0.000

Figure 3.4-9 Kinematics Template Dialog.

2. The Templates field to 6R (PUMA) is changed.
3. A dialog box shown "match with inverse kinematics for 6R" is left-clicked OK.

3.4.5 Working Envelope of the designed PUMA Robot

In Workspace, the working envelope of a robot can be displayed. Even though, it is not so much important to enable the robot working envelope in this study, however, as stated in section 3.2.4, it is necessary to indicate how far the manipulator can reach within a space. There are two choices in showing the working envelope of the robot, which are 2-joint envelope and 3-joint envelope.

The 2-joint envelope only displays the working envelope of two specified joints, which allows the user to specifically select two joints on a robot. The 3-joint envelope will display the full working envelope of joints 1, 2, and 3. There are two envelopes displayed, one is the external volume and the second is the internal volume of the envelope. Below are the steps to enable working envelope of the selected robot:

1. From the Robot main menu, Envelope is selected. Then, a Robot Envelope dialog is represented.
2. If to enable 2-joint envelope, the Two Joint Envelope radio button is left clicked. Then, the two selected joints are entered into the data field i.e. Joint 1 and Joint 2. OK is left clicked to accept the envelope and return back to the CAD Viewport.
3. If to enable 3-joint envelope, the Three Joint Envelope radio button is already selected. OK is left clicked to accept the envelope and return back to the CAD Viewport.
4. To remove the robot envelope, Robot from the main menu is selected and Hide Envelope is left clicked.

3.5 Simulate a PUMA Robot by using Workspace 5.04 Software

In this project, to exemplify the application of the PUMA Robot simulation in workspace, a box is created in front of the created robot so that it can simulate an example of welding task movement. Before simulating the PUMA Robot, a set of Geometry Points (GP's) and a path of those GP's must be created.

3.5.1 Creating a box in front of the PUMA Robot

The purpose of creating a box in front of the PUMA Robot is to exemplify the robot movement implementing a task during simulation. Below is the step to creating the box:

1. The Create Box icon in the tool bar is left clicked. Then, the "I" shortcut key is pressed. 1175 for x, 0 for y, 525 for z, 300 for length, 1000 for depth, and 300 for height are being entered within the dialog. The box is then named as BOX1.

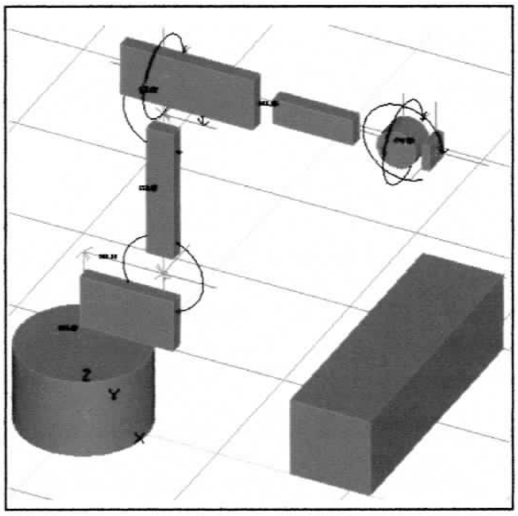


Figure 3.4-10 A box is created in front of the created PUMA Robot

3.5.2 Creating Geometry Points (GPs) and Path

In Workspace, Geometry Points (GPs) are robot endpoint target locations and can be manipulated in much the same way as any other object within Workspace (Brown 2003). A robot model may be jogged to a particular position and then the point saved as a GP for later use, or the GP may be created independent from the robot.

The GP can also be created on CAD objects which means by creating it on an objects face or edge. In this project, the Geometry Points (GPs) are created on an edge of the previous created box, with the GP being relative to the edge.

A path is a list of all Geometry Points (GPs) that a robot follows during a sequence of motions (Brown 2003). A path is displayed graphically as a series of lines linking the GPs with arrows showing the direction of the motion.

When a GP is placed in a path, it is represented by a GP Move, the attributes describing the nature of the motion to be used when traveling towards the GP move from a previous GP move on the same path, as well as attributes describing the actions to be performed when the GP move is reached.

Below are the steps for creating GPs on an edge of the box and simultaneously creating a path:

1. From the Edit main menu, Selection Mode and Edge is selected. The selection mode will change from body to edge, indicated by a tick.
2. An edge of the box is selected, thus it is highlighted.
3. From the Create main menu, GP and "Created GPs on Edge" is selected. Then, Select Path dialog is presented as shown in Figure 3.4-11. A new path is created and named as Path 1. OK button is left clicked.

4. Path1 in the Select Path dialog is selected. Then, OK button is left clicked.

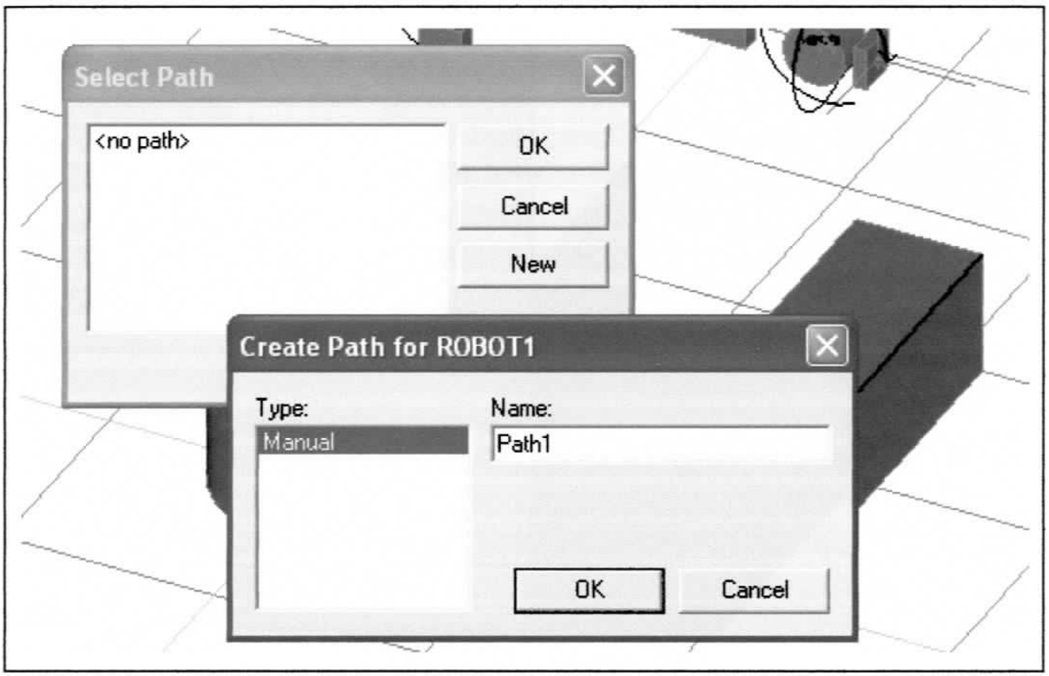
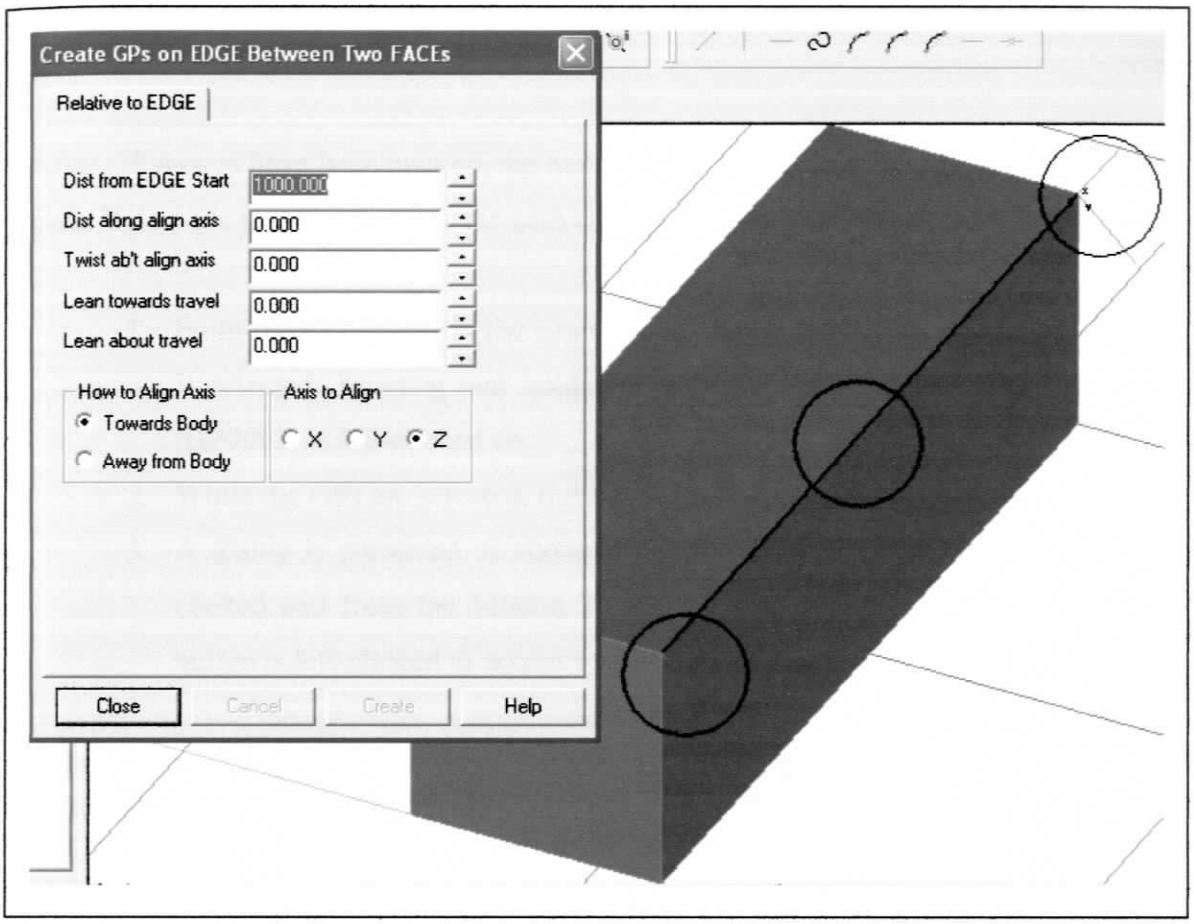


Figure 3.4-11 Creating GPs and Path

5. A Create GPs on Edge dialog is presented as shown in Figure 3.4-12. Create button is left-clicked. Thus, a GP is created at the default position of the GP preview.
6. In the Dist from Edge field, 500 is entered and the GP preview moves to the midpoint of the box, 500 mm distance from the EDGE start. The Create button is left clicked.
7. In the Dist from EDGE field, 1000 is entered and the GP preview moves to the endpoint of the selected edge of the box, 1000 mm distance from the EDGE start. The Create button is left clicked.



Create GPs on EDGE Between Two FACEs

Relative to EDGE

Dist from EDGE Start: 1000.000
Dist along align axis: 0.000
Twist ab't align axis: 0.000
Lean towards travel: 0.000
Lean about travel: 0.000

How to Align Axis: ● Towards Body ○ Away from Body

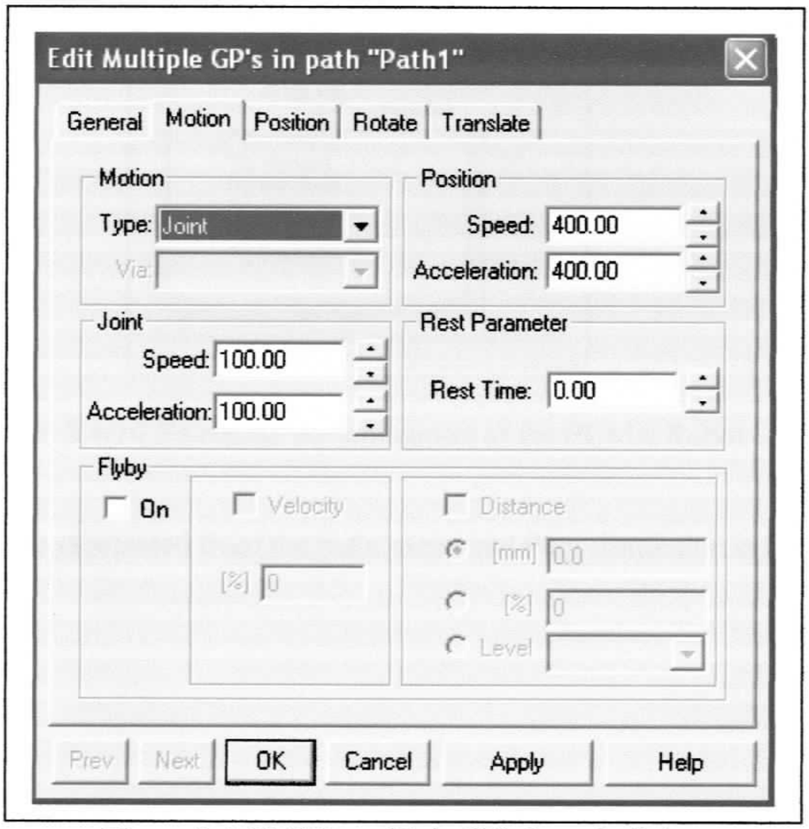
Axis to Align: ○ X ○ Y ● Z

Figure 3.4-12 Three GPs has been created, one on the midpoint of the box and the other two on either end vertex of the box.

3.5.3 Simulating the Path

After GP moves have been created, the next stage is to simulate the robot following the path. Below are steps to simulate the path created:

1. From the path folder in the simulation window, Path1 left click and GP0001 is selected. Pressing and holding the SHIFT key, the last GP in the list (GP0003) is left-clicked on.
2. While the GPs are selected, right click and "Properties" tab is selected.
3. A dialog is presented as shown in Figure 3.4-13. The Motion tab is left-clicked and from the Motion Type field, Linear is changed to Joint. OK button is left-clicked to accept settings and return back to CAD Viewport.



Edit Multiple GP's in path "Path1"

Motion

Type: Joint

Via:

Position

Speed: 400.00

Acceleration: 400.00

Joint

Speed: 100.00

Acceleration: 100.00

Rest Parameter

Rest Time: 0.00

Flyby

☐ On

☐ Velocity

[%] 0

☐ Distance

● [mm] 0.0

○ [%] 0

○ Level

Figure 3.4-13 Edit multiple GPs in path dialog

4. The name of the robot (ROBOT1 or PUMA) is right-clicked under the Robots branch in the Simulation tab of the project view. A floating menu appears.
5. Simulate on the floating menu is left-clicked, as shown in Figure 3.4-14. A tick indicates that it is enabled for simulation.

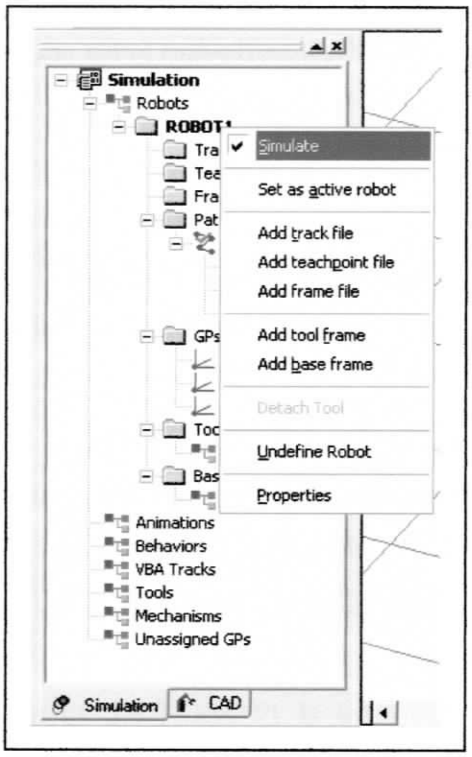


Figure 3.4-14 To enable the simulation of the PUMA Robot

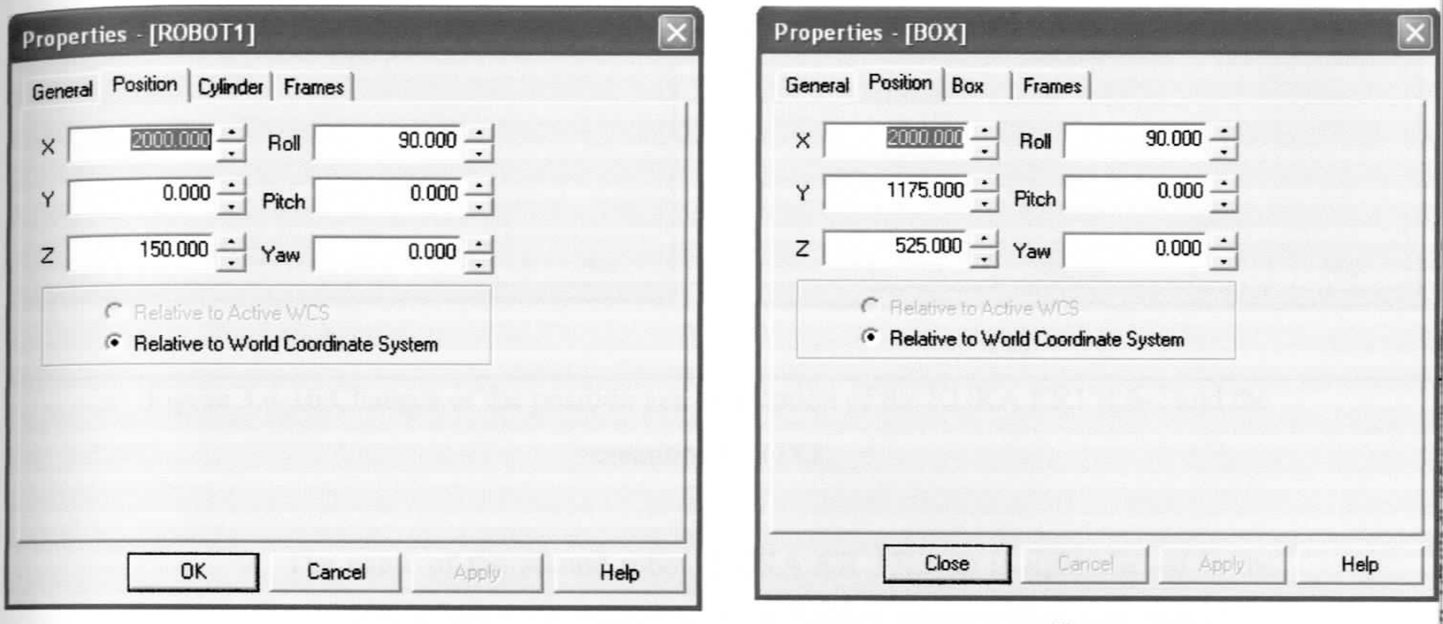
6. Simulate is selected from the main menu and Play simulation is left-clicked.

3.5.4 Creating Simulation of Two Robots each following its own Path

In studying the configuration of the PUMA Robot, it is a good idea to differentiate between two robots movement doing the same task at the same time in its own path. Therefore, the created PUMA Robot is put in a same cell with a KUKA Robot KR 15 L6-2. The purpose of the method is to observe both of the robots configurations (position and orientation of the robot end-effectors) while doing the same task initiated at the same starting time, each following its own path. Below are steps to implement the ideas:

1. In the PUMA Robot project file, the base of the ROBOT1 or PUMA robot is left clicked to select it. The CAD Viewport is right clicked and "properties" is selected.
2. Position tab is left clicked and 2000 is entered in the x-field and 90 in the roll field, to change the position and orientation of the PUMA robot, as shown in Figure 3.4-15(a). OK button is left clicked to exit back to the CAD Viewport. The CAD Viewport is right clicked and Clear selection is selected.
3. The box in front of the ROBOT1 is left clicked to select it. The CAD Viewport is right clicked and "properties" is selected.
4. Position tab is left clicked and 2000 is entered in the x-field, 1175 for y-field and 90 in the roll field, to change the position and orientation of the box, as shown in Figure 3.4-15(b). OK button is left clicked to exit back to the CAD Viewport. The CAD Viewport is right clicked and Clear selection is selected.
5. From the File main menu, Insert file is selected. A KUKA KR 15L6-2 is inserted from the dialog.
6. The base of the KUKA KR 15L6-2 is left-clicked to select it. The CAD Viewport is right clicked and "properties" is selected.

7. Position tab is left clicked and 90 is entered in the roll field, to change the position and orientation of the PUMA robot. OK button is left clicked to exit back to the CAD Viewport. The CAD Viewport is right clicked and Clear selection is selected.



(a)

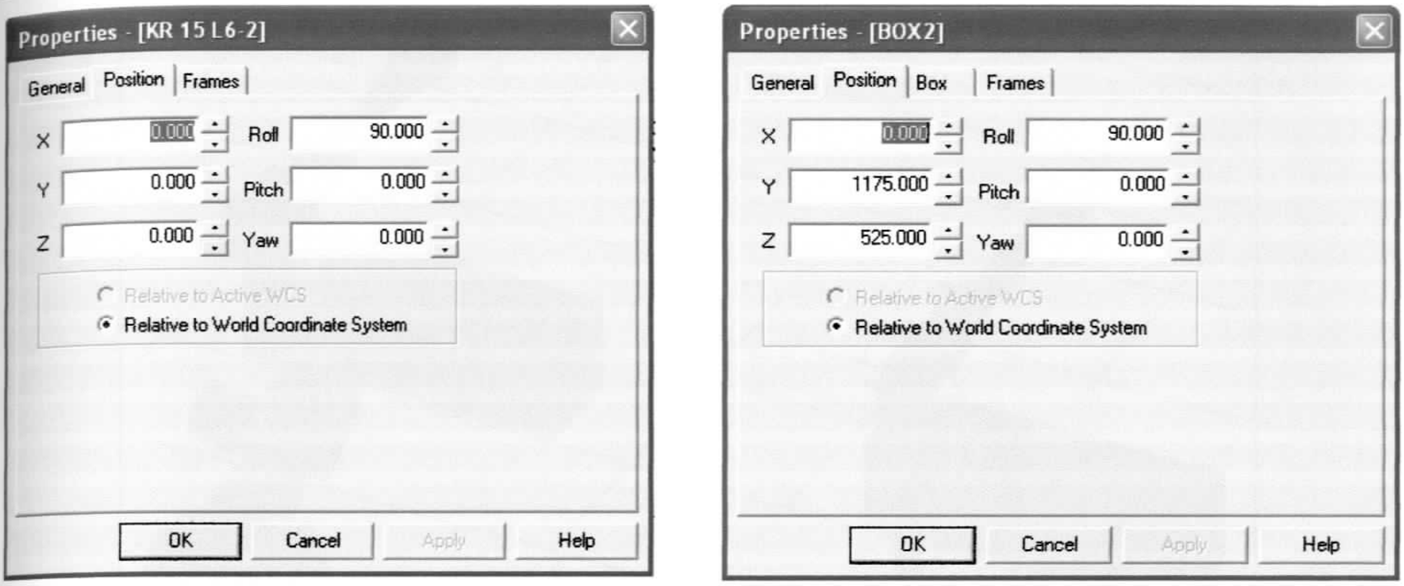
X 2000.000 Roll 90.000
Y 0.000 Pitch 0.000
Z 150.000 Yaw 0.000
○ Relative to Active WCS
● Relative to World Coordinate System

(b)

X 2000.000 Roll 90.000
Y 1175.000 Pitch 0.000
Z 525.000 Yaw 0.000
○ Relative to Active WCS
● Relative to World Coordinate System

Figure 3.4-15 Changes of the position and orientation of the PUMA Robot and BOX1

8. The Create Box icon in the tool bar is left clicked. Then, the "I" shortcut key is pressed. 0 for x, 1175 for y, 525 for z, 90 for roll, 300 for length, 1000 for depth, and 300 for height are being entered within the dialog. The box is then named as BOX2.



Properties - [KR 15 L6-2]

X 0.000 Roll 90.000
Y 0.000 Pitch 0.000
Z 0.000 Yaw 0.000

○ Relative to Active WCS
● Relative to World Coordinate System

Properties - [BOX2]

X 0.000 Roll 90.000
Y 1175.000 Pitch 0.000
Z 525.000 Yaw 0.000

○ Relative to Active WCS
● Relative to World Coordinate System

(a) (b)

Figure 3.4-16 Changes of the position and orientation of the KUKA KR15L6-2 and the creation of BOX2

9. The name of the second robot (KUKA KR 15L6-2) is right-clicked in the Simulation tab of the Project view. A floating menu will appear. Select Set as active robot. The robot name should now be bold. The same method in creating GPs and path in section 3.5.2 is repeated for the KUKA KR 15L6-2 and BOX2. The new path created for this robot is named as Path2.
10. For simulating the both of the robots, the name of the first robot (ROBOT1 or PUMA Robot) and the second robot (KUKA KR 15L6-2) is right-clicked in the Simulation tab of the Project view. A floating menu appears. Simulate is selected, which sets the both of the robots ready for simulation. This method must be implemented consequently, from the first robot to second robot.
11. From the Simulation main menu, select Play simulation.

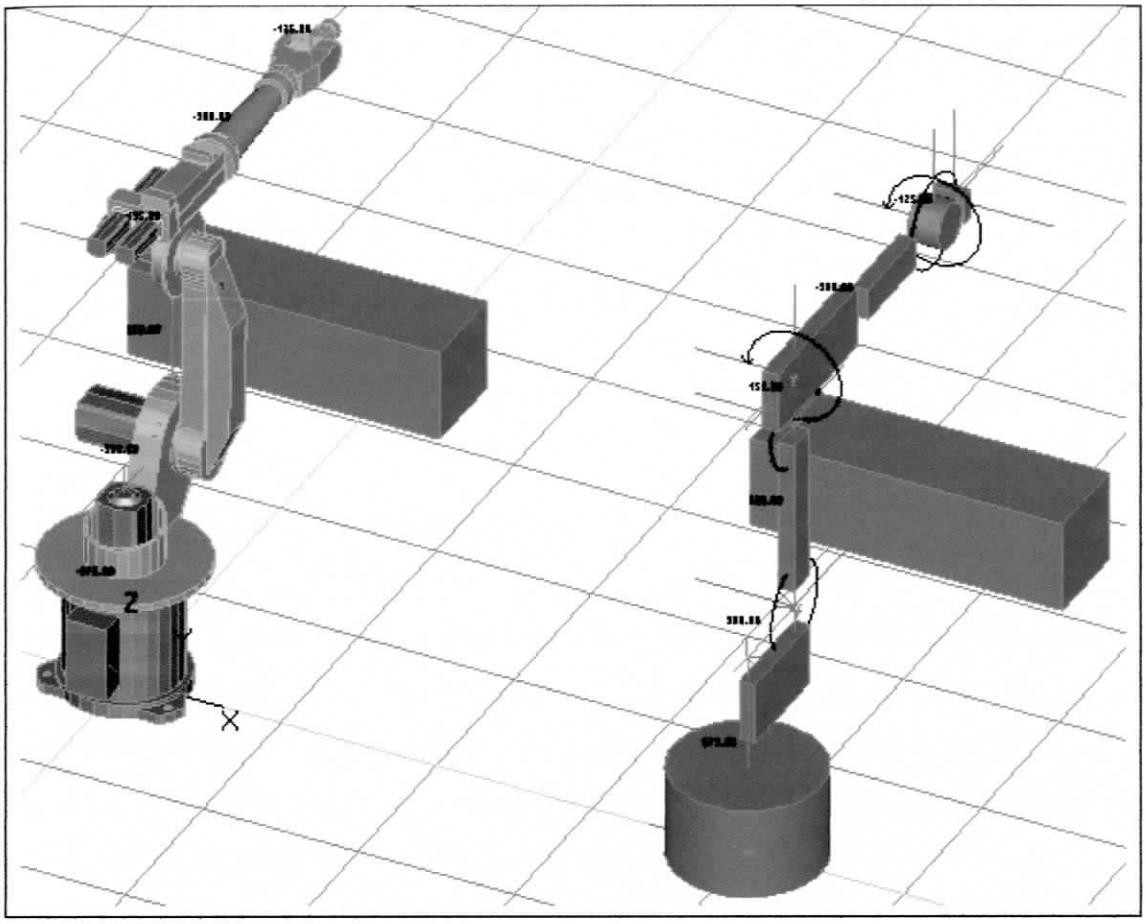


Figure 3.4-17 Creating a simulation of two robots each following its own path

CHAPTER 4

RESULT

4.1 Kinematics of the PUMA Robot

The kinematics of the PUMA Robot has been obtained from the Denavit-Hartenberg Algorithm method. From the algorithm, the assigned frame and parameters identification has been implemented as in Figure 4.1-1 below, which is an approach in obtaining the PUMA Robot Arm Parameters. The arm parameters and its value of the PUMA Robot are presented in the table 5 below:

Table 7 Arm Parameters of PUMA Robot

Joint	θ_i	d_i	a_i	α_i
1	θ_1	d_1	a_1	90°
2	θ_2	0	a_2	0
3	θ_3	0	a_3	90°
4	θ_4	d_4	0	-90°
5	θ_5	0	0	90°
6	θ_6	d_4	0	-180°

