

**REPUBLIC OF TURKEY
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES**

**AUTOMATION OF END-OF-LINE SYSTEMS USING
COLLABORATIVE ROBOTS**



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A thesis submitted by Mohamad SAWAS in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE** is approved by the committee on 13.06.2018 in Control and Automation Engineering Graduate Program.

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TABLE OF CONTENTS

	Page
LIST OF SYMBOLS	vii
LIST OF ABBREVIATIONS.....	viii
LIST OF FIGURES	ix
LIST OF TABLES.....	xi
ABSTRACT.....	xii
ÖZET	xiv
CHAPTER 1	
INTRODUCTION	16
1.1 Literature Review	16
1.2 Objective of the Thesis	17
1.3 Hypothesis	18
1.4 Workplace Organization in World Class Manufacturing	18
CHAPTER 2	
METHODS AND MATERIALS.....	20
2.1 Universal Robot UR5.....	20
2.2 Simulation Tool	23
2.2.1 Robot Programming in Simulation Tool	23
CHAPTER 3	
ROBOT KINEMATICS	26

CHAPTER 4

DENAVIT-HARTENBERG REPRESENTATION.....	32
4.1 Denavit-Hartenberg D-H Parameters.....	32
4.2 Link Transformation Matrix	35
4.3 D-H Convention.....	36
4.4 D–H Parameters of UR5:.....	36

CHAPTER 5

RESULTS AND DISCUSSION	39
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CHAPTER 6

CONCLUSIONS	58
REFERENCES	60
APPENDIX-A	
ORIENTATION DESCRIPTION AND TRANSFORMATION.....	62
APPENDIX-B	
COMPONENTS OF THE PROJECT.....	67
CURRICULUM VITAE.....	70

LIST OF SYMBOLS

i	Number of joint or link
O_i	Origin of joint or link
d_i	Link offset
a_i	Distance between links
α_{i-1}	Angle between the lines along joints
θ_i	Link rotation angle
X_A	The X axis for known reference frame A
γ	Rotation angle about X_A
β	Rotation angle about Y_A
T	Transformation matrix
dT	Differential motions
$[\Delta]$	Differential operator
${}^i T_{i+1}$	Link Transformation Matrix

LIST OF ABBREVIATIONS

AM	Autonomous Maintenance
CAD	Computer-Aided Design
D-H	Denavit-Hartenberg
DOF	Degree-of-Freedom
EOL	End-of-Line
LCC	Life Cycle Cost
MP	Manufacturing Performance
NVAA	Not Value-Added Activities
OEE	Overall Equipment Efficiency
OLP	Off-line Programming
PnP	Pick and Place
RSL	Robot Sequence Language
STEM	Science, Technology, Engineering and Math
UR5	Universal Robot 5
VC	Visual Components
WCM	World Class Manufacturing
WO	Workplace Organization

LIST OF FIGURES

	Page
Figure 2.1 Advanced Technologies in Industrial Production	20
Figure 2.2 The rotation of the joints	22
Figure 2.3 Joints Names and Links Dimensions	23
Figure 3.1 Pure Translation	27
Figure 3.1 Describing the Gripper in Prismatic Motion	28
Figure 3.2 Describing the Gripper in Cylindrical Coordinates.....	29
Figure 3.3 Describing the Gripper in Articulated Coordinates.....	30
Figure 3.4 Describing the Fixed-Angles Convention	30
Figure 4.1 General Purpose Robot Representation	33
Figure 4.2 The Origin Location Using D-H Representation	33
Figure 4.3 Link Parameters for Intermediate Link Using D-H Representation	34
Figure 4.5 D-H Representation for The First Link According to Bias Frame.....	35
Figure 4.6 The Link Coordinate Frames of UR5.....	38
Figure 4.7 D-H Parameters of UR5 Links	38
Figure 5.1 The layout of the End-of-Line.....	39
Figure 5.2 CAD of the Layout from Top View	40
Figure 5.3 Cobot's I/O Signal in Simulation Environment	45
Figure 5.4 Simulation Tool and Statistics.....	45
Figure 5.5 Joint Analysis without Constraints.....	46
Figure 5.6 Cobot Utilization and Cumulative Number of Parts Entered.....	46
Figure 5.7 Cobot Utilization with Constraints.....	46
Figure 5.7 Cumulative Number of Parts Entered with Constraints	47
Figure 5.9 Joints Analysis with Constraints on Joint 3	47
Figure 5.10 Cost Gap between Cobotic and Robotic Case Packer	51
Figure 5.11 Shipping Carton.....	54

Figure 5.12	Ready to Pick	55
Figure 5.13	Pick Process	55
Figure 5.14	Ready to Place	55
Figure 5.15	Place Process	56
Figure 5.16	Ready for Next Pick	56
Figure A.1	Frame Example of Vector	62
Figure B.1	Shape Feeder	67
Figure B.2	Straight Conveyor	67
Figure B.3	Slope Conveyor	67
Figure B.4	Pusher	67
Figure B.5	AC Motor	68
Figure B.6	Straight Packaged Conveyor	68
Figure B.7	Robot Support Facilities	68
Figure B.8	Universal Robot 5	68
Figure B.9	Folding Case Mechanism	68

LIST OF TABLES

	Page
Table 2.1 Evolved robots in Industry 4.0	21
Table 2.2 Specifications of Universal Robot 5	22
Table 2.3 Robotics Simulation Software	24
Table 3.1 Robot Advantages According to the End-Effector Motions	31
Table 3.2 Robot Disadvantages According to the End-Effector Motions	31
Table 4.1 D-H Link Parameters UR5	37
Table 5.1 Objects Information	40
Table 5.2 Program Configuration	41
Table 5.3 Suction Gripper Properties	43
Table 5.4 Objects Properties of Flat Case	43
Table 5.5 Objects Properties of Tea Skillets	44
Table 5.6 Robot Signals I/O	44
Table 5.7 LCC Comparison between Manual and Automation Operation	48
Table 5.8 LCC Comparison between Robotic and Conventional Case packer	49
Table 5.9 LCC Comparison between Robotic and Cobotic Case packer	50
Table 5.10 Comparison of Cobotic and Conventional Packaging.....	51
Table 5.11 D-H Parameters in MATLAB Command Window	57
Table B.1 Comparison between Simulation tools and Software	69

ABSTRACT

AUTOMATION OF END-OF-LINE SYSTEMS USING COLLABORATIVE ROBOTS

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MSc. Thesis

Adviser: Assoc. Prof. Dr. Şeref Naci ENGIN

Collaborative robots have been widely used in the factories where the production lines are automated. The new industrial revolution, usually referred to as Industry 4.0, is based on the smart manufacturing, which can be implemented by means of the automation systems. Recently, the automated robotic systems have found a great interest in the factories of food and beverages since they provide a high reliability and accuracy in production lines. Furthermore, collaborative robots reduce the human labor and increase the efficiency of the line.

This thesis studies the effectiveness of implementation of an automated robotic system at the End-of-Line and, shows the process of packaging and palletizing by the collaborative robots using visualization in 3D world. It also shows the representation of the collaborative robot with 6 Degree-of-Freedom using Denavit-Hartenberg method.

Furthermore, it presents the appropriate layout of End-of-Line using a simulation tool of the Visual Components program and Robot Sequence Language. The collaborative robot Universal Robot 5 is the main element in this project. Therefore, the purpose is to simulate, analyse and implement the automation solution for End-of-Line systems in which collaborative robot Universal Robot 5 can be utilized and adapted for accomplishing the entire process.

This research discusses also on the cost effectiveness of implementing automation solution at the End-of-Line and the Workplace Organization principles from perspective of World Class Manufacturing.

Simulation tool is the significant part of this study, using Off-Line Programming and statistica which allow to make analysis for the joints movements of Universal Robot 5 in order to make good and sufficient utilization with a safety design to operate with max speed.

Key words: Collaborative robot, End-of-Line, Automation, Simulation, Foods and Beverages, Packaging, Palletizing, Industry 4.0, WCM (World Class Manufacturing)



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İŞBİRLİKÇİ ROBOTLAR KULLANARAK HAT SONU SİSTEMLERİNİN OTOMASYONU

Mohamad SAWAS

Kontrol ve Otomasyon Mühendisliği Anabilim Dalı

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İşbirlikçi robotlar, üretim hatlarının otomatikleştirildiği fabrikalarda yaygın olarak kullanılmaktadır. Genellikle Endüstri 4.0 olarak anılan yeni sanayi devrimi, otomatik sistemler aracılığıyla uygulanabilen akıllı üretime dayanmaktadır. Son zamanlarda, otomatik robotik sistemler, üretim hatlarında daha yüksek güvenilirlik ve doğruluk sağladıkları için gıda ve içecek fabrikalarında büyük ilgi kazanmışlardır. Ayrıca, işbirlikçi robotlar insan emeğini azaltır ve hattın verimliliğini artırır.

Bu tez, otomatik robotik sisteminin etkinliğini Hat-Sonu uygulamasında inceler ve 3D dünyasında görselleştirmeyi kullanarak işbirliği yapan robotlar tarafından paketleme ve paletleme sürecini sunar. Aynı zamanda Denavit-Hartenberg yöntemini kullanarak 6 serbestlik derecesi ile ortak robotun temsilini göstermektedir.

Ayrıca, Görsel Bileşenler programı ve Robot Dizi Dilinin simülasyon aracı kullanılarak Hat Sonu'nun uygun düzenlenmesini sunar. Bu projede işbirlikçi robot Universal Robot 5 ana unsurdur. Bu nedenle amaç, ortak Robot Universal Robot 5'in tüm süreci başarmak için kullanılabileceği ve adapte edilebildiği Hat-Sonu sistemleri için otomasyon çözümünü simüle etmek, analiz etmek ve uygulamaktır.

Bu araştırma, aynı zamanda Dünya Klasında Üretim perspektifinden, Hat-Sonu ve Dünya Standardında İmalat ilkelerinde uygulamalı otomasyon çözümünün maliyet etkinliğine de değinmektedir.

Simülasyon aracı, bu çalışmanın önemli bir parçasıdır; bu araçla çevrim-dışı programlama ve "statistica" kullanılarak, Universal Robot 5'in eklem hareketlerinin analizlerinin yapılmasına izin veren, maksimum hızda emniyetle çalışan bir sistem tasarımı sunulmaktadır.

Anahtar Kelimeler: İşbirlikçi robot, Hat Sonu, Otomasyon, Simülasyon, Gıda Sanayii, Paketleme, Paletleme, Endüstri 4.0, WCM (World Class Manufacturing)



INTRODUCTION

1.1 Literature Review

Fourth industrial revolution or Industry 4.0 refers to the new stage in digitalization of manufacturing where the Internet of Things (IoT) takes an important part that has the capacity to give information into it and raise the value to manufacturing industry in order to receive maximum benefits with improving operations [1].

Industry 4.0 also covers both the management and community of the entire process of the manufacturing factories. Different organizations have been releasing Industry 4.0 principles to create smarter factories [2].

In the very old eras the packaging began with natural materials such as leaves, while paper is the oldest re-shapeable packaging material [6]. Mulberry tree barks were used in China in the 1st and 2nd centuries [6]. The first commercial cardboard box was produced in England in 1817 [6]. The fact that the packaging by paper and cardboard have become important packaging materials in 1900s [6] and could now be used in high amounts, meant that the process could be done and spread more easily amongst production areas. Replacing wooden boxes in trade was with the invention of corrugated cardboard [6]. The 20th century was the brightest era for paper and cardboard [6].

The next revolution in packaging has been with 3D packaging, whereas the package becomes as unique as the products [7]. 3D packaging emerges immediately and attracts customers' interest [7]. In general, the end of line packaging is done by automation sequential layers until the desired package is formed. The moving forward in technology has driven spectacularly for industrial productivity since the aurora of the Industrial Revolution [8].

