

# **Modular reconfigurable robots**

*A Dissertation submitted*  
In Partial Fulfillment of the Requirements  
for the Degree of

**Master of Engineering**  
in  
**Production Engineering**

By  
**Manpreet Singh**  
University roll no:- 801282012

Under the supervision of

**Dr. V.P. Agrawal**  
**Visiting Professor**



*to the*

**MECHANICAL ENGINEERING DEPARTMENT**  
**THAPAR UNIVERSITY, PATIALA**

July, 2014

# CERTIFICATE

I hereby declare that the thesis entitled "Modular reconfigurable robots" is an authentic record of my study carried out as requirements for the award of the degree of **Master of Engineering in Production Engineering at Thapar University, Patiala** under the supervision of **DR. V.P Agrawal**, Visiting professor, Department of Mechanical Engineering, Thapar University. The matter embodied in this report has not been submitted in partial or full to any other university or institute for the award of any degree.

Date: 18 July 2014

  
Manpreet Singh  
801282012

It is certified that the above statement made by the student is correct to the best of my/our knowledge and belief.

  
\_\_\_\_\_

**Dr. V.P Agrawal**


Mechanical Engineering Department  
Thapar University, Patiala – 147004

Countersigned by

  
\_\_\_\_\_

**Dr. Ajay Batish**

Professor & Head  
Mechanical Engineering Department  
Thapar University, Patiala - 147004

  
\_\_\_\_\_

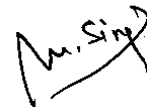
**Dr. S. K. Mohapatra**

Dean of Academic Affairs  
Thapar University, Patiala - 147004

## ACKNOWLEDGEMENTS

I would like to express a deep sense of gratitude and thank profusely to my guide **Dr. V. P AGRAWAL** for his sincere & invaluable guidance, suggestions and attitude, which inspired me to submit thesis report in the present form. His dynamism and diligent enthusiasm have been highly instrumental in keeping my spirits high. His flawless and forthright suggestions blended with an innate intelligent application have crowned my task with success.

I am also thankful to **Dr. AJAY BATISH**, Professor and Head, Department of Mechanical Engineering for his encouragement and inspiration for execution of the seminar work



**(MANPREET SINGH)**  
**Roll No. 801282012**

## **ABSTRACT**

This thesis work presents design of a Parallel reconfigurable modular robot. The major objective of this thesis is to design a robot using modules that are cost effective, reduce downtime and are flexible. These modules can be assembled together to achieve various robot configuration. Parallel reconfigurable robot is designed taking modules commercially of the shelf (MCOTS). Taking an example of a robot Fanuc 200iB, robot is designed in order to show the possibility of a robot design using MCOTS. The best matched modules are examined through various company catalogs keeping consideration of factors like cost, modularity, actuation, safety, ease of repair, connection between them, etc. The modules are then designed in a CAD software Pro-engineer and then finally assembly is done. The benefits of using MCOTS related to user, manufacturer, and designer is also discussed in this thesis. Further in this thesis a design structure table is made which indicates the connectivity of components with each other and then design structure matrix (DSM) is made showing the between the components and the DSM is used to determine degree of modularity of product and modularity of each component is calculated using the concept of in-degree and out-degree of a components. At last MADM (multiple attribute decision making) approach, TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) used to evaluate, rank and select parallel robot link.

# TABLE OF CONTENTS

Certification.....	i
Acknowledgements.....	ii
Abstract.....	iii
Table of contents.....	iv
List of figure.....	vi
List of tables.....	viii
Abbrivation.....	ix
<b>1. INTRODUCTION.....</b>	<b>1</b>
1.1 Introduction to modular reconfigurable robots.....	1
1.2 Modularity.....	2
1.3 Modular reconfigurable robots.....	4
1.3.1 Need of modular reconfigurable robots.....	4
1.3.2 Benefits of modular reconfigurable robots.....	5
1.4 Robot motion.....	6
1.5 Robot modules.....	7
1.5.1 Modules category.....	7
1.6 Aim of the Thesis.....	7
<b>2. LITERATURE REVIEW.....</b>	<b>8</b>
<b>3. METHODOLOGY.....</b>	<b>17</b>
3.1. Introduction.....	17
3.2. Benefits of taking modules commercially of the shelf .....	17
3.2.1. For user.....	17
3.2.2. For designer.....	17
3.2.3. For manufacturer.....	18
3.3. Methodology.....	18
3.3.1. Module determination.....	18

3.3.2. Possibility to design robot using MCOTS.....	23
3.3.3. Modularity.....	26
3.3.4. Multiple attribute decision making (MADM) .....	27
3.3.4.1. Step by Step procedure .....	28
3.3.4.2. Robot attributes.....	28
3.3.4.3. Coding Scheme.....	32
3.3.4.4. Three stage elimination procedure.....	37
<b>4. RESULTS AND DISCUSSION.....</b>	<b>41</b>
4.1. Module determination.....	41
4.1.1. Replacement parts.....	41
4.1.1.1. Result.....	42
4.1.1.2. Discussion.....	43
4.2. Possibility to design robot using MCOTS.....	43
4.2.1. Results.....	48
4.2.2. Discussion.....	48
4.3. Modularity.....	48
4.3.1. Product modularity.....	48
4.3.1.1. Result .....	50
4.3.2. Component modularity.....	50
4.3.2.1. Result.....	50
4.3.2.2. Discussion.....	51
4.4. Multiple attribute decision making.....	51
4.4.1. Result.....	58
4.4.2. Discussion.....	58
<b>5. CONCLUSION.....</b>	<b>59</b>
<b>References.....</b>	<b>60</b>
<b>Appendix.....</b>	<b>62</b>

# LIST OF FIGURES

<b>Figure 1.1:</b> System with 4 modules .....	2
<b>Figure 1.2:</b> Effect of standardization and modularization on cost.....	3
<b>Figure 1.3:</b> Component-swapping (Left) and Component sharing (Right) .....	4
<b>Figure 1.4:</b> Universal joint showing connections.....	6
<b>Figure 2.1:</b> Nodes and connectivity between them.....	11
<b>Figure 2.2:</b> Hierarchical decomposition of product.....	14
<b>Figure 3.1:</b> (a) Boston universal joint, (b) Lovejoy universal joint.....	20
<b>Figure 3.2:</b> Electric drive system (HIWIN) .....	20
<b>Figure 3.3:</b> MAXIM Hydraulic cylinder.....	21
<b>Figure 3.4:</b> Spherical bearing (SKF) .....	21
<b>Figure 3.5:</b> Bracket clevis (Grainger) .....	22
<b>Figure 3.6:</b> Metal pin (Grainger) .....	22
<b>Figure 3.7:</b> Spherical bearing made in CAD software.....	23
<b>Figure 3.8:</b> Top view (left) and Side view (Right) .....	24
<b>Figure 3.9:</b> Top view (left) and Side view (Right) .....	24
<b>Figure 3.10:</b> Top view (left) and Side view (Right) .....	24
<b>Figure 3.11:</b> Hydraulic cylinder .....	25
<b>Figure 3.12:</b> Side view (left) and Front view (Right) of part PNTF 1 .....	25
<b>Figure 3.13:</b> Pin.....	25
<b>Figure 3.14:</b> Electrical switch.....	26
<b>Figure 4.1:</b> Fanuc F-200iB (left) and Face plate (Right) .....	43
<b>Figure 4.2:</b> Base plate (left) and Assembly top view (Right) .....	44
<b>Figure 4.3:</b> shows connectivity of five modules.....	44
<b>Figure 4.4:</b> Hydraulic cylinder and hook connectivity.....	45
<b>Figure 4.5:</b> Connectivity of 6 modules.....	45
<b>Figure 4.6:</b> Side view (Left) and Front view (Right) .....	46
<b>Figure 4.7:</b> Side view (Left) and Front view (Right) .....	46

<b>Figure 4.8:</b> Movement of face plate 1 .....	47
<b>Figure 4.9:</b> Movement of face plate 2 .....	47
<b>Figure 4.10:</b> Sparse pattern .....	49
<b>Figure 4.11:</b> Leg 1 .....	52
<b>Figure 4.12:</b> Leg 2 .....	53
<b>Figure 4.13:</b> Leg 3 .....	54