$a_1 = 300$, $d_1 = 675$ $a_4 = 0$, $d_4 = -900$

$a_2 = 650$, $d_2 = 0$ $a_5 = 0$, $d_5 = 0$

$a_3 = 155$, $d_3 = 0$ $a_6 = 0$, $d_6 = -125$

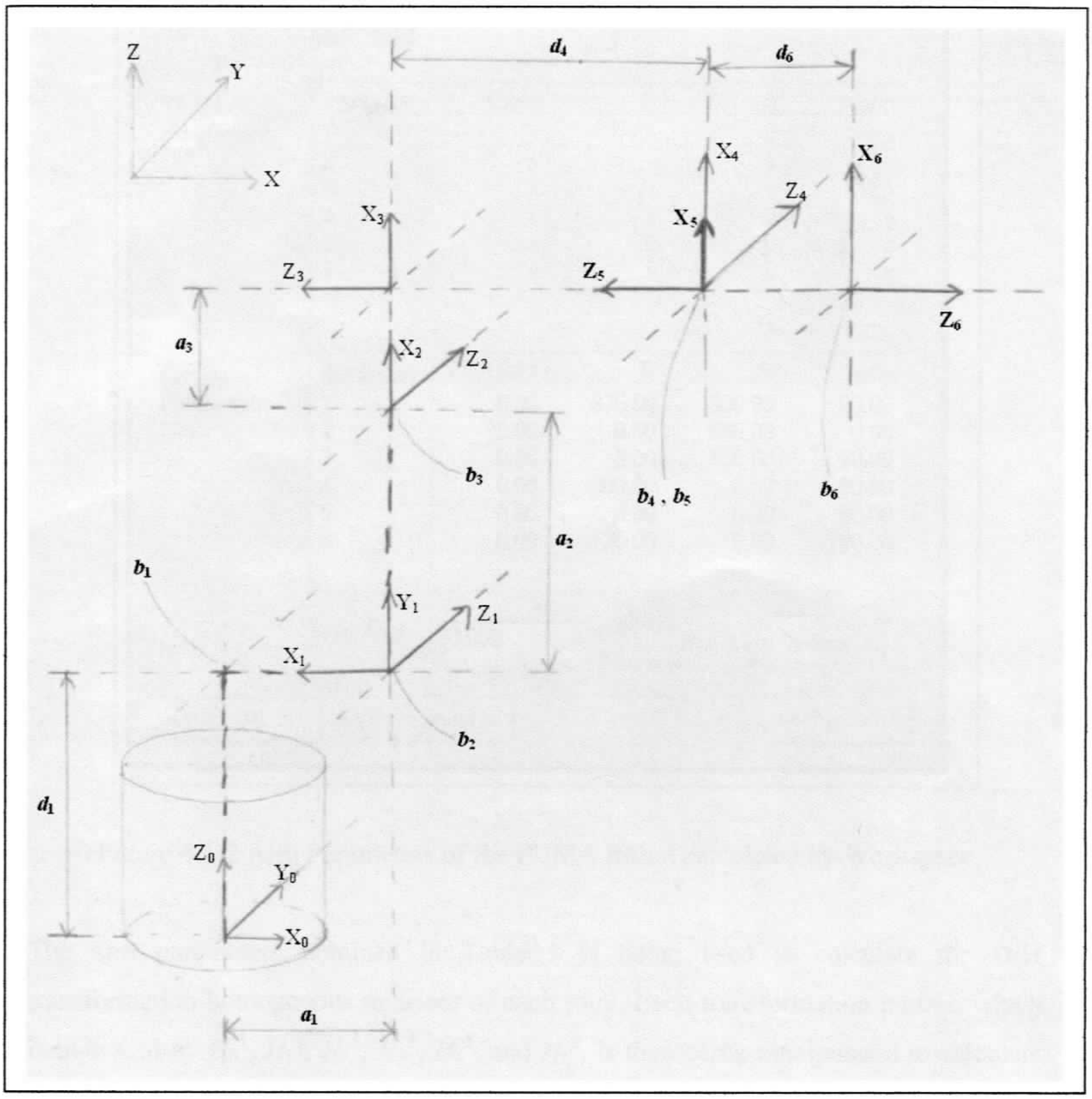
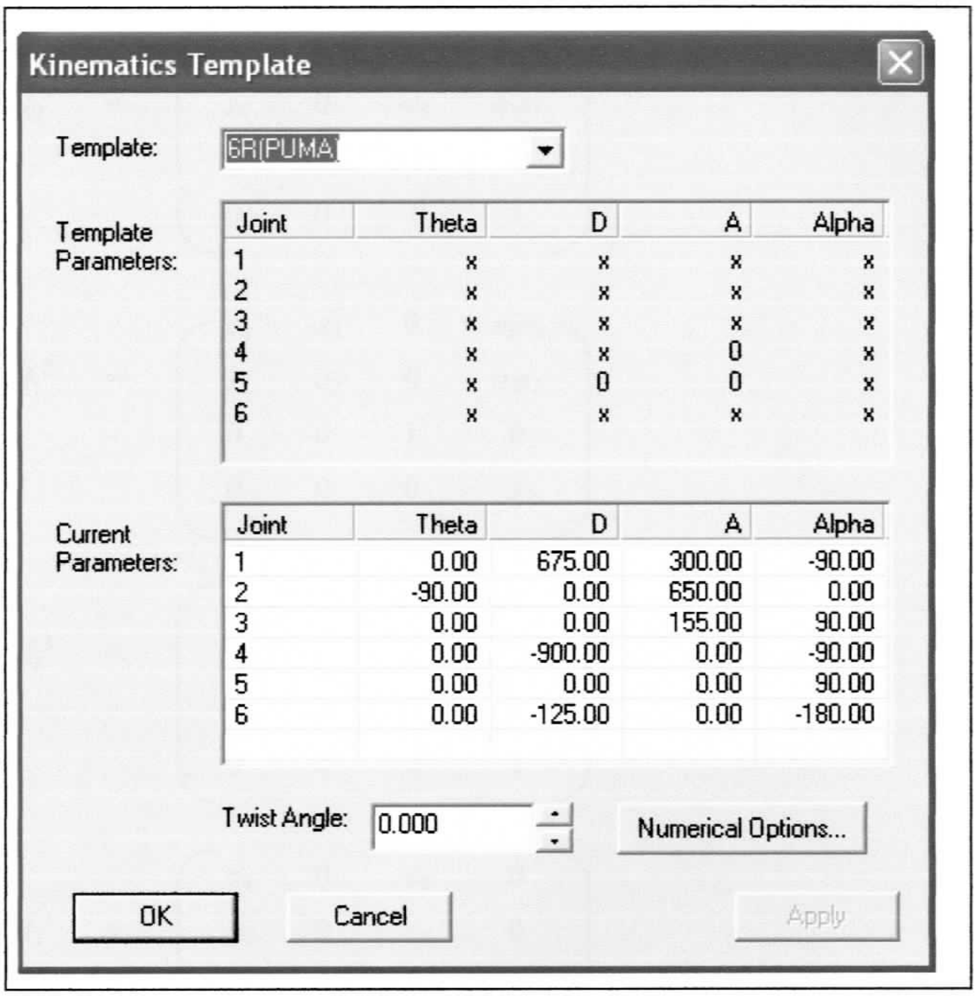


Figure 4.1-1 PUMA Robot kinematics parameters identification

In Workspace, the Arm Parameters of the PUMA Robot after defining each axis of the joints, which is calculated by the Workspace, are shown in Figure 4.1-2 below.



Template: 6R(PUMA)

Template Parameters:

Joint	Theta	D	A	Alpha
1	x	x	x	x
2	x	x	x	x
3	x	x	x	x
4	x	x	0	x
5	x	0	0	x
6	x	x	x	x

Current Parameters:

Joint	Theta	D	A	Alpha
1	0.00	675.00	300.00	-90.00
2	-90.00	0.00	650.00	0.00
3	0.00	0.00	155.00	90.00
4	0.00	-900.00	0.00	-90.00
5	0.00	0.00	0.00	90.00
6	0.00	-125.00	0.00	-180.00

Twist Angle: 0.000

Figure 4.1-2 Arm Parameters of the PUMA Robot calculated by Workspace

The arm parameters obtained in Table 5 is being used to calculate the D-H transformation homogenous matrices of each joint. Each transformation matrix, which is indicated by H_0^1, H_1^2, H_2^3, H_3^4, H_4^5, and H_5^6, is then being manipulated to calculate the forward kinematics solution of the PUMA Robot.

The forward kinematics solutions or arm matrix describes the position and orientation of the end-effectors of the created PUMA Robot, which is indicated by a homogenous transformation matrix, H_0^6.

$$H_0^{\,1} = \begin{pmatrix} c_1 & 0 & s_1 & a_1c_1 \\ s_1 & 0 & -c_1 & a_1s_1 \\ 0 & 1 & 0 & d_l \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$H_1^{\,2} = \begin{pmatrix} c_2 & -s_2 & 0 & a_2c_2 \\ s_2 & c_2 & 0 & a_2s_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$H_2^{\,3} = \begin{pmatrix} c_3 & 0 & s_3 & a_3c_3 \\ s_3 & 0 & -c_3 & a_3s_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$H_3^{\,4} = \begin{pmatrix} c_4 & 0 & -s_4 & 0 \\ s_4 & 0 & c_4 & 0 \\ 0 & -1 & 0 & d_4 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$H_4^{\,5} = \begin{pmatrix} c_5 & 0 & s_5 & 0 \\ s_5 & 0 & -c_5 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$H_5^{\,6} = \begin{pmatrix} c_6 & s_6 & 0 & 0 \\ s_6 & c_6 & 0 & 0 \\ 0 & 0 & 1 & d_6 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Note that c_{i} is $cos\ \theta_i$ and s_{i} is and $sin\ \theta_i$.

Forward Kinematics, $H_0^6 = H_0^1 \,.\, H_1^2 \,.\, H_2^3 \,.\, H_3^4 \,.\, H_4^5 \,.\, H_5^6$

$$\boldsymbol{H_0^6} = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{pmatrix}$$

$$a_{11} = c_1 c_{23} (c_4 c_5 c_6 - s_4 s_6) + s_1 (s_4 c_5 c_6 + c_4 s_6) + c_1 s_{23} (- s_5 c_6)$$
$$a_{21} = s_1 c_{23} (c_4 c_5 c_6 - s_4 s_6) - c_1 (s_4 c_5 c_6 + c_4 s_6) + s_1 s_{23} (- s_5 c_6)$$
$$a_{31} = s_{23} (c_4 c_5 c_6 - s_4 s_6) + c_{23} (s_5 c_6)$$
$$a_{41} = 0$$

$$a_{12} = c_1 c_{23} (c_4 c_5 c_6 - s_4 s_6) + s_1 (s_4 c_5 s_6 + c_4 s_6) + c_1 s_{23} (s_5 s_6)$$
$$a_{22} = s_1 c_{23} (s_4 c_5 s_6 + c_4 c_6) - c_1 (s_4 c_5 s_6 + c_4 c_6) - s_5 s_6 (s_1 s_{23})$$
$$a_{32} = s_{23} (c_4 c_5 s_6 - s_4 s_6) + c_{23} (s_5 c_6)$$
$$a_{42} = 0$$

$$a_{13} = c_1 c_{23} (c_4 s_5) + s_1 (s_4 s_5) + c_1 s_{23} c_5$$
$$a_{23} = s_1 c_{23} (c_4 s_5) - c_1 (s_4 s_5) + s_1 s_{23} c_5$$
$$a_{33} = s_{23} (c_4 s_5) - c_{23} c_5$$
$$a_{43} = 0$$

$$a_{14} = c_1 c_{23} (c_4 s_5 d_6) + s_1 (s_4 s_5 d_6) + c_1 s_{23} (c_5 d_6 + d_4) + c_1 (a_1 + a_2 c_2 + a_3 c_{23})$$
$$a_{24} = s_1 c_{23} (c_4 s_5 d_6) - c_1 (s_4 s_5 d_6) + s_1 s_{23} (c_5 d_6 + d_4) + s_1 (a_1 + a_2 c_2 + a_3 c_{23})$$
$$a_{34} = s_{23} (c_4 s_5 d_6) + c_{23} (c_5 d_6 + d_4) + a_2 s_2 + a_3 s_{23} + d_1$$
$$a_{44} = 1$$

Note that that c_{23} is $cos\ (\theta_2 + \theta_3)$ and s_{23} is $sin\ (\theta_2 + \theta_3)$.

4.2 PUMA Robot

From the methodology described before, there are several steps in creating a PUMA Robot. They are pre-creating the shell of the PUMA Robot; creating the shell of the PUMA Robot; defining the axis of the PUMA Robot; and Modeling the Kinematics. The results obtained are presented and represented in figures below.

4.2.1 The Shell of the PUMA Robot

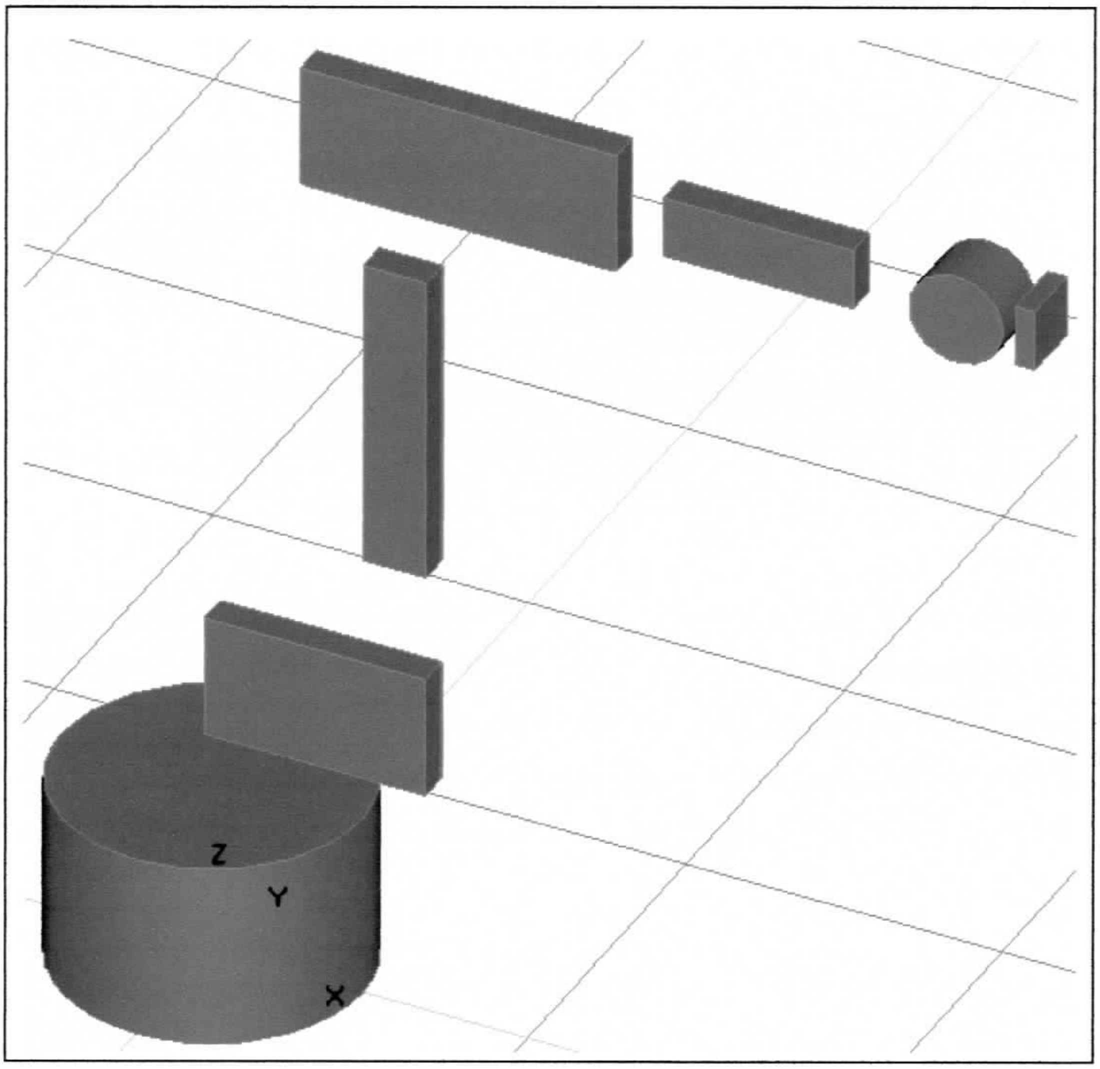


Figure 4.2-1 Shell of the PUMA Robot

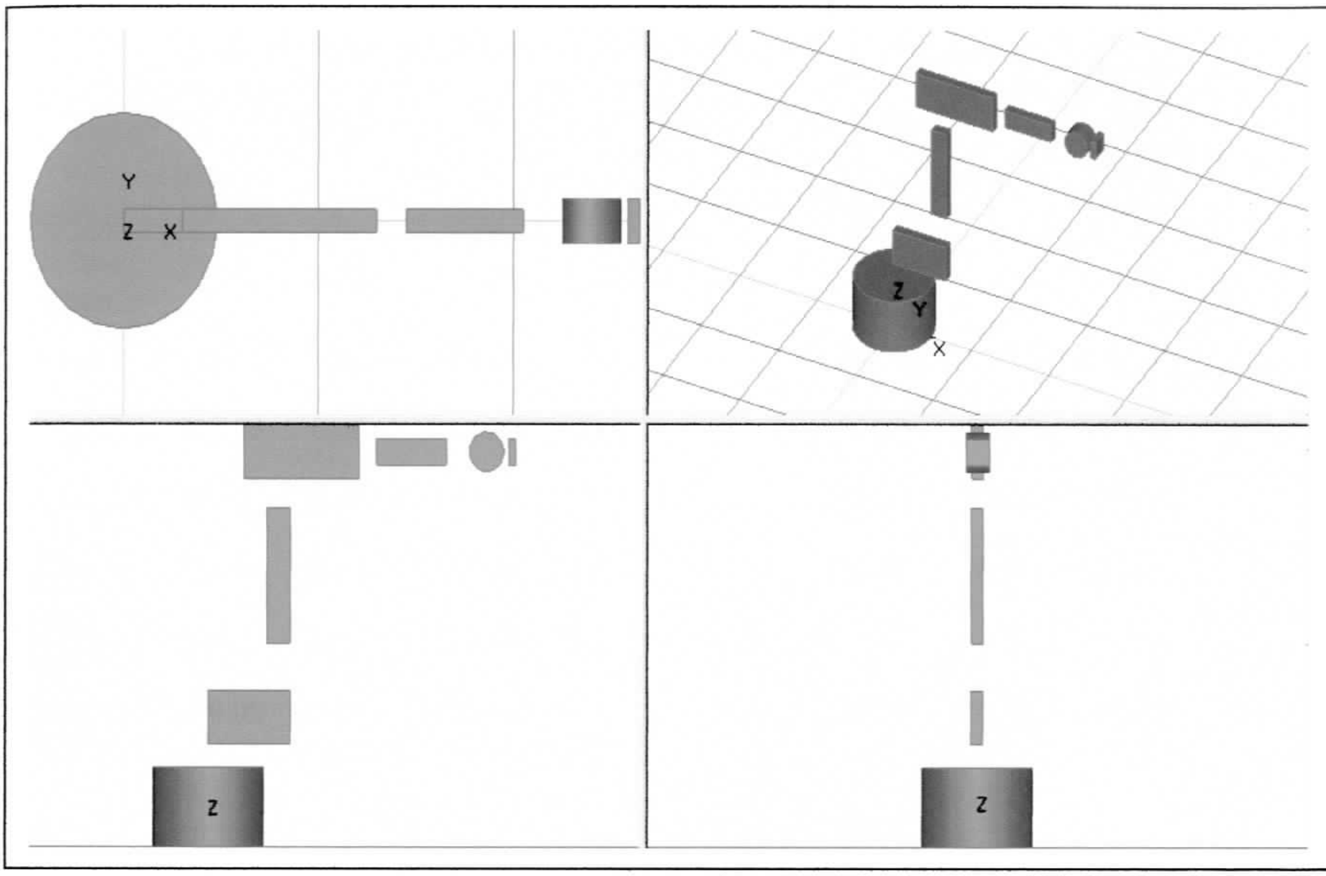


Figure 4.2-2 Top (top-left), Side (bottom-left), Isometric (top-right) and Front (bottom-right) View of the Shell of PUMA Robot

Figure 4.2-1 shows the overall result of PUMA Robot Shell design. Figure 4.2-2 shows the top, side, front, and isometric of the PUMA Robot. Each component parameters of the created PUMA Robot has been determined by the early sketches as described in the Methodology chapter. The positional dimensional of each component of the PUMA Robot created in the Workspace is presented in Table 6 below.

Table 8 Position and Dimension of the PUMA Robot Components

	Position			Dimension				
	x	y	z	Height	Radius	Length	Depth	Height
Robot Base	0.00	0.00	150.00	300.00	240.00	-	-	-
Link 1	175.00	0.00	487.50	-	-	350.00	50.00	200.00
Link 2	300.00	0.00	1016.25	-	-	100.00	50.00	507.50
Link 3	400.00	0.00	1480.00	-	-	500.00	50.00	200.00
Link 4	875.00	0.00	1480.00	-	-	300.00	50.00	100.00
Link 5	1200.00	0.00	1480.00	100.00	75.00	-	-	-
Link 6	1310.00	0.00	1480.00	-	-	30.00	100.00	100.00

Table 9 Position and Orientation of the PUMA Robot Joint

Joint	x	y	z	Roll	Pitch	Yaw
1	0.00	0.00	0.00	0.00	0.00	0.00
2	300.00	0.00	675.00	180.00°	0.00	90.00°
3	300.00	0.00	1325.00	0.00	-90.00°	-90.00°
4	300.00	0.00	1480.00	0.00	-90.00°	0.00
5	1200.00	0.00	1480.00	0.00	-90.00°	-90.00°
6	1200.00	0.00	1480.00	0.00	-90.00°	0.00
World	0.00	0.00	0.00	0.00	0.00	0.00
Flange	1325.00	0.00	1480.00	0.00	90.00°	0.00

4.2.2 Joints of the PUMA Robot

The joints and axes of the created PUMA Robot has been designed and determined during the early sketch of the PUMA Robot as described in Methodology chapter. The joints position and orientation parameters are presented in previous Table 7. Figure 4.2-3 depicts the visible axis and joints possessed by the created PUMA Robot.

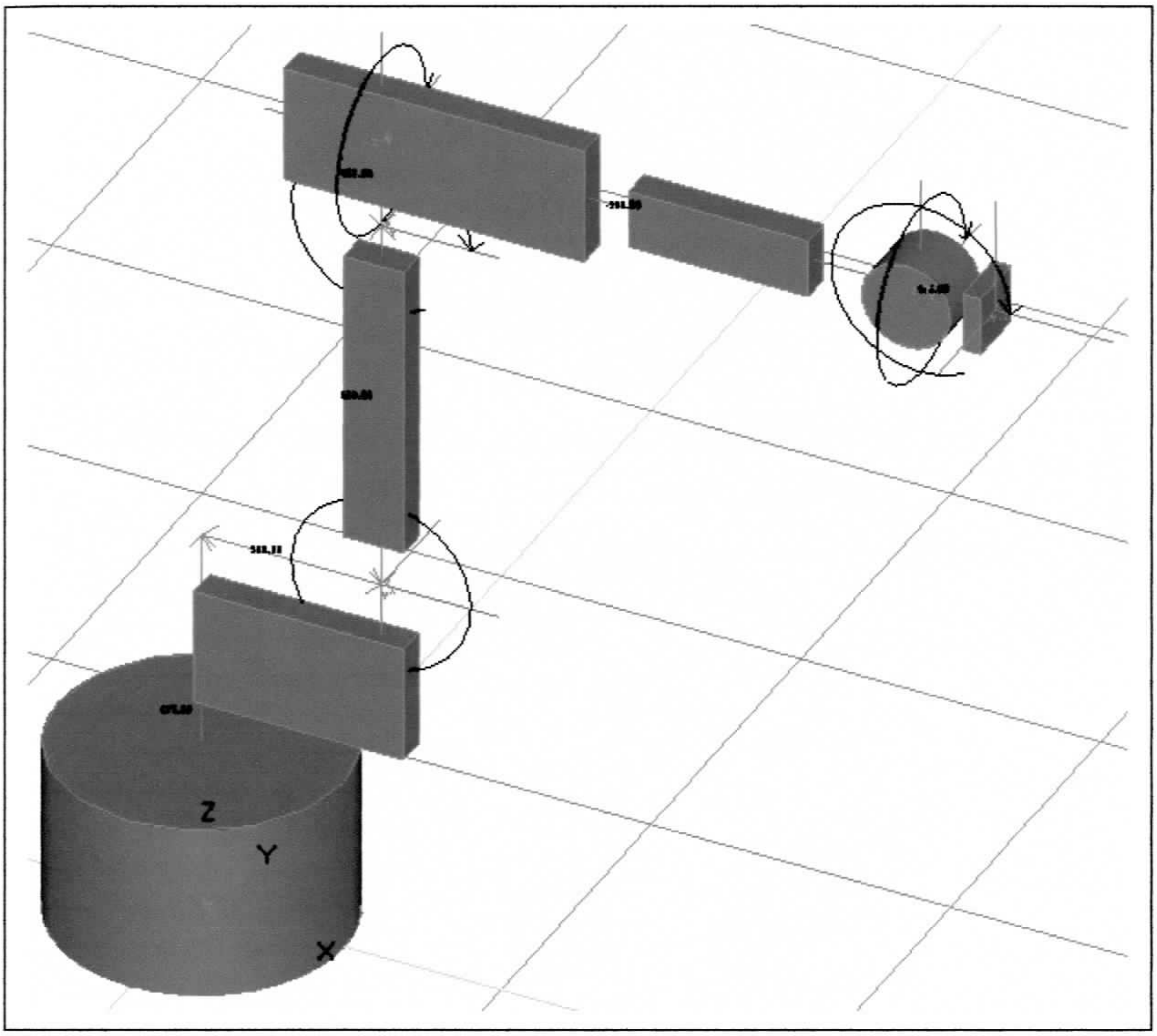


Figure 4.2-3 Joints at of the PUMA Robot

4.2.3 Working Envelope of the PUMA Robot

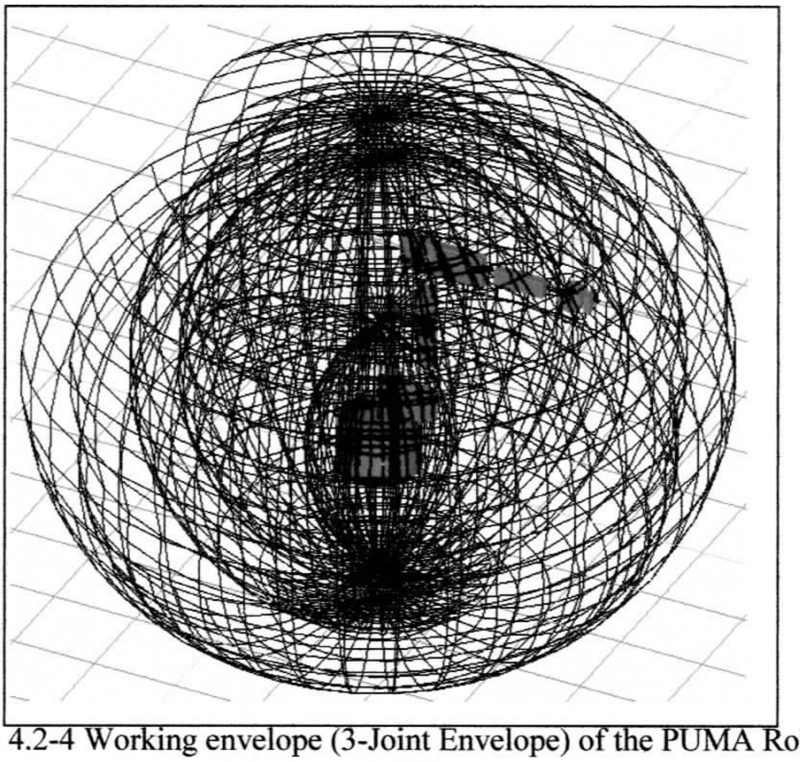


Figure 4.2-4 Working envelope (3-Joint Envelope) of the PUMA Robot

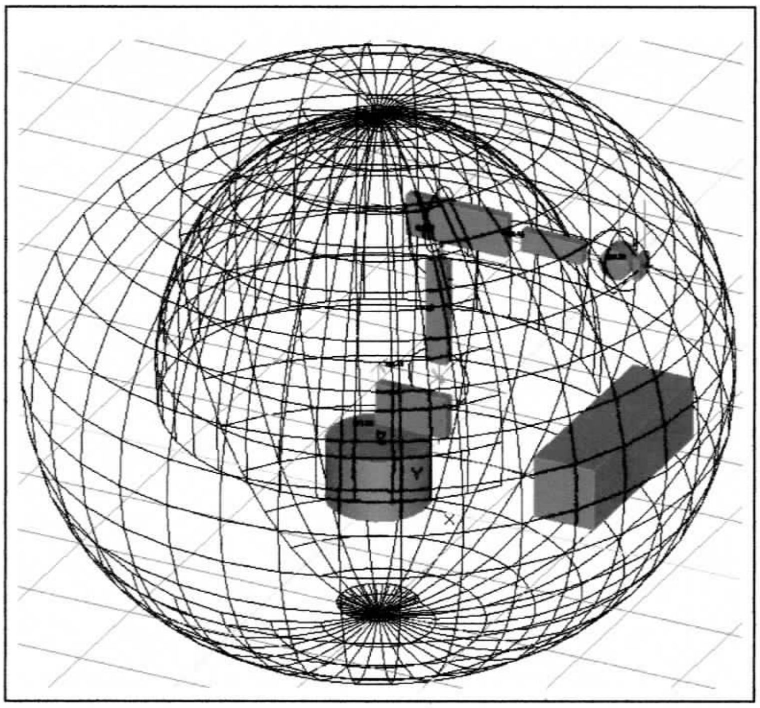
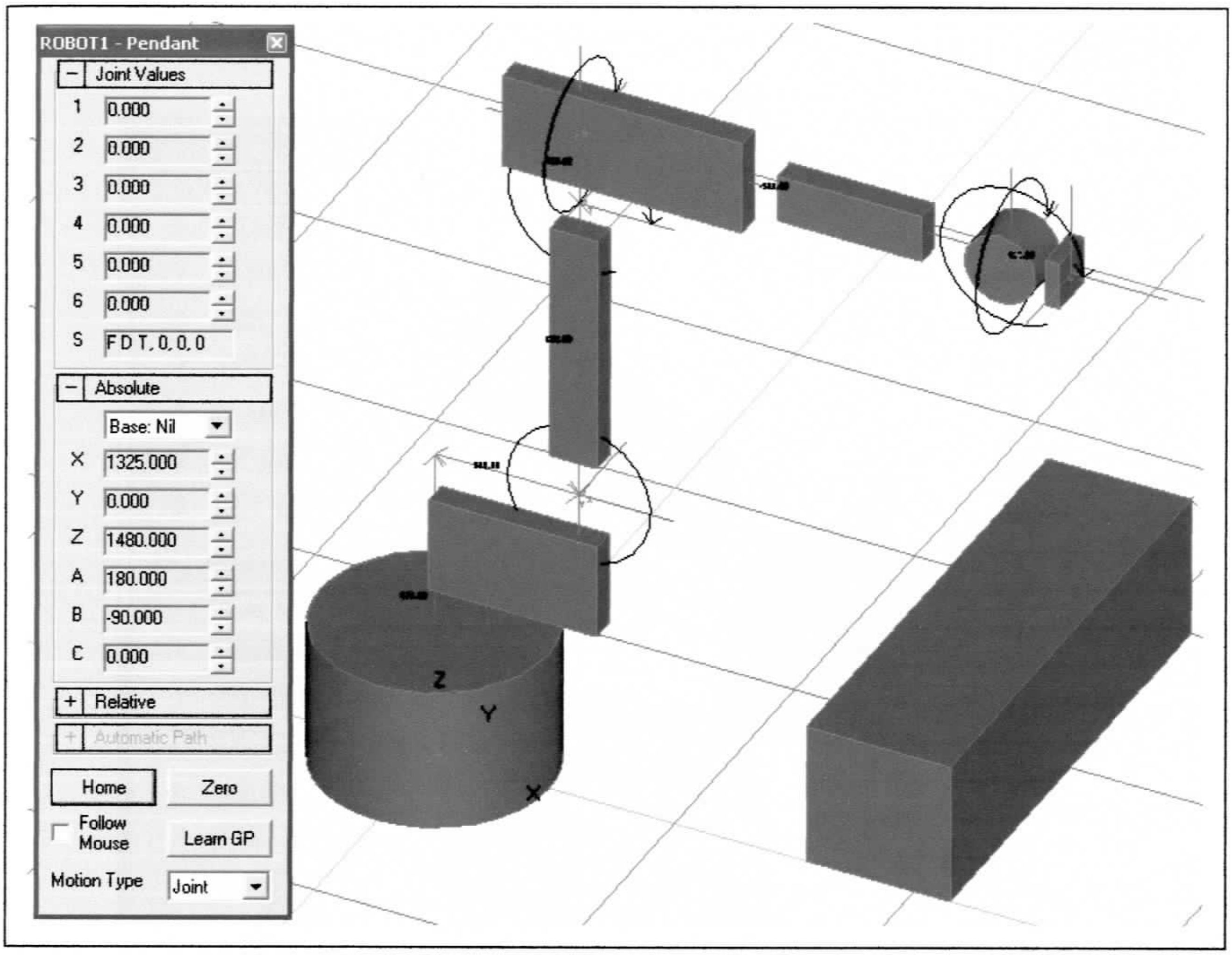


Figure 4.2-5 Working envelopes (2-Joint Envelope) of the PUMA Robot with box

4.3 Simulation of the PUMA Robot

In this section, there are several figures present the process and robot end-effectors configuration (position and orientation) during the simulation.