The robots have been used for long terms in industrial manufacturing to outfit with complex tasks and they have been developed to be more autonomous, capable of bending with flexibility and working collaboratively [8]. Several robots have been designed to react with each other and to work with human side by side in a safe way [8]. For example, Kuka which is a European robotic manufacturer, the Kuka LBR iiwa is lightweight can be assigned for high sensitive operations and can operate alone making optimization and recording all the outcomes of its operations to the cloud [8] [9]. Likewise, ABB has manufactured the industrial robot which named “you and me”, which has been designed with dual arm with multi-functionality to adopt vast automation operations in industry and has been introduced in Hannover Messe in 2015.

1.2 Objective of the Thesis

This study provides introduction of the new method in packaging using collaborative robot to automate and control the main process which is pick-and-place. An example of end-of-line packaging and palletizing was studied, trying to find and an ultimately proposal layout of a fully automated packaging solution. This production line handles beverages products. The aim is to use the new system and technologies to increase the speed of the process and to reduce the footprint of the layout. Moreover, reducing manual labor activities and optimized costs. Therefore, in this research the motivation is to be able to automate the process and utilize the collaborative robot to achieve high performance of forming the package and shipping it to a desired location in order to pick and place the tea skillets inside the package. The Universal Robot 5 is the main item of this study, it has 6 Degrees of Freedom (DOF) robotic arm.

In order to optimize the utilization of the robot, both MATLAB and Visual Components Simulation tools used in this study. In MATLAB, using robotics and Peter Corke toolboxes to define a set of kinematic constraints on the joints and compute and generate a sequence of robot configurations that satisfy the following criteria of automatic operations:

- Picking 6 skillets in one time.
- Filling (placing skillets into cartons with pneumatic gripper).
- Repeat the pick and place operation.

In VC, with 3D simulation and visualization, the motivation is to visualize the entire process in 3D world of the following sequence:

- Box preparation (box erecting).
- Carton transfer / Shipping carton to be shaped.
- Start in the home configuration (initial position).

In addition, programming the robot in VC using Robot Sequence Language (RSL), and analyzing the robot joints movements in order to find the minimum cycle time of the process and optimize the robot utilization.

1.3 Hypothesis

This thesis consists of 6 chapters. After the general introductory chapter, Chapter 1, where a literature review, WO, motivation and organization of the thesis are presented, Chapter 2 gives details about the materials and methods that are used in this study, where UR5 is introduced in first section of this chapter, and simulation tools are presented in the next section.

In Chapter 3, the forward and inverse kinematics of the robot are discussed. As well as, the configuration of the end-effector motions is important; therefore, the possibilities of these motions and both advantages and disadvantages for each of them are mainly discussed in this chapter.

Chapter 4 shows Denavit-Hartenberg representation method for robot motions and studies all parameters of this method in the first section of this chapter. The second section of Chapter 4 shows how to form the link transformation matrix of the robot starting with the first joint and ending with the end-effector. The D-H method convention steps and D-H parameters of UR5 are presented in the third and fourth sections of Chapter 4.

The results and discussion are in Chapter 5, where the programs configurations, the layout designs, the cost effectiveness comparison, the simulation results and robot joints analysis are shown with details.

Chapter 6 is the conclusion part of the thesis where all project results are summarized in this chapter.

1.4 Workplace Organization in World Class Manufacturing

The new generation of manufacturing intends to become world class with the new-found confidence in the future of industry [11]. The World Class Manufacturing has ten pillars

which they work together collaboratively to establish sustainable manufacturing for improving the performance and enhancing the quality of the products [12]

Workplace Organization is a 7 steps pillar and a part of Autonomous Maintenance pillar [13]. The aim of WO is to improve productivity, remove variation and stabilize processes, by restoring basic conditions, eliminating Not Value-Added Activities (NVAA) and involving shop floor people [13].

It is recommended to use this method when the production processes are affected by chronicle NVAA losses, where there are several operators performing manual activities (areas usually affected by significant chronical NVAA). The Objective of step 0 in WO is to classify the factory areas in order to define the priorities for the pillar [14].

WO areas classification in based on NVAA and Quality Defect losses (due to man and method). NVAA are all the activities which do NOT add value to the product and that a customer is not willing to pay for.

Main activities you need to complete in Step 1 [14]:

- 5S training and application
- TAG training and application
- List and map of contamination sources
- Initial cleaning schedule
- Countermeasures against Sources of contamination

WO areas classification needs to be done based on NVAA losses and Quality Defects losses due to man and method. Step 1 in WO focuses on initial cleaning, where the objective is to create a tidy and well-organized area by eliminating unnecessary materials and removing dust and contamination sources [14] using a variety of different programs, standards and lean tools [15]. 5S is a powerful tool to create tidy and well-organized area [16].

METHODS AND MATERIALS

At present, we are in the middle of the fourth stage of technological advancement, the rising of modern digital industrial technology called as Industry 4.0, a conversion that is leaded by nine basics in technology advances [8].

The advanced technologies in industrial production can be seen from Figure 2.1.

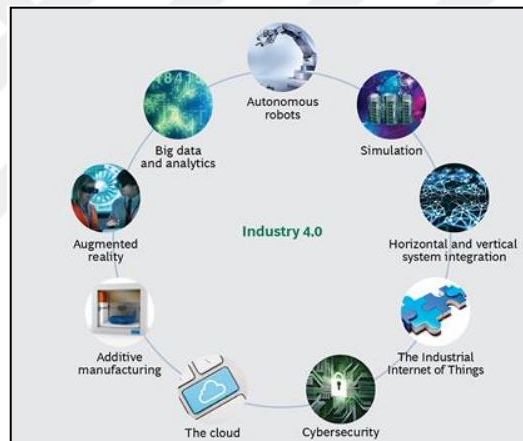


Figure 2.1 Advanced Technologies in Industrial Production [8]

2.1 Universal Robot UR5

Universal robots (UR) with its easy-to use and cost-effective collaborative robots (cobots) which have been widely used in manufacturing to operate pick-and-place tasks with high utilities. The UR series has the three collaborative robots (UR3-UR5 and UR10), provides robot with high flexible and low-weight arms that can deal with collaborative process. The comparison between models of collaborative robots are listed Table 2.1 shows other collaborative robots which have also evolved to keep up with the trend of Industry 4.0.

Table 2.1 Evolved robots in Industry 4.0

No	Manufacturer	Name	Axes	Weight	Payload	Speed	Applications	Range
1	Fanuc	CR-35iA	6-axis	990 kg	35 kg	250 mm/s	Automotive Packaging	1.813 mm
2	Universal robots	UR 5	6-axis	18.4 kg	5 kg	1 m/s	PnP Process and Packaging	850 mm
3	ABB	YuMi	7-axis arms	38 kg	0.5 kg	1.5 m/s	Consumer Products and assemble of Small parts	500 mm
4	APAS	Bosch	6-axis	230 kg	2 kg	0.5 m/s	PnP Process, Assembly Packaging	911 mm
5	KUKA	IIWA	7-axis	22.3 kg	7 kg	180°/s	PnP Process, Assembly Packaging	911 mm

The specification of UR5 is listed in the following Table 2.2. The robot UR5, is the key of this study so it is important know more about this robot. We introduce in an overview on this robot and its capabilities.

Table 2.2 Specifications of Universal Robot 5 [17]

Weight	18.4 kg / 40.6 lbs
Payload	5 kg / 11 lbs
Reach	850 mm / 33.5 in
Joint ranges	+/- 360° on all joints
Speed	180°/sec
Repeatability	+/- 0.1 mm / +/- 0.0039 in (4 mil)
Footprint	149 mm / 5.9 in
Degree of Freedom	6 rotating joints
Calculated Operating Life	35,000 Hours

UR5 with the rotation direction of the joints is shown in the Figure 2.2. This robotic arm has six revolute joints and they are referred to the base.

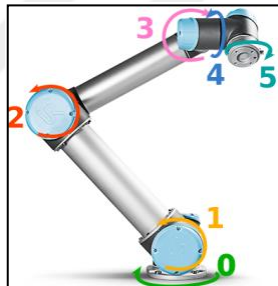


Figure 2.2 The rotation of the joints

The joints names and the dimension measurements of the links are also shown in this figure 2.3.

These joints are:

1. Base
2. Shoulder
3. Elbow
4. Wrist 1
5. Wrist 2
6. Wrist 3

The first three joints have the same equipment and the same type of servo motors used to rotate the joints, they are also connected to each other with long links and this make the reachability of the robot arm longer.

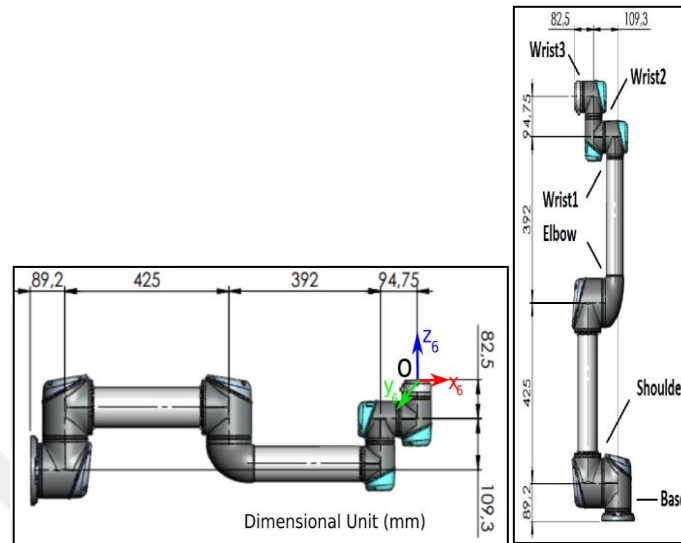


Figure 2.3 Joints Names and Links Dimensions [17]

2.2 Simulation Tool

The next sections show what we can use the Off-line Programming (OLP) in simulation tool and the benefits of off-line programming.

2.2.1 Robot Programming in Simulation Tool

Another advanced technology has been used in industrial production is simulation. Most factories use commercial software to simulate manufacture processes or handling of materials systems [10]. There are some of simulation applications that can be done in manufacturing as following [10]. Visual Components is a master and developer of 3D manufacturing simulation tool, it provides solutions for layout design, off-line programming, system and cost-effective solutions to build and simulate process on production lines [18]. Visual Components software is trusted by hundreds of organizations worldwide to support critical planning and decision-making processes [18].

Evaluation of changeover in products [18]:

- Planning of labor
- Schedule production
- Analysis of bottleneck

- Strategies of quality-control
- The effectiveness of new device on an existed system

The following table 2.3 shows the trend in robotics simulation software that are used in manufacturing areas.

Table 2.3 Robotics Simulation Software

Name	Description
Virtual Robotics Toolkit	Focuses on STEM education, useful for robotics competitions
Visual Components	Entire manufacturing processes can be simulated in 3D world and analyzed, including robotics equipment, material flow, human operator actions and has 3D models for almost all industrial and collaborative robots
RoboDk	Scripting using Python or creating programs visually thanks to its integrated 3D simulation environment, 3D models for 200 industrial robots and tools from ABB, KUKA and Yaskawa
Robot Virtual Worlds	Can program virtual Mindstorms EV3, VEX or TETRIX robots, and observe behavior in the 3D simulation environment.