## LIST OF TABLES

<b>Table 1.1</b> Comparison between a modular and integral robot.....	5
<b>Table 1.2</b> Motion and degree of freedom by different type of joints.....	6
<b>Table 3.1</b> Design structure.....	27
<b>Table 3.2</b> Attributes.....	29
<b>Table 3.3</b> Illustration of coding.....	33
<b>Table 3.4</b> 97 digit coding scheme for parallel robot.....	33
<b>Table 3.5</b> Example Fanuc parallel robot F-200iB.....	33
<b>Table 3.6</b> Representation of coding scheme for Fanuc F-200iB.....	26
<b>Table 4.1</b> Components used for modular design.....	41
<b>Table 4.2</b> Replacement part.....	42
<b>Table 4.3</b> Design structure matrix.....	48
<b>Table 4.4</b> Component modularity.....	50
<b>Table 4.5</b> Requirement Specifications .....	51
<b>Table 4.6</b> Attribute for the shortlisted legs.....	52

## TABLE OF ABBREVIATION

S.no	Abbreviates	Description
1.	MCOTS	Modules commercially of the shelf
2.	DSM	Design structure matrix
3.	PNTF	Part new to the firm
4.	CAD	Computer aided design
5.	MTTR	Mean time to repair
6.	MADM	Multiple attribute decision making
7.	TOPSIS	Technique for Order Preferences by Similarity to Ideal Solution
8.	NZF	Non-zero fraction
9.	RSI	Robot selection index
10.	SMI	Singular modular index
11.	DOF	Degree of freedom
12.	SCARA	Selective Compliance Assembly Robot Arm

# CHAPTER 1

## Introduction

---

### 1.1 Introduction of modular reconfigurable robots

In various stages of a manufacturing cycle industrial robot have become crucial tool covering a variety of application. Fascinating features of parallel robot like high positioning capabilities, rigidity, speed, high accuracy and large load carrying capability makes parallel robot beneficial over serial robots and is used in various applications like industry, space, medical science, etc. A parallel robot is a close-loop machine comprises two platform that is base platform and mobile platform connected by at least two serial kinematic chains or legs. The total of degree of freedom is equal to legs of the robot such that every leg is manipulated by one actuator and all actuation are mounted at or near the fixed base. Fascinating features of parallel robot in several fields indicates that it is suitable machine covering wide application like motion platform for pilot training simulators, precision assembly tools, parallel type multi-axis machining tools, positioning device for high precision surgical tools, etc. . As the demand of parallel robot increases it is difficult for the robot manufacturing industries to provide variety of robot to fulfill customer or user need.

Now day's quick change in customer requirement is a great challenge for every manufacturing company. Customer expect product diversity, high quality, low price, long durability, etc. To fulfill customer requirement robot user purchase a robot which is supplied as an integrated package whose feature are fixed for example in FANUC 200iB robot whose payload capacity is 100 kg and workspace is fixed. As the demand of customer fluctuates several new task need to be perform and in order to perform new task the user is forced to buy a new robot which is a displeasing expense.

The requirement of robot user with respect to parallel robot as customer demand changes:

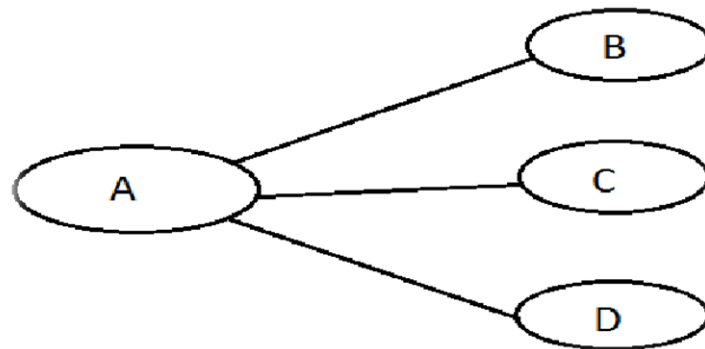
- Need more load carrying capability with no changes in workspace
- Need more workspace without any change in load carrying capability.
- Need more workspace and more load carrying capability.

So for these operative requirements robots with different configuration are required whose load carrying capabilities and workspace varies within a range. So with a change in requirement

user can't buy robot every time also it is a great challenge for robot manufacturing companies to provide as much variety at low cost. The best way to treat this quandary would be to standardize and modularize the product. Standardization and modularization helps to accomplish various robot configuration with a little investment rather than buying a new robot.

## 1.2 Modularity

Modularity means constructing a large composition by joining standardize units or modules. The modules can be recoupled in different arrangement so it can accomplish a large number of classes of task through the reconfiguration of inventory of modules. These modules can be universal joints, revolute joint, spherical joints, etc. The modules like pin can be used for different product, as the pin used is standard there is no extra cost incurred by the company for its manufacturing therefore there is no setup cost and the product is manufactured in mass. So the main focus is to use standard components in order to control the cost. The term modularity of a system depends upon the independence of components used in the product means more independent the components are, more modular it is.



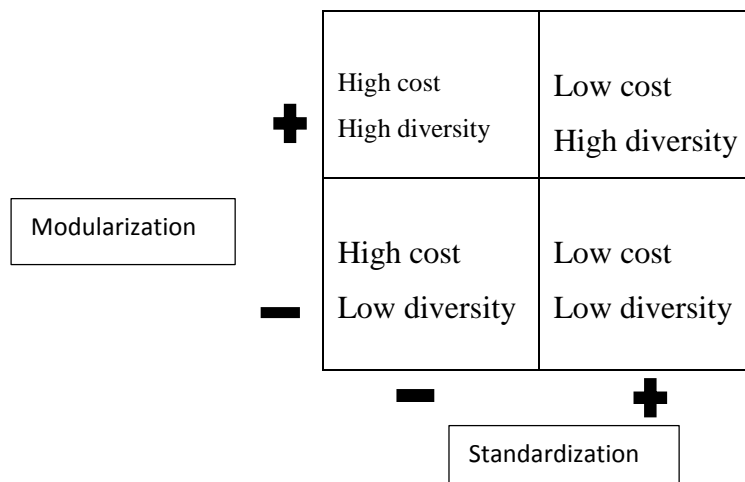
**Figure 1.1** System with four modules

Figure 1.1 shows product composed of 4 components i.e. A, B, C and D. Functionality of component A depends upon other 3 component i.e. component A has dependency on B, C and D and plays a part of integral component in the system therefore that product is less modular or we can say degree of modularity of the product is less because of dependency. The degree of modularity increase as independence between the components increases.

As compared to immobile structure robot modular robot permit versatility, robustness, low cost. Cost of a robot is always an essential factor for everyone linked with robot i.e. manufacturer and user in order to earn more profit and to gain competitive edge.

Designing a low cost component which can perform task similar to the expensive one is a main consideration of the designer. There are 2 ways by which low cost can be achieved

1. To design robot component which can be shared by other products.
2. To use components which are produced in mass.



**Figure 1.2** Effect of standardization and modularization on cost

The main concentration of the designer to achieve high diversity at low cost. Low cost and high diversity can only be achieved by using highly standardized and modular components.

Based on interaction within a product modularity is categorize in 3 ways: -

- Component-swapping modularity** Figure 1.3 (Left) shown below shows The IDAPT universal charger has docks for plugging in one of their twenty adapters, each of which charges a several device. The adapters can be popped out of the base with the pushing button and can be substituted with other adapters from the set as needed. Means a set of interchangeable modules that can be used in combination with a single product.
- Component-sharing modularity** Figure 1.3 (Right) showing The Artecnic Garland Light Shade that can be fitted around light bulbs of different shapes and configurations. Means module that can be used interchangeably in combination with other products.



**Figure 1.3** Component-swapping (Left) and Component sharing (Right)

- c) **Bus modularity** is adding modules to an existing frame designed to accept the modules. The modules can be detached and substituted by other modules.