ROBOT1 - Pendant

Joint Values

1 0.000
2 0.000
3 0.000
4 0.000
5 0.000
6 0.000
S FDT,0,0,0

Absolute

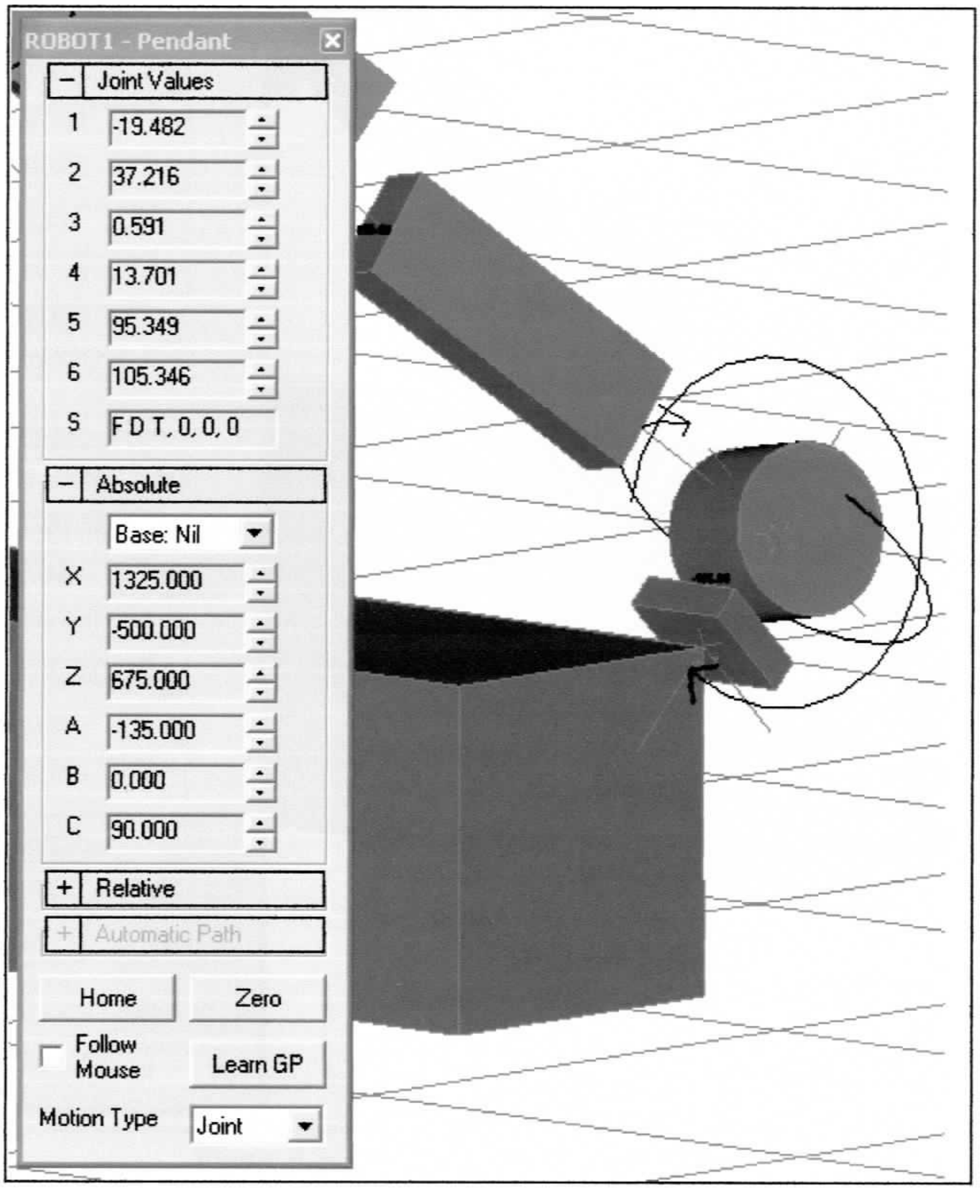
Base: Nil
X 1325.000
Y 0.000
Z 1480.000
A 180.000
B -90.000
C 0.000

Motion Type Joint

Figure 4.3-1 Early process of the simulation

Figure 4.3-1 presents the beginning process of the simulation of the PUMA Robot. The robot pendant shows the configuration of the robot in the space that is relative to universal coordinate system.

The "joint value" indicates the numerical position of the six robot joints, which means the orientation of each joint relative to the base of the robot. The "absolute" value indicates the position and orientation of the end-effectors frame of the robot. Each of joint value shows 0.000° and for the absolute value of the robot end-effectors, the frame is at position X for 1325.000, Y for 0.000, and Z for 1480.000; and orientation roll (A) for 180.000°, pitch (B) for -90.000°, and yaw (C) for 0.00°.



ROBOT1 - Pendant

Joint Values

1 -19.482
2 37.216
3 0.591
4 13.701
5 95.349
6 105.346
S F D T, 0, 0, 0

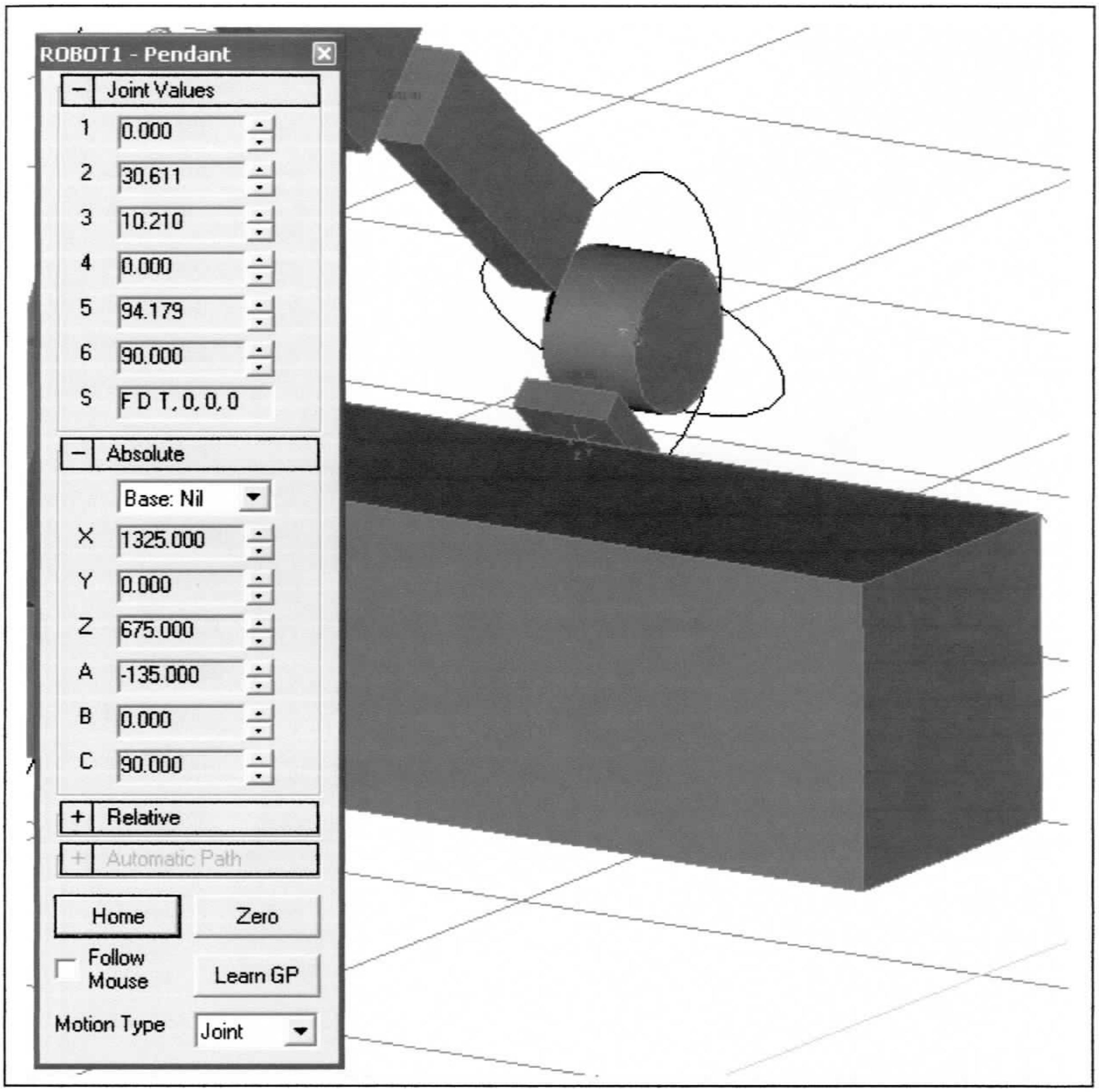
Absolute

Base: Nil
X 1325.000
Y -500.000
Z 675.000
A -135.000
B 0.000
C 90.000

Motion Type Joint

Figure 4.3-2 Running simulation at GP0001

In Figure 4.3-2, the pendant shows that the end-effectors is at position 1325.000 (X), -500.000 (Y), 675.000 (Z), -1325.000° (roll, A), 0.000° (pitch, B), and 90.000° (yaw, C). For the joint value, the robot moves each of its components with -19.482° (Joint 1), 37.216° (Joint 2), 0.591° (Joint 3), 13.701° (Joint 4), 95.349° (Joint 5), and 105.346° (Joint 6).



ROBOT1 - Pendant

Joint Values

1 0.000
2 30.611
3 10.210
4 0.000
5 94.179
6 90.000
S F D T, 0, 0, 0

Absolute

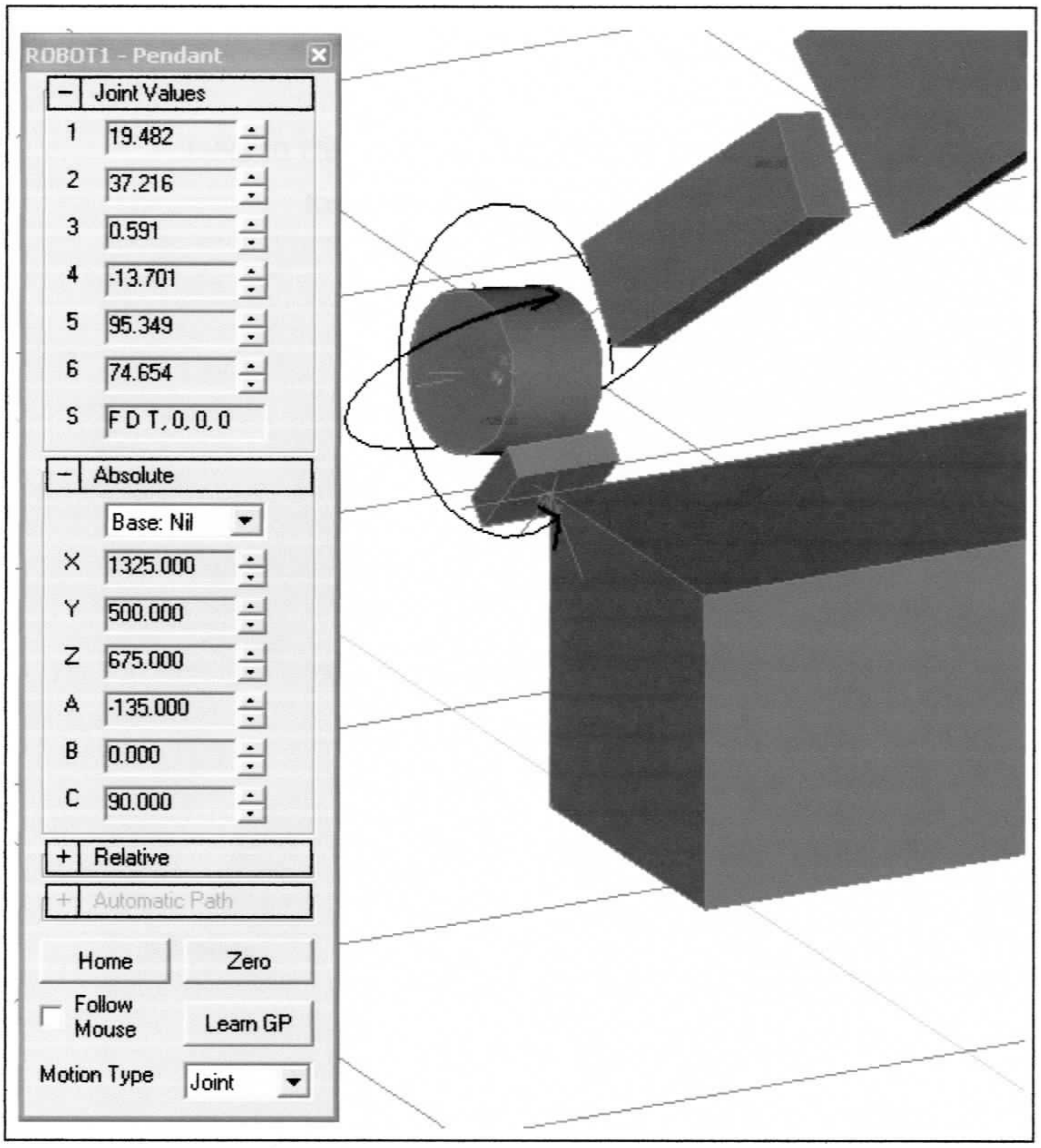
Base: Nil
X 1325.000
Y 0.000
Z 675.000
A -135.000
B 0.000
C 90.000

☐ Follow Mouse

Motion Type: Joint

Figure 4.3-3 Running simulation at GP0002

In Figure 4.3-3, the pendant shows that the end-effectors is at position 1325.000 (X), 0.000 (Y), 675.000 (Z), -1325.000° (roll, A), 0.000° (pitch, B), and 90.000° (yaw, C). For the joint value, the robot moves each of its components with 0.000° (Joint 1), 30.611° (Joint 2), 10.210° (Joint 3), 0.000° (Joint 4), 94.179° (Joint 5), and 90.000° (Joint 6).



1 19.482
2 37.216
3 0.591
4 -13.701
5 95.349
6 74.654
S F D T, 0, 0, 0

Base: Nil
X 1325.000
Y 500.000
Z 675.000
A -135.000
B 0.000
C 90.000

☐ Follow Mouse
Motion Type Joint

Figure 4.3-4 Running simulation at GP0003

In Figure 4.3-3, the pendant shows that the end-effectors is at position 1325.000 (X), 500.000 (Y), 675.000 (Z), -1325.000° (roll, A), 0.000° (pitch, B), and 90.000° (yaw, C). For the joint value, the robot moves each of its components with 19.482° (Joint 1), 37.216° (Joint 2), 0.591° (Joint 3), -13.701° (Joint 4), 95.349° (Joint 5), and 74.654° (Joint 6). The summary of each of the values described above is represented in Table 8 below. Note that GP0000 indicates the early of the simulation's Geometry Point (GP).

Table 10 The Joint Value and Absolute value of PUMA Robot at each Geometry Point (GP)

		GP0000	**GP0001**	**GP0002**	**GP0003**
Joint value	**1**	0.000	-19.482	0.000	19.482
	2	0.000	37.216	30.611	37.216
	3	0.000	0.591	10.210	0.591
	4	0.000	13.701	0.000	-13.701
	5	0.000	95.349	94.179	95.349
	6	0.000	105.346	90.000	74.654
Absolute	**X**	1325.000	1325.000	1325.000	1325.000
	Y	0.000	-500.000	0.000	500.000
	Z	148.000	675.000	675.000	675.000
	A	180.000	-135.000	-135.000	-135.000
	B	-90.000	0.000	0.000	0.000
	C	0.000	90.000	90.000	90.000

4.4 PUMA Robot and KUKA KR 15L6-2

As an approach to study the configuration of the created PUMA Robot, the simulation of the robot is being compared with KUKA Robot KR 15 L6-2. Both of the robots are being put in a same cell, and simulated in same initial time, doing the same task, each robot followed its own path. In Figure 4.4-1 (and also related figure afterward), the KUKA Robot KR 15L6-2 is indicated by the robot with yellow color and created PUMA Robot is indicated with pink color.

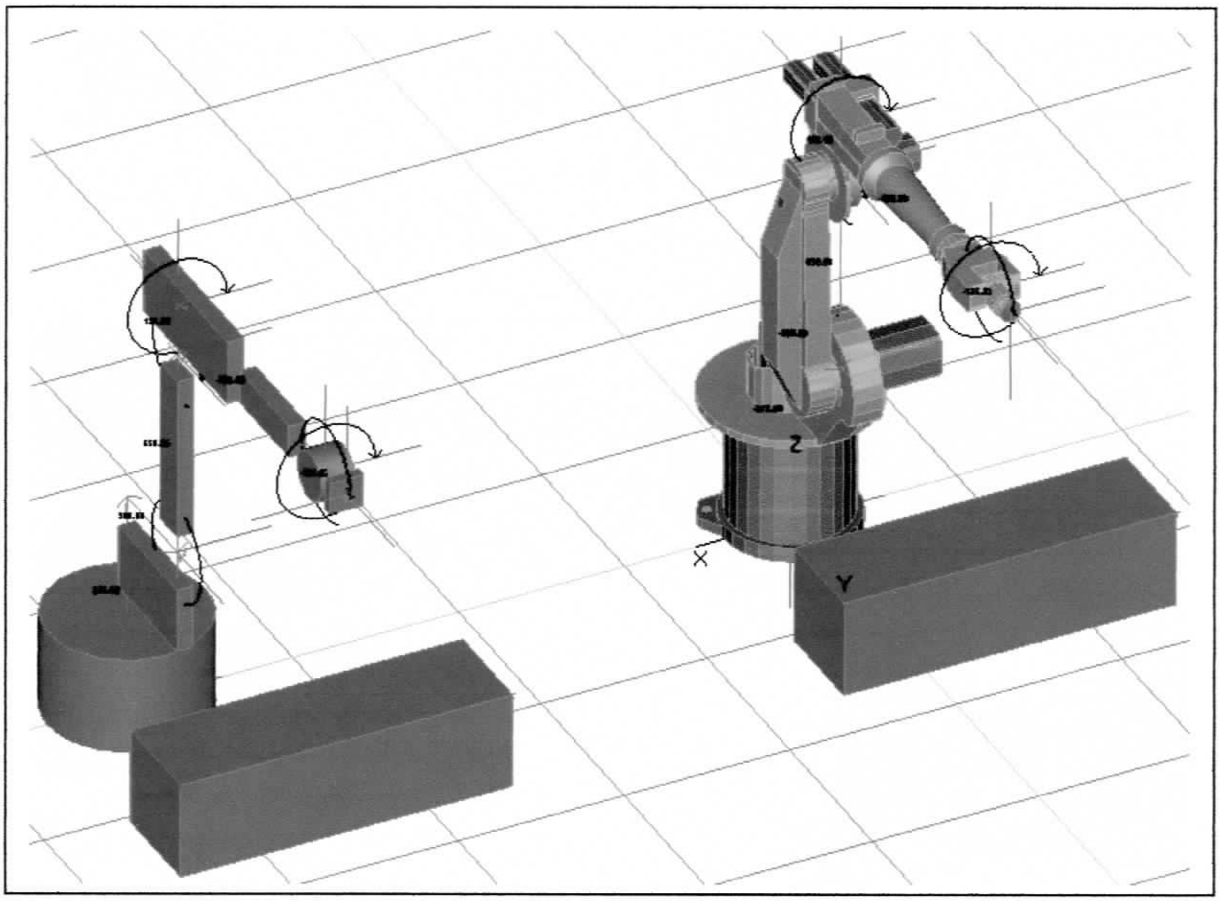


Figure 4.4-1 PUMA Robot and KUKA KR 15L6-2

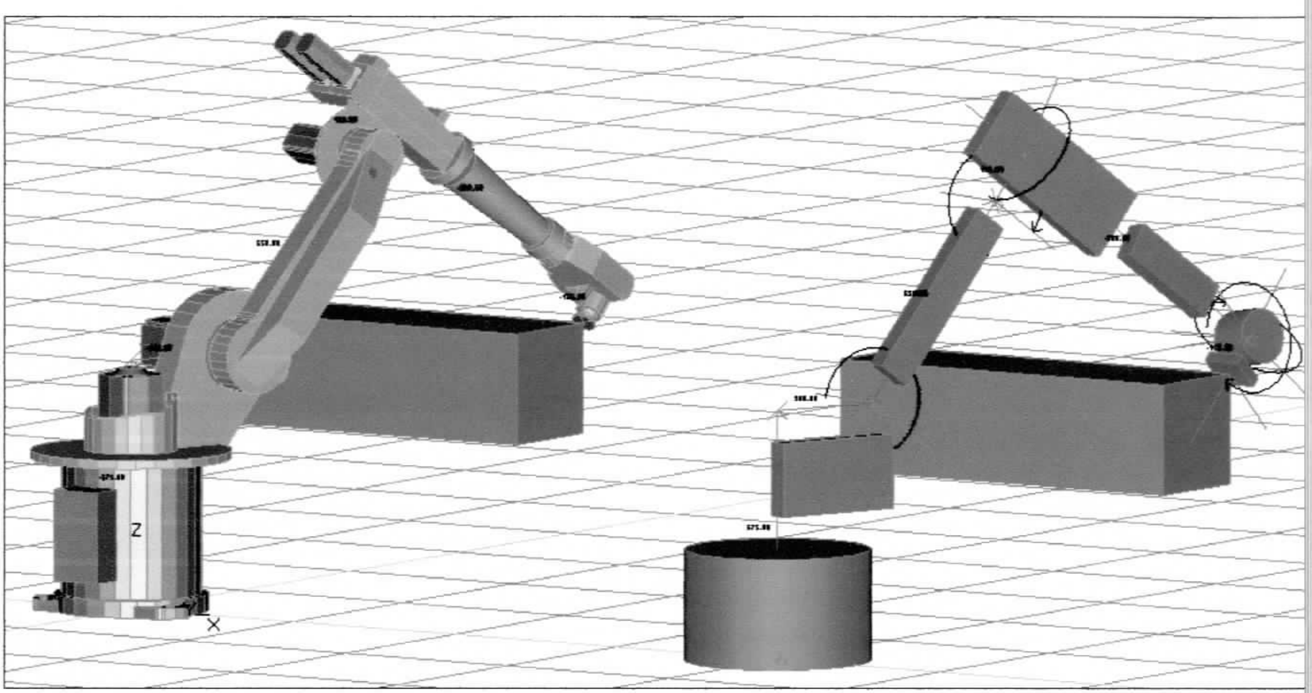


Figure 4.4-2 The simulation process at GP0001

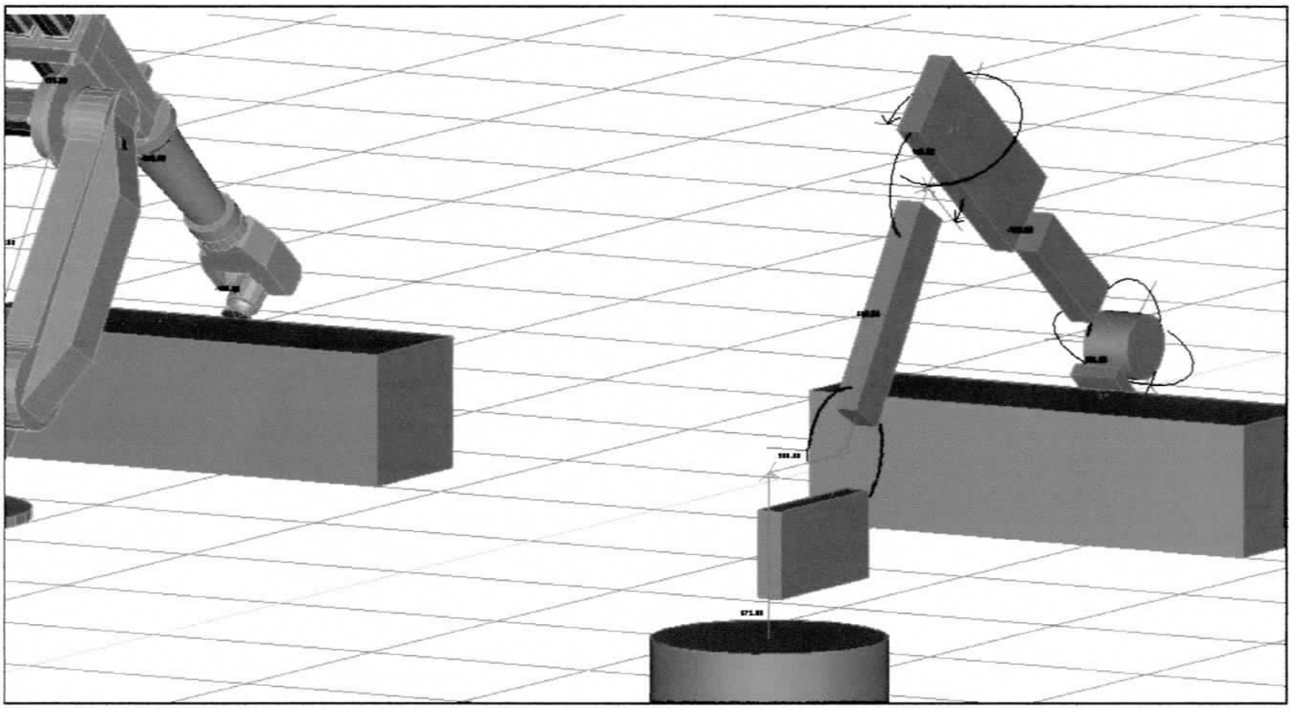


Figure 4.4-3 The simulation process at GP0002

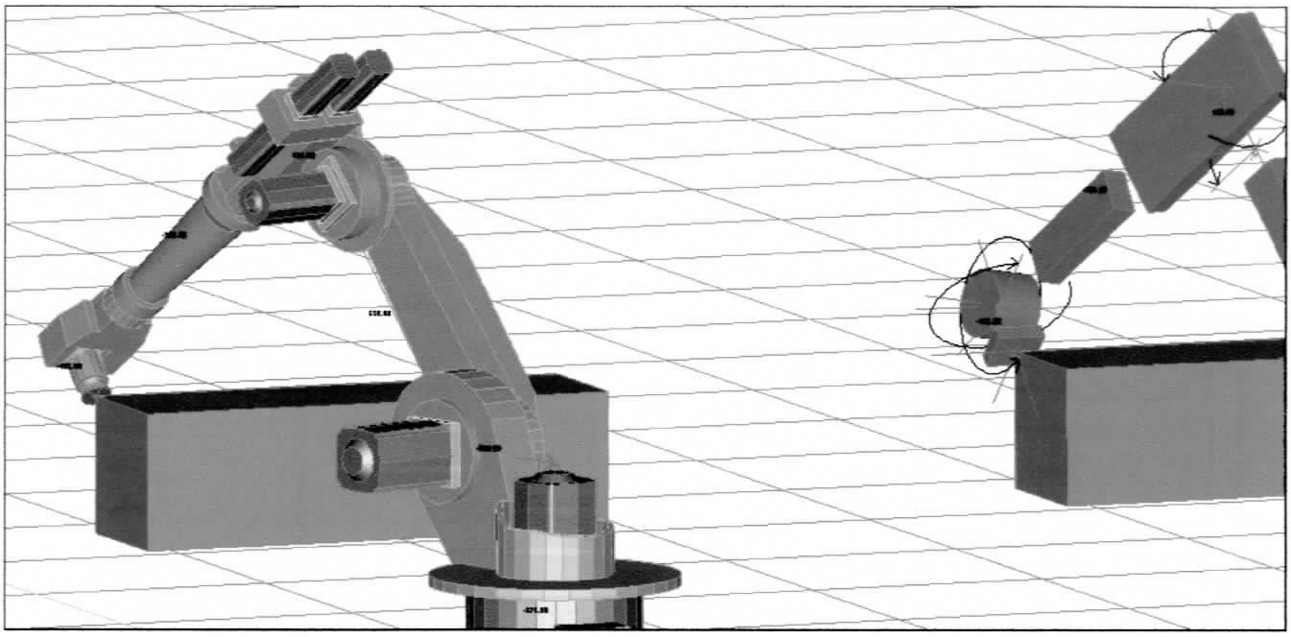
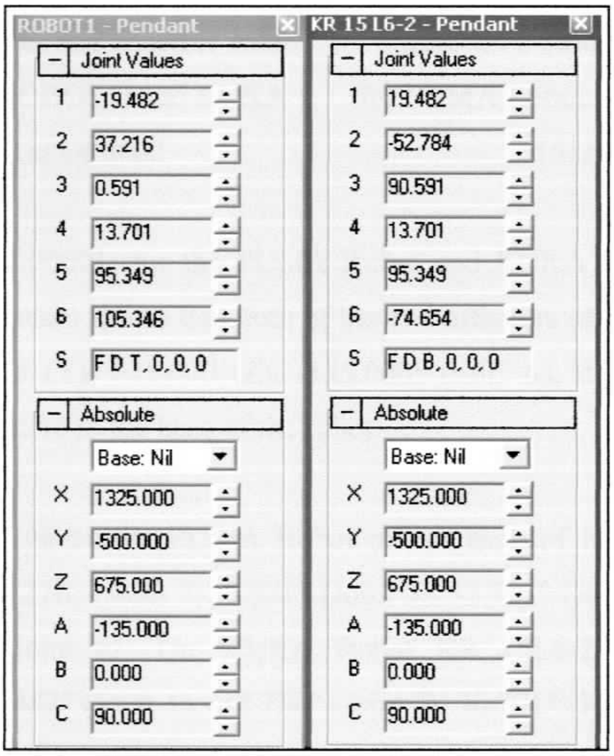


Figure 4.4-4 The simulation process at GP0003



ROBOT1 - Pendant

Joint Values

1	-19.482
2	37.216
3	0.591
4	13.701
5	95.349
6	105.346
S	F D T, 0, 0, 0

Absolute

Base: Nil

X	1325.000
Y	-500.000
Z	675.000
A	-135.000
B	0.000
C	90.000

KR 15 L6-2 - Pendant

Joint Values

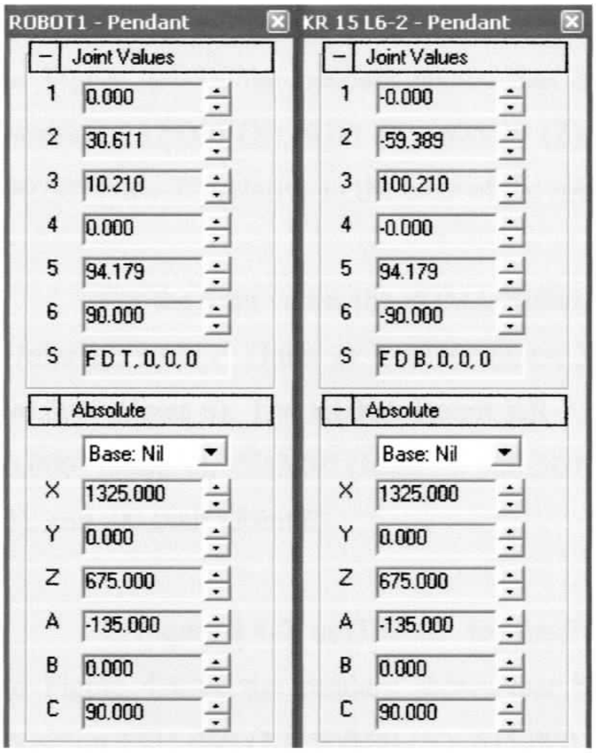
1	19.482
2	-52.784
3	90.591
4	13.701
5	95.349
6	-74.654
S	F D B, 0, 0, 0

Absolute

Base: Nil

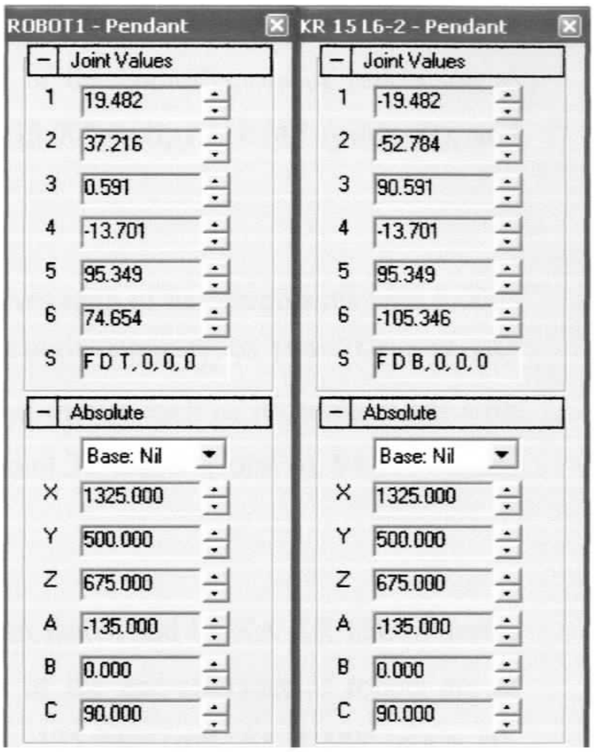
X	1325.000
Y	-500.000
Z	675.000
A	-135.000
B	0.000
C	90.000

Figure 4.4-5 Joint value and absolute value for PUMA Robot (ROBOT1) and KUKA KR 15L6-2 at GP0001



ROBOT1 - Pendant		KR 15 L6-2 - Pendant	
Joint Values		Joint Values	
1	0.000	1	-0.000
2	30.611	2	-59.389
3	10.210	3	100.210
4	0.000	4	-0.000
5	94.179	5	94.179
6	90.000	6	-90.000
S	F D T, 0, 0, 0	S	F D B, 0, 0, 0
Absolute		Absolute	
	Base: Nil		Base: Nil
X	1325.000	X	1325.000
Y	0.000	Y	0.000
Z	675.000	Z	675.000
A	-135.000	A	-135.000
B	0.000	B	0.000
C	90.000	C	90.000

Figure 4.4-6 Joint value and absolute value for PUMA Robot (ROBOT1) and KUKA KR 15L6-2 at GP0002



ROBOT1 - Pendant		KR 15 L6-2 - Pendant	
Joint Values		Joint Values	
1	19.482	1	-19.482
2	37.216	2	-52.784
3	0.591	3	90.591
4	-13.701	4	-13.701
5	95.349	5	95.349
6	74.654	6	-105.346
S	F D T, 0, 0, 0	S	F D B, 0, 0, 0
Absolute		Absolute	
	Base: Nil		Base: Nil
X	1325.000	X	1325.000
Y	500.000	Y	500.000
Z	675.000	Z	675.000
A	-135.000	A	-135.000
B	0.000	B	0.000
C	90.000	C	90.000

Figure 4.4-7 Joint value and absolute value for PUMA Robot (ROBOT1) and KUKA KR 15L6-2 at GP0003

In Figure 4.4-5, at GP0001, for the PUMA Robot and KUKA KR 15L6-2 (refer to Figure 4.4-2), the pendant shows that both of the end-effectors of robots are at position 1325.00 (X), -500.00 (Y), 675.000 (Z), -135.000° (roll, A), 0.000° (pitch, B), and 90.000° (yaw, C) relative to the base of the robot.