The OLP has come to be used over years ago, it was expensive and complex technology while it is now more developed, much easier to be used and affordable [21]. Many automation projects can be done with OLP in a way that it saves time and improve the productivity by significant return of saving costs [21]. We can create robot model in a 3D visualization using OLP, this can be done by teaching the robot path of positions, for example; the robot completes sequence of path positions provided by the programmer

with path statement [21]. In MATLAB also, Peter Corke toolbox has many functions which are helpful for simulation of collaborative robots' motions and dynamics such as generation of path trajectory and robot kinematics [19].



ROBOT KINEMATICS

Forward Kinematic of the robot means calculating the position and orientation of a frame (e.g., gripper or a hand etc.) [26]. This is very helpful in forward kinematic analysis of a robot. In other words, if all robot joint variables are known, using forward kinematic one could know where is the robot located.

On the other hand, Inverse Kinematics of the robot means locating the robot at a desired location and orientation by knowing each link length or joint angle [27].

In order to start the study of robot kinematics, we must first know the composite of orientation matrix caused by the rotations around X, Y, Z axes, while it is possible to multiply basic rotation matrices in an order of definite rotation angles about the base coordinate system OXYZ whereas the principal axes OX, OY, OZ.

Since the multiplication of matrices is not commutative, then the sequence order is important in which the multiplication is carried out. For example, the sequence order to get a composite rotation matrix for three rotations can be given as follows:

1. A rotation of angle α about OX
2. A rotation of angle θ about OZ
3. A rotation of angle β about OY

Consequently, the composite matrix can be written as follows,

$$R_{\text{Comp}} = R(Y, \beta), R(Z, \theta), R(X, \alpha) \quad (3.1)$$

In case of Pure Translation as shown in Figure 3.1, which means that the object orientation has no changing after its moving in the space, the composite matrix takes the following shape:

$$R_{\text{Comp}} = R(Z, \theta), R(Y, \beta), R(X, \alpha) \quad (3.2)$$

Hence,

$$R_{\text{comp}} = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \beta & 0 & \sin \beta \\ 0 & 1 & 0 \\ -\sin \beta & 0 & \cos \beta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha & -\sin \alpha \\ 0 & \sin \alpha & \cos \alpha \end{bmatrix}$$

$$R_{\text{comp}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3.3)$$

As we can see and since the rotation about the base frame is zero (no rotation founded), i.e., the rotation matrix becomes unity matrix.

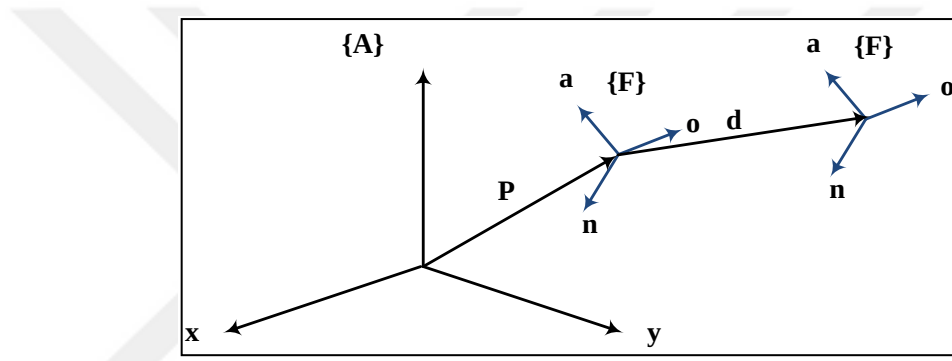


Figure 3.1 Pure Translation [31]

In this chapter we deal also with combined transformations which consist of a number of translations and rotations about relative fixed reference or known frame axes. The rule stays as previous where the sequence order is important to able to make the transformation resolved into a set of motions. Let us describe the following order sequence for rotating a frame around x-axis, then translating about x, y and z, and at the end rotating about y-axis in order to accomplish the transformation. Therefore, the required transformation about reference base frame OXYZ is:

1. Rotation of angle α about OX.
2. Translation of (l_1) , (l_2) and (l_3) relative to x, y and z respectively.
3. Rotation of angle β about OY.

The combined transformation can be represented as follows:

$$P_{\text{xyz}} = R(y, \beta) \times \text{Trans}(l_1, l_2, l_3) \times R(x, \alpha) P_{\text{noa}} \quad (3.4)$$

As seen before, the sequence and the order of transformation is significant and important. For the combined transformation the first ordered is last arranged and this is called a pre-multiplication.

It is important to know about the configuration of end-effector motions, the motion can take one of the following possibilities:

- Cartesian coordinates (prismatic motion): In this type of a robot, all actuators are linear such as hydraulic arm or linear motion of a linear motor or power screw [28]. The positioning of a robot hand is accomplished by moving the three linear joints along the three axes. Since there are no rotations, the transformation matrix representing this motion to any point referred to reference coordinates is considered as a homogenous transformation matrix. In other words, the only information needed for describing the gripper motion is the position of the rigid body in which the gripper is to move i.e., $P \{P_x, P_y, P_z\}$. See Figure [3.1].

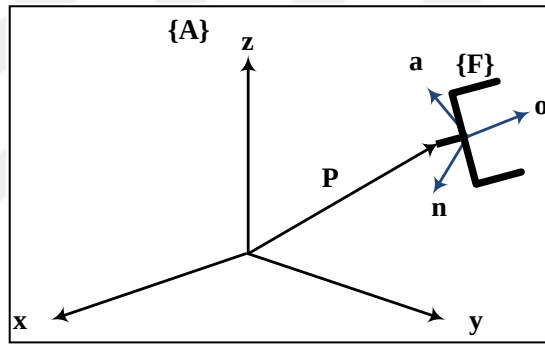


Figure 3.1 Describing the Gripper in Prismatic Motion [31]

Then, the transformation matrix can be defined as the following:

$${}^A T_P = \begin{bmatrix} 1 & 0 & 0 & P_x \\ 0 & 1 & 0 & P_y \\ 0 & 0 & 1 & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.4)$$

- Cylindrical Coordinates: this system has translations of two linear (r , l) and only one rotation (α). Figure 3.2 shows the gripper description of this type where in the first comes the translation of (r) along x-axis, the rotation of (α) about z-axis is the second and the third sequence is the (l) translation along z-axis [31].

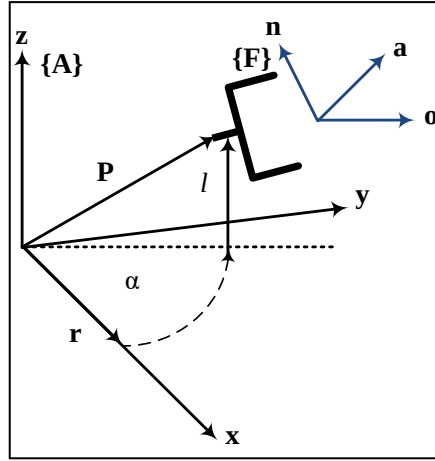


Figure 3.2 Describing the Gripper in Cylindrical Coordinates

Therefore, the final transformation which occurs by all the three transformations can be as follows:

$${}^A T_P = T_{cyl}(r, \alpha, 1) = \text{Trans}(0,0,l)R(z, \alpha)\text{Trans}(r, 0,0) =$$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C\alpha & -S\alpha & 0 & 0 \\ S\alpha & C\alpha & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & r \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} C\alpha & -S\alpha & 0 & rC\alpha \\ S\alpha & C\alpha & 0 & rS\alpha \\ 0 & 0 & 1 & L \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.5)$$

- Spherical coordinates: This system has two rotation motions and only one linear translation. First comes the translation of (r) along z-axis, then in the second comes the rotation of (β) about the y-axis, and at the end the rotation of (γ) about the z-axis. Figure 3.3 shows the gripper description of the spherical coordinates type.

$${}^A T_P = T_{sph}(r, \beta, \gamma) = R(z, \gamma)R(y, \beta)\text{Trans}(0,0,r) \quad (3.6)$$

$${}^A T_P = \begin{bmatrix} C\gamma & -S\gamma & 0 & 0 \\ S\gamma & C\gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C\beta & 0 & S\beta & 0 \\ 0 & 1 & 0 & 0 \\ -S\beta & 0 & C\beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & r \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.7)$$

$${}^A T_P = \begin{bmatrix} C\beta C\gamma & -S\gamma & S\beta C\gamma & rS\beta C\gamma \\ C\beta S\gamma & C\gamma & S\beta S\gamma & rS\beta S\gamma \\ -S\beta & 0 & C\beta & rC\beta \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.8)$$

Therefore, the final transformation which occurs by all the three transformations can be as follows:

- Articulated coordinates (all-revolute): in this type of systems, the all three motions are rotation ones. Those rotations can be shown in Figure 3.3

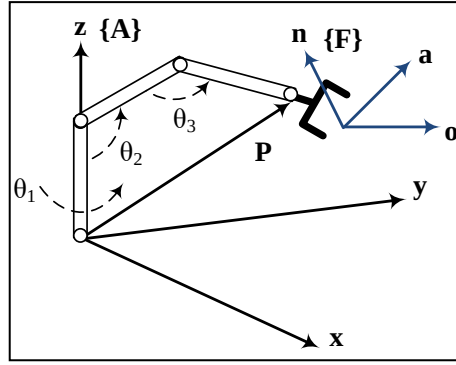


Figure 3.3 Describing the Gripper in Articulated Coordinates

So that, to describe a frame (B) in the orientation using this type we can start from a known frame which called (A) and supposing it as a reference frame. First, we rotate the frame (B) about (X_A) by an angle (γ), then rotate about (Y_A) by an angle β , and then rotate about (Z_A) by an angle (α). So, in this way, each of the rotations can make a rotation about an axis of the fixed reference frame (A). Figure 3.4 describes this type as well.

This convention is called fixed-angles for specifying an orientation of X, Y and Z. Though this convention means that the motion rotations are done about known reference frame. in some other studies, this convention is called as Roll, Pitch, and Yaw, which refers to the three rotation angles [29].

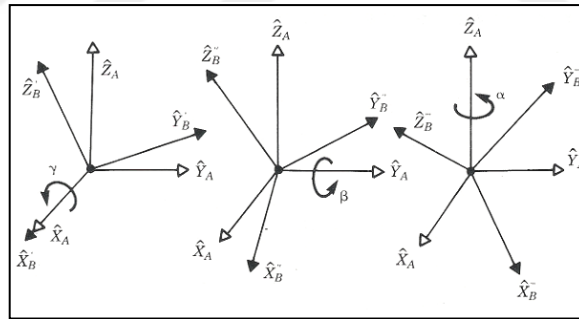


Figure 3.4 Describing the Fixed-Angles Convention

Since all the rotation motions occur about the reference frame axes, then the derivation of the related matrix of rotation shown in the equation (3.10) is straight forward.

$${}^A_B R_{xyz}(\gamma, \beta, \alpha) = R_z(\alpha)R_y(\beta)R_x(\gamma) \quad (3.9)$$

$$= \begin{bmatrix} c\alpha & -s\alpha & 0 \\ s\alpha & c\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c\beta & 0 & s\beta \\ 0 & 1 & 0 \\ -s\beta & 0 & c\beta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\gamma & -s\gamma \\ 0 & s\gamma & c\gamma \end{bmatrix} \quad (3.10)$$

Thus,

$${}^A_B R_{xyz}(\gamma, \beta, \alpha) = \begin{bmatrix} c\alpha c\beta & c\alpha s\beta s\gamma - s\alpha c\gamma & c\alpha s\beta c\gamma + s\alpha s\gamma \\ s\alpha c\beta & s\alpha s\beta s\gamma + c\alpha c\gamma & s\alpha s\beta c\gamma - c\alpha s\gamma \\ -s\beta & c\beta s\gamma & c\beta c\gamma \end{bmatrix} \begin{bmatrix} c\beta & 0 & s\beta \\ 0 & 1 & 0 \\ -s\beta & 0 & c\beta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\gamma & -s\gamma \\ 0 & s\gamma & c\gamma \end{bmatrix} \quad (3.11)$$

According to the end-effector motions, robots can be classified to four types as shown in Table 3.1 and Table 3.2. The advantages of each type are presented in Table 3.1, while these disadvantages of each type are presented in Table 3.2.