### **1.3 Modular reconfigurable robots**

Modular reconfigurable robot consist of a small units called as “modules”. These modules can be joint, link, gripper, batteries, sensors, etc. These modules can be disconnected and reconnected in different arrangement so it can accomplish a large number of classes of task through reconfiguration of inventory of modules and enables modular robots to adapt to change in the environment. Modular robots have ability to morph into different structure so they are referred to as reconfigurable. New configuration and workspace can be varied by changing the leg position, joint type, link length for variety of task. This allow flexibility, variety in use, rapid changeover and ease of maintenance.

The main motive of modularity concept is to make a robot that can be configure to number of configuration through component swapping or component sharing, thus reducing the cost of robot. As modular robot are costlier than non-modular robots its cost need to be reduced which can be done if the modules used are produced in mass.

#### **1.3.1 Need of modular reconfigurable robots**

1. For a desired operation user purchases a robot which is designed for a fixed application and is supplied as an integrated package. Its payload capacity, positioning accuracy, reach, and workspace are fixed as designed by designer for a task. So as the demand

changes new operation need to be perform and in order to complete the job user is forced to buy a new robot which is a heavy expenditure for every industry. So modular reconfigurable robot is a solution as different configuration can be achieved instead of buying a new robot.

2. Nowadays product are various and changing rapidly on the other hand customer expect low price, high quality, long durability, etc. The best way of treating this dilemma is to modularize the product. The system topology can be changed by removal and addition of modules. So the range of task can be fulfill to a finite amount.
3. As NASA keep on exploring the moon, mars and other bodies in space. If they want to take a robot in space due to fixed structure of robot it procure a lot of space as space shuttle has small and very limited space. So the modular robot helps us to save space and its adaptive proficiency make it advantageous over the fixed structure.

**Table 1.1** Comparison between a modular and integral robot

	<b>Modular robot</b>	<b>Integral robot</b>
1. Reconfigurability	Possible	Not possible
2. Overall mass	Higher (because of presence of interfaces)	Lower
3. MTTR	Very low (set of spares parts in hand)	High (require specialized worker)
4. MTBF	High (if designed properly)	High (if properly designed)
5. Availability	100% (because set of spares parts in hand)	Influenced by MTTR
6. Initial cost	Slightly higher	Lower
7. Component outsourcing	Easy	Difficult
8. Component separability	High	Low
9. Component recombinality	High	Low

### 1.3.2 Benefits of a modular design

- Decrease time to market
- Increase number of product variant
- Decrease number of unique part
- Decrease time to repair
- Easy outsourcing
- Product update possible and easy

- Flexibility in component reuse
- Easy maintenance
- Ease in assemblability/disassemblability
- Faster assembly and less production time

## 1.4 Robot motion

The robots are designed to perform desirable work and can only be performed by manipulating the body i.e. the mobile platform of a parallel robot is manipulated to achieve desirable position and orientation in 3 dimensional space. In order to achieve these position robot joints provide relative motion between the links. These links have one input connection and 1 output connection. Parallel robot are mostly mounted on a fixed base i.e. base plate connected to ground for example Fanuc 200iB is also connected to the ground. Now the base plate is connected to other component whose input is connected with base plate and output on this components is input for the next component.



**Figure 1.4** Universal joint showing connections

**Table 1.2** Motion and degree of freedom by different type of joints

Joint type	Motion Type	Degree of freedom
1. Prismatic	Rectilinear	1
2. Revolute	Circular	1
3. Screw	Helical	1
4. Cylindrical	Cylindrical	2
5. Spherical	Spherical	3

## **1.5 Robot modules**

The most common type of module joints are spherical, revolute, prismatic, universal joint that are used to construct number of parallel robot configuration like UPU, UPS, RPS, etc. There are two standard modules i.e. base plate and face plate and rest of the modules are either standard or design in a cost effective way.

### **1.5.1 Modules category**

a. Fixed dimension modules: -

Fixed dimension modules are the modules whose dimensions remains the same but and can be connected to the modules with variation in specification to cop up with the desired requirement. These modules are spherical joints, revolute joints, universal joints, etc.

b. Variable dimension modules: -

Variable dimension modules are the modules whose dimensions can be customized for different task. It include mobile and base platform, hydraulic cylinder, etc.

## **1.6 Aim of the thesis**

The aim of this thesis is to put the concept of modularization and standardization in robotics and create a parallel robot at low cost. And further

1. Module determination
2. Show possibility to design robot using MCOTS
3. Find product and component modularity
4. Multiple attribute decision matrix for link selection for parallel robot

# CHAPTER 2

## Literature review

---

This literature review presents the summary of work carried out by researchers in the field of modular product and modular robots and selection technique for finding an optimum solution out of number of alternative.

### **Toloui-rad and dhull (2012)**

For the use of robot in various industrial applications various stages of design and prototyping of modular robot is done in this paper. They focus to design robot and robotic joint at low cost and assemble them to achieve different arrangements. The objective of this paper was to develop, manufacture, test and evaluate modular joints that meet required design specification, capabilities and are cost effective. They design and manufacture five different joint in order to achieve low cost, optimal strength size, etc. There are five joints which are created and is analyzed using CAD software called solidworks. They concluded that it is possible to design a modular joints and assemble in order so that different configuration can be achieved.

### **Acaccia et al. (2008)**

A modular robotic system was developed for industrial application. They develop a design library of robotic module for designing a modular robot and divide this library into 2 categories.

- a) Link module, not actuated
- b) Joint module, actuated

While designing a robot general purpose requirement are kept in mind

1. To compose a robotic arm with good weigh ratio/ payload
2. Compact shape of module
3. Quick and reliable connection among the modules
4. Library of modules with a limited number of modules

The prototype of two joints model and some link are also develop in this paper and SCARA is designed using these modules and then simulation is done using CAD software

**Dash et al. (2005)**

Dash presented two stage design methodology. First stage is structure determination stage, second stage is parameter determination stage. Structure determination stage is further divided into 2 stages that is an appropriate parallel manipulator is selected, second database for a reconfigurable robot assembly is created using fixed dimension modules and variable dimension modules. For a parallel robot topology with different degree of freedom is contained within a database.

They also proposed a TaskToRobot map that is built in the knowledge of designer for suitable robot configuration to accomplish various task. They presented a methodology with six degree of freedom three legged parallel robot with the aid of fixed and variable dimension modules.

**Jose and Tollenaere (2004)**

This research focus mainly upon standardization and modularization concept. These tools allow variety of product design. Product are designed using same modules called as platform which allow designs saving, easy manufacturing, etc. Combined effect of standardization and modularization is also discussed in this paper. This paper was divided into 3 sections

1. They discuss about modularity for development of product variety
2. Product architecture for a modular design. In this section they discuss the difference between integral and modular design
3. Various modular methods are discussed that is cluster method, group technology, Graph and matrix method. Etc.

**Dahmus et al. (1999)**

Dahmus presented a new architecting approach that share modules that can be interchanged. To achieve this goals following objectives were considered

- a. Traditional method- variety requirement of each market
- b. Usage variance- variety needed by the user or purchaser like swappable modules on standard interface
- c. Technology change- Rapid change in product design when design require update

Taking example design matrix based on functionality of product was made to calculate modularity. The approach presented was to take advantage of reusing module across the product.

### **Pozna (2007)**

For a changing demand of the customer a cheap and improved robot was developed. And optimizing procedure is implemented in the modular design of industrial robot and different topology for certain task is obtained. Considering modularity for user a user-friendly interface is generated which transfer information robot manufacture to robot user. As user is a task specialist not a robot specialist he don't have any knowledge of robot module connectivity to achieve a topology.

So the user-friendly interface proposed allow user to configure, allow robot maintenance, etc. In this paper kinematics of rotational joints and an algorithm was also achieved which allows the homogeneous transformation between the modular robot joints.

### **Huang et al. (1988)**

For modularity problem for mechanical, electrical, mixed process product, model and solution approach was developed. In this paper they discussed different type of modules and different type of modularity

#### Module types

- a. Basic module
- b. Auxiliary module
- c. Adaptive module

#### Type of modularity

- a. Component swapping modularity
- b. Component sharing modularity
- c. Bus modularity

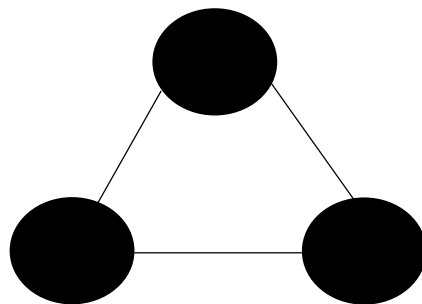
Potential benefits of modularity is also discuss in this paper. Taking an example of table lamp three type of modularity is explained and a matrix was made showing connectivity among those modules.