For the joint value, the PUMA Robot moves each of its components with -19.482° (Joint 1), 37.216° (Joint 2), 0.591° (Joint 3), 13.701° (Joint 4), 95.349° (Joint 5), and 105.346° (Joint 6). The KUKA Robot KR 15L6-2 moves each of its components with 19.482° (Joint 1), -52.784° (Joint 2), 90.591° (Joint 3), 13.701° (Joint 4), 95.349° (Joint 5), and -74.654° (Joint 6).

In Figure 4.4-6, at GP0002, for the PUMA Robot and KUKA KR 15L6-2 (refer to Figure 4.4-3), the pendant shows that both of the end-effectors of robots are at position 1325.00 (X), 0.00 (Y), 675.00 (Z), -135.00° (roll, A), 0.00° (pitch, B), and 90.00° (yaw, C) relative to the base of the robot.

For the joint value, the PUMA Robot moves each of its components with 0.000° (Joint 1), 30.611° (Joint 2), 10.210° (Joint 3), 0.000° (Joint 4), 94.179° (Joint 5), and 90.000° (Joint 6). The KUKA Robot KR 15L6-2 moves each of its components with 0.000° (Joint 1), -59.389° (Joint 2), 100.210° (Joint 3), 0.000° (Joint 4), 94.179° (Joint 5), and -90.000° (Joint 6).

In Figure 4.4-7, at GP0003, for the PUMA Robot and KUKA KR 15L6-2 (refer to Figure 4.4-4), the pendant shows that both of the end-effectors of robots are at position 1325.000 (X), 500.00 (Y), 675.000 (Z), -135.000° (roll, A), 0.000° (pitch, B), and 90.000° (yaw, C) relative to the base of the robot.

For the joint value, the PUMA Robot moves each of its components with 19.482° (Joint 1), 37.216° (Joint 2), 0.591° (Joint 3), -13.701° (Joint 4), 95.349° (Joint 5), and 74.654° (Joint 6). The KUKA Robot KR 15L6-2 moves each of its components with 19.482° (Joint 1), -52.784° (Joint 2), 90.591° (Joint 3), -13.701° (Joint 4), 95.349° (Joint 5), and -105.346° (Joint 6). The summary of each of the values described above is represented in Table 9 below:

Table 11 The Joint Value and Absolute value of PUMA Robot and KR 15L6-2 at each Geometry Point (GP)

		PUMA Robot			**KUKA Robot KR 15L6-2**		
		GP0001	**GP0002**	**GP0003**	**GP0001**	**GP0002**	**GP0003**
Joint value	**1**	-19.482	0.000	19.482	19.482	0.000	-19.482
	2	37.216	30.611	37.216	-52.784	-59.389	-52.784
	3	0.5911	10.210	0.591	90.591	100.210	90.591
	4	13.701	0.000	-13.701	13.701	0.000	-13.701
	5	95.349	94.179	95.349	-14.654	-90.000	-105.346
	6	105.346	90.000	74.654	-74.654	-90.000	-105.346
Absolute	**X**	1325.000	1325.000	1325.000	1325.000	1325.000	1325.000
	Y	-500.000	0.000	500.000	-500.000	0.000	500.000
	Z	675.000	675.000	675.000	675.000	675.000	675.000
	A	-135.000	-135.000	-135.000	-135.000	-135.000	-135.000
	B	0.000	0.000	0.000	0.000	0.000	0.000
	C	90.000	0.000	90.000	90.000	0.000	90.000

CHAPTER 5

DISCUSSION

Back to the core of the Study and Simulation on PUMA Robot Configuration, all of the efforts of calculations, designs and simulation of the robot are resulted from the aim, objectives and scopes of the project. The aim of the project is to simulate the PUMA Robot by using Workspace Software, in purpose of studying the configuration of the robot itself.

Thus, several objectives has been decided in succeeding this project which are designing, creating, simulating the PUMA Robot by using Workspace and relate the kinematics calculated during the early stage of the project with the configuration of the robot.

The result of the project is consisting of the early design; early arm parameters and kinematics calculation; creating and simulate; and showing the configuration of PUMA Robot, which are presented in the Result chapter.

These results can be discussed in several niches topics. The topics that will be discussed are the kinematics and its relationship with configuration of the created robot; the differences of KUKA KR 15L6-2 and the created PUMA Robot; and the important consideration during creating and simulating robot in Workspace.

5.1 Kinematics and configuration of the PUMA Robot

From the experiences in creating and simulating the PUMA Robot, the study of arm parameters are necessary to defined the axes, joints and dimensions of the robot. Thus, the forward kinematics solution can be determined from the arm parameters.

The calculation of the forward kinematics of the PUMA robot is made, in purpose of tracking back the computation in Workspace Software, on how the end-effectors of the robot will be positioned and orientated in a space relative to its base frame.

Hence, the arm parameters determined by the entered of any values will be calculated or computed by Workspace, by referring to the calculated matrices and forward kinematics solution, to determine the end-effectors of the robot during the robot is executing movements due to each determined Geometry Points (GPs).

To be concluded, the forward kinematics solution calculated manually at the early stage of the project is the same matrix used by the Workspace database internally, in defining the configuration of the created PUMA Robot. Thus, the study of the PUMA Robot configuration can be shown by the forward kinematics matrix obtained.

In this project, the forward kinematics solution of the PUMA Robot, H_0^6, are obtained from the multiply calculation of each joint transformation matrices. Hence, the forward kinematics matrix obtained is as followed matrix:

$$H_0^6 = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{pmatrix}$$

$$\begin{aligned}
a_{11} &= c_1 c_{23} (c_4 c_5 c_6 - s_4 s_6) + s_1 (s_4 c_5 c_6 + c_4 s_6) + c_1 s_{23} (- s_5 c_6) \\
a_{21} &= s_1 c_{23} (c_4 c_5 c_6 - s_4 s_6) - c_1 (s_4 c_5 c_6 + c_4 s_6) + s_1 s_{23} (- s_5 c_6) \\
a_{31} &= s_{23} (c_4 c_5 c_6 - s_4 s_6) + c_{23} (s_5 c_6) \\
a_{41} &= 0
\end{aligned}$$

$$\begin{aligned}
a_{12} &= c_1 c_{23} (c_4 c_5 c_6 - s_4 s_6) + s_1 (s_4 c_5 s_6 + c_4 s_6) + c_1 s_{23} (s_5 s_6) \\
a_{22} &= s_1 c_{23} (s_4 c_5 s_6 + c_4 c_6) - c_1 (s_4 c_5 s_6 + c_4 c_6) - s_5 s_6 (s_1 s_{23}) \\
a_{32} &= s_{23} (c_4 c_5 s_6 - s_4 s_6) + c_{23} (s_5 c_6) \\
a_{42} &= 0
\end{aligned}$$

$$\begin{aligned}
a_{13} &= c_1 c_{23} (c_4 s_5) + s_1 (s_4 s_5) + c_1 s_{23} c_5 \\
a_{23} &= s_1 c_{23} (c_4 s_5) - c_1 (s_4 s_5) + s_1 s_{23} c_5 \\
a_{33} &= s_{23} (c_4 s_5) - c_{23} c_5 \\
a_{43} &= 0
\end{aligned}$$

$$\begin{aligned}
a_{14} &= c_1 c_{23} (c_4 s_5 d_6) + s_1 (s_4 s_5 d_6) + c_1 s_{23} (c_5 d_6 + d_4) + c_1 (a_1 + a_2 c_2 + a_3 c_{23}) \\
a_{24} &= s_1 c_{23} (c_4 s_5 d_6) - c_1 (s_4 s_5 d_6) + s_1 s_{23} (c_5 d_6 + d_4) + s_1 (a_1 + a_2 c_2 + a_3 c_{23}) \\
a_{34} &= s_{23} (c_4 s_5 d_6) + c_{23} (c_5 d_6 + d_4) + a_2 s_2 + a_3 s_{23} + d_1 \\
a_{44} &= 1
\end{aligned}$$

Note that that c_{23} is $cos\ (\theta_2 + \theta_3)$ and s_{23} is $sin\ (\theta_2 + \theta_3)$.

As an analysis, the transformation homogenous matrix obtained from the calculation above is the analogous as followed matrix:

$$\boldsymbol{H_0^n} = \begin{pmatrix} \boldsymbol{n_x} & \boldsymbol{s_x} & \boldsymbol{a_x} & \boldsymbol{p_x} \\ \boldsymbol{n_y} & \boldsymbol{s_y} & \boldsymbol{a_y} & \boldsymbol{p_y} \\ \boldsymbol{n_z} & \boldsymbol{s_z} & \boldsymbol{a_z} & \boldsymbol{p_z} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} \end{pmatrix} = \begin{bmatrix} \boldsymbol{n} & \boldsymbol{s} & \boldsymbol{a} & \boldsymbol{P} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} \end{bmatrix}$$

Therefore,

$$\boldsymbol{H_0}^6 = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{pmatrix} = \begin{pmatrix} \boxed{\begin{matrix} n_x \\ n_y \\ n_z \end{matrix}} & \boxed{\begin{matrix} s_x \\ s_y \\ s_z \end{matrix}} & \boxed{\begin{matrix} a_x \\ a_y \\ a_z \end{matrix}} & \boxed{\begin{matrix} p_x \\ p_y \\ p_z \end{matrix}} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} \end{pmatrix}$$

$$\boldsymbol{n} = \begin{pmatrix} n_x \\ n_y \\ n_z \end{pmatrix}, \boldsymbol{s} = \begin{pmatrix} s_x \\ s_y \\ s_z \end{pmatrix}, \boldsymbol{a} = \begin{pmatrix} a_x \\ a_y \\ a_z \end{pmatrix}, \boldsymbol{P} = \begin{pmatrix} p_x \\ p_y \\ p_z \end{pmatrix}$$

$$\begin{array}{llll} a_{11} = n_x & , a_{12} = s_x & , a_{13} = a_x & , a_{14} = p_x \\ a_{21} = n_y & \ \ a_{22} = s_y & \ \ a_{23} = a_y & \ \ a_{24} = p_y \\ a_{31} = n_z & \ \ a_{32} = s_z & \ \ a_{33} = a_z & \ \ a_{34} = p_z \end{array}$$

The matrices shown above are an analysis to the forward kinematics solution obtained from the calculation, as stated in the result chapter (refer to Chapter 4.1).

In the above expression, ***a*** is called the *approach vector*, which is aligned with the *z*-axis of the tool or flange frame of the PUMA Robot, z_6-axis; ***s*** is called the *sliding vector*, which is aligned with the *y*-axis of the tool or flange frame of the PUMA Robot, y_6-axis; and ***n*** is called the *normal vector*, which is aligned with the *x*-axis of the tool or flange frame of the PUMA Robot, x_6-axis.

In this sense, the first three column vectors, $\boldsymbol{a}_{11}$ $\boldsymbol{a}_{21}$ $\boldsymbol{a}_{31}$, of homogenous transformation matrix, $\boldsymbol{H_0}^6$, express the coordinates of the unit vectors $\boldsymbol{n}_x$ $\boldsymbol{n}_y$ $\boldsymbol{n}_z$, respectively, from the base frame of the robot, x_0 y_0 z_0. ***P*** is the *position vector* of the robot hand, pointing from the origin of the robot base frame to the origin of the robot hand or flange frame (Manseur, 2006).

To be concluded, the vectors *a*, *s*, and *n*, specify the orientation of the robot hand or flange frame, and the vector *P* describes the position of the robot hand or flange frame respect to the base frame of the PUMA Robot (Zhihong, 2005). Figure 5.1 represents the analysis described above.

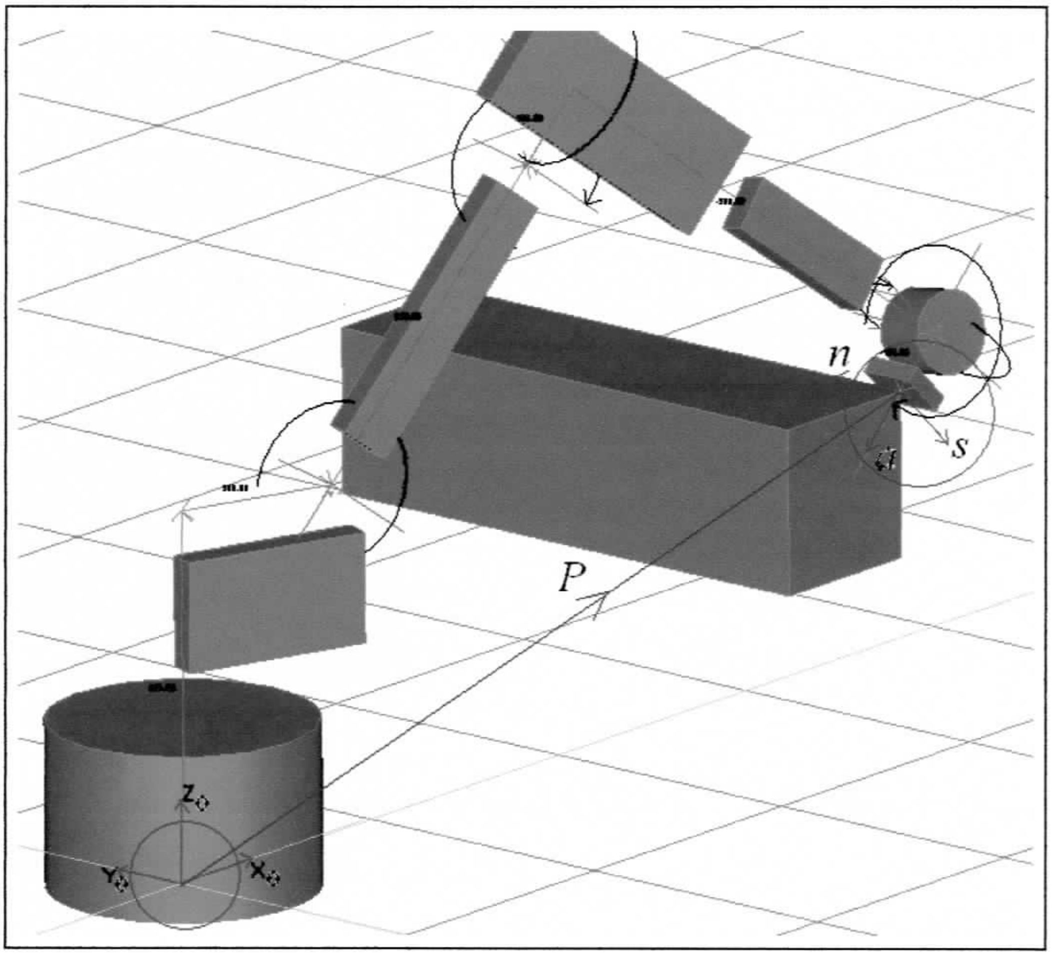
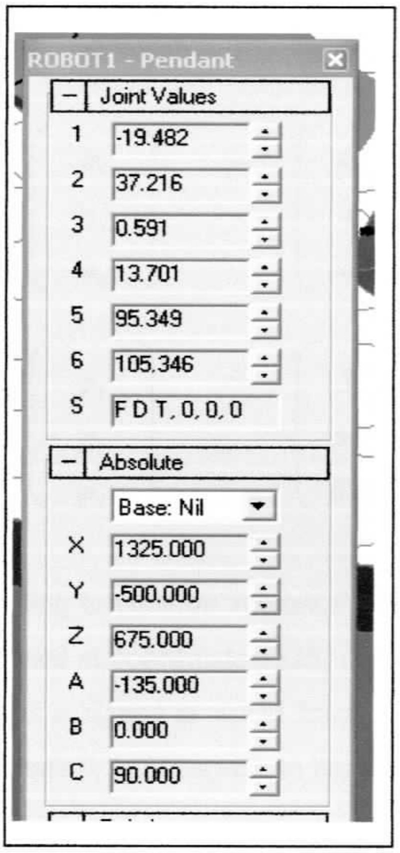


Figure 5.1-1 The approach vector ***a***, the sliding vector ***s***, the normal vector ***n***, and the position vector ***P*** to describe the orientation and position of the tool or flange frame respect in the PUMA Robot base frame.

As an example, from result Chapter 4.3 and Figure 4.3-2, after the PUMA Robot is moved to GP0001, each Joint Value is -19.482 (θ_1), 37.216 (θ_2), 0.591 (θ_3), 13.701 (θ_4), 95.349 (θ_5), and 105.346 (θ_6), as shown in Figure5.2 below. Each Joint Values, θ_1 - θ_6, is entered into the calculation of H_0^6. The calculation can be computed manually or by using Matlab software. The computation program of Matlab and the calculation result can be observed in Appendix, E1.



1 -19.482
2 37.216
3 0.591
4 13.701
5 95.349
6 105.346
S FDT,0,0,0

Base: Nil
X 1325.000
Y -500.000
Z 675.000
A -135.000
B 0.000
C 90.000

Figure 5.1-2
The robot pendant that shows Joint Values and Absolute Values of PUMA Robot when moved to GP0001

After calculate the homogenous transformation matrix, H_0^6, the forward kinematics solution obtained as followed;

$$H_0^6 = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{pmatrix} = \begin{pmatrix} 0 & 0.7 & -0.7 & 1325 \\ 1.0 & 0.0 & 0.0 & -500 \\ 0 & -0.7 & -0.7 & 675 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Therefore,

$$\boldsymbol{n} = \begin{pmatrix} \boldsymbol{n}_x \\ \boldsymbol{n}_y \\ \boldsymbol{n}_z \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$$

$$\boldsymbol{s} = \begin{pmatrix} \boldsymbol{s}_x \\ \boldsymbol{s}_y \\ \boldsymbol{s}_z \end{pmatrix} = \begin{pmatrix} 0.7 \\ 0 \\ -0.7 \end{pmatrix}$$

$$\boldsymbol{a} = \begin{pmatrix} \boldsymbol{a}_x \\ \boldsymbol{a}_y \\ \boldsymbol{a}_z \end{pmatrix} = \begin{pmatrix} -0.7 \\ 0 \\ -0.7 \end{pmatrix}$$

$$\boldsymbol{P} = \begin{pmatrix} \boldsymbol{p}_x \\ \boldsymbol{p}_y \\ \boldsymbol{p}_z \end{pmatrix} = \begin{pmatrix} 1325 \\ -500 \\ 675 \end{pmatrix}$$

According to position vectors P above, the tool or flange frame of the PUMA Robot is positioned at coordinate 1325, -500, and 675, respects to its base frame (note that base frame is assigned at world frame). For normal vector n, the x_6-axis will be pointed to coordinate 0, 1, 0 respects to base frame, which means it is rotated 90° about x_0-axis.

For sliding vector s, the y_6-axis will be pointed to coordinate 0.7, 0, -0.7 respects to base frame, which means it is rotated -135° about z_0-axis. For approach vector a, the z_6-axis will be pointed to coordinate -0.7, 0, -0.7 respects to base frame, which means it is rotated -135° about z_0-axis. This tool frame orientation and coordination is shown in Figure 5.1-3 below.

By referring back to the result in Chapter 4.3, the values of position and orientation of tool frame of PUMA Robot when move to GP0001 is the same result as values obtained from the calculated forward kinematics matrix.

As shown in Figure 5.1-2, in Absolute Value section, the X, Y, and Z presents the position of the tool or flange frame x_6, y_6, z_6, respects to its base frame. The value A, B, and C presents the transformation angles of tool frame x_6, y_6, z_6 after GP0001 movement, respects to its base frame. These means that X, Y, Z, A, B, and C are p_x, p_y, p_z, yaw, pitch, roll of the tool frame, respectively.

As resulted from running the robot manipulator movement to GP0001, as seen in the pendant, the values of tool frame position are 1325 (X), -500 (Y), and 675 (Z); and values of its orientation are A = -135°, B = 0°, and C = 90°, all respects to PUMA Robot base frame.

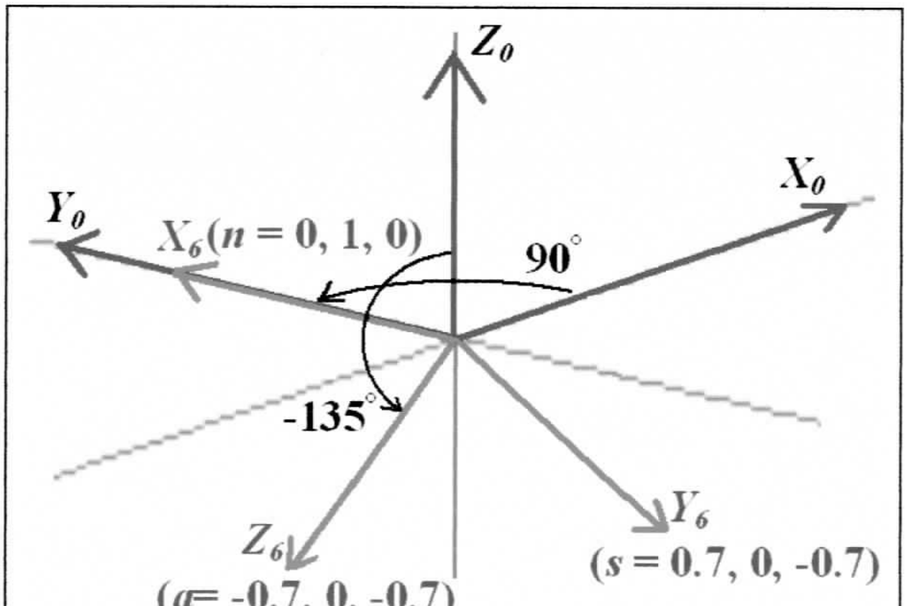


Figure 5.1-3 Tool frame orientation and coordination of PUMA Robot respects to its base frame at GP0001

5.2 PUMA Robot VS KUKA Robot KR 15L6-2

In this project, in purpose of creating and studying the configuration a PUMA Robot, a model of existed PUMA type robot is being selected as a carbon copy or reference material. Therefore, an existed in real industrial field, PUMA type Robot named by KUKA Robot KR 15 L6-2 is selected. As stated in Chapter 3.2 and 4.4, there are no particular reason why the KR 15 L6-2 is selected as a reference robot, as it being selected randomly.

By comparing between of the robots - one is just being created and another has been exist in robotics field, the PUMA Robot does not different much from KR 15 L6-2 besides as stated in each section below.

5.2.1 Assigned Frame

The assigned of the robot base frame, which the *z*-axis of PUMA Robot base frame is pointing upward and the KR 15 L6-2 is pointing downward.

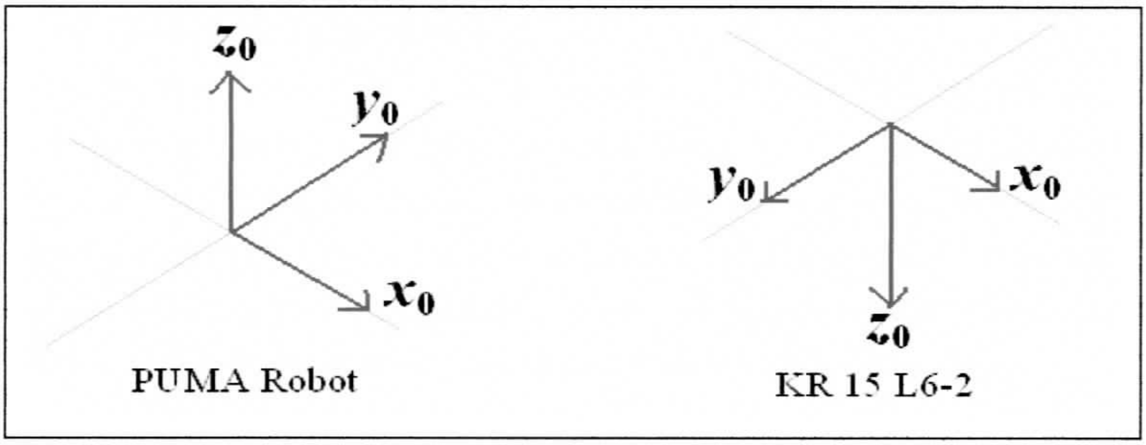


Figure 5.2-1 Differences of assigned base frame between PUMA Robot and KUKA KR 15 L6-2

5.2.2 Arm Parameters

In specifying the robot kinematics, the Denavit-Hartenberg Parameters (Arm Parameters) of both robots are a little bit different of sign of values at the joint distance, d_i; and link length, a_i. This is occurring because of the orientation of the assigned base frame of each of the robot. The arm parameters values differences of both robots can be observed in Table 12 below:

Table 12 Differences of arm parameters values of each robot

Joint	**PUMA Robot**				**KR 15 L6-2**			
	θ_i	d_i	a_i	α_i	θ_i	d_i	a_i	α_i
1	θ_1	675	300	-90°	θ_1	-675	-300	-90°
2	θ_2	0	650	0	θ_2	0	650	0
3	θ_3	0	155	90°	θ_3	0	155	90°
4	θ_4	-900	0	-90°	θ_4	-900	0	-90°
5	θ_5	0	0	90°	θ_5	0	0	90°
6	θ_6	-125	0	-180°	θ_6	-125	0	-180°

5.2.3 Features of PUMA Robot

Externally, the robots are different at the features aspect. The PUMA Robot created in the project may not look like a robot, because it features the basic structure and line of the robot, where as the KR 15 L6-2 represent in full feature of its design. The reason why the created PUMA Robot just features the basic line is to show that the orientation and position of the robot is more easily to observe because it is consists of components that is squared in shape, as all of the movement of the robot joints are revolute.

5.2.4 Joint Configuration Differences

In the configuration aspect, the PUMA Robot and KUKA KR 15 L6-2 are set to do the same movements at the same period of time. Even though, both of the tool frames are showing the same position and orientation relative to each base frames, there are slight differences in the configuration of the robot components, which are the joint value at each joint of the robots. After an analysis has been made referring to Table 9 in Chapter 4.4, the Table 10 below is presented.

The joint value differences between both of the robots occur because of the value differences in each Arm Parameters, and during assigning joint frames in accessing Workspace; the orientation of each joint frame of PUMA Robot might be different from the KR 15 L6-2.

For example, when both of the robots tool frames are moved to GP0001, the joint values for PUMA Robot are -19.482 (θ_1), 37.216 (θ_2), 0.591 (θ_3), 13.701 (θ_4), 95.349 (θ_5), and 105.346 (θ_6); and for KUKA KR 15 L6-2 are 19.482 (θ_1), -52.784 (θ_2), 90.591 (θ_3), 13.701 (θ_4), -14.654 (θ_5), and -74.654 (θ_6).

At joint 1 (frame 0), the assigned frame of KR 15 L6-2 Robot Base is different by 180° opposite from the PUMA Robot. At joint 2, 3, 5, and 6, the assigned frame of each link of KR 15 L6-2 are different from PUMA Robot by 90°, 90°, 110°, and 180°, respectively. Both robots have the same orientation of assigned frame at Joint 4.

This means that even though both robots achieve the same position and orientation of tool frames, there are several possibilities of the joints to rotate and move. In this case, to analyze each joint configuration, the Inverse Kinematics of the robot, which is consists of inverse position and inverse orientation, must be developed. However, this project is just focusing on forward kinematics solution in studying the configuration of the robots.