Table 3.1 Robot Advantages According to the End-Effector Motions

End-effector	Advantages
Cartesian	Simple control system since it has only prismatic motions
Spherical	Ability to make a full rotation of 360° and ability for long horizontal reach
Cylindrical	Ability to reach horizontal structure into machines and it has a good repeatability and rigid body which allows to deal with large payloads
Articulated	Minimum footprint, speed and agility

Table 3.2 Robot Disadvantages According to the End-Effector Motions

End-effector	Disadvantages
Cartesian	Difficult maintenance
Spherical	No linear actuator for Z-axis,
Cylindrical	Limitation design that makes the robot unable to rotate a full 360°
Articulated	The need for more sophisticated and high control requirements, and high costs

There are also several methods to represent and model the robot motions. In our study we use D-H (Denavit-Hartenburg) which is studied in the next chapter.

Denavit-Hartenberg Representation

The Denavit-Hartenberg (D-H) is a useful tool for robot motion modelling and a way of representing robots. Applications of D-H representation [24] [31]

1. Transformation in any coordinates (Cartesian, Cylindrical, Spherical and Articulated)
2. All revolute and articulated robots
3. Any possible combinations of joints and links

Thus, any general set of joints and links may create a robot that we would like to model and represent. To model or represent a robot using D-H representation, we need to [23]:

1. Assign a reference frame to each joint
2. Define a general procedure to transform from one joint to the next (one frame to the next).

If all transformations have been combined from the base to the first joint, from the first joint to the second joint and so on to the last joint, then one can get the robot total transformation matrix.

4.1 Denavit-Hartenberg D-H Parameters

To Derive the D-H representation, let us have the following general-purpose robot as shown in Figure 4.1 which describes three intermediate rotary joints in a manipulator.

The axis of the joints (i-1), (i), and (i+1), are labeled (Z_{i-1}), (Z_i) and (Z_{i+1}). The links (i-2), (i-1), (i) and (i+1), are connected to the joints. The coordinates (i-1) and (i) are attached to links (i-1) and (i).

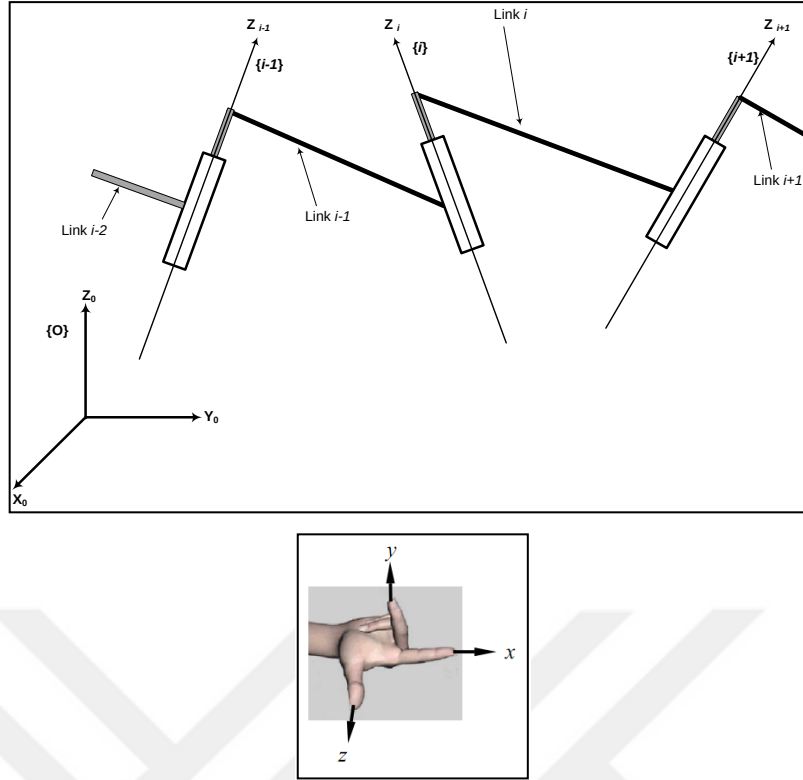


Figure 4.1 General Purpose Robot Representation [31]

The origin $O(i-1)$ and $O(i)$ are located on the joints axis (Z_{i-1}), (Z_i) respectively, as shown in Figure 4.2

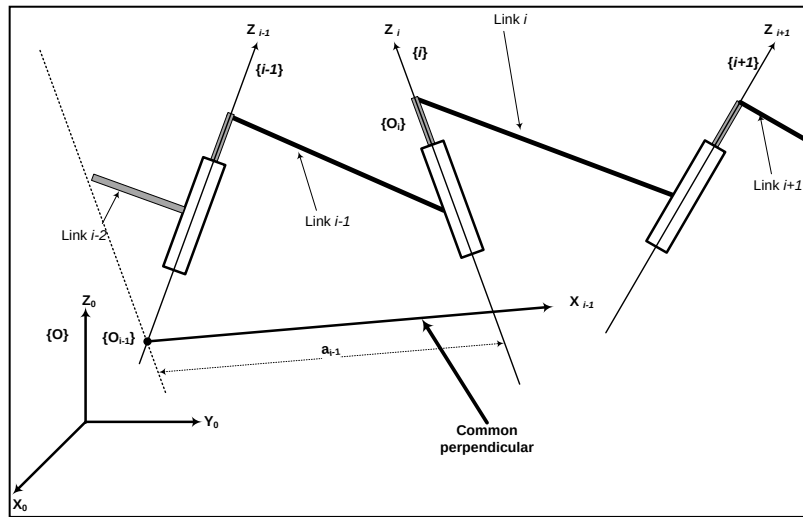


Figure 4.2 The Origin Location Using D-H Representation [31]

Likewise, the coordinate axis (Z_i) is along the joint axis (i). (X_i) is along the common perpendicular between (Z_i) and (Z_{i+1}). (O_i) is the point of intersection of the line along (X_i) and the line along (Z_i). The first parameter for link (i) is the twist angle (α_{i-1}). (α_{i-1}) is defined as the angle between the lines along joints ($i-1$) and (i) measured about the

common perpendicular (X_{i-1}). According to right-hand rule, the twist angle α_{i-1} ranges between 0 & $(\pm\pi)$ rad.

The second parameter for link (i) is (a_{i-1}) which represents the distance between the lines along joint (i-1) and (i) along the common perpendicular.

The third parameter is the link offset (d_i) which represents the distance along (Z_i) from the line parallel to (X_{i-1}) to the line parallel to (X_i).

We have to notice that if the joint is revolute then (d_i) is constant; whereas if the joint is prismatic then d_i is a variable and it can be positive or negative.

The fourth parameter is the link rotation angle (θ_i) which is the angle between (X_{i-1}) and (X_i) measured about (Z_i) according to right hand-rule. If the joint is prismatic then (θ_i) is constant, and if the joint is revolute then (θ_i) is a variable. (θ_i) is signed quantity and ranges between $(0 \text{ \& } \pm\pi)$.

Figure 4.3 shows link parameters for intermediate links, and summarize the all parameters.

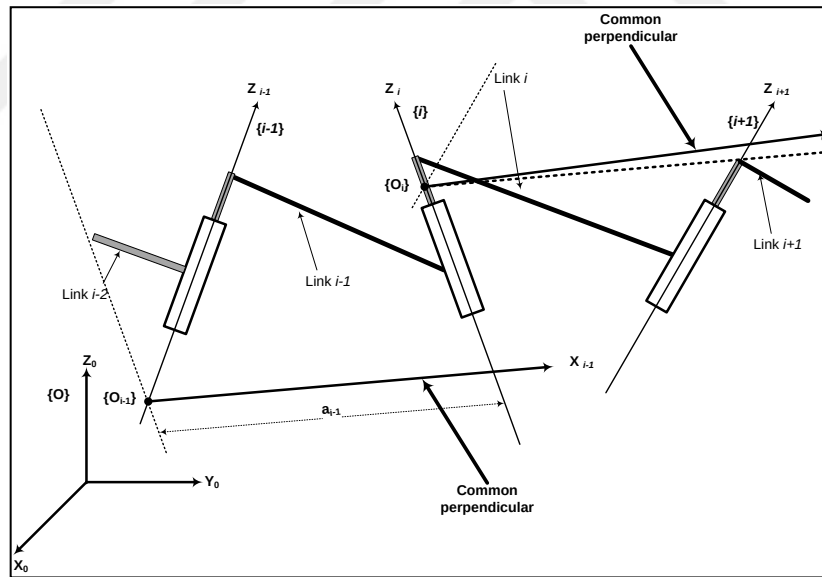


Figure 4.3 Link Parameters for Intermediate Link Using D-H Representation

D-H parameters define the motion of actuators connected by rigid links, D-H is efficient for forward and inverse kinematics calculation. First, we have to put the base frame which is generally the “previous joint”.

The process begins by defining Z axis along the axis of rotation or the axis of translation for prismatic joints. The X axis for base frame is a free choice, for later joints each X axis

will point always from the previous joint. Y axis is now constrained to complete right-hand coordinate frame. The next joint, again Z axis is defined by the axis of actuation, and now we can determine the transformation between them. As before, Z axis points along the axis of rotation.

From this section we can understand that D-H parameters are derived from common normal between consecutive Z axes. The common normal is orthogonal to both vectors, as also the shortest line between them.

The new X axis points along the intersection of the new Z. But we have to notice that the origin is not at the center of the actuator (physically) but it can be in “open space” because D-H parameters are only concerned with the motion of the components.

With these joint axes, four parameters specify the joint-to-joint transformation. According to DH, first we put the Z0 axis in rotation and X0 particular on Z0, for Y0 we can put it according to the right-hand rule, as shown in Figure 4.5, where Z0 and X0 are very important for bias frame.

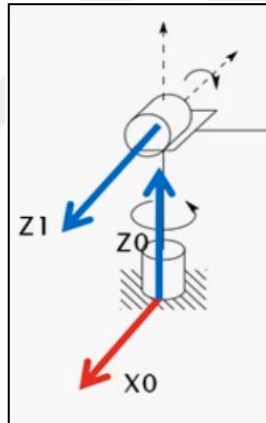


Figure 4.5 D-H Representation for The First Link According to Bias Frame

After the D-H representation has been established, the next step is to follow the necessary motions to transform from one reference frame to the next, and this is shown in the next section.

4.2 Link Transformation Matrix

If the axes of two consecutive joints (i-1) and (i) are parallel, then there are many common perpendiculars. Assuming that we are at the local reference frame ($X_i - Z_i$), then we can do the following standard motions to get to the next local reference frame ($X_{i+1} - Z_{i+1}$).

$${}^i T_{i+1} = A_{n+1} = \text{Rot}(z, \theta_{i+1}) \text{Trans}(0, 0, d_{i+1}) \text{Trans}(a_{i+1}, 0, 0) \text{Rot}(x, \alpha_{i+1}) \quad (4.1)$$

At the base of the robot we can start with the first joint and transform to the second joint, then to the third and so on till the hand (gripper of the robot) eventually to the end effector.

Calling each transformation (A_{i+1}), there will be many A matrices that represent the transformation. The total transformation between the base of the robot and the hand will be as follow:

$${}^R T_H = {}^0 T_1 {}^1 T_2 {}^2 T_3 {}^3 T_4 \dots {}^{i-1} T_i = A_1 A_2 A_3 A_4 \dots A_i \quad (4.2)$$

The next step is to make the convention of D-H by following the steps which are shown in the next section.