### **Chen et al. (2001)**

Kinematic design issue related to modular reconfigurable robot was described in this paper. For complex design two type of modules that is fixed dimension and variable dimension modules are used. By mean of these modules design can be customized rapidly. The forward kinematics of 3 legged robot containing either revolute or prismatic joints is expressed as a product of matrix exponential. The robot made using these fixed and variable dimension modules are visualized and workspace is measured and is shown in this paper.

### **Anupam Agrawal (2009)**

Two measure of modularity was defined and developed. First measure strength of design dependency which is used to find the degree of modularity. Second measures bridge modularity which is calculated considering criticality of components. Taking an example of delta jigsaw and climate control system design structure matrix is developed. In this matrix dependency is marked as 1 and zero for no dependency. Also product network is also discussed and used to calculate the modularity of the product.



**Figure 2.1** Nodes and connectivity between them

Figure 2.1 shows a network of modules connected to each other. These modules can be directly linked to each other or they are connected indirectly. Using graph theory network adjacency matrix was made and in-degree and out-degree of modules are visualized using adjacency matrix. Product network and adjacency matrix of a jigsaw is represented in this paper.

These methods are useful to check whether the product is modular if yes up to what degree the product us modular. Modular and integral product modularity is also shown in this paper.

### **Gershenson et al. (1999)**

They introduce modularity definition and its benefits. Steps to calculate modularity is also introduced in this paper

- a. Generating a component tree
- b. Generating process graph
- c. Construction of matrices
- d. Calculation of relative modularity using the modularity evaluation matrix

Taking an example of mechanical pencil table is drawn showing partial similarity and dependency

$$modularity = \frac{S_{in}}{S_{in} + S_{out}} + \frac{D_{in}}{D_{in} + D_{out}}$$

$S_{in}$  = High similarity between components within a module

$S_{out}$  = Low similarity between components within a module and other components outside the module.

$D_{in}$  = High dependency between a components within the modules.

$D_{out}$  = Low dependency between a component within a module and component outside the modules.

### **Stryker and Jacques (2009)**

For reducing the time for launching spacecraft a strategy is identified. Approach used in this is to increase the modularity of the spacecraft by increasing the modularity of its subsystem, modules and components. To check whether modularity is achieved or not a new measure, a functionality measure was introduced to be developed and correlated to modularity. Taking an example of laser guided bomb (LGB) and joint direct attack munitions (JDAM) modularity is measured by making Bipartite graph and then making design structure matrix (DSM) of the product. Modularity of each component is also measure in term of in-degree and out-degree.

$$modularity = \frac{Actual\ dependencies}{maximum\ possible\ dependencies}$$

### **Holtta-otto and Weck (2007)**

A approach to measure degree of connectedness (Sparsity) and degree of modularity is introduced. For calculating sparsity and modularity a design structure matrix (DSM) is made. The non-zero fraction (NZF) method is used which shows the sparsity of interrelationship among components and its value lies between 0 and 1. Singular modular index shows the degree of inner coupling and its values lies between 0 and 1.

Singular modular index

$$SMI = U \sum_{DSM} V^T$$

Where summation DSM is a diagonal matrix represent singular values in descending order.

Using DSM a sparse matrix was made for 3 type of system

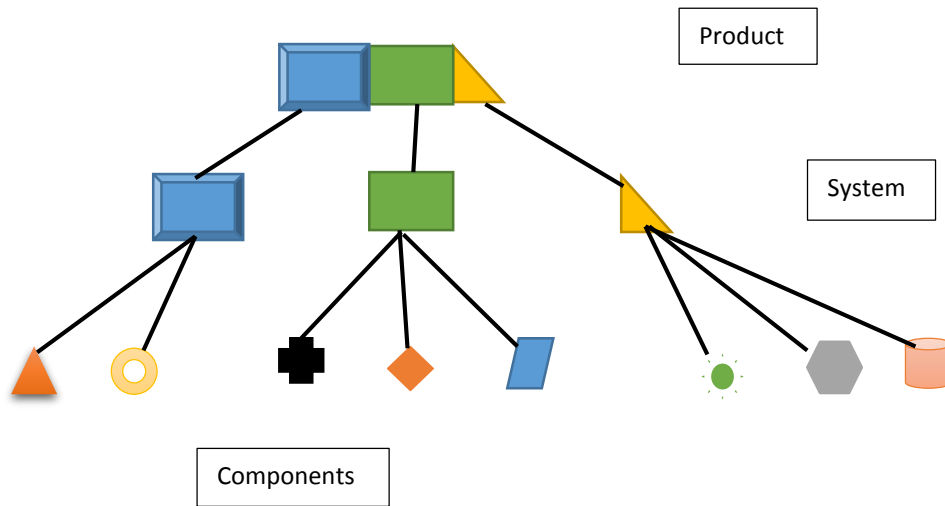
- a. Integral
- b. Bus modular
- c. Modular

$$NZF = \frac{\sum_{i=1}^N \sum_{j=1}^N DSM_{ij}}{N(N-1)}$$

Design structure, design structure matrix, sparse pattern for desk phone, cellular phone, desktop and laptop is also plotted in this paper.

### **Sosa et al. (2007)**

They define different level of modularity i.e. at product level, system level and at component level. Figure 2.2 shows the product, system, component level of a product. They consider product as a network of component that share technical interfaces. This paper mainly focus on component modularity and its definition is well defined. They define component modularity as the level of independence of a component from the other component within a product. Taking an example of PW4098 which is a commercial aircraft engine is studied in this paper



**Figure 2.2** Hierarchical decomposition of product

In this paper they define design dependencies and their type

- a. Spatial
- b. Structural
- c. Material
- d. Energy
- e. Information

**Rao and padmanabhan (2005)**

For evaluation of alternative robot a methodology was developed which is based on diagraph and matrix method and a robot selection diagraph was also proposed. This diagraph shows the importance of one attribute with remaining attributes. Diagraph consist of set of number of nodes (N) which is equal to number of attributes and set of edges directed toward each other (E). If the node 1 has a relative importance over node 2 then the arrow of the edge is directed from node 1 to node 2. To make calculation simpler this diagraph is converted into a matrix form.

$$\begin{bmatrix} A_1 & a_{12} & a_{13} & a_{14} \\ a_{21} & A_2 & a_{23} & a_{24} \\ a_{31} & a_{32} & A_3 & a_{34} \\ a_{41} & a_{42} & a_{43} & A_4 \end{bmatrix}$$

$A_i$  Represent value of  $i$ th attribute and  $a_{12}$  represent importance of node 1 over node 2. To solve this matrix computer program PERMANENT – FUNCTION was developed using C++ language. Robot selection index (RSI) was also prepared which is a measure of degree by which a robot can be successfully selected for a given application. To consider a qualitative attribute a procedure is also shown in this paper. At last ranking of alternative is done taking both quantitative and qualitative attributes.