Table 12 Differences at each Geometry Point (GP) of PUMA Robot and KR 15L6-2 at each Geometry Point (GP)

		GP0001		GP0002		GP0003	
		PUMA Robot	**KUKA KR15L6-2**	**PUMA Robot**	**KUKA KR15L6-2**	**PUMA Robot**	**KUKA KR15L6-2**
Joint value	**1**	-19.482	19.482	0.000	0.000	19.482	-19.482
	2	37.216	-52.784	30.611	-59.389	37.216	-52.784
	3	0.5911	90.591	10.210	100.210	0.591	90.591
	4	13.701	13.701	0.000	0.000	-13.701	-13.701
	5	95.349	-14.654	94.179	-90.000	95.349	-105.346
	6	105.346	-74.654	90.000	-90.000	74.654	-105.346
Absolute	**X**	1325.000	1325.000	1325.000	1325.000	1325.000	1325.000
	Y	-500.000	-500.000	0.000	0.000	500.000	500.000
	Z	675.000	675.000	675.000	675.000	675.000	675.000
	A	-135.000	-135.000	-135.000	-135.000	-135.000	-135.000
	B	0.000	0.000	0.000	0.000	0.000	0.000
	C	90.000	90.000	0.000	0.000	90.000	90.000

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

In overall, this project entitled "Study and Simulation on PUMA Robot Configuration with Workspace" has achieved its aim, which is to simulate PUMA Robot by using Workspace Software, and thus study its configuration. The objectives of the project have also been accomplished within its scopes during the period of implementing the project.

The PUMA Robot has been designed, created, and simulated by using Workspace software; the calculation of forward kinematics solution by using Denavit-Hartenberg algorithm; and relationship between the kinematics and robot configuration have been presented in this thesis. In addition, the literature review about the history and others information of PUMA type robot has also been presented in this thesis.

As a conclusion, the robot configuration can be studied through the methods and approaches presented in this thesis. The assigned frames of the robot are the basic prerequisite in getting the Arm Parameters of the PUMA Robot, which will be applied in creating and simulating the PUMA Robot by using Workspace Software. The Arm Parameters are also necessary in calculating the Forward Kinematics Solution, which will be applied during analyzing and studying the configuration of the PUMA Robot.

Even though this project has been achieving its aims and accomplishing its scopes and objectives, there are recommendation for other researchers in studying the configuration of PUMA Robot and the usage of the Workspace Software.

The study of robot configuration can be enhanced by studying the PUMA Robot inverse kinematics solution to define the possible values of the joint variables at each joint of the robot. The forward and inverse kinematics solution can be related with the configuration movement of the PUMA Robot, from the possible joint values and the position and orientation of the end-effectors of the robot relative to its robot base.

Furthermore, in accessing the Workspace Software, the user must be early-prepared e.g. sketching first a design of a robot or mechanism and define its parameters and appropriate mathematical requirement before implementing building a robot project. This is because the software has design limitations on the form of robot structure (Brown 2003), which the workspace has to fit a mathematical model to the particular structure.

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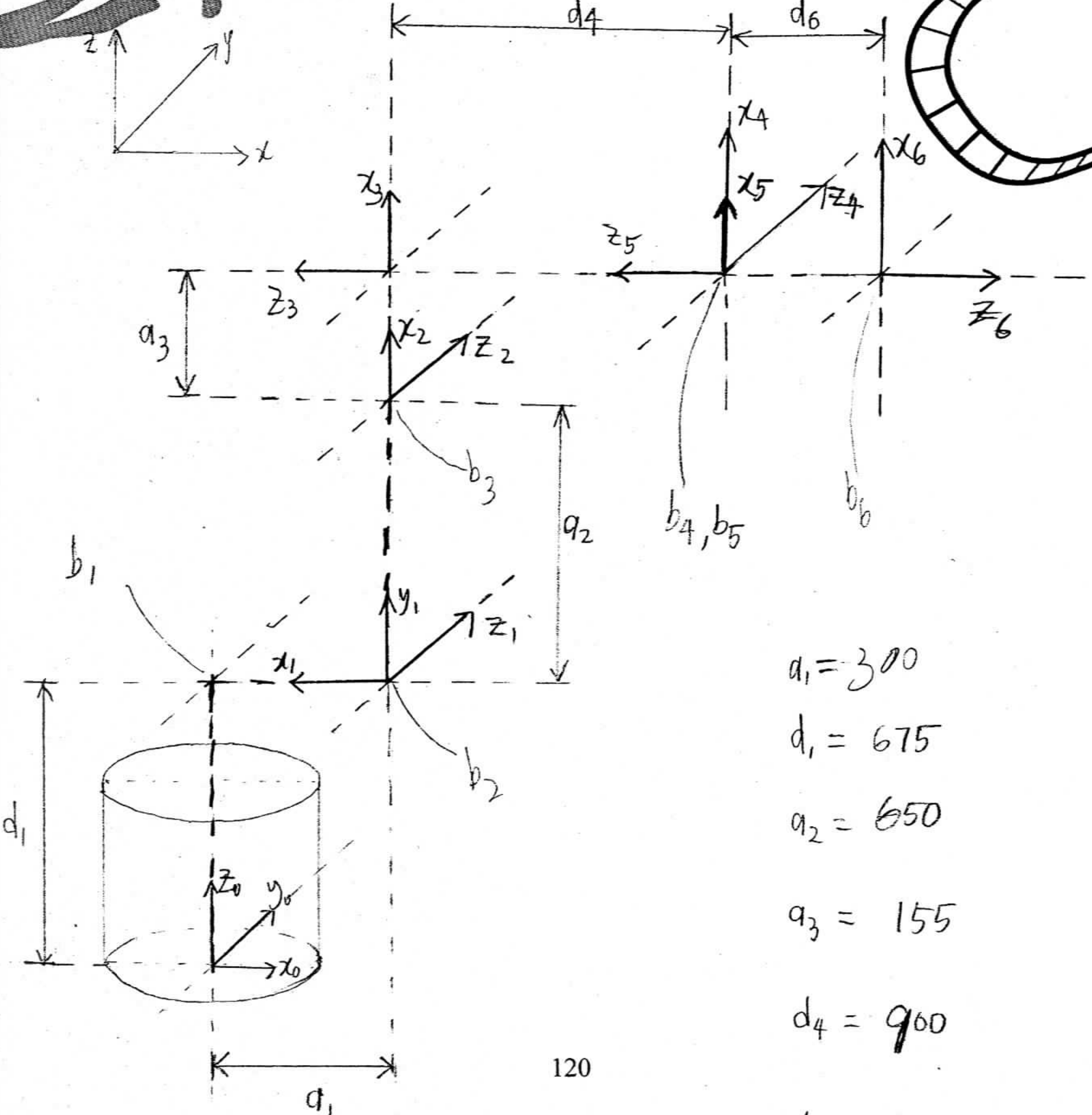
APPENDICES

APPENDICES

A1

PUMA Robot D-H Assigned Frame

PUMA robot 1



a1 = 300

d1 = 675

a2 = 650

a3 = 155

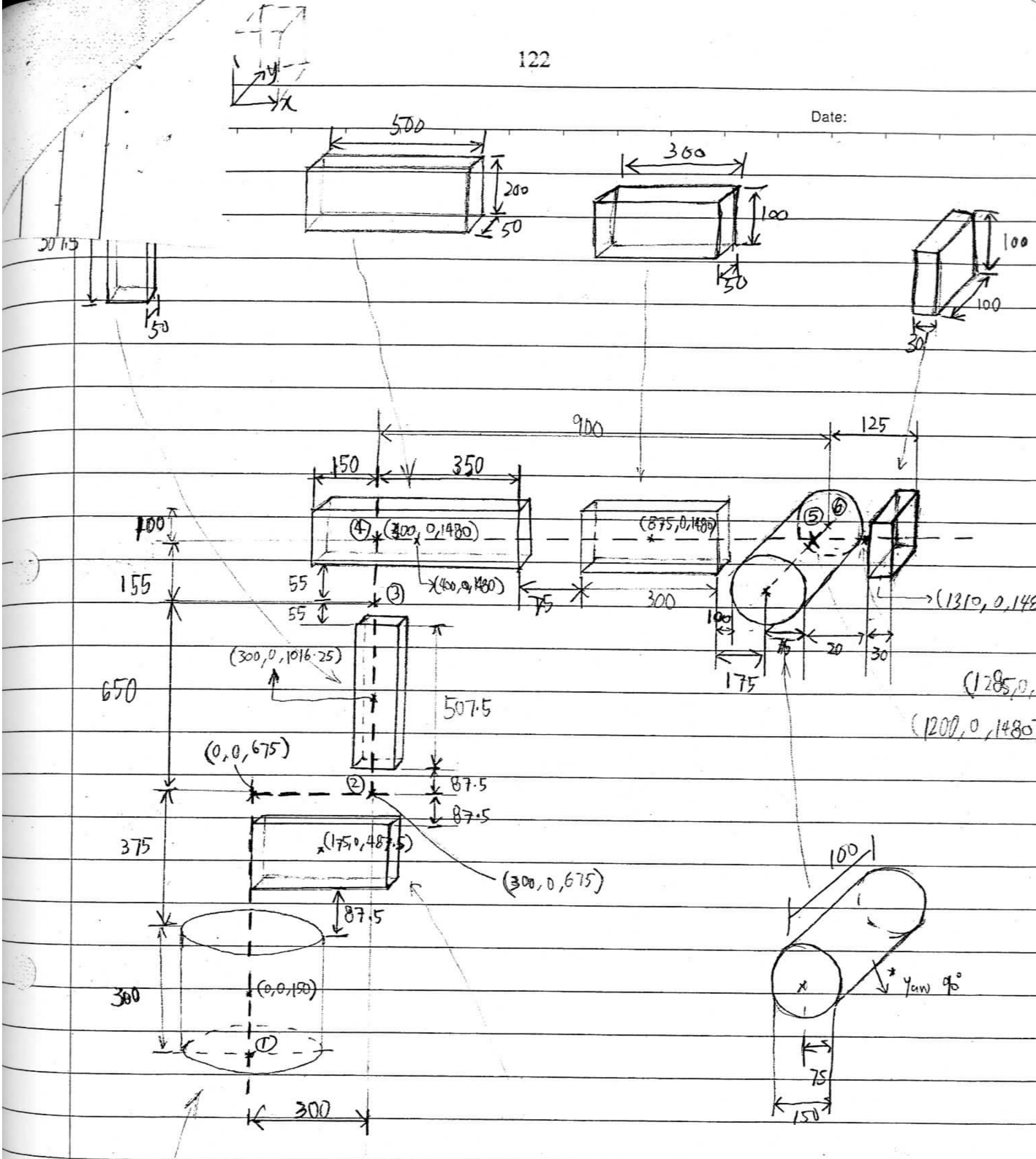
d4 = 900

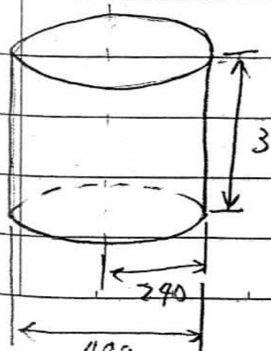
d6 = 125

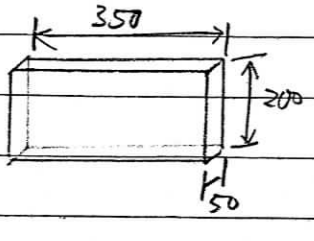
APPENDICES

A2

PUMA Robot Component Structure







world ⓪ 0,0,0

① 0,0,0

② 300,0,675.

③ 300,0,1325

④ 300,0,1480

⑤ 1200,0,1480

⑥ 1200,0,1480.

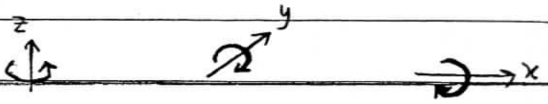
flange ⑦ 1325,0,1480

APPENDICES

A3

PUMA Robot Data

PUMA robot



	position					
Joint	x	y	z	roll	pitch	Yaw
1	0	0	0	0	0	0
2	300	0	675	180	0	90
3	300	0	1325	0	-90	-90
4	300	0	1480	0	-90	0
5	1200	0	1480	0	-90	-90
6	1200	0	1480	0	-90	0
world	0	0	0	0	0	0
flange	1325	0	1480	0	90	0

D-H parameters:

Joint	θ_i	d_i	a_i	α_i
1	θ_1	d_1	a_1	-90
2	θ_2	0	a_2	0
3	θ_3	0	a_3	90
4	θ_4	d_4	0	-90
5	θ_5	0	0	90
6	θ_6	d_6	0	-180

$a_1 = 300$, $d_1 = 675$
$a_2 = 650$, $d_2 = 0$
$a_3 = 155$, $d_3 = 0$
$a_4 = 0$, $d_4 = -900$
$a_5 = 0$, $d_5 = 0$
$a_6 = 0$, $d_6 = -125$

Subject :

Date:

	Position				Dimension				
	X	Y	Z		Cylinder Height	Cylinder Radius	Box Lenght	Box Depth	Box Height
Robot Base	0	0	150		300	240	–	–	–
Link 1	175	0	487.5		–	–	350	50	200
Link 2	300	0	1016.25		–	–	100	50	507.5
Link 3	400	0	1480		–	–	500	50	200
Link 4	875	0	1480		–	–	300	50	100
Link 5	1200	0	1480		100	75	~~0~~	~~0~~	~~0~~
Link 6	1310	0	1480		–	–	30	100	100

Link 5:

roll = 0.00

pitch = - 90.00

Yaw = - 90.00

APPENDICES

A4

PUMA Robot Forward Kinematics Calculation

	θ_i	a_i	d_i	α_i
1	θ_1	a_1	d_1	90°
2	θ_2	a_2	0	0
3	θ_3	a_3	0	90°
4	θ_4	0	d_4	-90°
5	θ_5	0	0	90°
6	θ_6	0	d_6	180°

$$H_0^1 = \begin{bmatrix} C\theta_1 & -C(90)S\theta_1 & S(90)S\theta_1 & a_1C\theta_1 \\ S\theta_1 & C(90)C\theta_1 & -S(90)C\theta_1 & a_1S\theta_1 \\ 0 & S(90) & C(90) & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} C_1 & 0 & S_1 & a_1C_1 \\ S_1 & 0 & -C_1 & a_1S_1 \\ 0 & 1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$H_1^2 = \begin{bmatrix} C\theta_2 & -C(0)S\theta_2 & S(0)S\theta_2 & a_2C\theta_2 \\ S\theta_2 & C(0)C\theta_2 & -S(0)C\theta_2 & a_2S\theta_2 \\ 0 & S(0) & C(0) & (0) \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} C_2 & -S_2 & 0 & a_2C_2 \\ S_2 & C_2 & 0 & a_2S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$H_2^3 = \begin{bmatrix} C\theta_3 & -C(90)S\theta_3 & S(90)S\theta_3 & a_3C\theta_3 \\ S\theta_3 & C(90)C\theta_3 & -S(90)C\theta_3 & a_3S\theta_3 \\ 0 & S(90) & C(90) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} C_3 & 0 & S_3 & a_3C_3 \\ S_3 & 0 & -C_3 & a_3S_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$H_3^4 = \begin{bmatrix} C\theta_4 & -C(-90)S\theta_4 & S(-90)S\theta_4 & (0)C\theta_4 \\ S\theta_4 & C(-90)C\theta_4 & -S(-90)C\theta_4 & (0)S\theta_4 \\ 0 & S(-90) & C(-90) & d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} C_4 & 0 & -S_4 & 0 \\ S_4 & 0 & C_4 & 0 \\ 0 & -1 & 0 & d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$H_4^5 = \begin{bmatrix} C\theta_5 & -C(90)S\theta_5 & S(90)S\theta_5 & (0)C\theta_5 \\ S\theta_5 & C(90)C\theta_5 & -S(90)C\theta_5 & (0)S\theta_5 \\ 0 & S(90) & C(90) & (0) \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} C_5 & 0 & S_5 & 0 \\ S_5 & 0 & -C_5 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$H_5^6 = \begin{bmatrix} C\theta_6 & -C(0)S\theta_6 & S(0)S\theta_6 & (0)C\theta_6 \\ S\theta_6 & C(0)C\theta_6 & -S(0)C\theta_6 & (0)S\theta_6 \\ 0 & S(0) & C(0) & d_6 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} C_6 & S_6 & 0 & 0 \\ S_6 & C_6 & 0 & 0 \\ 0 & 0 & 1 & d_6 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Forward Kinematics.

$$H_0^6 = H_0^1 \cdot H_1^2 \cdot H_2^3 \cdot H_3^4 \cdot H_4^5 \cdot H_5^6$$

$\cos\theta_2 \sin\theta_3$

$\cos(\theta_2 \pm \theta_3) = \cos\theta_2 \cos\theta_3 \mp \sin\theta_2 \sin\theta_3$ $\qquad C_{23} = \cos(\theta_2+\theta_3) = \cos\theta_2 \cos\theta_3 - \sin\theta_2 \sin\theta_3$.

Subject : Date:

$$H_0^{\,3} = \begin{bmatrix} C_1(C_2C_3 - S_2S_3) & S_1 & C_1(C_2S_3 + S_2C_3) & a_3C_1(C_2C_3 - S_2S_3) + C_1(a_1 + a_2C_2) \\ S_1(C_2C_3 - S_2S_3) & -C_1 & S_1(C_2S_3 + S_2C_3) & a_3S_1(C_2C_3 - S_2S_3) + S_1(a_1 + a_2C_2) \\ S_2C_3 + C_2S_3 & 0 & (S_2S_3 - C_2C_3) & a_3(S_2C_3 + C_2S_3) + a_2S_2 + d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} C_1C_{23} & S_1 & C_1S_{23} & C_1(a_1 + a_2C_2 + a_3C_{23}) \\ S_1C_{23} & -C_1 & S_1S_{23} & S_1(a_1 + a_2C_2 + a_3C_{23}) \\ S_{23} & 0 & -C_{23} & a_2S_2 + a_3S_{23} + d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$H_3^{\,6} = \begin{bmatrix} C_4C_5C_6 - S_4S_6 & C_4C_5S_6 - S_4S_6 & C_4S_5 & C_4S_5d_6 \\ S_4C_5C_6 + C_4S_6 & S_4C_5S_6 + C_4C_6 & S_4S_5 & S_4S_5d_6 \\ -S_5C_6 & -S_5S_6 & C_5 & C_5d_6 + d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$H_0^{\,6} = H_0^{\,3} \cdot H_3^{\,6}$$

$$= \begin{bmatrix} C_1C_{23} & S_1 & C_1S_{23} & C_1(a_1 + a_2C_2 + a_3C_{23}) \\ S_1C_{23} & -C_1 & S_1S_{23} & S_1(a_1 + a_2C_2 + a_3C_{23}) \\ S_{23} & 0 & -C_{23} & a_2S_2 + a_3S_{23} + d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_4C_5C_6 - S_4S_6 & C_4C_5S_6 - S_4S_6 & C_4S_5 & C_4S_5d_6 \\ S_4C_5C_6 + C_4S_6 & S_4C_5S_6 + C_4C_6 & S_4S_5 & S_4S_5d_6 \\ -S_5C_6 & -S_5S_6 & C_5 & C_5d_6 + d \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$H_0^{\,6} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix}$$

$a_{11} = c_1 c_{23}(c_4 c_5 c_6 - s_4 s_6) + s_1(s_4 c_5 c_6 + c_4 s_6) + c_1 s_{23}(-s_5 c_6)$

$a_{21} = s_1 c_{23}(c_4 c_5 c_6 - s_4 s_6) - c_1(s_4 c_5 c_6 + c_4 s_6) + s_1 s_{23}(-s_5 c_6)$

$a_{31} = s_{23}(c_4 c_5 c_6 - s_4 s_6) + c_{23}(s_5 c_6)$

$a_{41} = 0$

$a_{12} = c_1 c_{23}(c_4 c_5 s_6 - s_4 s_6) + s_1(s_4 c_5 s_6 + c_4 c_6) - c_1 s_{23}(s_5 s_6)$

$a_{22} = s_1 c_{23}(s_4 c_5 s_6 + c_4 c_6) - c_1(s_4 c_5 s_6 + c_4 c_6) - s_5 s_6(s_1 s_{23})$

$a_{32} = s_{23}(c_4 c_5 s_6 - s_4 s_6) + c_{23}(s_5 s_6)$

$a_{42} = 0$

$a_{13} = c_1 c_{23}(c_4 s_5) + s_1(s_4 s_5) + c_1 s_{23} c_5$

$a_{23} = s_1 c_{23}(c_4 s_5) - c_1(s_4 s_5) + s_1 s_{23} c_5$

$a_{33} = s_{23}(c_4 s_5) - c_{23} c_5$

$a_{43} = 0$

$a_{14} = c_1 c_{23}(c_4 s_5 d_6) + s_1(s_4 s_5 d_6) + c_1 s_{23}(c_5 d_6 + d_4) + c_1(a_1 + a_2 c_2 + a_3 c_{23})$

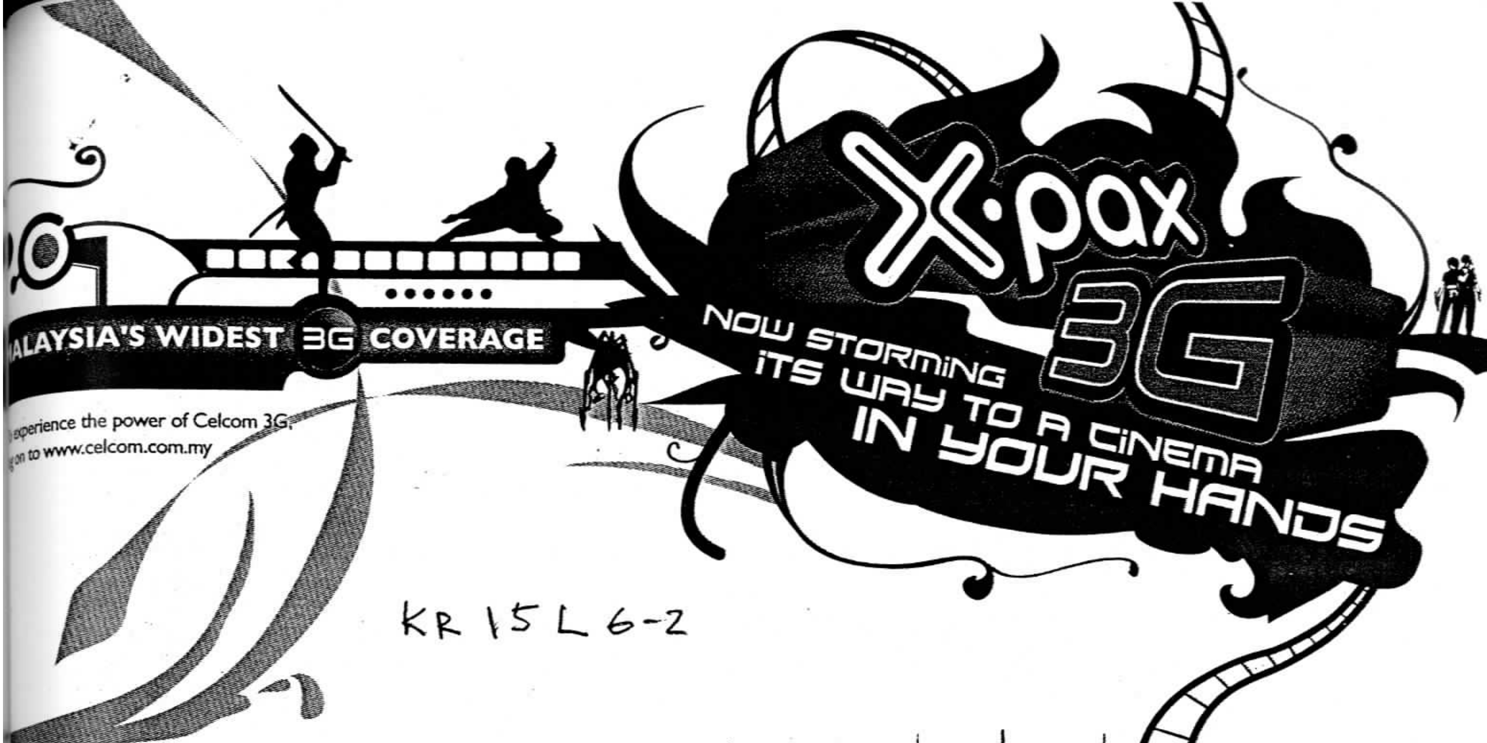
$a_{24} = s_1 c_{23}(c_4 s_5 d_6) - c_1(s_4 s_5 d_6) + s_1 s_{23}(c_5 d_6 + d_4) + s_1(a_1 + a_2 c_2 + a_3 c_{23})$

$a_{34} = s_{23}(c_4 s_5 d_6) - c_{23}(c_5 d_6 + d_4) + a_2 s_2 + a_3 s_{23} + d_1$

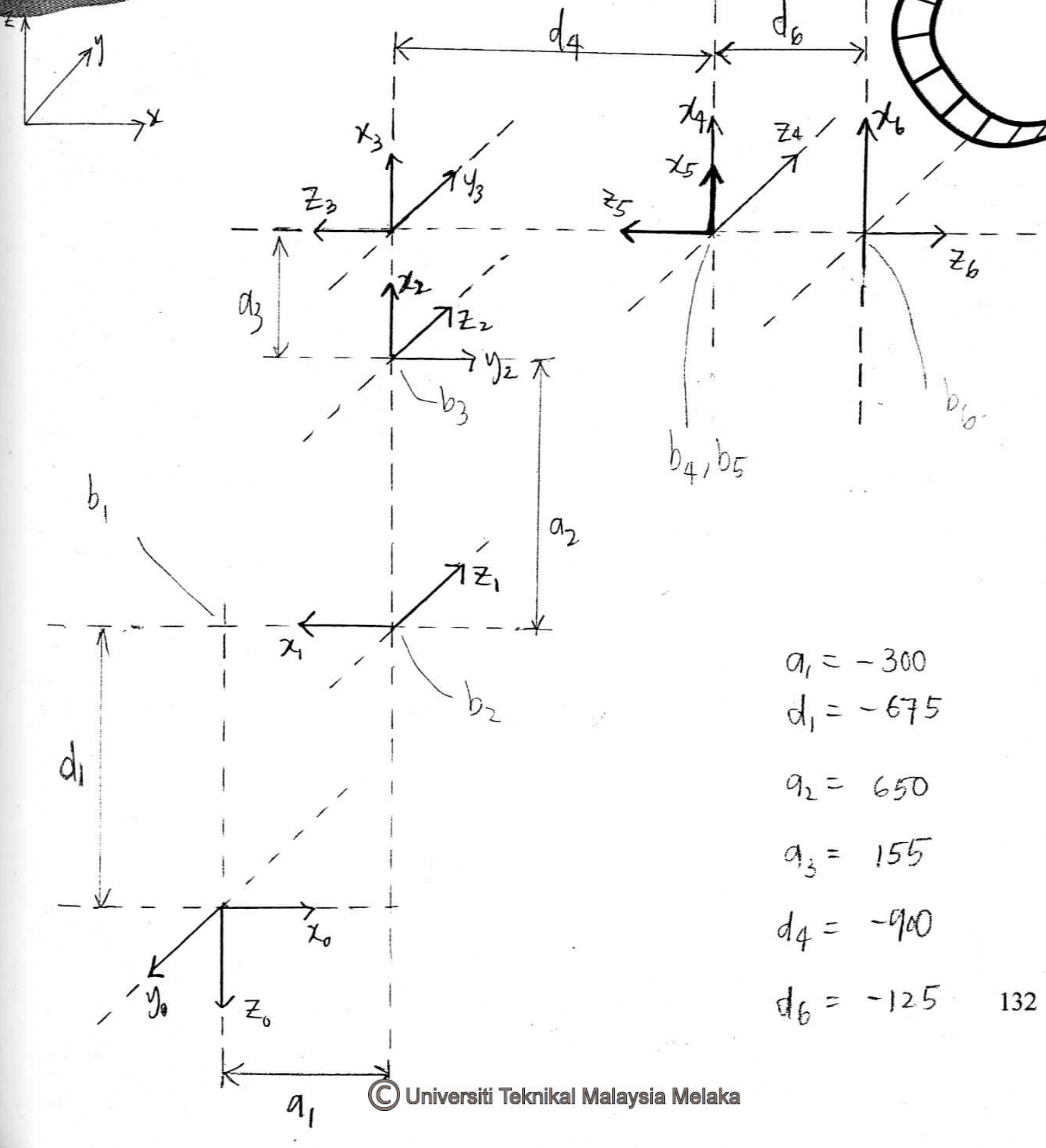
APPENDICES

B1

KUKA Robot KR 15 L6-2 D-H Assigned Frame



KR 15 L 6-2



$a_1 = -300$

$d_1 = -675$

$a_2 = 650$

$a_3 = 155$

$d_4 = -900$

$d_6 = -125$

APPENDICES

B2

KUKA Robot KR 15 L6-2 Data

KUKA 15 L6-2

	position			z	y	x
Joint	x	y	z	roll	pitch	Yaw
1	0	0	0	0	0	180
2	300	0	675	180	0	90
3	300	0	1325	0	-90	-90
4	300	0	1480	0	-90	0
5	1200	0	1480	0	-90	-90
6	1200	0	1480	0	-90	0
World	0	0	0	0	0	0
Flange	1325	0	1480	0	90	0

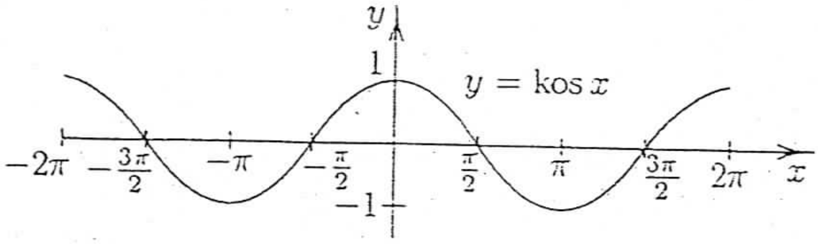
Kinematics Template 6R (PUMA)

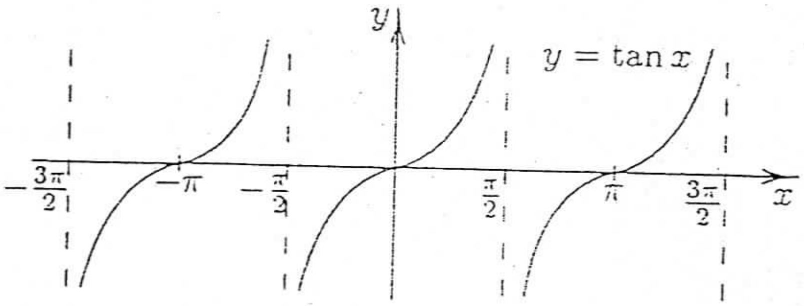
Template Parameters					Current Parameters				
Joint	θ_i	d_i	a_i	α_i	Joint	θ_i	d_i	a_i	α_i
1	x	x	x	x	1	180	-675	-300	-90
2	x	x	x	x	2	180	0	650	0
3	x	x	x	x	3	-90	0	155	90
4	x	x	0	x	4	0	-900	0	-90
5	x	0	0	x	5	0	0	0	90
6	x	x	x	x	6	180	-125	0	-180

APPENDICES

C1

Trigonometry Identity





B.3 Identiti

1. $\sin(-\theta) = -\sin\theta, \quad \text{kos}\,(-\theta) = \text{kos}\,\theta, \quad \tan\theta = \dfrac{\sin\theta}{\text{kos}\,\theta}$