4.3 D-H Convention

The convention of D-H can be done with the following steps [25]:

- Number the joints from (1) to (n) starting with the base and ending with the end-effector.
- Establish the base coordinate system.
- Establish a right-hand orthogonal coordinate system (X_0, Y_0, Z_0) at the supporting base with Z_0 axis lying along the axis of motion of joint 1.
- Establish joint axis. Align the (Z_i) with the axis of motion (rotary or sliding) of joint (i+1).
- Establish the origin of the (i^{th}) coordinate system. Locate the origin of the (i^{th}) coordinate at the intersection of the (Z_i) & (Z_{i-1}) or at the intersection of common normal between the (Z_i) & (Z_{i-1}) axes and the (Z_i) axis.
- Establish (X_i) or along the common normal between the (Z_{i-1}) & (Z_i) axes when they are parallel.
- Assign (Y_i) to complete the right-hand coordinate system.
- Find the link and joint parameters.

4.4 D-H Parameters of UR5:

In this section we apply the previous steps of D-H convention and notes on our collaborative robot UR 5.

The UR5 collaborative robot uses D–H parameters which are determined in [22]. D-H Link Parameters are used in the analysis which is presented in Table 2.1

Table 4.1 D-H Link Parameters UR5

Joint	α_i (alpha)	a_i	d_i	θ_i
Base	1.570796327	0	0.089459	θ_0
Upper Arm	0	-0.42500	0	θ_1
Lower Arm	0	-0.39225	0	θ_2
Wrist 2	1.570796327	0	0.10915	θ_3
Wrist 3	-1.570796327	0	0.09465	θ_4
Tool Mounting Bracket	0	0	0.0823	θ_5

d_i : Distance from origin of (i-1) coordinate to intersection of (Z_{i-1}) and (X_i) along (Z_{i-1}).

a_i : Distance from intersection of (Z_{i-1}) and (X_i) to origin of (i) coordinate along (X_i).

α_{i-1} : Rotation angle from (Z_{i-1}) to (Z_i) about (X_i).

θ_i : Rotation angle from (X_{i-1}) to (X_i) about (Z_{i-1}).

The order of the links for UR5 is shown as following:

[Base, Upper Arm, Lower arm, Wrist 2, Wrist 3, Tool Mounting Bracket]

As well as the mass calculations can be given as following [22]:

mass = [3.7000, 8.3930, 2.33, 1.2190, 1.2190, 0.1897]

Center_of_Mass = [[0,-0.02561, 0.00193], [0.2125, 0, 0.11336], [0.15, 0, 0.0265], [0, -0.0018, 0.01634], [0, -0.0018, 0.01634], [0, 0, -0.001159]]

In the following Figure 4.6 shows the UR5 with its link coordinate frames of joints¹using D-H method and the last results [22].

¹ We should know the parameters: mass, center of mass, a, d and alpha for each “rigid body” and the actual joint angle to make it possible to calculate the center of mass for the complete robot [22]

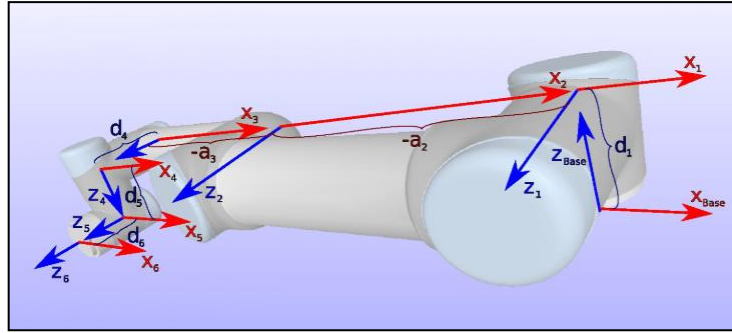


Figure 4.6 The Link Coordinate Frames of UR5 [22]

On the other hand, Figure 4.7 shows the UR5 links and D-H parameters [22]

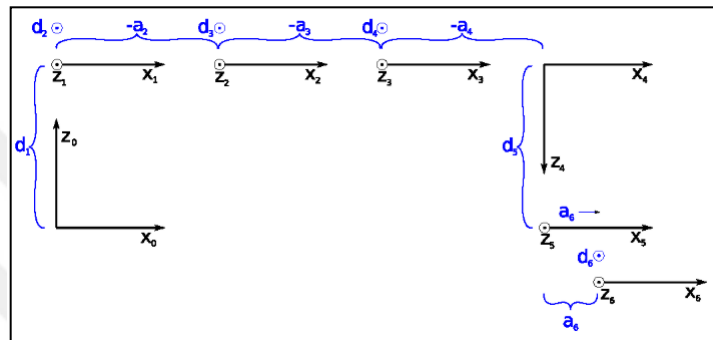


Figure 4.7 D-H Parameters of UR5 Links²[22]

²The constants can be found in the robot, in the urcontrol.conf file. And script codes can be used to find the actual joint angel [22].

RESULTS AND DISCUSSION

In this project we are concerned in the layout of the system, in which it can make the lowest footprint of the space, so that the design is done to accomplish both of forming the package and feeding materials into it, the following figure, Figure 5.1, shows the layout of the project using simulation tool:



Figure 5.1 The layout of the End-of-Line

To simulate this layout in the simulation program, the CAD design file has been drawn and prepared to make the best simulation using OLP. Figure 5.2 shows the CAD design of the layout.

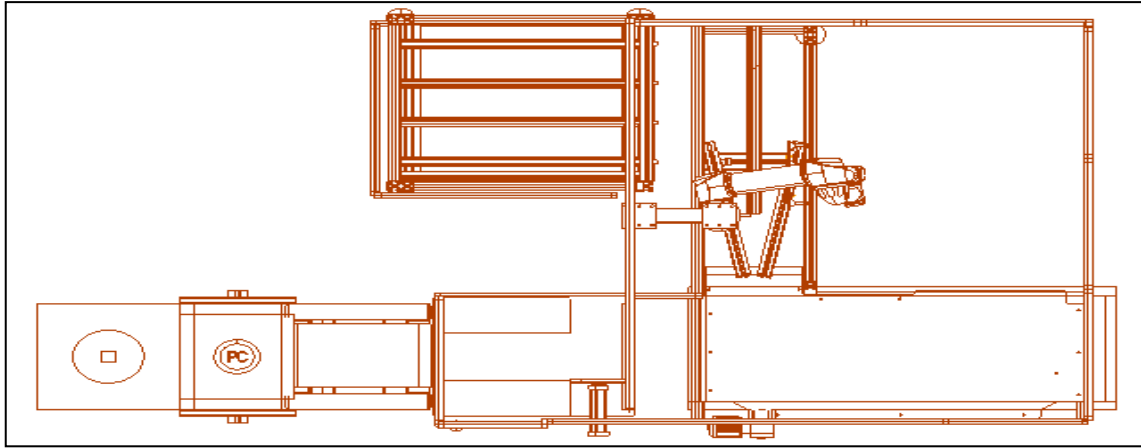


Figure 5.2 CAD of the Layout from Top View

The machine which produces the produces has two different types of tea which have to be packed and palletized. This can be shown in Table 5.1

Table 5.1 Objects Information

Category	Sub-Category	Packaging Line	Format	Weight	#case	weight of full pallet (kg)	Speed (pallet per hour)
TEA	Tea bag	F200-3/4	25 tb	0,86	150	210	1,3
TEA	Tea bag	F200-3/4	100 tb	1,74	90	246	1,0

With the previous provided information, Visual Components simulation tool has been used in this project. The following Table 5.2 shows the program structure and the statements which have been written to program the cobot to process the operation.

Table 5.2 Program Configuration

Sub-program	Point	Statement
PickBox	P 08	Linear Motion: Executes a linear motion to a specific target
	P 12	Linear Motion
	P 13	Linear Motion
	P 07	Linear Motion
	P 15	Linear Motion
	P 16	Linear Motion
	P 09	Linear Motion
	P 06	Point-to-Point
	P 20	Linear Motion
Sub-program	Point	Statement
PcikMulti	P 14	Linear Motion: Executes a linear motion to a specific target
	P 02	Linear Motion
	P 17	Linear Motion
Sub-program	Point	Statement
	P 05	Linear Motion
Sub-program	Point	Statement

Table 5.2 (cont'd)

PlaceMulti 1	P 01	Linear Motion: Executes a linear motion to a specific target
	P 04	Linear Motion
	P 18	Linear Motion
	P 22	Linear Motion
Sub-program	Point	Statement
PlaceMulti 2	P 03	Linear Motion: Executes a linear motion to a specific target
	P 19	Linear Motion
	P 10	Linear Motion

The following table, Table 5.3, shows the suction gripper properties that have been used in the simulation aligned with the values as well.

Table 5.3 Suction Gripper Properties

Property	Value
SuctionCups_X	3
SuctionCups_Y	4
SuctionCupDistance_X	60 mm
SuctionCupDistance_Y	90 mm
CupHeight	50 mm
CupDiameter	40 mm
PlateOverhangX	15 mm
PlateOverhangY	15 mm
MountHeight	70 mm
MountDiameter	80 mm

The following Table 5.4 shows the objects properties, whereas two different objects have been used, one is for package which comes from the feed case magazine at the input of the layout, and the other object has been designed for the skillets of tea as shown in Table 5.5.

Table 5.4 Objects Properties of Flat Case

Property	Value
BoxHeight	150 mm
BoxLength	300 mm
BoxWidth	250 mm

Table 5.5 Objects Properties of Tea Skillets

Property	Value
BoxHeight	75 mm
BoxLength	150 mm
BoxWidth	60 mm

On the other hand, to make the cobot program ready and full to be able to work properly with RSL, the signals of all sensors and motors have been configured and shown in Table 5.6.

Table 5.6 Robot Signals I/O

Input and Output Port	Signal Type	Function
150:In	Sensor #1	Robot Start Signal
150:Out	Sensor #1	Robot Done Signal
200:Out	SignalTester #4	Shape Flat Case
201:Out	SignalTester #5	Shape Front Bottom
202:Out	SignalTester #6	Shape Bottom Side
203:Out	SignalTester #2	Conveyor Grab
250:Out	Motor	Motor Signal
300:Out	SignalTester #3	Delete Physics Signal
FrontBottom (of flat case)	SignalTester #6	Shape Bottom Side
Shape	SignalTester #4	Shape Flat Case
PhysicSignal	SignalTester #3	Physics Signal
ConveyorGrabSignal	SignalTester #2	Conveyor Grab

The Figure 5.3 shows all of the cobot's I/O signals in the simulation environment.

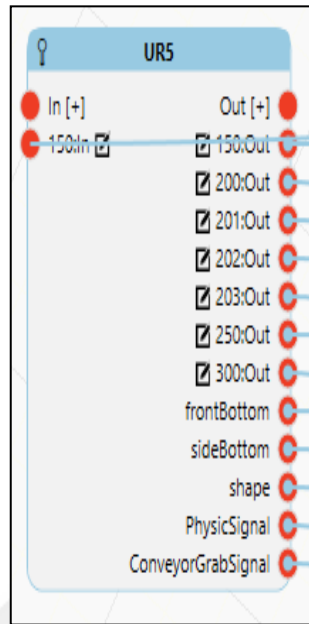


Figure 5.3 Cobot's I/O Signal in Simulation Environment

After executing the final program of the simulation, the probable statistics have been assigned to be shown in order to analyze the cobot's joints movements and obtain the utilization of the robot as shown in Figure 5.