### **Agrawal et al. (1991)**

An approach for an optimum robot selection is presented and is named as multiple attribute decision making (MADM). This approach shortlist a large number of robot to suitable robots. For this number attributes are identified and out of these only a few pertinent attributes are used for the selection procedure. The various steps involved in this paper are

1. Database containing all the information regarding all attribute is made.
2. Information from this database is used to create a decision matrix in which rows is allocated to the alternatives and column is allocated to attributes
3. Information acquired from user or expert is used to give relative importance of one attribute over other and a relative importance matrix is generated
4. Now the Eigen values of relative importance matrix is calculated and is used to calculate weight vector
5. As all the attributes have different scale so to make all attribute lie in a same scale i.e. between 0 and 1 vector is normalized
6. An ideal and negative ideal solution is calculated, these solution is a hypothetical values for a robot which can give a best results. These solution are used to calculate an optimum solution out of all attributes. The chosen alternative should be close from ideal solution and far from negative ideal solution
7. From above solution separation from ideal solution and negative ideal solution is measured
8. From these separation values relative closeness to ideal solution is measured
9. At last ranking of all alternatives is done in descending order

### **Bhangle et al. (2004)**

This paper concerns with the robot selection for various manufacturers. Due to increasing complexity, features and facilities provided by different robot manufacturer, an

approach called multiple attribute decision making (MADM) and TOPSIS (Technique for order preferences by similarity to ideal solution) to calculate, rank and solution of robot for particular application. In this paper various robot attributes are identified and coding for these attribute is done. Taking an example of maximum speed of manipulator coded scheme is elaborated. The 3 stage procedure for robot selection is discussed in this paper a graphical method for robot selection is also discussed. These graphical methods are

1. Line graph representation

In this magnitude of different attribute are plotted along vertical axis and attributes on horizontal axis.

2. Spider diagram

This method consider attributes to form a spider diagram. Angle between attribute is calculated as  $\theta = \frac{2\pi}{n}$  where n is number of attribute under consideration.

# CHAPTER 3

## Methodology

---

### 3.1 Introduction

To accomplish goals of the thesis work, modules used for the design of robot are taken commercially of the shelf (MCOTS). As these modules are manufactured by thousands of companies in mass will help us to reduce cost of our product. Modules like spherical joint, universal joint, pins, etc.

### 3.2 Benefits of taking module commercially of the shelf for user, designer, manufacturer

#### 3.2.1 For user

The user purchase a robot for particular application but in case of failure if user do not have any spare module in hand have to wait for the robot expert for its repair or module have to be delivered and this procedure is time consuming, thus proves to be counterproductive. If complete set of modules used in robot are easily available in the market the time during counterproductive period can be saved. Time to repair can be reduce and thus improve its overall availability. Also user can buy module as per his requirement like more workspace, etc. so the best solution is to design a modular robot using MCOTS.

#### 3.2.2 For designer

The user or buyer specifies his need, now its designer job to design a robot fulfilling the customer need. The designer have to design a modules that are best suited for the design and to design these module the designer have to calculate various dimensions. Some of the components are present in the market with its specification chart or catalog that can be used to choose the module for robot design, thus saving time.

Not only making design, designer have to keep some other factors like:

1. For organization
  - Cost of manufacturing
  - Inventory cost

- Material saving
2. For user
    - Flexibility
    - Variety in use
    - Low cost
    - Ease of maintenance
    - Quick and reliable connection among modules
  3. For manufacturer
    - Tools and die requirement
    - Fast supply of product

### **3.2.3 For manufacturer**

In today's competitive world companies are focusing on the quick changeover of customer requirement and due to large variety, robot production time increases due to number of steps involved before making a robot, thus time to supply a robot also increases. To reduce time to market and production cost a solution is to use module or components that are commercially available in the market. In robot manufacturing industry there are some standard module and some of them are new to the firm. For manufacturing these new modules setup may be required which causes increase in cost of product. But if the designer while designing the robot use module that are commercially available the production time required to produce those modules is saved and last thing to do for a manufacture is to assemble the modules and time to market is reduced to large extent and gives a competitive edge over competitor.

## **3.3 Methodology**

### **3.3.1 Module determination**

Designing a module which is cost effective is very difficult, thus increases product cost. Two solution for getting a low cost product is given

1. Using common modules within different product configuration
2. Using components which are produced in mass

Considering the second solution modules used for the construction of robot are used which are commercially available in the market we call it module commercially of the shelf (MCOTS).

These modules are the standard product manufactured by thousands of companies across the world. As shown by Jose and Tollenare.

For a good modular product what we are going to have is low cost with maximum standardization and high diversity with modularization. Low cost can only be achieved if the modules are produced in mass and we are using MCOTS which have standard specification and are produced in mass. These modules are assembled to form different configuration and product with low cost and high diversity can be achieved.

For a robot some component may need to be designed and are new to the firm (PNTF). The new module should be design in such a way so that it can be used by other configuration too. Module should not be unique and is limited to one configuration. MCOTS helps to reduce MTTR as the availability of module are 100 percent.

In this paper we take Fanuc 200iB parallel robot as an example and modules are taken commercially of the shelf to construct the legs of this robot. These modules are searched from various companies catalogue and through online search and then designed in CAD software and finally modules which are fit for our robot is added to CAD module library and finally these legs are used for robot design. Using fixed dimension base and face plate, modules is interchanged so that different configuration can be achieved for different task for example hydraulic cylinder of bailey with same dimension and working pressure but different stroke length and load carrying capability is available and can be interchanged among fixed dimension modules. MCOTS like spherical, revolute, prismatic, spherical joint are manufactured by many companies with different price and different specification. Few of them are specified below

### ***1. Universal joints***

- Belden
- Lovejoy
- Ashley power
- Hitork
- Atlanta
- Mbo
- Curtis
- JEGS
- Boston



(a)



(b)

**Figure 3.1** (a) Boston universal joint, (b) Lovejoy universal joint

## 2. *Prismatic joint*

### a. *Electric drive*

- Thomson
- SKF
- LINAK
- Duff Norton
- Hiwin



**Figure 3.2** Electric drive system (HIWIN)

### b. *Hydraulic and pneumatic drive*

- Bailey
- Eaton
- Parker
- FRC

- ITT
- Atlas
- Energy
- Energpac
- International hydraulics
- Hydrowa



**Figure 3.3** MAXIM Hydraulic cylinder

### ***3. Spherical joint***

- GLT
- THK
- Spherco
- SKF
- RBC



**Figure 3.4** Spherical bearing (SKF)

### ***4. Brackets and rod Clevis***

- Parker
- Cylinder repair components

- Bimba
- TRD
- YATES
- Best metal products
- Atos
- Sheffer
- Bosch
- Grainger



**Figure 3.5** Bracket clevis (Grainger)

#### 5. *Pins*

- Sharp cut tools
- VE TO clamping systems
- Taha associates
- Lord krisha engineering works
- Joy engineering
- Grainger



**Figure 3.6** Metal pin (Grainger)

Each manufacturing companies provide different model of module made as per light, medium, heavy duty series, different pressure series, mounting style, etc.

Sometime a new module need to be design which is new to the firm and in this section there are two new modules. The cost and weight of this module which is NTF are designed in solidworks. Solidworks software now has a tool for cost estimation which helps to find an approximate cost of the new module before being manufactured thus saves time. This feature give us both material, manufacturing cost and other costs related to this module.

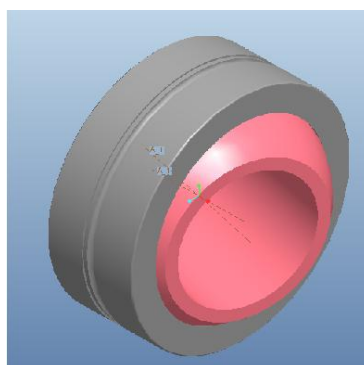
Information required by software is to specify

- a) Material for module
- b) Drilling cost of machine per hour
- c) Milling cost of machine per hour
- d) Machining Center cost per hour
- e) Type of tools to be used according to operation

### **3.3.2 Possibility to design robot using MCOTS**

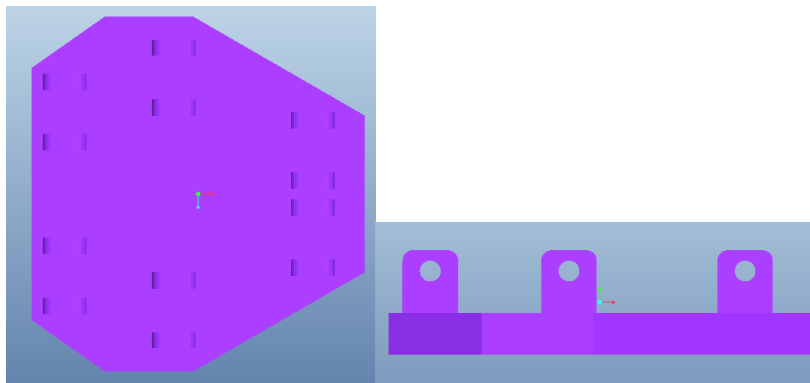
As discussed Fanuc 200iB is considered as an example having fixed geometry and fixed workspace. Module determined in first stage are used to design robot in CAD software called Pro engineer. The main motive is to make this Fanuc robot modular using MCOTS and to prove the possibility of robot design using MCOTS. Modules used for this purpose are