2. $\sin^2\theta + \text{kos}^2\theta = 1, \quad \tan^2\theta + 1 = \text{sek}^2\theta, \quad 1 + \text{kot}^2\theta = \text{kosek}^2\theta$

3. $\sin(x \pm y) = \sin x\ \text{kos}\, y \pm \text{kos}\ x\ \sin y$

4. $\sin 2x = 2\sin x\ \text{kos}\, x$

$\boxed{\text{Kos}\ 2x = \text{kos}^2 x - \sin^2 x}$

5. $\text{kos}(x \pm y) = \text{kos}\, x\ \text{kos}\, y \mp \sin x\ \sin y$

6. $\text{kos}\, 2x = \text{kos}^2 x - \sin^2 x = 2\,\text{kos}^2 x - 1 = 1 - 2\sin^2 x$

7. $\tan(x \pm y) = \dfrac{\tan x \pm \tan y}{1 \mp \tan x \tan y}$

8. $\tan 2x = \dfrac{2\tan x}{1 - \tan^2 x}$

9. $\sin(x + y) + \sin(x - y) = 2\ \sin x\ \text{kos}\, y$

10. $\sin(x + y) - \sin(x - y) = 2\,\text{kos}\, x\ \sin y$

11. $\text{kos}(x + y) + \text{kos}(x - y) = 2\,\text{kos}\, x\ \text{kos}\, y$

12. $\text{kos}(x + y) - \text{kos}(x - y) = -2\ \sin x\ \sin y$

13. $\sin S + \sin T = 2\sin \tfrac{1}{2}(S + T)\,\text{kos}\,\tfrac{1}{2}(S - T)$

14. $\sin S - \sin T = 2\,\text{kos}\,\tfrac{1}{2}(S + T)\ \sin\tfrac{1}{2}(S - T)$

15. $\text{kos}\, S + \text{kos}\, T = 2\,\text{kos}\,\tfrac{1}{2}(S + T)\,\text{kos}\,\tfrac{1}{2}(S - T)$

16. $\text{kos}\, S - \text{kos}\, T = -2\ \sin\tfrac{1}{2}(S + T)\ \sin\tfrac{1}{2}(S - T)$

APPENDICES

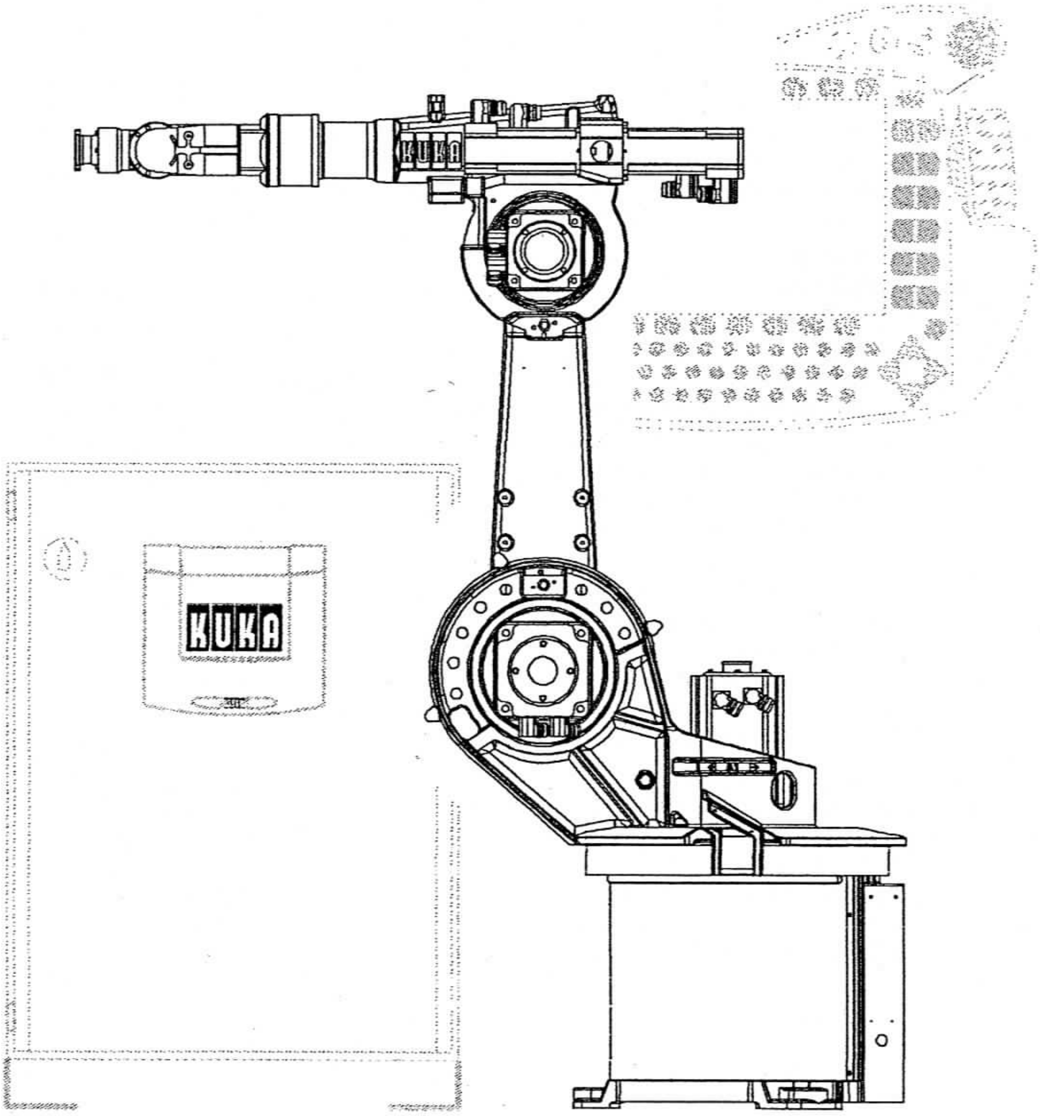
D1

KUKA Robot KR 15 L6-2 D-H Specification

pezifikation
pecification
pécification

Roboter
Robots

KR 6/2
KR 15/2
KR 15 L6/2



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Contents

1 SYSTEM DESCRIPTION

1.1 General

The KR 6/2, KR 15/2 and KR 15 L6/2 robots (Fig. 1-1) are six-axis industrial robots with articulated kinematics for all continuous-path controlled tasks. The main areas of application of the KR 6/2 and KR 15/2 robots are

- handling
- assembly
- application of adhesives, sealants and preservatives
- machining
- MIG/MAG welding
- YAG laser beam welding.

The main areas of application of the KR 15 L6/2 robot are

- handling
- assembly
- application of adhesives, sealants and preservatives
- MIG/MAG welding
- YAG laser beam welding.

The robots KR 6/2 and KR 15/2 can be installed in a variable position. The robot KR 15 L6/2 is designed for installation on the floor or ceiling.

The rated payload of 6 kg (15 kg) on the wrist of the KR 6/2 and KR 15 L6/2 (KR 15/2) and a maximum supplementary load (for this rated payload) of 10 kg (10 kg) on the robot's arm can be moved at maximum speed even with the arm fully extended.

All the main bodies of the moving principal assemblies are made of cast light alloy. This design concept has been optimized by means of CAD and FEM with regard to cost-effective lightweight construction and high torsional and flexural rigidity. As a result, the robot has a high natural frequency and is thus characterized by good dynamic performance with high resistance to vibration.

The joints and gears are virtually free from backlash; all moving parts are covered. All the axes are powered by brushless AC servomotors of plug-in design, which require no maintenance and offer reliable protection against overload.

The main axes are lifetime-lubricated, i.e. an oil change is necessary after 20,000 operating hours at the earliest.

All the robot components are of intentionally simple and straightforward configuration; the number of them has been minimized and they are all readily accessible. The robot can also be quickly replaced as a complete unit without any major program corrections being required. Overhead motion is possible.

These and numerous other design details make the robots fast, reliable and easy to maintain, with minimal maintenance requirements. They occupy very little floor space and can be located very close to the workpiece on account of the special structural geometry. Like all KUKA robots, they have an average service life of 10 to 15 years.

Each robot is equipped with a controller, whose control and power electronics are integrated in a common cabinet (see separate specification). The controller is compact, user-friendly and easy to service. It conforms to the safety requirements specified in the EU machinery directive and the relevant standards (including DIN EN 775).

The connecting cables between the robot and the cabinet contain all the relevant energy supply and signal lines. The cable connections on the robot are of the plug-in type, as too are the energy and fluid supply lines for the operation of end effectors (accessory "integrated energy supply for axis 1"). These lines are permanently installed inside main axis 1 of the robot and can be routed along the downstream axes to the end effector with the aid of system interfaces if required.

1.2 Robot mechanics

The robot consists of a fixed base frame, on which the rotating column turns about a vertical axis together with the link arm, arm and wrist (Fig. 1-1).

The wrist (Fig. 1-2) is provided with a mounting flange for the attachment of end effectors (e.g. grippers, welding tools).

The possible movements of the robot axes are depicted in Figure 1-3.

The positions of the main and wrist axes (A1 to A3 and A4 to A6) are sensed by means of a cyclically absolute position sensing system featuring a resolver for each axis.

Each axis is driven by a transistor-controlled, low-inertia AC servomotor. The brake and resolver are space-efficiently integrated into the motor unit.

The working range of the robot is limited by means of software limit switches on all axes. The working ranges of axes 1, 2, 3 and 5 are mechanically limited by end stops with a buffer function.

Mechanical stops for the application-specific limitation of the respective working ranges of axes 1 to 3 are available as the "working range limitation" accessory.

1.3 Installation

There are several possible methods of installing the robot:

- **Variant 1**

  This variant is available with anchors and drilling plan as the "floor mounting kit" accessory.
  The robot is placed onto the prepared shop floor without intermediate plates and fastened by means of three anchor bolts (Fig. 1-4).

- **Variant 2**

  This variant is available with locating pins and bolts as the "frame mounting kit" accessory.
  The robot is placed on a prepared steel construction and fastened with three bolts (Fig. 1-5). Its position of installation is fixed by means of two locating pins, enabling it to be exchanged in a repeatable manner.

- **Variant 3**

  This variant is available with intermediate plate, locating pins, anchors and bolts as the "mounting base kit" accessory.
  The robot is mounted together with an intermediate plate (Fig. 1-6) on the prepared shop floor. Its position of installation is fixed by means of two locating pins, enabling it to be exchanged in a repeatable manner. The robot is fastened to the intermediate plate with three bolts.
  The intermediate plate is fastened to the shop floor with three anchor bolts before the robot is mounted on it.

IMPORTANT with regard to variants 1 and 3: When preparing the foundation, the pertinent construction specifications regarding the grade of concrete (≥ B 25 according to DIN 1045) and the load bearing capacity of the ground must be observed. It must be ensured that the surface of the foundation is level and sufficiently smooth.

The insertion of the anchors must be carried out with great care to ensure that the forces occurring during operation (Fig. 1-8) will be safely transmitted to the ground. Figure 1-8 can also be used as a basis for more extensive static investigations.

1.4 Interchangeability

In manufacturing systems with a large number of robots, it is important for the robots to be readily interchangeable. This is ensured by

- the reproducibility of the synchronization positions marked by the manufacturer on all axes, the so-called mechanical zero positions, and
- the computer-aided zero adjustment procedure,

and is additionally supported by

- off-line programming, which can be carried out in advance and remotely from the robot, and
- the reproducible installation of the robot.

After service and maintenance work (on the wrist and motors, for example), it is necessary to establish coincidence between the electrical and mechanical zero positions (calibration) of the robot. A gage cartridge is mounted by the manufacturer on each robot axis for this purpose.

These gage cartridges are set by the manufacturer when the robot is calibrated prior to shipment. The fact that measurements on each axis are always made using the same cartridge means that maximum accuracy is achieved both when first calibrating the mechanical zero position and when subsequently relocating it.

The position of the mechanical probe fitted in the gage cartridge can be displayed by screwing an electronic probe (KTL adjustment set), available as an accessory, onto the cartridge. The position sensing system is automatically set to electrical zero when the probe passes the reference notch during the adjustment procedure.

The robot can resume operation once the zero adjustment has been carried out on all axes.

The procedures described make it possible for the programs, once defined, to be transferred at any time to any other robot of the same type.

1.5 Transportation

It must be ensured that the robot is stable while it is being transported. The robot must remain in its transport position as long as it is not fastened to the foundation.

There are three methods of transporting the robot (Fig. 1-7):

a With lifting tackle and crane (or fork lift truck)
The robot can be suspended from the hook of a crane or the fork of a fork lift truck by means of lifting tackle attached to three openings on the rotating column.

Only approved lifting tackle with an adequate carrying capacity may be used for transporting the robot by crane.

b With fork lift truck and turnover fixture
When transported with a fork lift truck and turnover fixture (accessory), the robot can very easily be turned into the ceiling-mounting position and thus brought to its designated site of installation.

c With fork lift truck and Euro-pallet
This method of transportation is intended primarily for shipment from the manufacturer to the customer. The robot is bolted onto the Euro-pallet.

Before being transported, the robot must be brought into its **transport position:**

A1	A2	A3	A4	A5	A6
0°	-55°	+70°	0°	+90°	any

These angle specifications are referred to the **mechanical** zero of the robot axis concerned.

Dimensions for packing the robot in a container:

Robot type	L (mm)	B (mm)	H (mm)
KR 6/2	990	550	1320
KR 15/2	990	550	1320
KR 15 L6/2	1220	550	1320

2 ACCESSORIES (selection)

2.1 Robot installation

There are three variants available for installing the robot:

- with floor mounting kit (Fig. 1-4)
- with frame mounting kit (Fig. 1-5)
- with mounting base kit (Fig. 1-6)

See Section 1.3 for a description.

2.2 Additional linear axis

With the aid of a linear unit as an additional traversing axis, based on the KL 250 series (Fig. 2-1), the robot can be moved translationally. The axis is freely programmable and can be installed on the floor or the ceiling.

2.3 Integrated energy supply for axis 1

Various energy supply systems are available, e.g. for the application "handling". In the area of axis 1, the necessary supply lines run inside the robot from the plug connection panel to an interface on the rotating column (Fig. 2-2).

From here, supply lines can additionally be routed externally along the link arm and arm to an appropriate interface on the end effector. This eliminates the need for a space-consuming supply boom.

2.4 Working range monitoring

Axes 1 and 2 can be equipped with position switches and slotted rings to which adjustable cams are attached. This allows the position of the robot to be continuously monitored.

Up to three sectors of the movement range can be monitored on axis 1, and one sector on axis 2.

2.5 Working range limitation

The movement ranges of axes 1 to 3 can be limited by means of additional mechanical stops as required by the application.

Axis 1:	from +80° to -80°, adjustable in 20° steps.
Axis 2:	from +60° to -20°, adjustable in 20° steps.
Axis 3:	from 0° to -150°, adjustable in 30° steps.

2.6 KTL adjustment set

The zero adjustment operation, which is necessary for all axes of the KR 15/2, can be performed with the aid of the electronic probe belonging to a KTL adjustment set (Fig. 2-3 and 3-7). On the KR 6/2 and the KR 15 L6/2, this is only possible for axes 1 to 3. The probe provides a particularly fast and simple means of measurement and allows automatic, computer-aided adjustment. It should be included in the order for the robot.

2.7 Belt tension measuring device for in-line wrist

Equipped with a microcontroller, the fully electronic measuring device enables the toothed belt tension to be quickly and easily measured by means of frequency measurement (Fig. 2-4).

2.8 Transport and turnover fixture

When picked up by a fork lift truck, this fixture can be used to hold the robot around the rotating column, to turn it into the correct position for mounting on the ceiling and to transport it thus to its installation location. It is recommended that this fixture should be employed whenever a robot of this type is transported within the plant.

2.9 Release device for robot axes

This device can be used to move the main axes of the robot mechanically via the drive motors after a malfunction. It is only for use in emergencies (e.g. for freeing personnel).

3 TECHNICAL DATA

Type	KR 6/2 KR 15/2 KR 15 L6/2
Number of axes	6 (Fig. 1-3)
Load limits	also see Fig. 3-1

Robot type	KR 6/2, KR 15 L6/2	KR 15/2
Wrist (IW) [1]	6 kg	15 kg
Rated payload [kg]	6	15
Supplementary load with rated payload [kg]	10	10
Max. total distributed load [kg]	16	25

The relationship between the payload and its center of gravity may be noted from Figures 3-2 to 3-4.

Axis data

The axis data may be noted from the tables below. The axes and their possible motions are depicted in Figure 1-3. Axes 1 to 3 are the main axes, axes 4 to 6 the wrist axes.

All specifications in the "Range of motion" column are referred to the **mechanical** zero of the robot axis concerned.

KR 6/2, KR 15 L6/2

D **In-line wrist, rated payload 6 kg**

Axis	Range of motion software-limited	Speed
1	±185°	152 °/s
2	+115° to -55°	152 °/s
3	+70° to -210°	152 °/s
4	±350°	250 °/s
5	±130°	357 °/s
6	±350°	660 °/s

KR 15/2

D **In-line wrist, rated payload 15 kg**

Axis	Range of motion software-limited	Speed
1	±185°	152 °/s
2	+115° to -55°	152 °/s
3	+70° to -210°	152 °/s
4	±350°	284 °/s
5	±135°	293 °/s
6	±350°	604 °/s

Repeatability	±0.1 mm	
Drive system	electromechanical, with transistor-controlled brushless AC servomotors	
Principal dimensions	see Figures 3-8 to 3-10	
Weight	KR 6/2 KR 15/2 KR 15 L6/2	approx. 220 kg approx. 235 kg approx. 220 kg
Sound level	< 75 dB (A) outside the working envelope	
Mounting position	variable	
Installation	see Section 1.3	

Load center of gravity P see Figures 3-2 to 3-4

For all rated payloads, the horizontal distance (Lz) of the center of gravity of the payload P from the face of the mounting flange is 100 mm (KR 6/2, KR 15 L6/2) or 150 mm (KR 15/2); the vertical distance (Lxy) from rotational axis 6 is 80 mm (KR 6/2, KR 15 L6/2) or 120 mm (KR 15/2) (nominal distance in each case).

---

[1] IW = in-line wrist

Special consumables none

Working envelope

The shape and dimensions of the working envelope may be noted from Figures 3-8 to 3-10.

Working volume

The volume of the working envelope for the KR 6/2 and KR 15/2 is approx. 13.1 m^3, for the KR 15 L6/2 22 m^3.

The reference point is the intersection of axes 4 and 5.

Ambient temperature

D During operation:
283 K to 328 K (+10 °C to +55 °C)

D During storage and transportation:
233 K to 333 K (-40 °C to +60 °C)

Other temperature limits available on request.

Installed motor capacity approx. 3 kW

Protection classification of the robot IP 64
(according to EN 60529)
ready for operation,
with connecting cables plugged in

Colors

Base (stationary): black (RAL 9005).
Moving parts: orange (RAL 2003).

Mounting flange on axis 6

The robot is fitted with a DIN/ISO mounting flange[1] (Fig. 3-5 and 3-6).

Screw grade for attaching end effector	10.9
Minimum screw grip	1.5 x d
Engagement length	min. 6 mm max. 7 mm (KR 6/2, KR 15 L6/2) max. 10 mm (KR 15/2)

NOTE: The flange is depicted with all axes of the robot, particularly axis 6, in the zero position (the symbol ⧫ indicates the position of the locating element).

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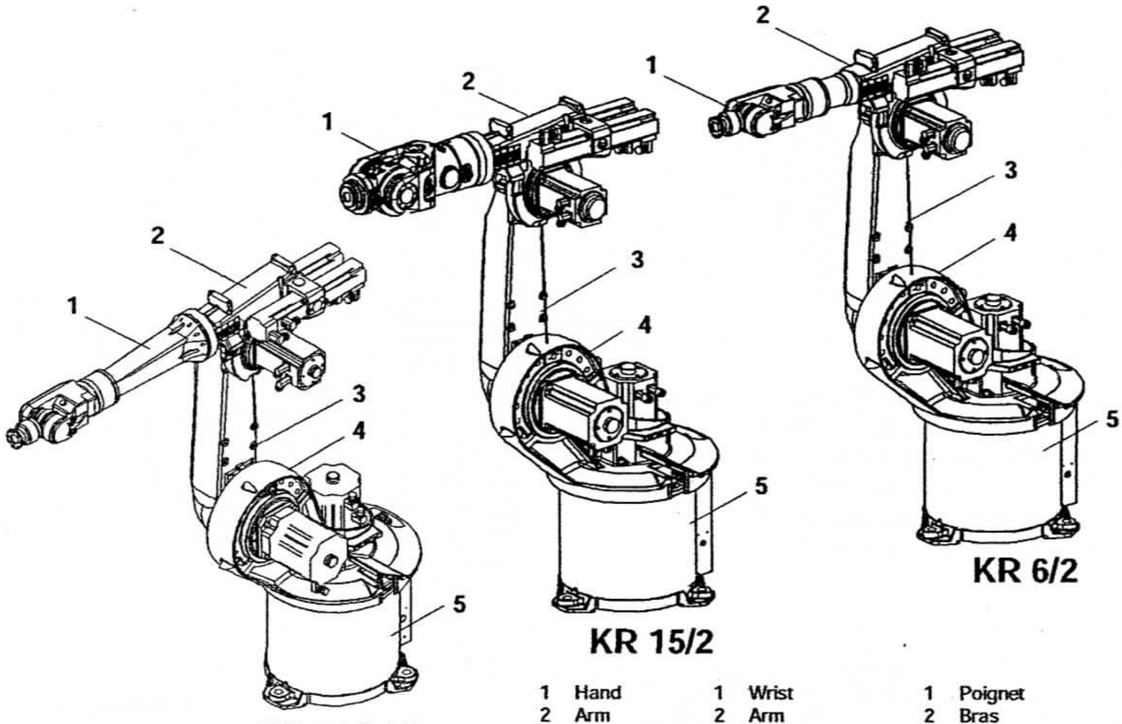
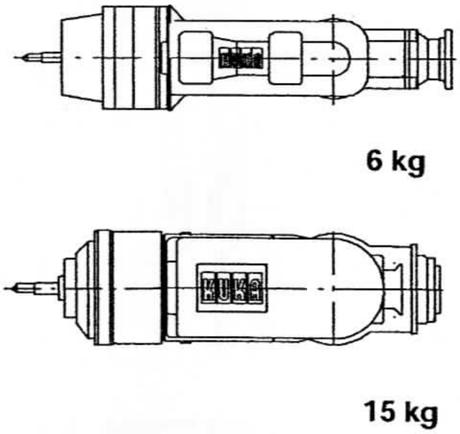
[1] DIN/ISO 9409-1-A50

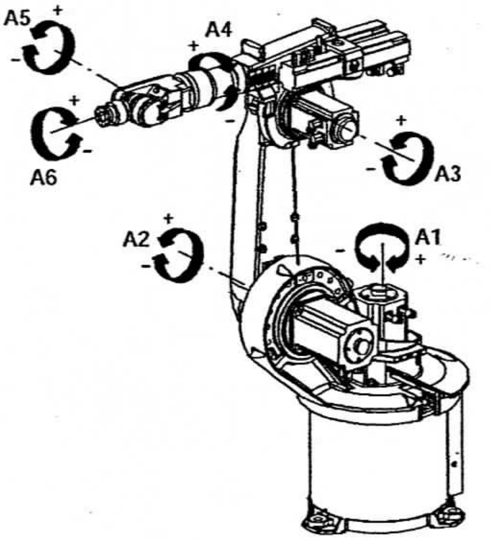


1	Hand	1	Wrist	1	Poignet
2	Arm	2	Arm	2	Bras
3	Schwinge	3	Link arm	3	Epaule
4	Karussell	4	Rotating column	4	Bâti de rotation
5	Grundgestell	5	Base frame	5	Embase

1-1 Hauptbestandteile des Roboters
Principal components of the robot
Sous-ensembles principaux du robot



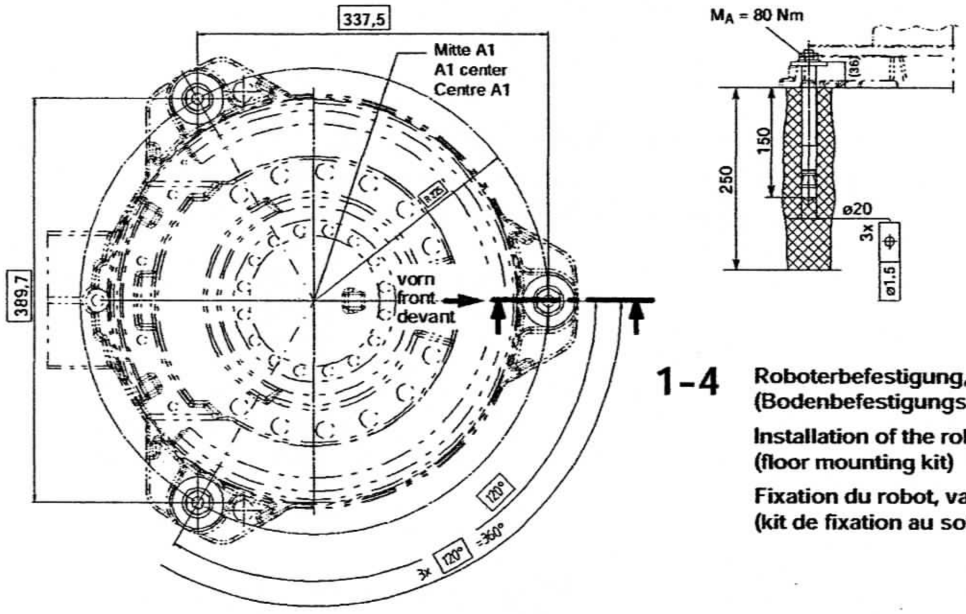
1-2 Zentralhand (ZH)
In-line wrist (IW)
Poignet en ligne (PL)



1-3 Drehachsen und Drehsinn beim Verfahren des Roboters

Rotational axes and directions of rotation in motion of the robot

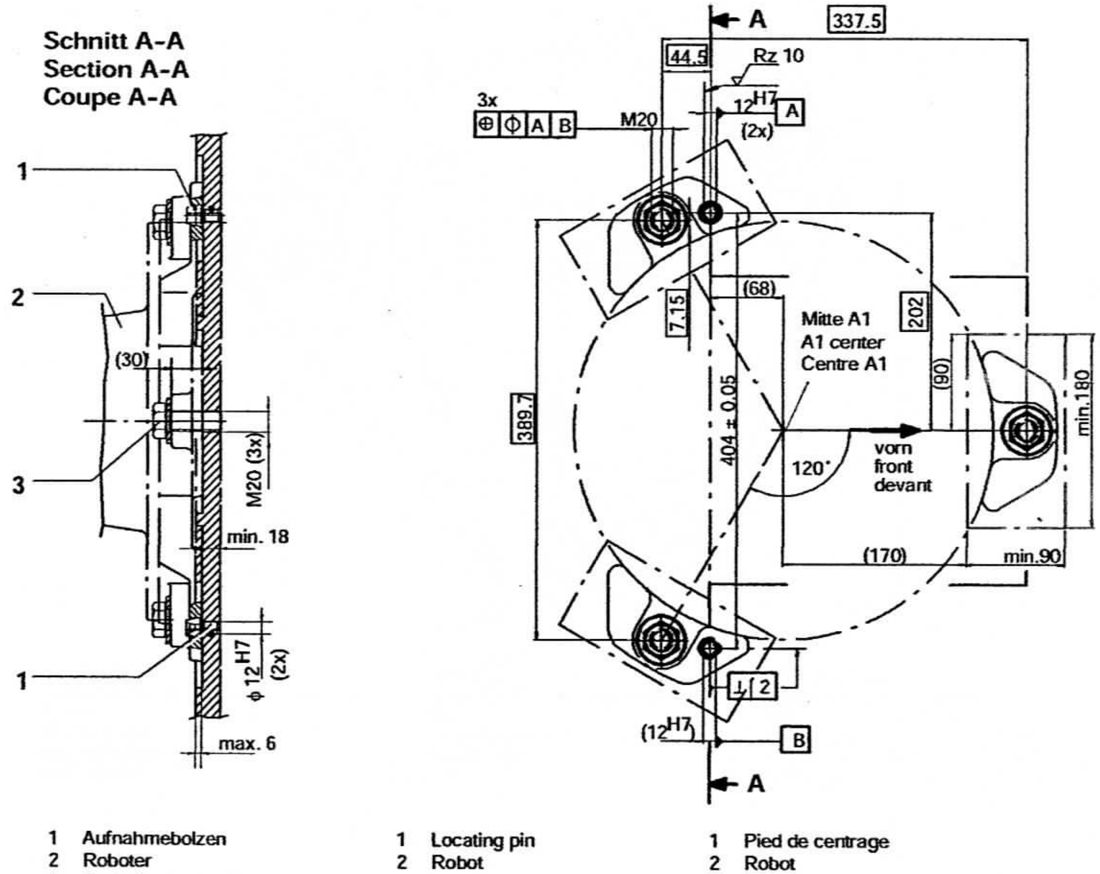
Axes de rotation du robot et sens de rotation lors du déplacement des axes



1-4 Roboterbefestigung, Variante 1 (Bodenbefestigungssatz)

Installation of the robot, variant 1 (floor mounting kit)

Fixation du robot, variante 1 (kit de fixation au sol)

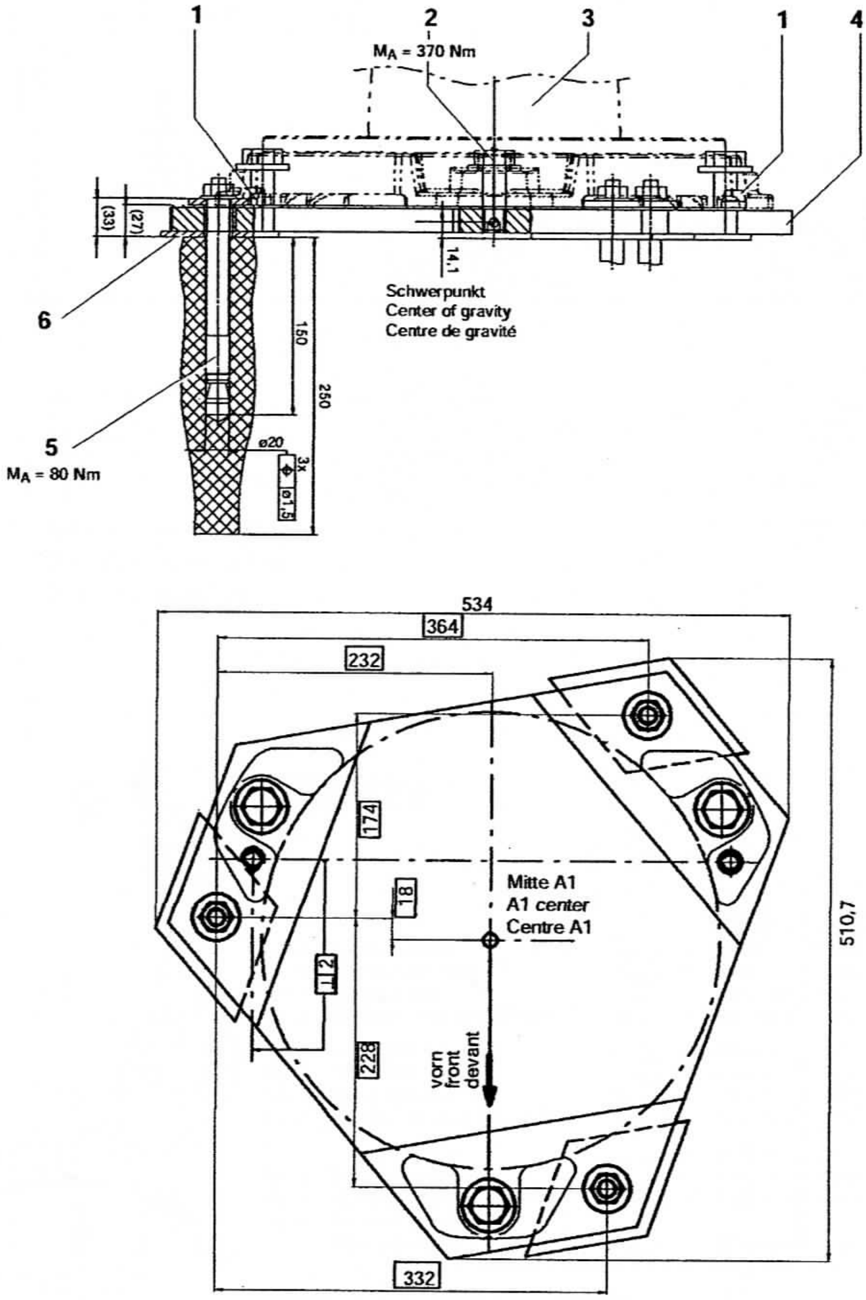


1	Aufnahmebolzen	1	Locating pin	1	Pied de centrage
2	Roboter	2	Robot	2	Robot
3	Sechskantschraube (ISO 4017 M20x55-8.8)	3	Hexagon bolt (ISO 4017 M20x55-8.8)	3	Vis à tête hexagonale (ISO 4017 M20x55-8.8)