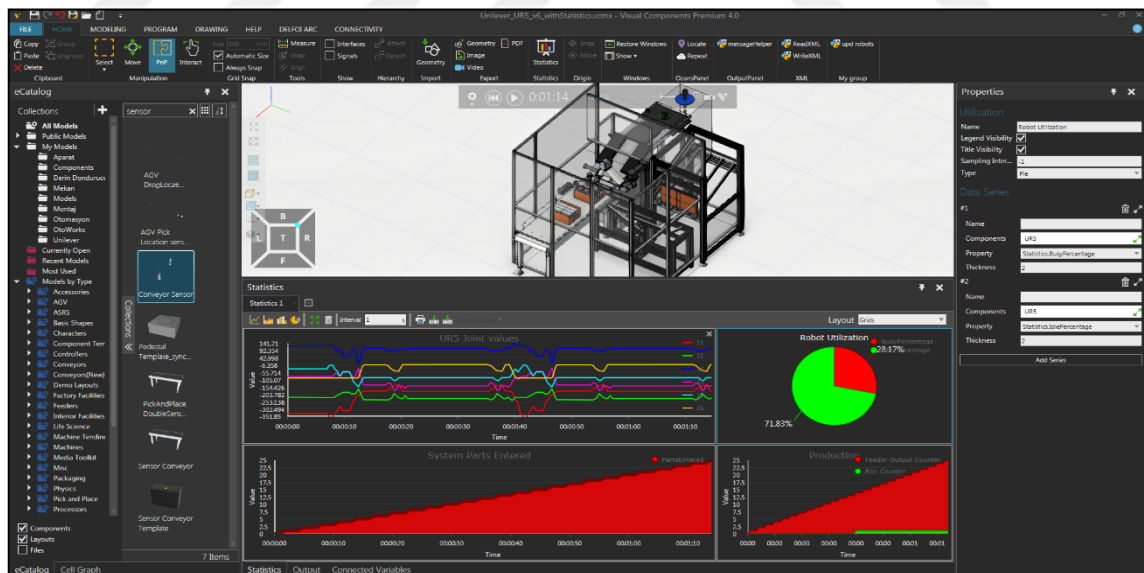


Figure 5.4 Simulation Tool and Statistics

According to the previous analysis, we recognized that joint three consume the most utilization of the cobot. However, the total utilization was low (around 35%) with the respect of the parts entered to the EOL, as shown in the following Figure 5.2 and Figure 5.3.

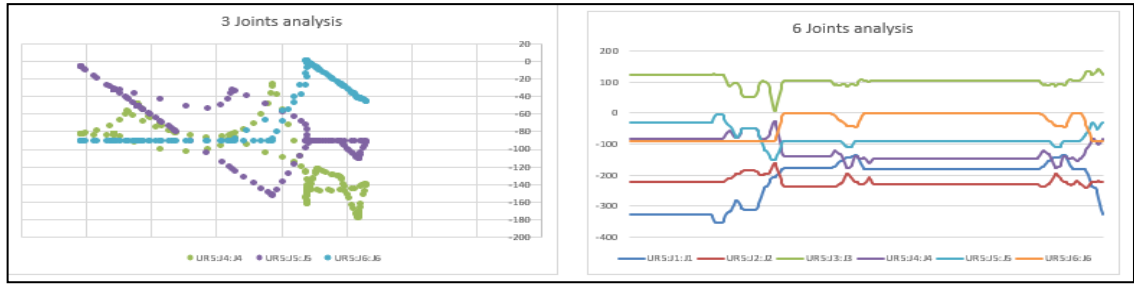


Figure 5.5 Joint Analysis without Constraints

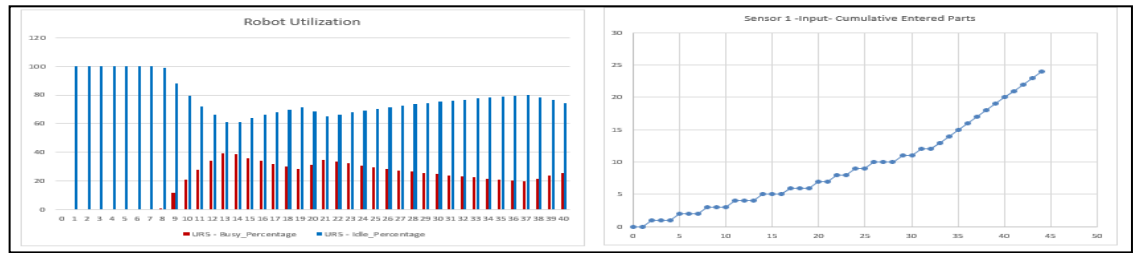


Figure 5.6 Cobot Utilization and Cumulative Number of Parts Entered

After we applied constraint on the joint three by limitation range of $[-2,2]$ and the joint limitation of rotation angle to be between $[-200,200]$ as shown in Figure 5.9. In addition, we manipulated the arrival time of the parts entered to the EOL to be (1.5) seconds of creating the objects, we found a better utilization of the robot as shown in Figure 5.7 and Figure 5.8.

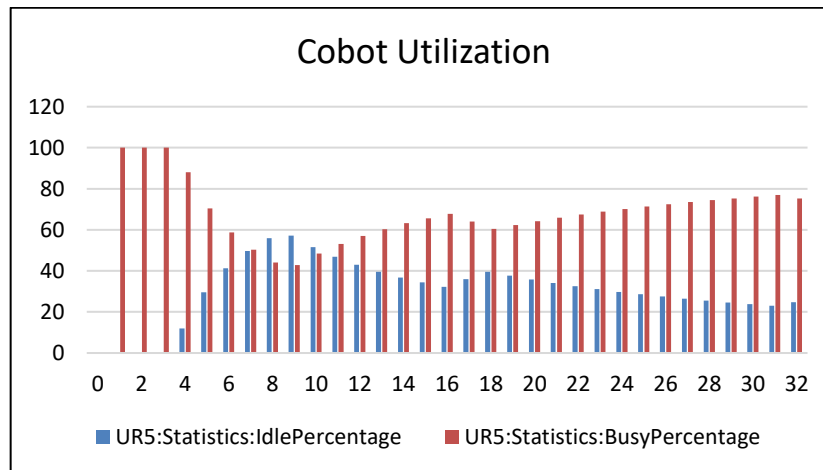


Figure 5.7 Cobot Utilization with Constraints

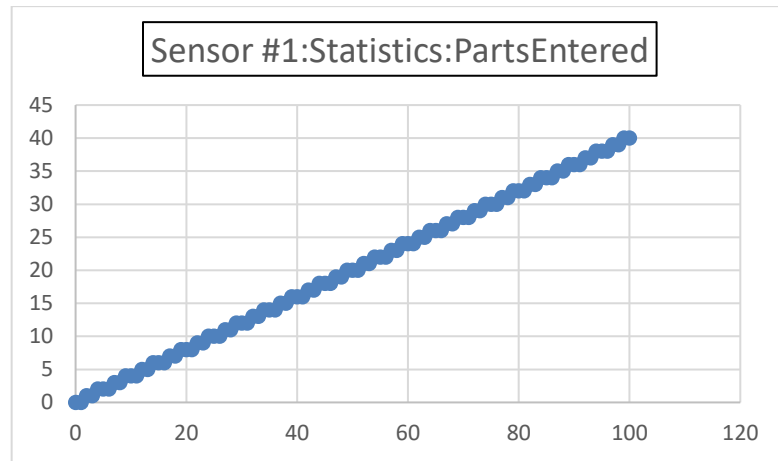


Figure 5.7 Cumulative Number of Parts Entered with Constraints

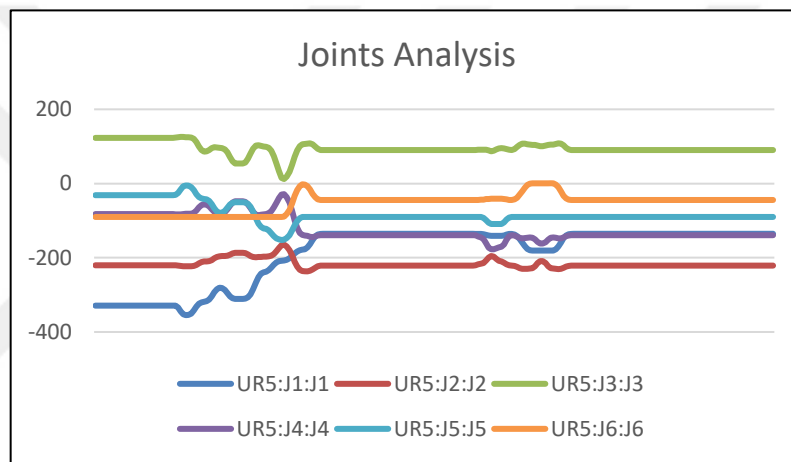


Figure 5.9 Joints Analysis with Constraints on Joint 3

The previous results show that after applying constraints on the joint three of the cobot, the system shows good utilization of the robot (around 80%). This value however can be more better, but it is still sufficient to accomplish the process in short time (around 24 seconds).

From the view of cost effectiveness, and with the principle of WCM, the comparison of initial cost for automation using cobotic system and manual packer system for packaging is shown in the following Table 5.7.

Table 5.7 LCC Comparison between Manual and Automation Operation

Initial Costs	Auto Feeding	Manual Operation
Purchase Price	500	0
Initial Spare Parts	20	0
Changes in Utilities	10	0
Changes to Building or Construction	24	0
Training Costs	6	0
Electrical Installation	20	0
Mechanical Installation	20	0
Total Initial Cost	600	0
Running Costs	Auto Feeding	Manual Operation
Resources to Operate	0	150
Maintenance Costs per Year	14	0
Forklift Rental	0	30
Spare Part Consumption per Year	10	0
Energy Consumption per Year	24	0
Total Running Cost per Year	48	180
Total Cost Per Year	90,9	180,0

As well as, the comparison of initial cost for automation using cobotic system and machine packer system for packaging is shown in the following Table 5.8.

Table 5.8 LCC Comparison between Robotic and Conventional Case packer

Initial Costs	Robotic Case packer	Conventional Case packer
Purchase Price	110	720
Initial Spare Parts	4	18
Changes in Utilities	6	6
Changes to Building	2	2
Training Costs	4	4
Electrical Inst.	4	8
Mechanical Inst.	4	8
Total Initial Cost	134	766
Running Costs	Robotic Case packer	Conventional Case packer
Resources to Operate	0	0
Maintenance Labor Cost/Year	0,4	1
Maintenance Material Cost/Year	3,6	8,4
Energy Consumption per Year	2,6	10
Total Running Cost per Year	6,6	19,4
Total Cost Per Year	16,2	74,1

Moreover, the comparison of initial cost for automation solutions between using the cobotics system and robotics system for packaging is shown in the following Table 5.9.

Table 5.9 LCC Comparison between Robotic and Cobot Case packer

Initial Costs	Cobotic Case packer	Robotic Case packer
Purchase Price	110	180
Initial Spare Parts	2	14
Changes in Utilities	6	6
Changes to Building/Construction	2	2
Training Costs	2	6
Electrical Installation	4	6
Mechanical Installation	4	4
Total Initial Cost	130	218
Running Costs	Cobotic Case packer	Robotic Case packer
Resources to Operate	0	0
Maintenance Labor Cost/Year	2	4
Maintenance Material Cost/Year	4	8
Energy Consumption per Year	6	10
Total Running Cost	12	22
Total Cost Per Year	21,3	37,6

According to the numbers provided and in terms of fourteen years of lifespan, the following Figure 5.10 shows the gap of cost effectiveness between cobotic and robotic case packer.