- a) Spherical bearing



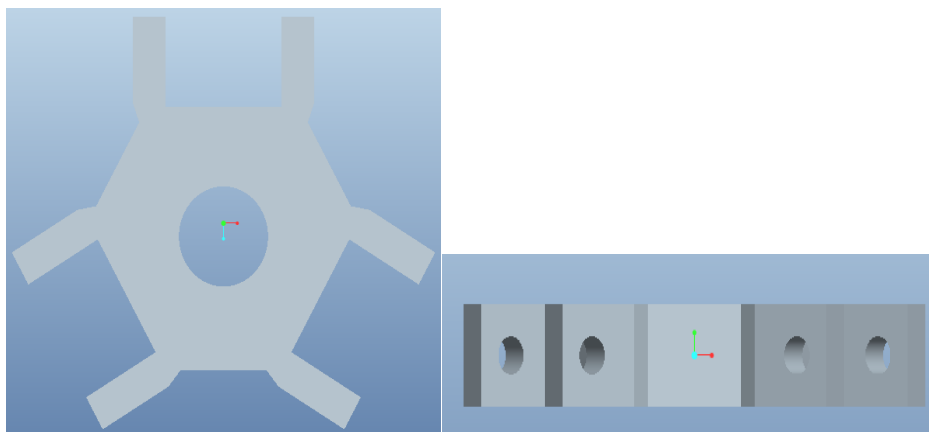
**Figure 3.7** Spherical bearing made in CAD software

b) Base plate



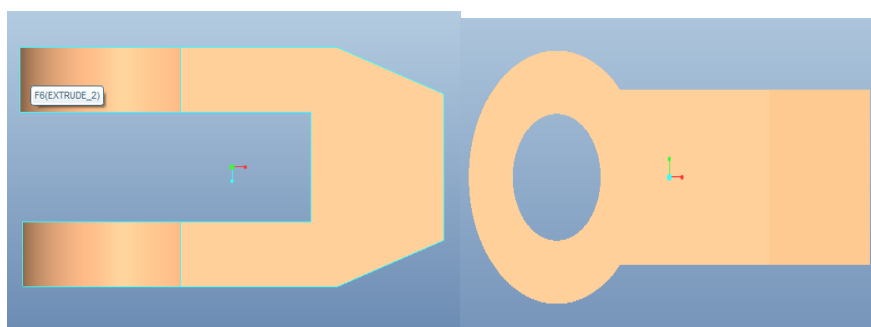
**Figure 3.8** Top view (left) and Side view (Right)

c) Face plate (mobile)



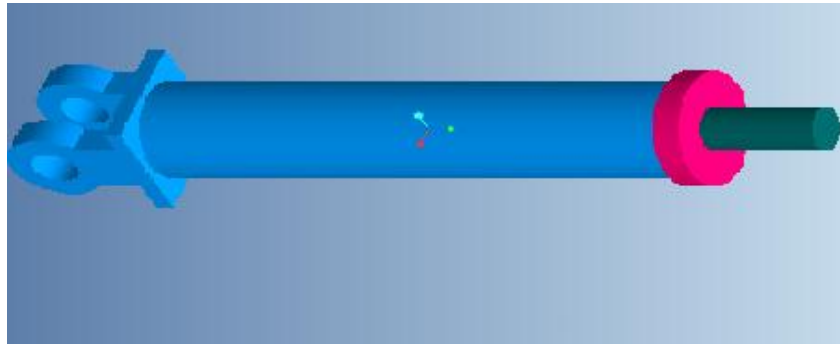
**Figure 3.9** Top view (left) and Side view (Right)

d) Hook



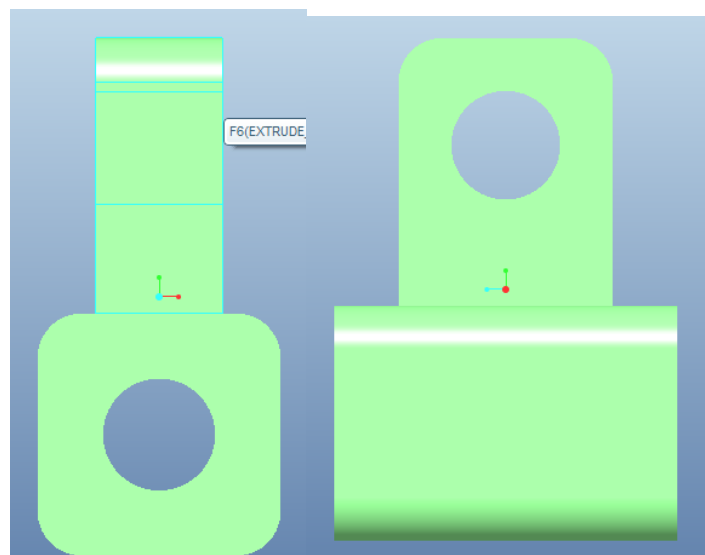
**Figure 3.10** Top view (left) and Side view (Right)

e) Hydraulic cylinder



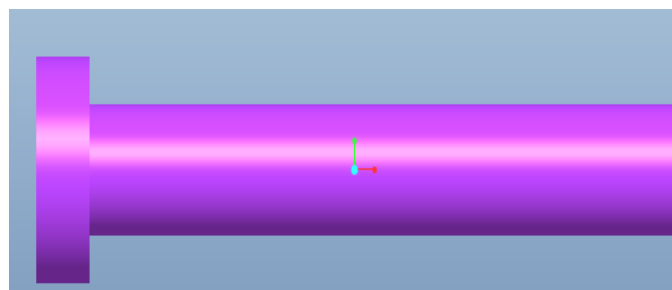
**Figure 3.11** Hydraulic cylinder

f) 2 new modules



**Figure 3.12** Side view (left) and Front view (Right) of part PNTF 1

g) 3 type of pins



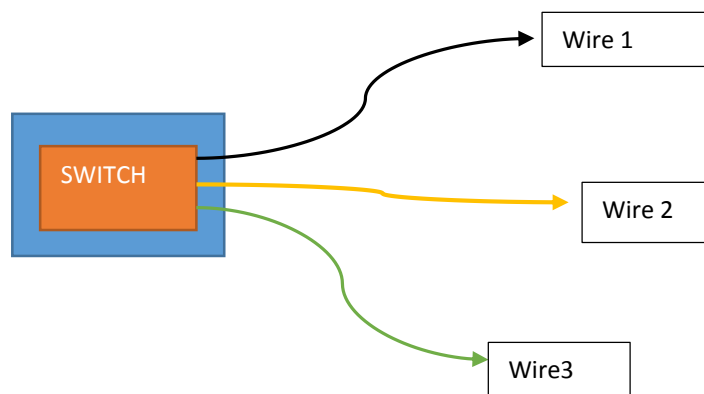
**Figure 3.13** Pin

The possibility is proved by joining all these chosen components in a Pro engineer software and is shown in picture and is compared with FANUC 200iB.

### 3.3.3 Modularity

As the goal of modularity is to design a module which is independent, standard and can satisfy our need. So the value for modularity of a component depends upon the connectivity of module with other modules or we can say dependency of module on rest of modules. For example an electrical switch is connected to 3 wires means switch functionality depends upon these 3 wires this means switch plays a part of integral component for the system. Using the concept of dependency we can find how sparse modules are. The module having high connectivity is marked as 1 and module without connection is marked as 0.

For calculations a design structure matrix is made and this matrix is pictured in term of their sparsity pattern which gives us non-zero values. Using these non-zero values of design structure matrix modularity of product and component is calculated. Matlab is used for the calculations, graph and tables.



**Figure 3.14** Example Electrical switch

$$modularity = 1 - \frac{\sum_{i=1}^N \sum_{j=1}^N DSM_{ij}}{N(N-1)}$$

The values of modularity always lies between 0 and 1. Value 0 shows that all components are connected to each other and are integral components or vice versa.