1-5 Roboterbefestigung, Variante 2 (Gestellbefestigungssatz)

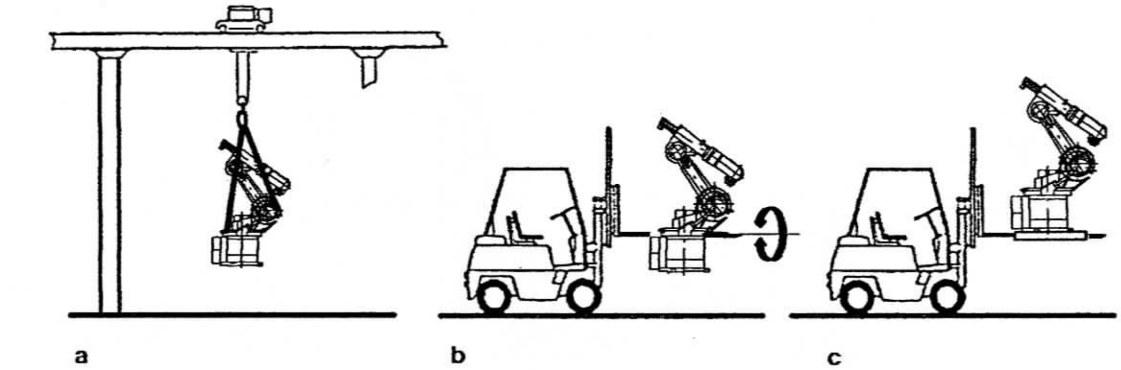
Installation of the robot, variant 2 (frame mounting kit)

Fixation du robot, variante 2 (kit de fixation de l'embase)



1	Aufnahmebolzen	1	Locating pin	1	Pied de centrage
2	Sechskantschraube ISO 4017 M20x55-8.8	2	Hexagon bolt ISO 4017 M20x55-8.8	2	Vis à tête hexagonale ISO 4017 M20x55-8.8
3	Roboter	3	Robot	3	Robot
4	Zwischenplatte	4	Intermediate plate	4	Plaque intermédiaire
5	Sicherheitsdübel	5	Safety anchor	5	Cheville de sûreté
6	Unterlegplatte	6	Shim	6	Entretoise

1-6 Roboterbefestigung, Variante 3 (Fundamentbefestigungssatz)
Installation of the robot, variant 3 (mounting base kit)
Fixation du robot, variante 3 (kit de fixation de l'embase)

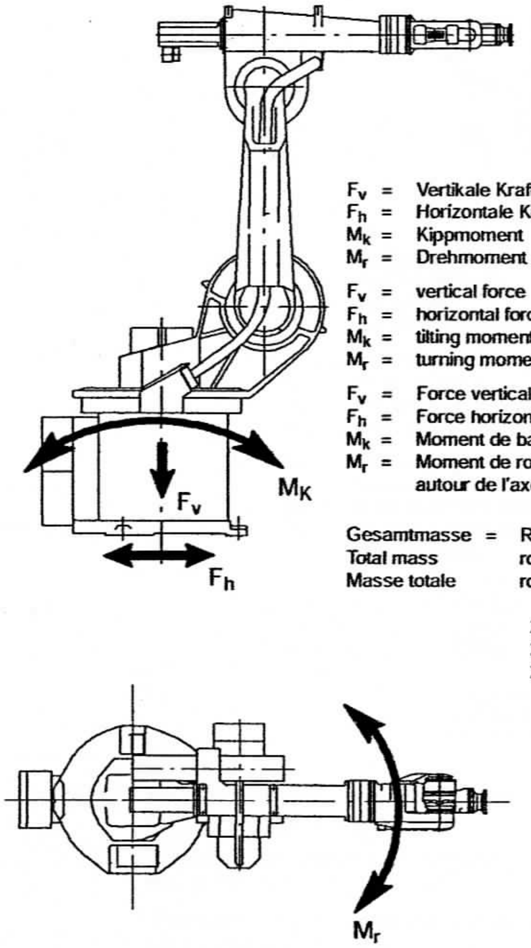


a) mit Transportgeschirr und Kran (oder Gabelstapler)
b) mit Wendevorrichtung (Zubehör) und Gabelstapler
c) mit Euro-Palette und Gabelstapler

a) with lifting tackle and crane (or fork lift truck)
b) with turnover fixture (accessory) and fork lift truck
c) with Euro-pallet and fork lift truck

a) avec dispositif de levage et grue (ou chariot élévateur à fourches)
b) avec dispositif de retournement (accessoire) et chariot élévateur à fourches
c) avec palette européenne et chariot élévateur à fourches

1-7 **Transport des Roboters**
Transporting the robot
Transport du robot



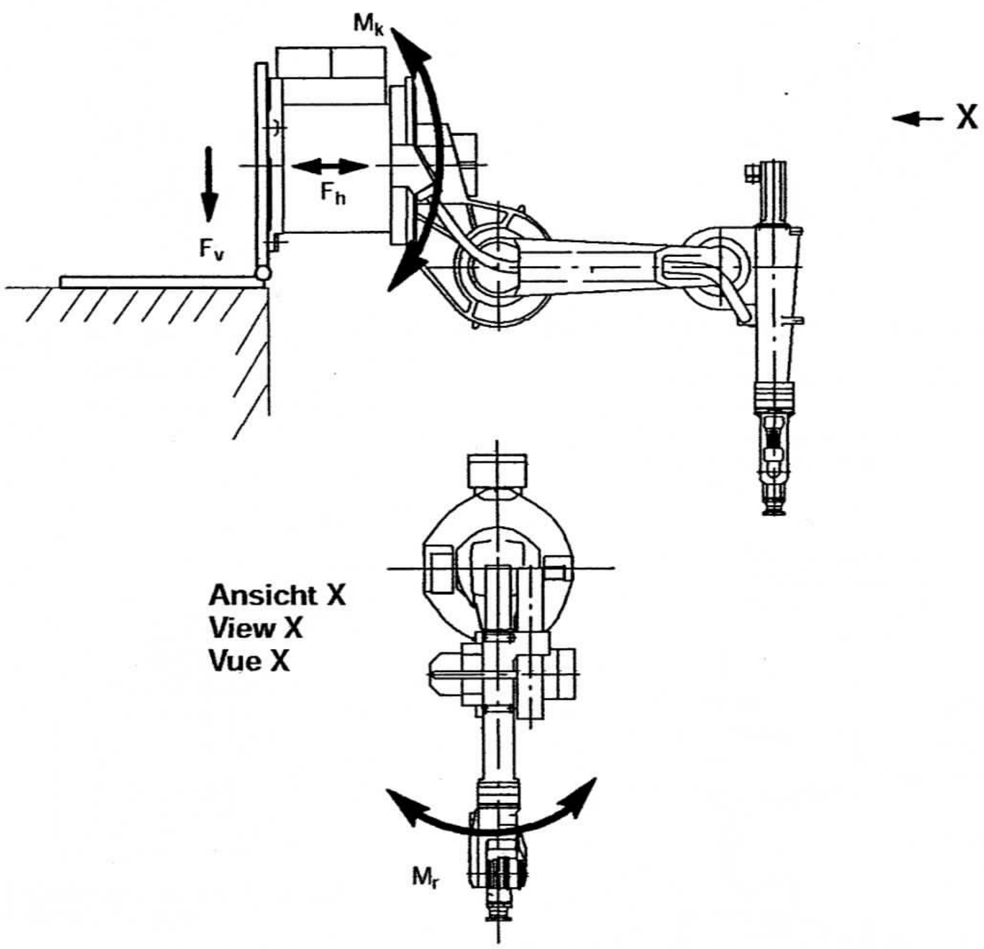
			KR 6/2	KR 15/2	KR 15 L6/2
F_v =	Vertikale Kraft	F_{vmax} =	3500 N	3800 N	3800 Nm
F_h =	Horizontale Kraft	F_{hmax} =	2600 N	4100 N	4100 Nm
M_k =	Kippmoment	M_{kmax} =	3400 Nm	4800 Nm	4800 Nm
M_r =	Drehmoment um Achse 1	M_{rmax} =	3200 Nm	3200 Nm	3200 Nm
F_v =	vertical force	F_{vmax} =	3500 N	3800 N	3800 Nm
F_h =	horizontal force	F_{hmax} =	2600 N	4100 N	4100 Nm
M_k =	tilting moment	M_{kmax} =	3400 Nm	4800 Nm	4800 Nm
M_r =	turning moment about axis 1	M_{rmax} =	3200 Nm	3200 Nm	3200 Nm
F_v =	Force verticale	F_{vmax} =	3500 N	3800 N	3800 Nm
F_h =	Force horizontale	F_{hmax} =	2600 N	4100 N	4100 Nm
M_k =	Moment de basculement	M_{kmax} =	3400 Nm	4800 Nm	4800 Nm
M_r =	Moment de rotation autour de l'axe 1	M_{rmax} =	3200 Nm	3200 Nm	3200 Nm

Gesamtmasse = Total mass Masse totale	Roboter robot robot	+	Gesamtlast total load charge totale	für Typ for type pour type
	220 kg	+	16 kg	KR 6/2
	235 kg	+	25 kg	KR 15/2
	220 kg	+	16 kg	KR 15 L6/2

1-8 **Hauptbelastungen des Bodens durch Roboter und Gesamtlast**

Principal loads acting on floor due to robot and total load

Sollicitations principales au niveau du sol dues au robot et à la charge totale



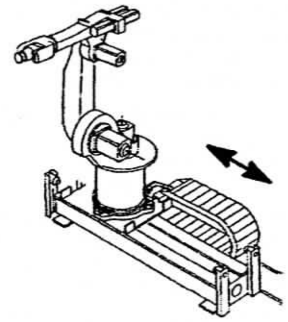
					KR 6/2	KR 15/2
F_v	=	Vertikale Kraft	F_{vmax}	=	5000 N	7000 N
F_h	=	Horizontale Kraft	F_{hmax}	=	1000 N	1000 N
M_k	=	Kippmoment	M_{kmax}	=	2800 Nm	3700 Nm
M_r	=	Drehmoment um Achse 1	M_{rmax}	=	3200 Nm	3500 Nm
F_v	=	vertical force	F_{vmax}	=	5000 N	7000 N
F_h	=	horizontal force	F_{hmax}	=	1000 N	1000 N
M_k	=	tilting moment	M_{kmax}	=	2800 Nm	3700 Nm
M_r	=	turning moment about axis 1	M_{rmax}	=	3200 Nm	3500 Nm
F_v	=	Force verticale	F_{vmax}	=	5000 N	7000 N
F_h	=	Force horizontale	F_{hmax}	=	1000 N	1000 N
M_k	=	Moment de basculement	M_{kmax}	=	2800 Nm	3700 Nm
M_r	=	Moment de rotation autour de l'axe 1	M_{rmax}	=	3200 Nm	3500 Nm

	Roboter	+	Gesamtlast	für Typ
Gesamtmasse =	Roboter	+	Gesamtlast	für Typ
Total mass	robot		total load	for type
Masse totale	robot		charge totale	pour type
	220 kg	+	16 kg	KR 6/2
	235 kg	+	25 kg	KR 15/2

1-9 Hauptbelastungen des Fundaments durch Roboter und Gesamtlast für Einbaulage "Wand"

Principal loads acting on mounting base due to robot and total load for "wall" mounting position

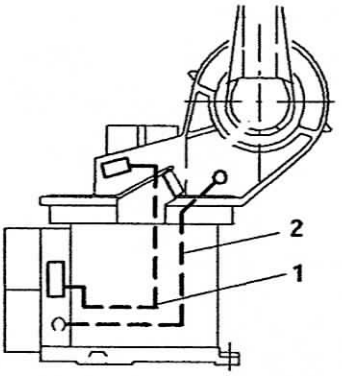
Sollicitations principales de la fondation par robot et charge totale pour le montage "au mur"



2-1 Zusätzliche Linearachse

Additional linear axis

Axe linéaire supplémentaire



1 Steuerleitung 25x0,5 mm^2, geschirmt
2 Druckluftleitung 3/8"

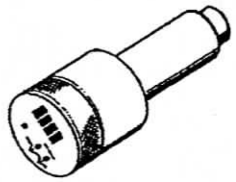
1 Control cable 25x0.5 mm^2, shielded
2 Compressed air line 3/8"

1 Câble de commande 25x0,5 mm^2, blindé
2 Flexible d'air comprimé 3/8"

2-2 Energiezuführung A1, Handhaben

Energy supply system A1, handling

Alimentation en enérgie A1, manutention



2-3 Elektronischer Meßtaster für KTL-Justage-Set

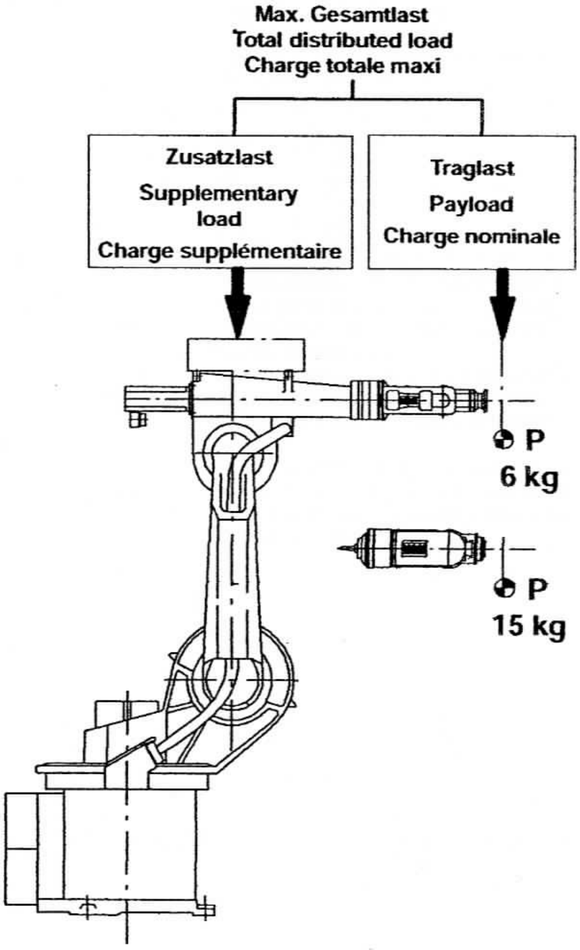
Electronic probe for KTL adjustment set

Mesureur électronique pour set de réglage KTL

2-4 Zahnriemenspannungs-Meßgerät für Zentralhand

Belt tension measuring device for in-line wrist

Dispositif de mesure de la courroie crantée pour poignet en ligne



3-1 Lastverteilung

Distribution of the total load

Distribution de la charge

ACHTUNG: Diese Belastungskurven und die Tabellenwerte entsprechen der <u>äußersten</u> Belastbarkeit! Es müssen immer beide Werte (Traglast und Eigenträgheitsmoment) geprüft werden. Ein Überschreiten geht in die Lebensdauer des Geräts ein, überlastet im allgemeinen Motoren und Getriebe und bedarf auf alle Fälle der Rücksprache mit KUKA.

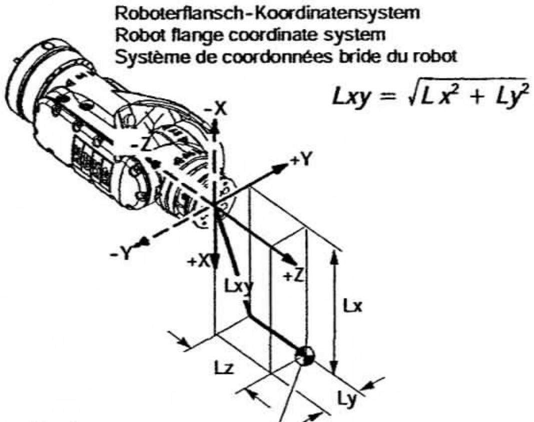
IMPORTANT: These loading curves and the values in the table correspond to the <u>maximum</u> load capacity. Both values (payload and principal moment of inertia) must be checked in all cases. Exceeding this capacity will reduce the service life of the robot and generally overload the motors and gears, in any such case KUKA must be consulted.

ATTENTION: Les courbes de charge et les valeurs du tableau représentent la capacité de charge <u>maximum</u>! Il faut toujours vérifier les deux valeurs (charge et moment d'inertie propre). Un dépassement de cette capacité réduit la durée de vie du robot et, en règle générale, surcharge les moteurs ainsi que les engrenages et transmissions. Il faudra en tous cas consulter KUKA auparavant.

HINWEIS: Die hier ermittelten Werte sind für die Robotereinsatzplanung notwendig. Für die Inbetriebnahme des Roboters sind gemäß KUKA-Softwaredokumentation zusätzliche Eingabedaten erforderlich.

NOTE: The values determined here are necessary for planning the robot application. For commissioning the robot, additional input data are required in accordance with the KUKA software documentation.

REMARQUE: Les valeurs ainsi déterminées sont indispensables pour définir le champ d'application du robot. Des données supplémentaires sont nécessaires pour la mise en service du robot conformément à la documentation du logiciel KUKA.



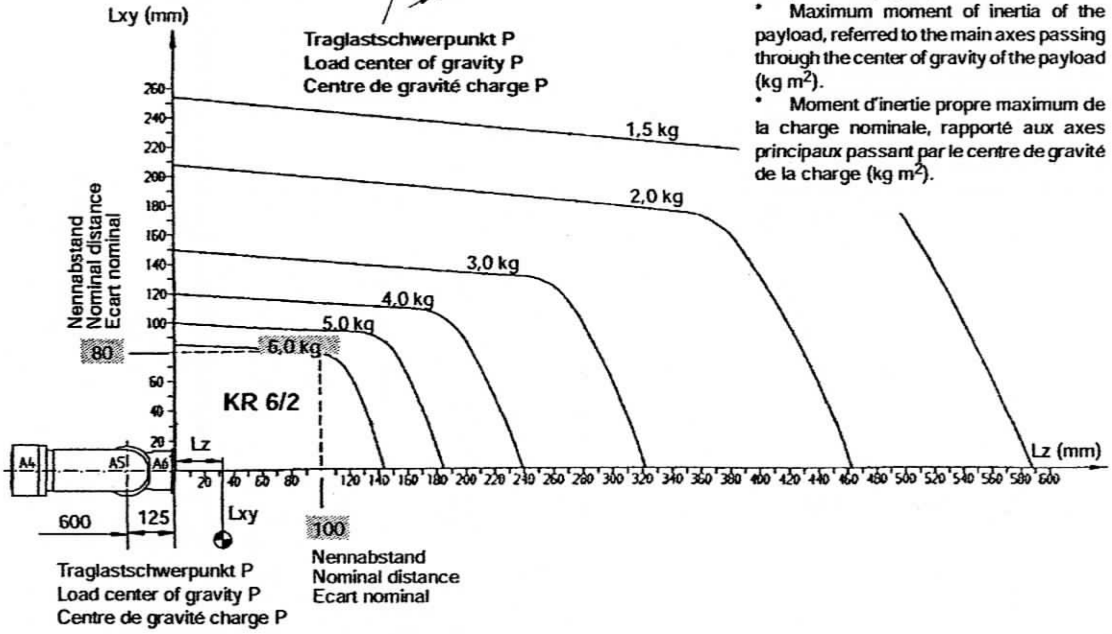
$$Lxy = \sqrt{Lx^2 + Ly^2}$$

Traglast (kg) Payload (kg) Charge nominale (kg)	Eigenträgheitsmoment I_S * für KR 6/2 [kg m²] Moment of inertia I_S * for KR 6/2 [kg m²] Moment d'inertie propre I_S * pour KR 6/2 [kg m²]
6,0	0,090
5,0	0,075
4,0	0,060
3,0	0,045
2,0	0,030
1,5	0,023

* *Maximales Eigenträgheitsmoment* der Traglast, bezogen auf die durch den Schwerpunkt der Traglast gehenden Hauptachsen (kg m²).

* Maximum moment of inertia of the payload, referred to the main axes passing through the center of gravity of the payload (kg m²).

* Moment d'inertie propre maximum de la charge nominale, rapporté aux axes *principaux passant* par le centre de gravité de la charge (kg m²).



3-2 Traglastschwerpunkt P und Belastungskurven für KR 6/2
Load center of gravity P and loading curves for KR 6/2
Centre de gravité de la charge P et courbes de charge pour KR 6/2

ACHTUNG: Diese Belastungskurven und die Tabellenwerte entsprechen der äußersten Belastbarkeit! Es müssen immer beide Werte (Traglast und Eigenträgheitsmoment) geprüft werden. Ein Überschreiten geht in die Lebensdauer des Geräts ein, überlastet im allgemeinen Motoren und Getriebe und bedarf auf alle Fälle der Rücksprache mit KUKA.

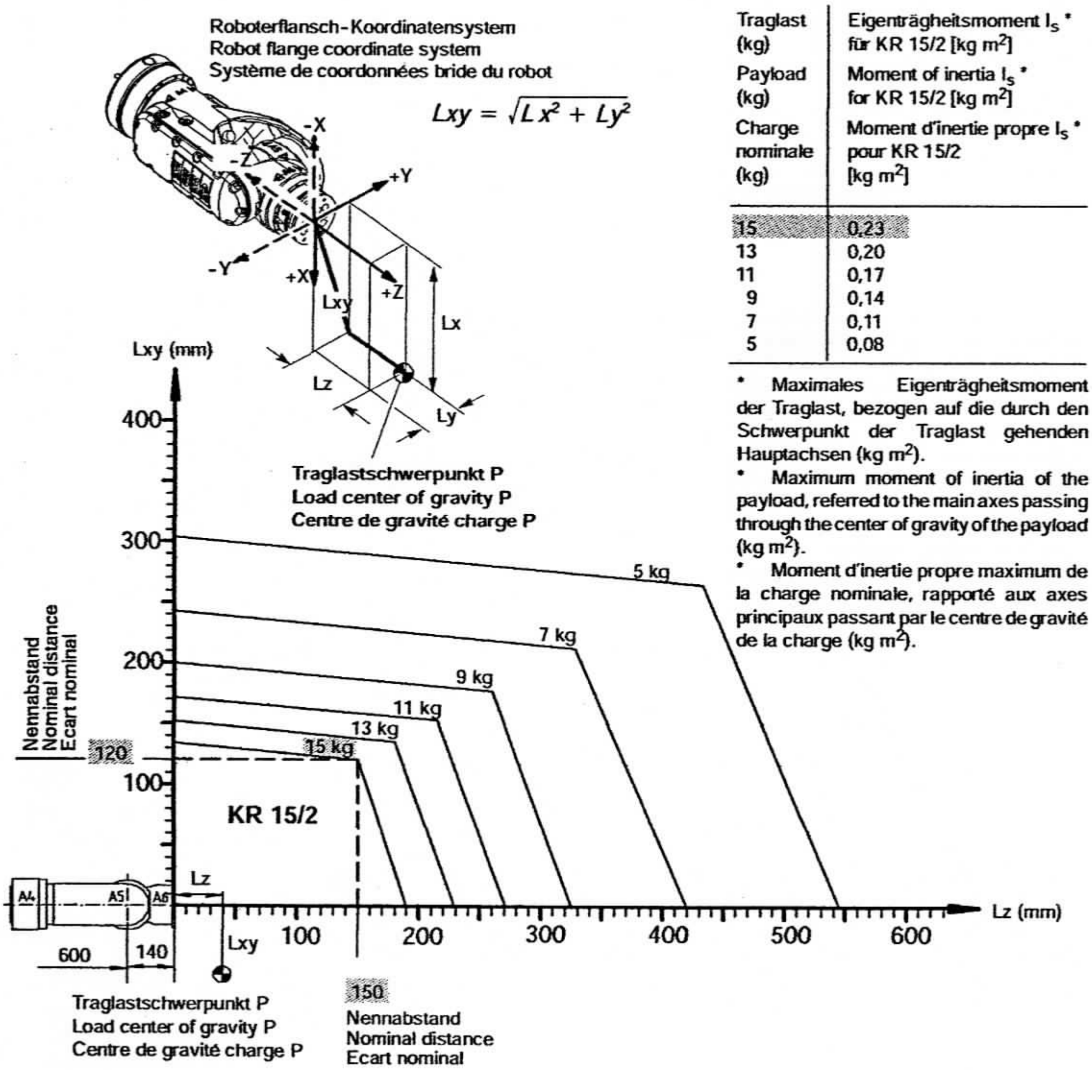
IMPORTANT: These loading curves and the values in the table correspond to the maximum load capacity. Both values (payload and principal moment of inertia) must be checked in all cases. Exceeding this capacity will reduce the service life of the robot and generally overload the motors and gears, in any such case KUKA must be consulted.

ATTENTION: Les courbes de charge et les valeurs du tableau représentent la capacité de charge maximum! Il faut toujours vérifier les deux valeurs (charge et moment d'inertie propre). Un dépassement de cette capacité réduit la durée de vie du robot et, en règle générale, surcharge les moteurs ainsi que les engrenages et transmissions. Il faudra en tous cas consulter KUKA auparavant.

HINWEIS: Die hier ermittelten Werte sind für die Robotereinsatzplanung notwendig. Für die Inbetriebnahme des Roboters sind gemäß KUKA-Softwaredokumentation zusätzliche Eingabedaten erforderlich.

NOTE: The values determined here are necessary for planning the robot application. For commissioning the robot, additional input data are required in accordance with the KUKA software documentation.

REMARQUE: Les valeurs ainsi déterminées sont indispensables pour définir le champ d'application du robot. Des données supplémentaires sont nécessaires pour la mise en service du robot conformément à la documentation du logiciel KUKA.



Traglast (kg) Payload (kg) Charge nominale (kg)	Eigenträgheitsmoment I_S * für KR 15/2 [kg m^2] Moment of inertia I_S * for KR 15/2 [kg m^2] Moment d'inertie propre I_S * pour KR 15/2 [kg m^2]
15	0,23
13	0,20
11	0,17
9	0,14
7	0,11
5	0,08

* Maximales Eigenträgheitsmoment der Traglast, bezogen auf die durch den Schwerpunkt der Traglast gehenden Hauptachsen (kg m^2).

* Maximum moment of inertia of the payload, referred to the main axes passing through the center of gravity of the payload (kg m^2).

* Moment d'inertie propre maximum de la charge nominale, rapporté aux axes principaux passant par le centre de gravité de la charge (kg m^2).

3-3 Traglastschwerpunkt P und Belastungskurven für KR 15/2
Load center of gravity P and loading curves for KR 15/2
Centre de gravité de la charge P et courbes de charge pour KR 15/2

ACHTUNG: Diese Belastungskurven und die Tabellenwerte entsprechen der <u>äußersten</u> Belastbarkeit! Es müssen immer beide Werte (Traglast und Eigenträgheitsmoment) geprüft werden. Ein Überschreiten geht in die Lebensdauer des Geräts ein, überlastet im allgemeinen Motoren und Getriebe und bedarf auf alle Fälle der Rücksprache mit KUKA.

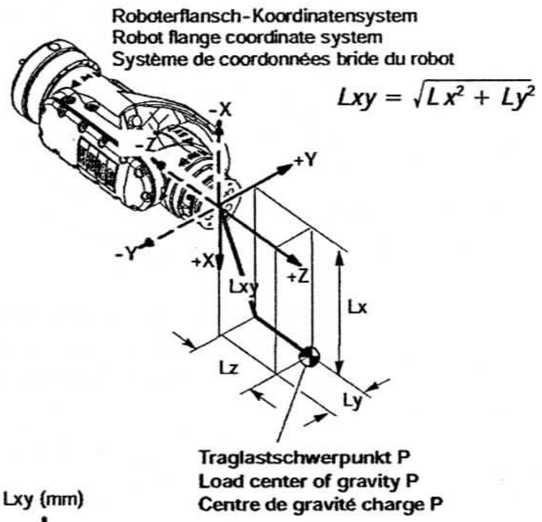
IMPORTANT: These loading curves and the values in the table correspond to the <u>maximum</u> load capacity. Both values (payload and principal moment of inertia) must be checked in all cases. Exceeding this capacity will reduce the service life of the robot and generally overload the motors and gears, in any such case KUKA must be consulted.

ATTENTION: Les courbes de charge et les valeurs du tableau représentent la capacité de charge <u>maximum</u>! Il faut toujours vérifier les deux valeurs (charge et moment d'inertie propre). Un dépassement de cette capacité réduit la durée de vie du robot et, en règle générale, surcharge les moteurs ainsi que les engrenages et transmissions. Il faudra en tous cas consulter KUKA auparavant.

HINWEIS: Die hier ermittelten Werte sind für die Robotereinsatzplanung notwendig. Für die Inbetriebnahme des Roboters sind gemäß KUKA-Softwaredokumentation zusätzliche Eingabedaten erforderlich.