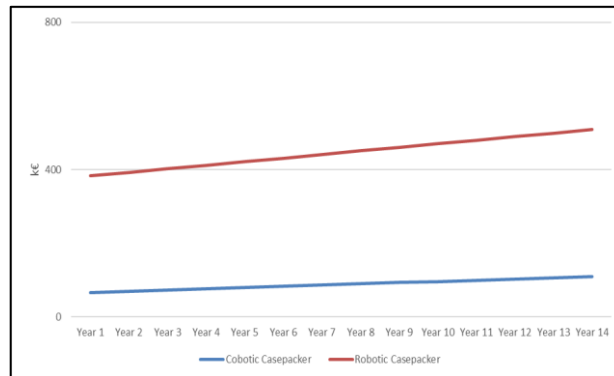


Figure 5.10 Cost Gap between Cobotic and Robotic Case Packer

Table 5.10 shows general comparison of the manufacturing performance while cycle time of the process and the footprint of the machine layout play important roll.

Table 5.10 Comparison of Cobotic and Conventional Packaging

Outcome	Conventional Packaging	Cobotic Packaging
FTE Reduction	3	3
Payload Range	1 kg to 6 kg	1 kg to 5 kg
Cycle Time	up to 50 box/min	up to 40 box/min
Footprint	8 m2	3.5 m2
Internal Experience	Yes	No

In MATLAB using Peter Corke toolbox, the path trajectory of the robot is configured and executed in the next following code. This toolbox has functions that can build and model the rigid body of the robot using D-H method. Therefore, the UR5 D-H parameters are used in this experiment. The different positions of the robot are chosen according to

the simulation tool program where the entire process is simulated and visualized. The robot trajectory is generated to follow those positions with an order.

MATLAB Code:

```
% clear all previous values in memory
clear all

% close all figures that currently open
close all

% clear the command window
clc

% initializaing the first position or frame of the robot
q0=[0 0 0 0 0 0];

% second position in which the package is borught to the desired location
q1b=[pi 0 0 0 0 0];

% first position of pick process
q1=[0 .9745 0 -.9 0 .4];

% second position of place process
q2=[.9 0 0 0 0 0];

% extra positions for path trajectory
q3=[0.9 1.18 0 -.9 0 .4];

q4=[.1745 .1745 0 .1396 .3191 .5236];

q5=[-.3491 -.3491 -.3491 0 -.0873 0];

%% defination of D-H parameters for Universal Robot 5

% define distance values for six joints
a = [0, -0.612, -0.5723, 0, 0, 0];
```

```

% define offset link values for six joints
d = [0.1273, 0, 0, 0.163941, 0.1157, 0.0922];

% define alpha values for six joints
alpha = [1.570796327, 0, 0, 1.570796327, -1.570796327, 0];

% for theta we can leave it empty

%% Initializing of the Robot

% Include D-H Parameters for UR5
% forming joints and links of the robot
% Link formula has the following shape, L=Link(theta d alpha)

% Starting for base
Base=Link([0 0.089459 0 1.570796327]);

% Upper Arm
U_Arm=Link([0 0 -0.42500 0]);

% Lower Arm
L_Arm=Link([0 0 -0.39225 0]);

% Wrist 2
W2=Link([0 0.10915 0 1.570796327]);

% Wrist 3
W3=Link([0 0.09465 0 -1.570796327]);

% Mounting Tool
Tool=Link([0 0.0823 0 0]);

%L7=Link([0 15.0 0 0 0 pi/2]);

```

```

% We can also show the full matrix if needed

%LinkMat=[0 12.4 0 pi/2 0 -pi/2;

% 0 0 0 -pi/2 0 0;

% 0 15.43 0 pi/2 0 0;

%0 0 0 -pi/2 0 0;

% 0 15.925 0 pi/2 0 0;

% 0 0 0 -pi/2 0 0;

%0 15 0 0 0 pi/2];

% initializing the robot

Rbt=SerialLink([Base U_Arm L_Arm W2 W3 Tool])

%Time steps
t=0:3:200;

%% path trajectories identification
%traj1=jtraj(q0,q1b,t);

% shipping carton, see Figure 5.11
traj1=jtraj(q1b,q2,t);

```

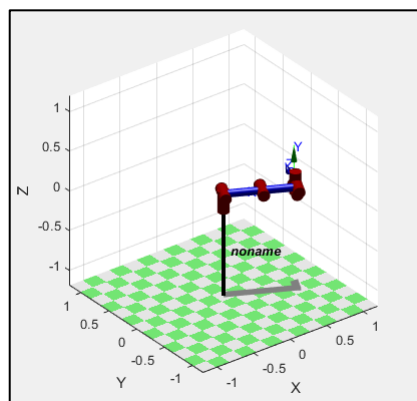


Figure 5.11 Shipping Carton

```

% ready to pick, see Figure 5.12

traj2=jtraj(q2,q1,t);

```

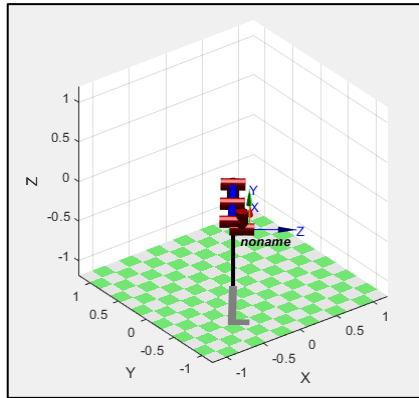


Figure 5.12 Ready to Pick

```
% pick process, see Figure 5.13
```

```
traj3=jtraj(q1,q0,t);
```

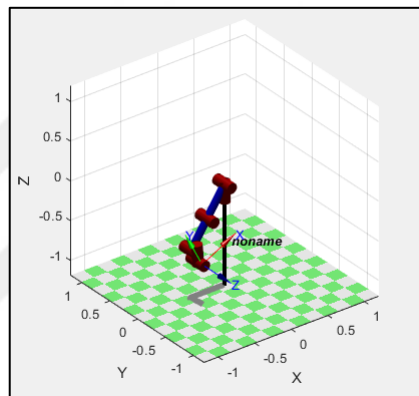


Figure 5.13 Pick Process

```
% ready to place, see Figure 5.14
```

```
traj4=jtraj(q0,q2,t);
```

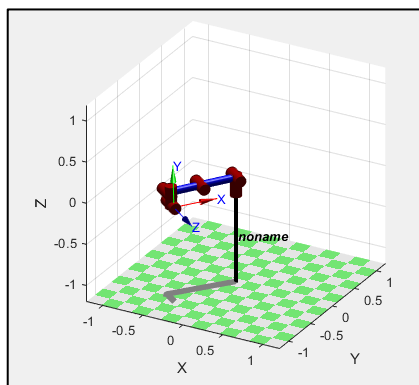


Figure 5.14 Ready to Place

```
% place process, Figure 5.15
```

```
traj5=jtraj(q2,q3,t);
```

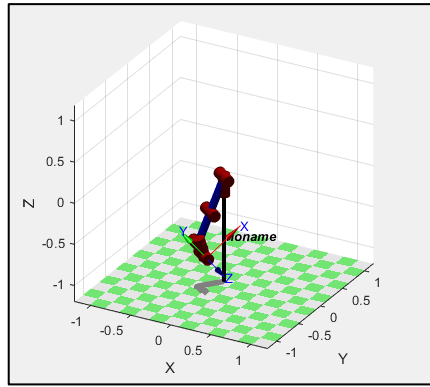


Figure 5.15 Place Process

```
% ready to pick, see Figure 5.16
```

```
traj6=jtraj(q3,q2,t);
```

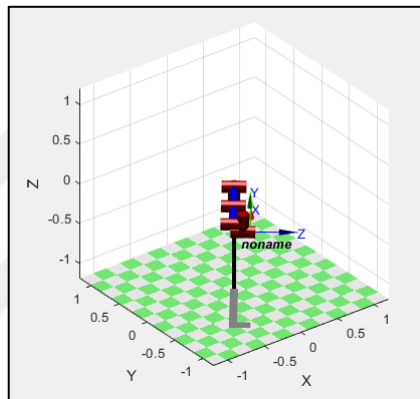


Figure 5.16 Ready for Next Pick

```
%% plot the path trajectories with an order sequence
```

```
% plot the path trajectory for position 1
```

```
Rbt.plot(traj1)
```

```
% plot the path trajectory for position 2
```

```
Rbt.plot(traj2)
```

```
% plot the path trajectory for position 3
```

```
Rbt.plot(traj3)
```

```
% plot the path trajectory for position 4
```

```
Rbt.plot(traj4)
```

```
% plot the path trajectory for position 5
```

```
Rbt.plot(traj5)
```

```
% plot the path trajectory for position 6
```

```
Rbt.plot(traj6)

%% End of the Code
```

After executing the m.file of the program, the following table appears in the command window. This table actually presents the D-H parameters of our robot and it gives the all information about each parameter.

Table 5.11 D-H Parameters in MATLAB Command Window

```
Rbt =
```

noname:: 6 axis, RRRRRR, stdDH, slowRNE

j	theta	d	a	alpha	offset
1	q1	0.089459	0	1.5708	0
2	q2	0	-0.425	0	0
3	q3	0	-0.39225	0	0
4	q4	0.10915	0	1.5708	0
5	q5	0.09465	0	-1.5708	0
6	q6	0.0823	0	0	0

CONCLUSIONS

In this project, an appropriate layout of the robot UR5 is proposed where it can perform the automated processes with the maximum speed and minimum loss under high safety considerations. The simulation tool Visual Components show agility in this project in which the joints movements analyses are shown with precise values. Furthermore, using the statistical properties of VC, the effective utilization of the robot is shown and its parameters are adapted to fit the automation process of interest.

In other words, by using a simulation tool for analyzing the cobot utilization and joints movements, we could add constraints and limitation on the joint 3 of the cobot in which the utilization performance is proven to be better. Therefore, the new system has reduced the total number of FTEs to zero. In addition, the NVAAs have been eliminated. The new cycle time of the operation was decreased by 4 seconds. Utilization of the cobot could have been much better, however, sufficient results on accomplishing the processes in a high efficiency are gathered and presented.

The representation of robot motions and path trajectory are implemented in MATLAB using Peter Corke toolbox, this toolbox has many functions that allow us to model the robot and its motions using D-H method. The UR5 D-H parameters are used with the toolbox functions to model the robot motions accordingly. The generated path route trajectory has four positions where the robot is transferred between them respectively.

The four positions have been collected from the simulation tool, Visual Components program, where the entire process has been simulated and presented in 3D visualization.

The simulation tool with statistics allow us to calculate the utilization of the robot, where the value operating time is divided by the entire time of the process. The system shows low utilization and that was seen in the joint 3.

The constraints limitation is applied on this joint to make the rotation between the range of $[-200, 200]$, thus the system shows sufficient utilization but still it needs to be much more better.

Moreover, NVAA has been eliminated but still the worker needs to feed the cobotic system manually with the case packages every thirty minutes approximately

Finally, using OLP in the simulation tool allows us to try different scenarios for the layout of this project. However, the Overall Equipment Efficiency of this EOL has shown increasing after the implementation of this project which is important for Manufacturing Performance.

Further work can be carried out in this field of study, such as, Predictive Maintenance of the Collaborative Robots and Automation of Logistic Areas Using Automated Guided Vehicles (AGV), etc.