So we are going to calculate modularity for our robot design previous section Table 3.1 shows a connectivity of modules with each other where “X” shows the connectivity of module with other and “--” shows that connectivity is not possible for example base plate cannot connect to itself so marked as “--”. The unoccupied places in this table signify no connection between modules.

**Table 3.1** Design structure

	<b>B</b>	<b>N1</b>	<b>P1</b>	<b>H</b>	<b>P2</b>	<b>RE</b>	<b>SB</b>	<b>N2</b>	<b>P3</b>	<b>F</b>	<b>P4</b>
<b>BASE PALTE</b> (B)	--	X	X								
<b>NTF1</b> (N1)	X	--	X	X	X						
<b>PIN1</b> (P1)	X	X	--								
<b>HYDRAULIC'S</b> (H)		X		--	X	X					
<b>PIN2</b> (P2)		X		X	--						
<b>ROD END</b> (RE)				X		--	X				
<b>SPHERICL BEARING</b> (SB)						X	--	X			
<b>NTF2</b> (N2)							X	--	X	X	X
<b>PIN3</b> (P3)								X	--		
<b>FACE PLATE</b> (F)								X		--	X
<b>PIN4</b> (P4)								X		X	--

Same concept can be used for calculating modularity of every single component of the system. This can be done by calculating in-degree and out-degree of the component. In-degree is the number of connectivity of i-th component with all jth components. Out-degree is the number of connectivity of j-th component with all i-th components. And component modularity is defined as

$$\text{component modularity} = \frac{\text{actual component disconnectivity}}{\text{maximum possible connectivity possible}}$$

### 3.3.4 Multiple attribute decision making

For a parallel reconfigurable robot, robot topology plays an important role for the functionality of robot to fulfill task. The designer have number of links that can be

connected between base and face plate but selecting best link fulfill customer requirement is a challenge for the modular robot manufacturing companies and takes a lot of time. So a database is required for the proper selection of the link. So to select optimum link and save time MADM approach solved by TOPSIS to evaluate, rank, and select optimum link. This ranking gives the best link for a particular demand.

### **3.3.4.1 Step by step procedure**

1. Aim and objective for which link need to be used
2. Identify attribute
3. Coding scheme
4. 3 stage elimination procedure
  - a) Elimination search
  - b) Evaluation procedure
    - Decision matrix
    - Normalized matrix
    - Relative importance matrix
    - Weight matrix
    - Weighted normalized specification
    - Positive and negative benchmark
    - Determination of separation measure
    - Relative closeness to positive benchmark
  - c) Raking procedure

### **3.3.4.2 Robot attribute**

It is critically important to identify robot attribute properly when comparing various alternatives. Therefore whenever the supplier is approached by user for purchasing a new robot, the attribute identification attain substantial importance. Thus the proper choice of robot directly affect the final product of industry. So the robot attribute must be identified properly. The attribute identified are Tabulated in Table 3.2

**Table 3.2** Attributes

<b>a. General</b>	
	1. Price range
	2. Type of robot
	3. DH parameter
	4. Versatility
	5. Operating system
<b>b. Physical</b>	
	6. Mounting method
	7. Type of actuator
	8. Number of actuator used
	9. Material used
	10. Weight of robot
	11. Size of robot
	12. Space requirement of robot
	13. Hydraulic drive system
	14. Pneumatic drive system
	15. Electrical drive system
	16. Type of cable used
	17. Cable layout
	18. Hydraulic lines
	19. Fluid filter used
	20. Number of axis
	21. Number of offset joints
	22. Physical dimension of cylinder
	23. Modular
	24. Type of gear used for power transmission
	25. AC current supply
	26. AC voltage requirement

*(continued on next page)*

	27. AC power consumption
	28. AC frequency
	29. Type of fluid used
	30. Type of pump used
	31. Size of reservoir
	32. Valves used
<b>c. Economical</b>	
	33. purchase cost
	34. Installation cost
	35. Special tooling cost
	36. Maintenance cost
	37. Labor cost
	38. Training cost
<b>d. Performance</b>	
	39. Singularity present
	40. Positioning accuracy
	41. Repeatability
	42. Stroke
	43. Dexterity
	44. Workspace
	45. Dexterous workspace
	46. Maximum force of linear actuator
	47. Overload capacity of robot
	48. Payload capacity
	49. Displacement per second
	50. Gallon per minute required
	51. Piston extension time
	52. Piston retraction time
	53. Cycle time
	54. Reach in x-direction
	<i>(continued on next page)</i>

	55. Reach in y-direction
	56. Reach in z-direction
	57. Force output
	58. Linear actuator backlash
	59. Rotating link backlash
	60. Resolution of optical encoder
	61. Resolution of linear encoder
	62. Resolution of rotating link
	63. Maximum torque of rotating link
	64. Maximum operating pressure
	65. Fluid flow rate
<b>e. Structure</b>	
	66. Type of configuration
	67. Degree of freedom of robot
	68. Joint sequence
	69. Joint orientation
	70. Type of structure
	71. Type of joint
	72. Number of legs used
<b>f. Application</b>	
	73. Usage of robot
	74. Humidity
	75. Working temperature
	76. Vibrations
<b>g. Sophistication of equipment's</b>	
	77. Maintainability
	78. Safety features
	79. Assemblability
	80. Dissemblability
	<i>(continued on next page)</i>

<b>h. Control and feedback</b>	81. Programming method
	82. Type of memory
	83. Memory capacity
	84. Number of input connection of controller
	85. Number of output connection of controller
	86. Input channel for robot
	87. Output channel for robot
	88. Force sensor
	89. Torque sensor
	90. Tactile sensor
	91. Internal state sensor
	92. External state sensor
	93. Sensor type
<b>i. Availability/Reliability</b>	94. Downtime
	95. Reliability
	96. Reason for downtime
	97. Vendor services

### 3.3.4.3 Coding scheme

Coding scheme is developed to simplify identification and characterization of robotic system. This helps to make procedure computational and user friendly. Coding scheme is shown in Table 3.3. This table consist of 4 column. In first column serial number for all the attributes is written, in second column all 97 attributes are written, in third column information regarding all attribute is written, in column 4 codes base on attribute is written.

#### Illustration of coding

The coding scheme is explained here by taking an example. Suppose we want to codify the stroke of the cylinder used in robot. Its coding scheme can be shown in Table 3.3

**Table 3.3** Illustration of coding

STROKE	CODE
Unspecified	0
0 to 4 inches	1
5 to 8 inches	2
9 to 12 inches	3
13 to 16 inches	4
17 to 20 inches	5
21 to 24 inches	6
25 to 28 inches	7
29 to 32 inches	8
>33 inches	9

All identified attribute can be arranged in form of coding scheme is shown in Table 3.4

**Table 3.4** 97 digit coding scheme for parallel robot

<i>-General</i>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>												
<i>-Physical</i>	<b>6</b>	<b>7</b>	<b>8</b>	<b>9</b>	<b>10</b>	<b>11</b>	<b>12</b>	<b>13</b>	<b>14</b>	<b>15</b>	<b>16</b>	<b>17</b>	<b>18</b>	<b>19</b>	<b>20</b>	<b>21</b>	
	<b>22</b>	<b>23</b>	<b>24</b>	<b>25</b>	<b>26</b>	<b>27</b>	<b>28</b>	<b>29</b>	<b>30</b>	<b>31</b>	<b>32</b>						
<i>-Economical</i>	<b>33</b>	<b>34</b>	<b>35</b>	<b>36</b>	<b>37</b>	<b>38</b>											
<i>-Performance</i>	<b>39</b>	<b>40</b>	<b>41</b>	<b>42</b>	<b>43</b>	<b>44</b>	<b>45</b>	<b>46</b>	<b>47</b>	<b>48</b>	<b>49</b>	<b>50</b>	<b>51</b>	<b>52</b>	<b>53</b>	<b>54</b>	
	<b>55</b>	<b>56</b>	<b>57</b>	<b>58</b>	<b>59</b>	<b>60</b>	<b>61</b>	<b>62</b>	<b>63</b>	<b>64</b>	<b>65</b>						
<i>-Structure</i>	<b>66</b>	<b>67</b>	<b>68</b>	<b>69</b>	<b>70</b>	<b>71</b>	<b>72</b>										
<i>-Application</i>	<b>73</b>	<b>74</b>	<b>75</b>	<b>76</b>													
<i>-Complexity of system</i>	<b>77</b>	<b>78</b>	<b>79</b>	<b>80</b>													
<i>-Control and feedback</i>	<b>81</b>	<b>82</b>	<b>83</b>	<b>84</b>	<b>85</b>	<b>86</b>	<b>87</b>	<b>88</b>	<b>89</b>	<b>90</b>	<b>91</b>	<b>92</b>	<b>93</b>				
<i>-Availability/reliability</i>	<b>94</b>	<b>95</b>	<b>96</b>	<b>97</b>													