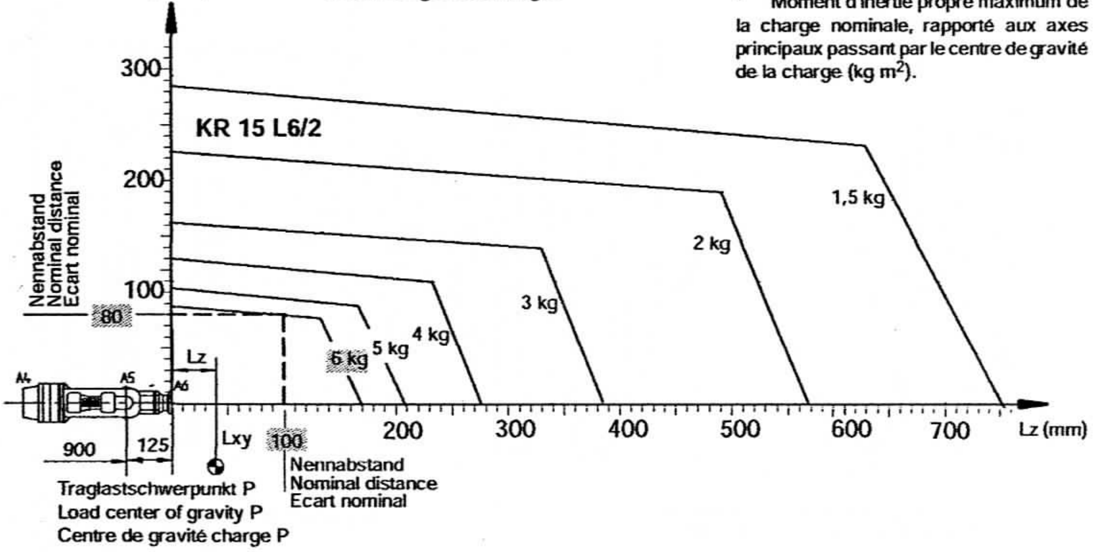
NOTE: The values determined here are necessary for planning the robot application. For commissioning the robot, additional input data are required in accordance with the KUKA software documentation.

REMARQUE: Les valeurs ainsi déterminées sont indispensables pour définir le champ d'application du robot. Des données supplémentaires sont nécessaires pour la mise en service du robot conformément à la documentation du logiciel KUKA.



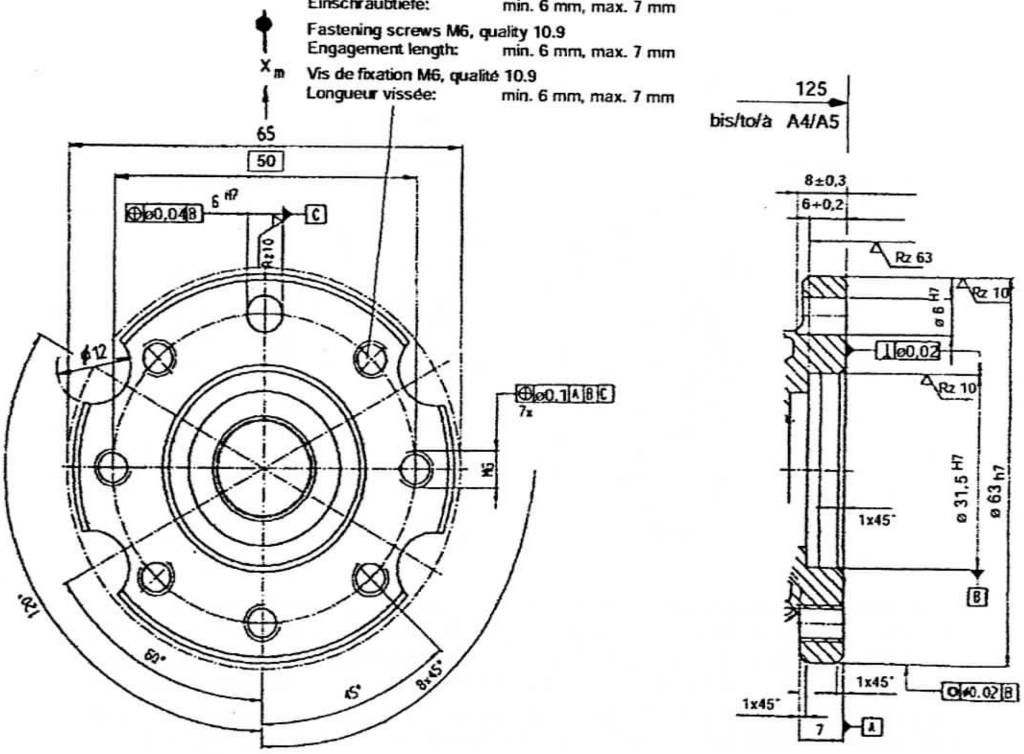
Traglast (kg) Payload (kg) Charge nominale (kg)	Eigenträgheitsmoment I_s * für KR 15 L6/2 [kg m²] Moment of inertia I_s * for KR 15 L6/2 [kg m²] Moment d'inertie propre I_s * pour KR 15 L6/2 [kg m²]
6,0	0,090
5,0	0,075
4,0	0,060
3,0	0,045
2,0	0,030
1,5	0,023

- * Maximales Eigenträgheitsmoment der Traglast, bezogen auf die durch den Schwerpunkt der Traglast gehenden Hauptachsen (kg m²).
- * Maximum moment of inertia of the payload, referred to the main axes passing through the center of gravity of the payload (kg m²).
- * Moment d'inertie propre maximum de la charge nominale, rapporté aux axes principaux passant par le centre de gravité de la charge (kg m²).



3-4

Traglastschwerpunkt P und Belastungskurven für KR 15 L6/2
Load center of gravity P and loading curves for KR 15 L6/2
Centre de gravité de la charge P et courbes de charge pour KR 15 L6/2

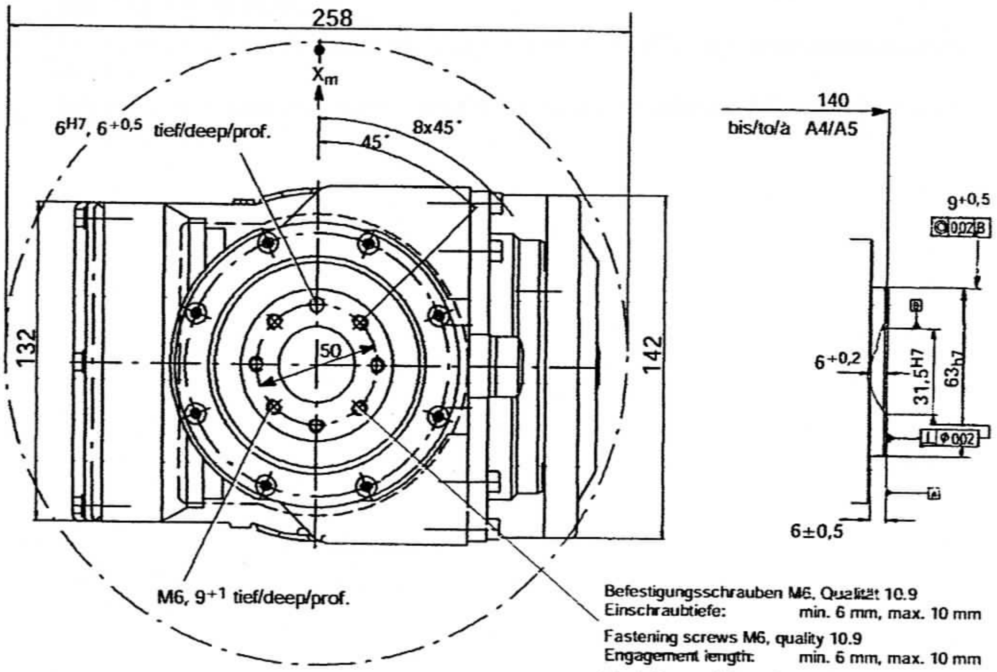


Befestigungsschrauben M6, Qualität 10.9
Einschraubtiefe: min. 6 mm, max. 7 mm

Fastening screws M6, quality 10.9
Engagement length: min. 6 mm, max. 7 mm

Vis de fixation M6, qualité 10.9
Longueur vissée: min. 6 mm, max. 7 mm

3-5 DIN/ISO-Anbauflansch für ZH 6 kg
DIN/ISO mounting flange for IW 6 kg
Bride de fixation DIN/ISO pour PL 6 kg

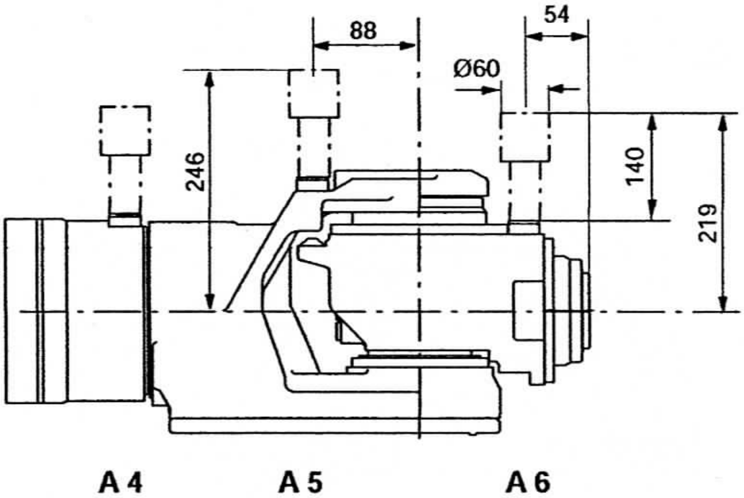


Befestigungsschrauben M6, Qualität 10.9
Einschraubtiefe: min. 6 mm, max. 10 mm

Fastening screws M6, quality 10.9
Engagement length: min. 6 mm, max. 10 mm

Vis de fixation M6, qualite 10.9
Longueur vissée: min. 6 mm, max. 10 mm

3-6 DIN/ISO-Anbauflansch für ZH 15 kg
DIN/ISO mounting flange for IW 15 kg
Bride de fixation DIN/ISO pour PL 15 kg



Für die Nullpunkt-Einstellung mit dem elektronischen Meßtaster (siehe Abschnitt 2.6) bei angebautem Werkzeug muß dieses so gestaltet sein, daß genügend Platz für Ein- und Ausbau des Meßtasters bleibt.

For zero adjustment with the electronic probe (see Section 2.6) when the tool is mounted, the latter must be designed to allow sufficient space for installation and removal of the probe.

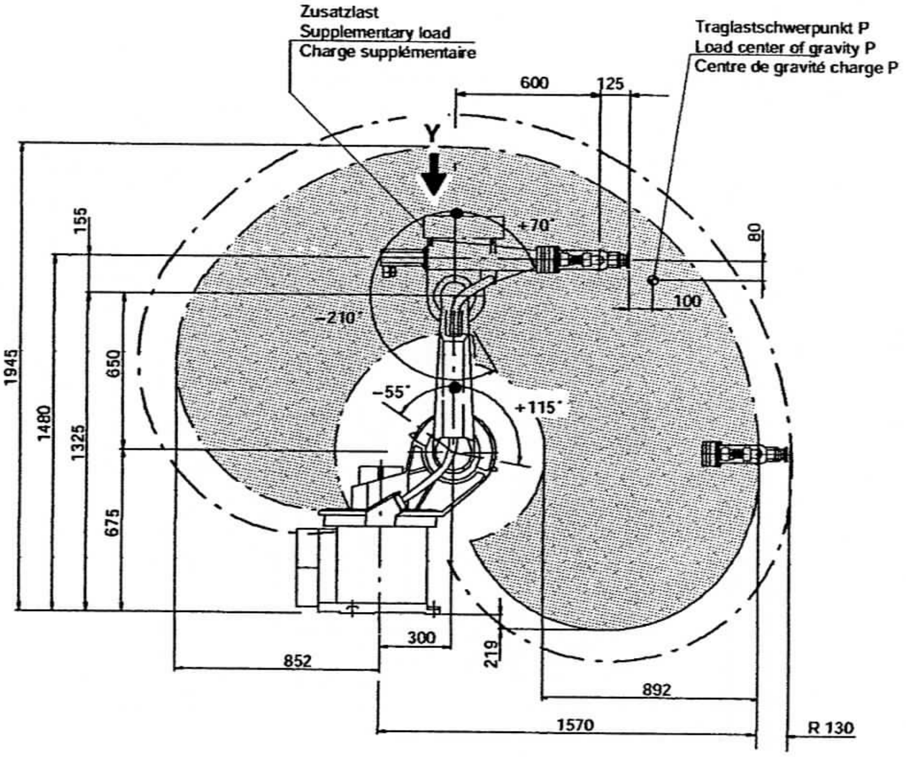
Pour le réglage du point zéro avec le palpeur de mesure électronique (voir par. 2.6) lorsque l'outil est monté, il faut qu'il soit tel qu'on ait encore de la place suffisante pour le montage et le démontage du palpeur.

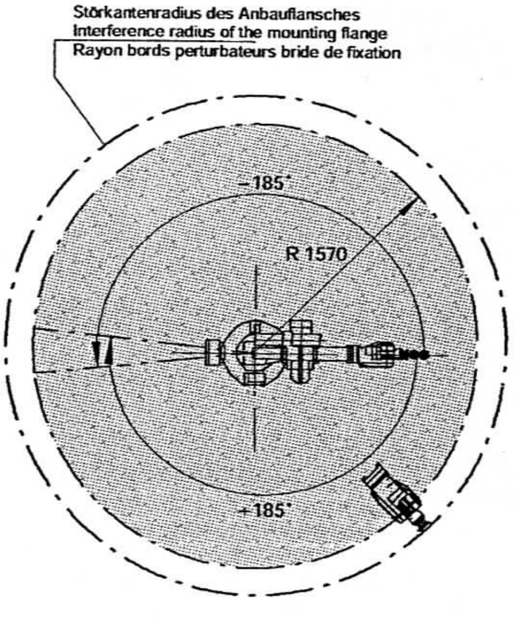
3-7

Elektronischer Meßtaster, Anbau an A4, A5 und A6 des KR 15/2, bei mechanischer Null-Stellung der A4 bis A6

Electronic probe, installation on A4, A5 and A6 of the KR 15/2, in mechanical zero position of A4 to A6

Palpeur de mesure électronique, montage sur A4, A5 et A6 du KR 15/2, en position zéro mécanique de A4 à A6



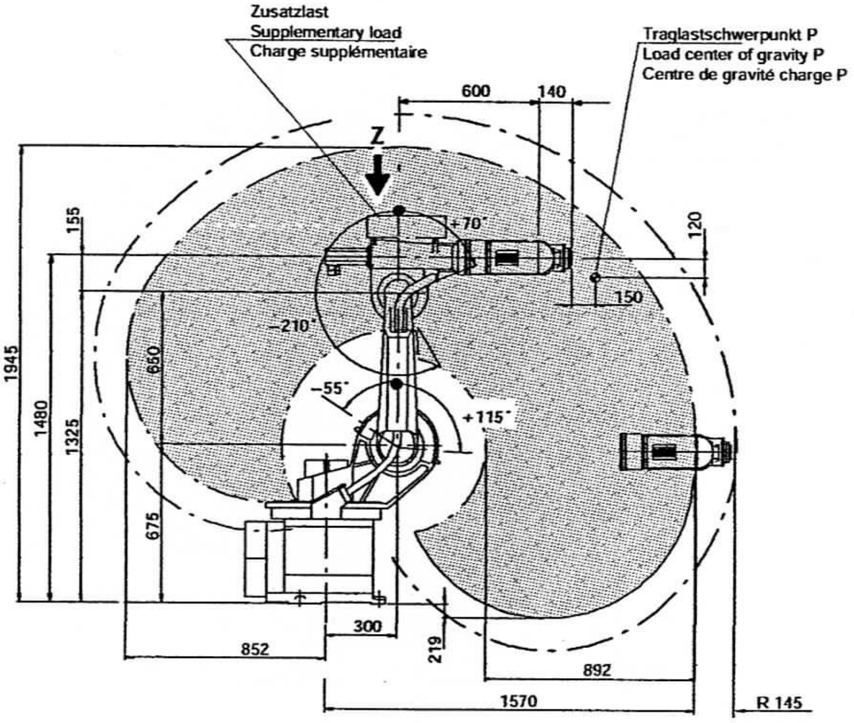


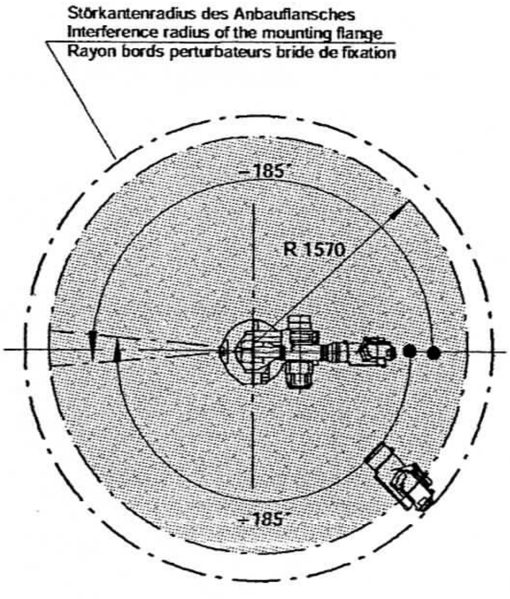
HINWEIS: Der Zusatzlast-Schwerpunkt muß so nahe wie möglich an der Drehachse 3 und an der Linie a in Bild 3-11 liegen. Bezugspunkt für den Arbeitsbereich ist der Schnittpunkt der Drehachsen 4 und 5. Ansicht Y siehe Bild 3-11.

NOTE: The center of gravity of the supplementary load must be located as close as possible to rotational axis 3 and to line a in Figure 3-11. The reference point for the working envelope is the intersection of rotational axes 4 and 5. View Y see Figure 3-11.

REMARQUE.- Le centre de gravité de la charge utile supplémentaire doit être aussi proche que possible de l'axe de rotation 3 et de la ligne a de la figure 3-11. Le point de référence de l'enveloppe d'évolution est le point d'intersection des axes de rotation 4 et 5. Vue Y voir figure 3-11.

3-8 **Hauptabmessungen und Arbeitsbereich (softwarebezogen) des KR 6/2**
Principal dimensions and working envelope (software values) of the KR 6/2
Dimensions principales et enveloppe d'évolution (se rapportant au logiciel) du KR 6/2



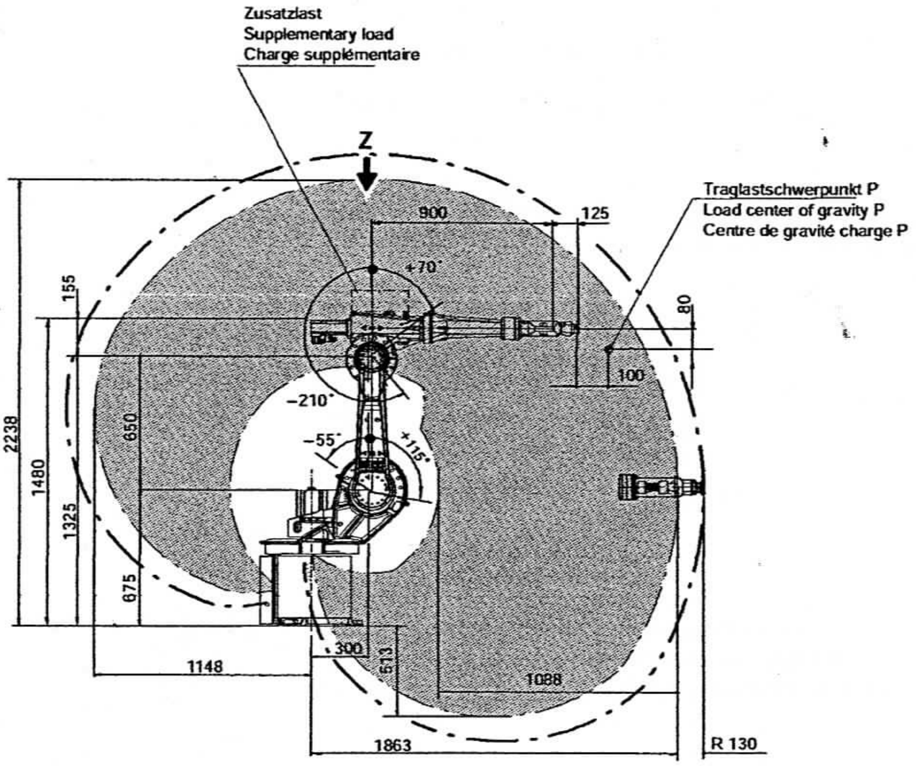


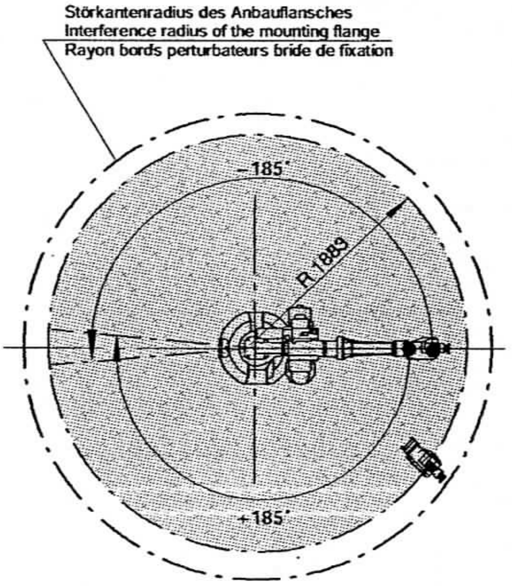
HINWEIS: Der Zusatzlast-Schwerpunkt muß so nahe wie möglich an der Drehachse 3 und an der Linie a in Bild 3-12 liegen. Bezugspunkt für den Arbeitsbereich ist der Schnittpunkt der Drehachsen 4 und 5.
Ansicht Z siehe Bild 3-12.

NOTE: The center of gravity of the supplementary load must be located as close as possible to rotational axis 3 and to line a in Figure 3-12. The reference point for the working envelope is the intersection of rotational axes 4 and 5.
View Z see Figure 3-12.

REMARQUE.- Le centre de gravité de la charge utile supplémentaire doit être aussi proche que possible de l'axe de rotation 3 et de la ligne a de la figure 3-12. Le point de référence de l'enveloppe d'évolution est le point d'intersection des axes de rotation 4 et 5.
Vue Z voir figure 3-12.

3-9 Hauptabmessungen und Arbeitsbereich (softwarebezogen) des KR 15/2
Principal dimensions and working envelope (software values) of the KR 15/2
Dimensions principales et enveloppe d'évolution (se rapportant au logiciel) du KR 15/2





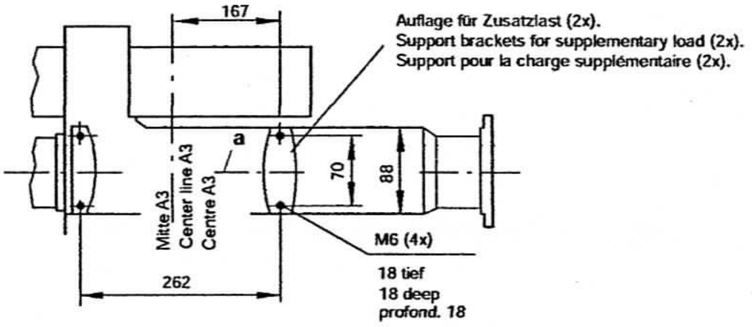
HINWEIS: Der Zusatzlast-Schwerpunkt muß so nahe wie möglich an der Drehachse 3 und an der Linie a in Bild 3-12 liegen. Bezugspunkt für den Arbeitsbereich ist der Schnittpunkt der Drehachsen 4 und 5. Ansicht Z siehe Bild 3-12.

NOTE: The center of gravity of the supplementary load must be located as close as possible to rotational axis 3 and to line a in Figure 3-12. The reference point for the working envelope is the intersection of rotational axes 4 and 5. View Z see Figure 3-12.

REMARQUE.- Le centre de gravité de la charge utile supplémentaire doit être aussi proche que possible de l'axe de rotation 3 et de la ligne a de la figure 3-12. Le point de référence de l'enveloppe d'évolution est le point d'intersection des axes de rotation 4 et 5. Vue Z voir figure 3-12.

3-10 Hauptabmessungen und Arbeitsbereich (softwarebezogen) des KR 15 L6/2
Principal dimensions and working envelope (software values) of the KR 15 L6/2
Dimensions principales et enveloppe d'évolution (se rapportant au logiciel) du KR 15 L6/2

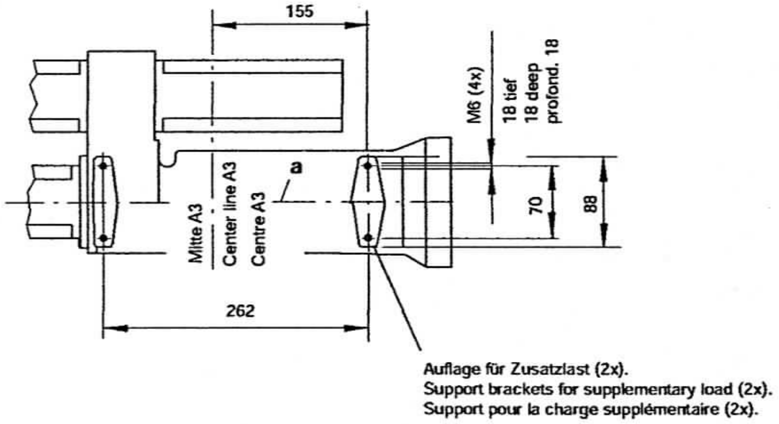
Ansicht Y siehe Bild 3-8
View Y see figure 3-8
Vue Y voir figure 3-8



Auflage für Zusatzlast (2x).
Support brackets for supplementary load (2x).
Support pour la charge supplémentaire (2x).

3-11 Befestigungsbohrungen für Zusatzlast am KR 6/2
Attachment holes for supplementary load on KR 6/2
Trous de fixation des charges supplémentaires sur le KR 6/2

Ansicht Z siehe Bild 3-9 und 3-10
View Z see figure 3-9 and 3-10
Vue Z voir figure 3-9 et 3-10



Auflage für Zusatzlast (2x).
Support brackets for supplementary load (2x).
Support pour la charge supplémentaire (2x).

3-12 Befestigungsbohrungen für Zusatzlast am KR 15/2 und KR 15 L6/2
Attachment holes for supplementary load on KR 15/2 and KR 15 L6/2
Trous de fixation des charges supplémentaires sur le KR 15/2 et KR 15 L6/2

APPENDICES

E1

Computation of Forward Kinematics Solution by Matlab

```
                                        matlab
Using Toolbox Path Cache.  Type "help toolbox_path_cache" for more info.

  To get started, select "MATLAB Help" from the Help menu.

>> j1=-19.482
j2=37.216-90
j3=0.591
j4=13.701
j5=95.349
j6=105.346
a1=300
a2=650
a3=155
a4=0
a5=0
a6=0
d1=675
d2=0
d3=0
d4=-900
d5=0
d6=-125
b1=-90
b2=0
b3=90
b4=-90
b5=90
b6=-180

c1=cos(deg2rad(j1))
s1=sin(deg2rad(j1))
c2=cos(deg2rad(j2))
s2=sin(deg2rad(j2))
c3=cos(deg2rad(j3))
s3=sin(deg2rad(j3))
c4=cos(deg2rad(j4))
s4=sin(deg2rad(j4))
c5=cos(deg2rad(j5))
s5=sin(deg2rad(j5))
c6=cos(deg2rad(j6))
s6=sin(deg2rad(j6))
cb1=cos(deg2rad(b1))
sb1=sin(deg2rad(b1))
cb2=cos(deg2rad(b2))
sb2=sin(deg2rad(b2))
cb3=cos(deg2rad(b3))
sb3=sin(deg2rad(b3))
cb4=cos(deg2rad(b4))
sb4=sin(deg2rad(b4))
cb5=cos(deg2rad(b5))
sb5=sin(deg2rad(b5))
cb6=cos(deg2rad(b6))
sb6=sin(deg2rad(b6))
a1
a2
a3
a4
a5
a6
d1
d2
d3
d4
```

```
d5
d6

h01= [ c1 -cb1*s1 sb1*s1 a1*c1; s1 cb1*c1 -sb1*c1 a1*s1; 0 sb1 cb1 d1; 0 0 0 1]

h12= [ c2 -cb2*s2 sb2*s2 a2*c2; s2 cb2*c2 -sb2*c2 a2*s2; 0 sb2 cb2 d2; 0 0 0 1]

h23= [ c3 -cb3*s3 sb3*s3 a3*c3; s3 cb3*c3 -sb3*c3 a3*s3; 0 sb3 cb3 d3; 0 0 0 1]

h34= [ c4 -cb4*s4 sb4*s4 a4*c4; s4 cb4*c4 -sb4*c4 a4*s4; 0 sb4 cb4 d4; 0 0 0 1]

h45= [ c5 -cb5*s5 sb5*s5 a5*c5; s5 cb5*c5 -sb5*c5 a5*s5; 0 sb5 cb5 d5; 0 0 0 1]

h56= [ c6 -cb6*s6 sb6*s6 a6*c6; s6 cb6*c6 -sb6*c6 a6*s6; 0 sb6 cb6 d6; 0 0 0 1]

h06= h01*h12*h23*h34*h45*h56

j1 =

  -19.4820


j2 =

  -52.7840


j3 =

    0.5910


j4 =

   13.7010


j5 =

   95.3490


j6 =

  105.3460


a1 =

   300


a2 =

   650


a3 =

   155
```

```
a4 =

     0


a5 =

     0


a6 =

     0


d1 =

   675


d2 =

     0


d3 =

     0


d4 =

  -900


d5 =

     0


d6 =

  -125


b1 =

   -90


b2 =

     0


b3 =

    90


b4 =

   -90
```

```
b5 =

    90

b6 =

  -180

c1 =

    0.9427

s1 =

   -0.3335

c2 =

    0.6048

s2 =

   -0.7964

c3 =

    0.9999

s3 =

    0.0103

c4 =

    0.9715

s4 =

    0.2369

c5 =

   -0.0932

s5 =

    0.9956

c6 =
```

```
   -0.2646


s6 =

    0.9643


cb1 =

  6.1232e-017


sb1 =

    -1


cb2 =

     1


sb2 =

     0


cb3 =

  6.1232e-017


sb3 =

     1


cb4 =

  6.1232e-017


sb4 =

    -1


cb5 =

  6.1232e-017


sb5 =

     1


cb6 =

    -1
```

```
sb6 =

 -1.2246e-016


a1 =

   300


a2 =

   650


a3 =

   155


a4 =

     0


a5 =

     0


a6 =

     0


d1 =

   675


d2 =

     0


d3 =

     0


d4 =

  -900


d5 =

     0


d6 =
```

```
  -125


h01 =

    0.9427    0.0000    0.3335  282.8239
   -0.3335    0.0000    0.9427 -100.0532
         0   -1.0000    0.0000  675.0000
         0         0         0    1.0000


h12 =

    0.6048    0.7964         0  393.1340
   -0.7964    0.6048         0 -517.6347
         0         0    1.0000         0
         0         0         0    1.0000


h23 =

    0.9999   -0.0000    0.0103  154.9918
    0.0103    0.0000   -0.9999    1.5988
         0    1.0000    0.0000         0
         0         0         0    1.0000


h34 =

    0.9715   -0.0000   -0.2369         0
    0.2369    0.0000    0.9715         0
         0   -1.0000    0.0000 -900.0000
         0         0         0    1.0000


h45 =

   -0.0932   -0.0000    0.9956         0
    0.9956   -0.0000    0.0932         0
         0    1.0000    0.0000         0
         0         0         0    1.0000


h56 =

   -0.2646    0.9643   -0.0000         0
    0.9643    0.2646   -0.0000         0
         0   -0.0000   -1.0000 -125.0000
         0         0         0    1.0000


h06 =

  1.0e+003 *

    0.0000    0.0007   -0.0007    1.3250
    0.0010   -0.0000    0.0000   -0.5000
   -0.0000   -0.0007   -0.0007    0.6750
         0         0         0    0.0010

>>
```