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-
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ORIENTATION DESCRIPTION AND TRANSFORMATION

The representation of a point in the world frame can be described as a 3x1 position vector in a reference coordinate system

$$A_P = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} \quad (A.1)$$

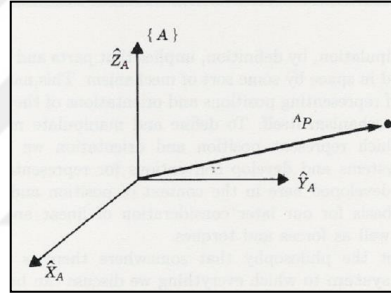


Figure A.1 Frame Example of Vector [31]

The representation of a point in space can be slightly modified to include such a scaling factor w :

$$P_x = x/w, P_y = y/w, P_z = z/w;$$

$$A_P = \begin{bmatrix} x \\ y \\ z \\ w \end{bmatrix} \quad (A.2)$$

Representation of a frame at the origin of a reference frame is represented by three appendiculate vectors. Each vector is represented by three components in the reference frame. Thus, a frame (F) can be represented the matrix form as:

$${}^A F_O = \begin{bmatrix} n_x & o_x & a_x \\ n_y & o_y & a_y \\ n_z & o_z & a_z \end{bmatrix} \quad (A.3)$$

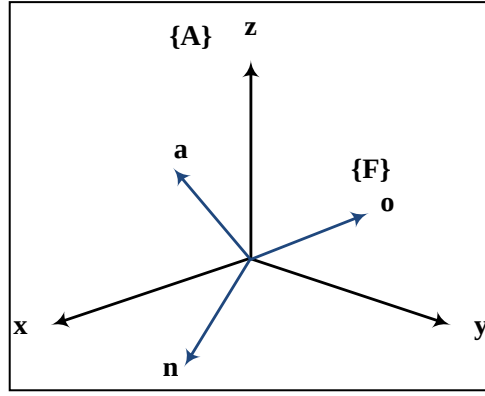


Figure A.2 Representation of Frame (F) Located at Origin of Frame (A)

The representation of a frame in a fixed frame means that if a frame (F) is not at the origin of frame (A) then the location of the frame (F) has to be expressed by a vector (P) which is drawn between the origin of the frame and the origin of the reference frame.

$${}^A F = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (A.4)$$

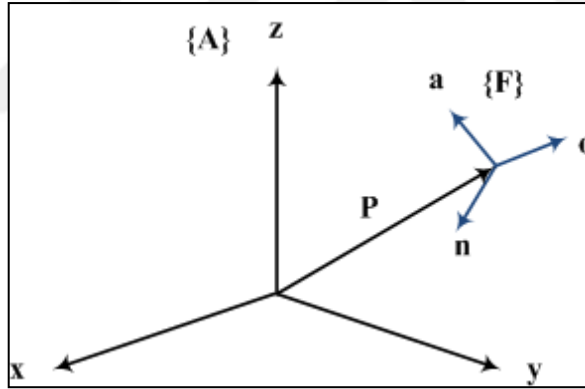


Figure A.3 Representation of (F) in the Fixed Frame (A)

Hence, the frame (F) can be represented and described by four vectors, the first three ones show its direction and the fourth vector for describing its location.

The representation of a transformation matrix for the frame (F) which is relative to the reference base frame (A) is consisted of 4 sub-transformation matrices (4x4 matrix) and the final transformation matrix can be found as follows:

$${}^A F = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (A.5)$$

The previous transformation matrix has the main perspective transformation(1x3), the position vector (3x1) and the scaling element (1x1) which is (1).

Furthermore, to locate an object in position and orientation as shown in Figure 5.1, the coordinate system (B) is attached to the body. The description of the frame (B) according to the frame (A) is now sufficient to get the body orientation.

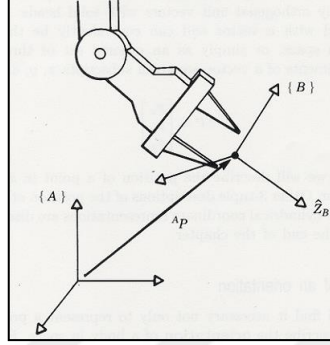


Figure A.4 Object Position and Orientation [31]

Therefore, the attached coordinate system that is related to the body can describe the positions of the points and the orientations. To describe this coordinate system of frame (B), we write the three vectors according to the axes in terms of the bias frame (A) as, ${}^A X_B$, ${}^A Y_B$, and ${}^A Z_B$.

Provided that the three vectors are stacked together as columns matrix of (3x3) dimensions with the respect of the order for ${}^A X_B$, ${}^A Y_B$, and ${}^A Z_B$, the resultant matrix is called the rotation matrix and it is notated by ${}^A_B R$.

$${}^A_B R = [{}^A X_B \quad {}^A Y_B \quad {}^A Z_B] \quad (A.6)$$

$${}^A_B R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \quad (A.7)$$

$${}^A_B R = \begin{bmatrix} X_B \cdot X_A & Y_B \cdot X_A & Z_B \cdot X_A \\ X_B \cdot Y_A & Y_B \cdot Y_A & Z_B \cdot Y_A \\ X_B \cdot Z_A & Y_B \cdot Z_A & Z_B \cdot Z_A \end{bmatrix} \quad (A.8)$$

The orientation matrix caused by rotations around (X, Y, Z) axes can be described as follows,

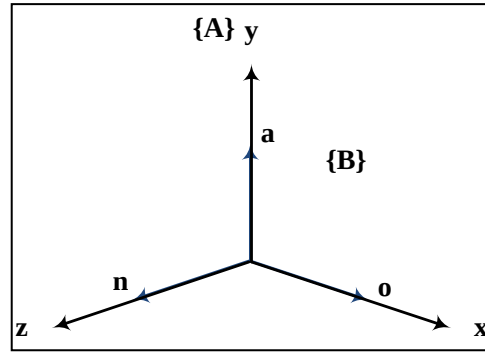


Figure A.5 The Basic Conditions of the Two Frames

Rotation around X-axis:

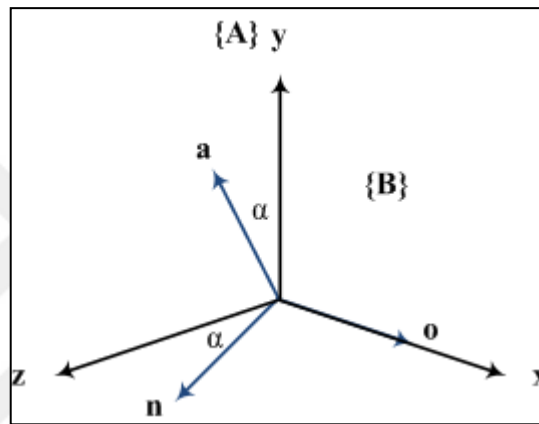


Figure A.6 Deriving Orientation Matrix around X-axis

Therefore, the orientation matrix is given by:

$${}^A_B R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} \quad (A.9)$$

Rotation around Y-axis:

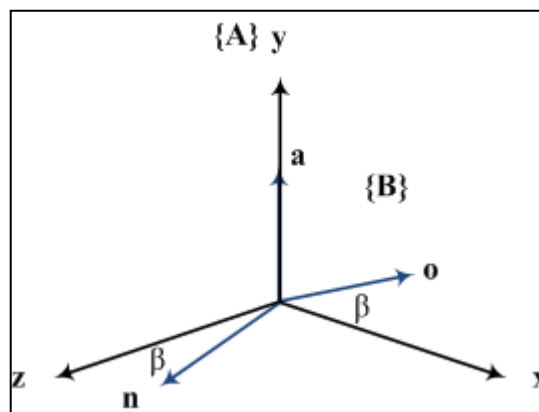


Figure A.7 Deriving Orientation Matrix around Y-axis

Therefore, the orientation matrix is given by:

$${}^A_B R = \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix} \quad (\text{A.11})$$

Rotation around Z-axis:

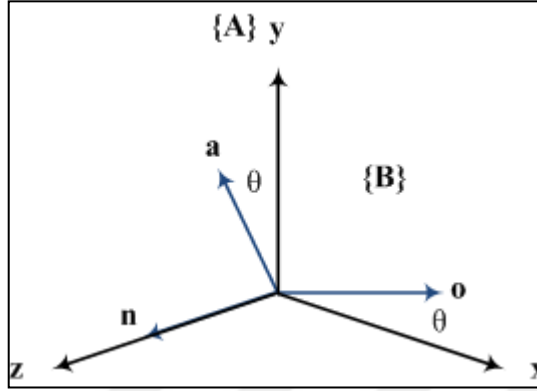


Figure A.8 Deriving Orientation Matrix around Z-axis

Therefore, the orientation matrix is given by:

$${}^A_B R = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (\text{A.12})$$

COMPONENTS OF THE PROJECT

- Shape Feeder (feeds skillets to the conveyor)



Figure B.1 Shape Feeder

- Skillets straight conveyor



Figure B.2 Straight Conveyor

- Conveyor with slope (skillets are moved down to be gathered)

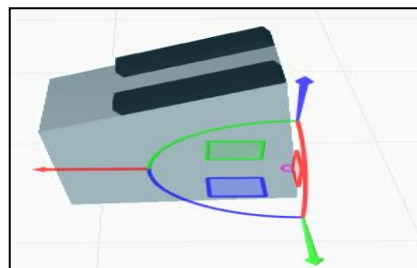


Figure B.3 Slope Conveyor

- Piston Pusher

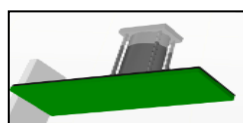


Figure B.4 Pusher

- Conveyor motor

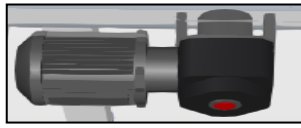


Figure B.5 AC Motor

- Filled cartons straight Conveyor

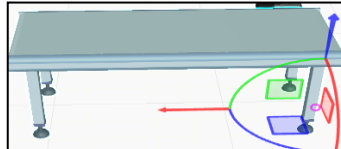


Figure B.6 Straight Packaged Conveyor

- Vertical and horizontal support facilities for robot

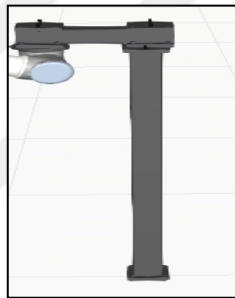


Figure B.7 Robot Support Facilities

- Universal robot 5 (UR5)

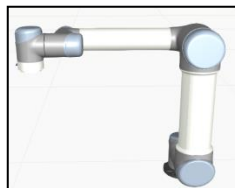


Figure B.8 Universal Robot 5

- Mechanism of folding the carto



Figure B.9 Folding Case Mechanism

In Table B.1, understanding the requirements of simulation tool software, this evaluation matrix has been done using the method of weighted criteria. This matrix gives the evaluation between the simulation tools based on fifteen benchmarks.

Table B.1 Comparison between Simulation tools and Software

Evaluation Criteria	Weight	RoboDK	RoboStudio	Visual Components
Ease-of-Use	4	2	3	4
Modelling Constructs	5	1	4	4
Modelling Flexibility	5	1	4	4
Graphics and Animation	4	1	3	4
Availability of Components	5	3	2	4
Statistical Capabilities	5	2	3	3
Hardware Requirements	2	2	2	2
Documentation	4	2	4	4
Cost	5	5	3	4
Support	5	3	3	3
Training	4	2	4	3
Modelling Services	4	2	4	4
Upgrade and Enhancements	2	2	2	2
Other Services	1	1	1	1
Total	62	29	42	46

CURRICULUM VITAE

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EDUCATION

Degree	Department	University	Date of Graduation
Undergraduate	Control and Automation	Aleppo University	2014
High School	General Science	Bassam Al-Omar	2008

WORK EXPERIENCE

Year	Corporation/Institute	Enrollment
2018	Unilever	ManEx Specialist
2017	Unilever	ManEx Specialist

PUBLISHMENTS

Conference Papers

1. Sawas, M., and Engin, Ş. N., (2018). “Automation Of End-Of-Line Systems Using Collaborative Robots”, Second Student International Congress, 4-5 May 2018, İzmir.