**Table 3.5** Example Fanuc parallel robot F-200iB

S. no.	Attribute	Information	code
1.	Price range	--	0
2.	Type of robot	Parallel	P
3.	DH parameter	--	0
4.	Versatility	--	0

5.	Operating system	--	0
6.	Mounting method	Floor	F
7.	Type of actuator	Electrical	E
8.	Number of actuator used	--	0
9.	Material used	--	0
10.	Weight of robot	160 kg	4
11.	Size of robot	--	0
12.	Space requirement of robot	--	0
13.	Hydraulic derive system	--	0
14.	Pneumatic derive system	--	0
15.	Electrical derive system	--	0
16.	Type of cable used	--	0
17.	Cable layout	--	0
18.	Hydraulic lines	--	0
19.	Fluid filter used	--	0
20.	Number of axis	6	3
21.	Number of offset joints	--	0
22.	Physical dimension of cylinder	--	0
23.	Modularity	--	0
24.	Type of gears used for power transmission	--	0
25.	AC current supply	--	0
26.	AC voltage requirement	--	0
27.	AC power consumption	--	0
28.	AC frequency	--	0
29.	Type of fluid used	--	0
30.	Type of pump used	--	0
31.	Size of Reservoir	--	0
32.	Valves used	--	0
33.	Purchase cost	--	0
34.	Installation cost	--	0
35.	Special tooling cost	--	0
36.	Maintenance cost	--	0
37.	Labor cost	--	0
38.	Training cost	--	0
39.	Singularity present	--	0
40.	Positioning accuracy	--	0
41.	Repeatability	$\pm 0.1mm$	5
42.	Stroke	--	0
43.	Dexterity	--	0
44.	Workspace	--	0
45.	Dexterous workspace	--	0
46.	Maximum force of linear actuator	--	0
47.	Overload capacity of robot	--	0

48.	Payload capacity	100 kg	2
49.	Piston displacement per second	--	0
50.	Gallons per minute	--	0
51.	Piston extension time	--	0
52.	Piston retraction time	--	0
53.	Cycle time for complete stroke	--	0
54.	Reach in x-direction	520 mm	2
55.	Reach in y-direction	511 mm	2
56.	Reach in z-direction	1237 mm	4
57.	Force output	--	0
58.	Linear actuator backlash	--	0
59.	Rotating link backlash	--	0
60.	Resolution of optical encoder	--	0
61.	Resolution of linear encoder	--	0
62.	Resolution of rotating link	--	0
63.	Maximum torque of rotating link	--	0
64.	Maximum operating pressure	--	0
65.	Fluid flow rate	--	0
66.	Type of configuration	--	0
67.	Degree of freedom of robot	6	6
68.	Joint sequence	--	0
69.	Joint orientation	--	0
70.	Type of structure	--	0
71.	Type of joint	--	0
72.	Number of legs used	6	6
73.	Usage of robot	--	0
74.	Working environment	--	0
75.	Working temperature	upto 45°C	5
76.	Vibrations	--	0
77.	Maintainability	--	0
78.	Safety features	--	0
79.	Assemblability	--	0
80.	Dissemblability	--	0
81.	Programming method	--	0
82.	Type of memory	--	0
83.	Memory capacity	--	0
84.	Number of input channel of controller	--	0
85.	Number of output channel of controller	--	0
86.	Input channel for robot	--	0
87.	Output channel for robot	--	0
88.	Force sensor	--	0
89.	Torque sensor	--	0
90.	Tactile sensor	--	0

91.	Internal state sensor	--	0
92.	External state sensor	--	0
93.	Sensor type	--	0
94.	Downtime	--	0
95.	Reliability	--	0
96.	Reason for downtime	--	0
97.	Vendor services	--	0

This table indicates all the information provided by the manufacturer to user. Here ‘--’ represent that information related to the attribute of a robot is not available. And code for this information is tabulated as 0.

**Table 3.6** Representation of coding scheme for Fanuc F-200iB

-General	0	P	0	0	0											
-Physical	F	E	0	0	4	0	0	0	0	0	0	0	0	0	3	0
	0	0	0	0	0	0	0	0	0	0	0					
-Economical	0	0	0	0	0	0										
-Performance	0	0	5	0	0	0	0	0	0	2	0	0	0	0	0	2
	2	4	0	0	0	0	0	0	0	0	0					
-Structure	0	6	0	0	0	0	6									
-Application	0	0	5	0												
-Complexity of system	0	0	0	0												
-Control and feedback	0	0	0	0	0	0	0	0	0	0	0	0	0			
-Availability/reliability	0	0	0	0												

### 3.3.4.4 Three stage elimination procedure

#### Elimination search (stage 1)

In previous section total 97 attributes for a parallel robot is identified. It is not necessary for end user or industry to use all 97 attributes for selection of a robot. The most

useful attributes attribute among all 97 attributes which are application specific are selected and are called as “pertinent attribute” and other attributes are eliminated. This procedure focus merely on pertinent attributes leaving out the rest.

## Evaluation approach (stage 2)

Database of all alternatives whose attribute please the acceptable level of target is formed. Now these alternate need to be ranked in order to find out an optimal one.

### a) Decision matrix (D)

All the information from the database of alternatives is represented in a matrix form. Such matrix is called as decision matrix “D”. Each row of decision matrix is allocated to one alternative and each column to one pertinent attribute which is under consideration. If there are m number of alternatives and n number of pertinent attributes which are under consideration, then the decision matrix is an m x n matrix.

$$D = (a_{ij})_{m \times n}$$

$$i = 1, 2 \dots m$$

$$j = 1, 2, \dots n$$

$$D = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & \ddots & \dots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix}$$

Where  $a_{1j}$  represent value of  $j$ th attribute for first alternative.

### b) Normalized matrix (N)

Elements in each column of a decision matrix have different units and scale thus the matrix is non-normalized. So to bring data within a range or scale normalization is done. This phenomenon is used to compute the normalized specification matrix. This brings the magnitude of the robot attributes on a common scale of 0 to 1.

Element  $n_{ij}$  of a normalized matrix can be calculated as

$$n_{ij} = \frac{a_{ij}}{(\sum_{i=1}^m a_{ij}^2)^{1/2}}$$

### c) Relative importance matrix (R)

In this step information on the relative importance of one attribute over other attribute is obtained from the group of expert or user for a given application. This information is required in term of ratio. This information is stored in a matrix called as relative importance matrix “R” which is n x n matrix. Here  $r_{ij}$  will hold the relative importance of  $i$ th attribute over  $j$ th attribute. This matrix contain all diagonal elements as unity.

$$r_{ij} = \frac{\text{importance of } i\text{th attribute}}{\text{importance of } j\text{th attribute}}$$

### d) Weight matrix (W)

In this step weight of all attribute is calculated and is formulated using Eigen values

$$Rx = \lambda x$$

Where  $\lambda$  an Eigen values of matrix R and  $x$  is a corresponding Eigen vector. For a n x n matrix (R) there are n Eigen values  $\lambda_i$ , for  $i=1,2,\dots,n$  and for  $\lambda_i$ , there are n Eigen vectors  $x_i$  for  $i=1,2,\dots,n$

Vector **W** is found now establish in following ways

1. Taking  $x_{max}$  corresponding to  $\lambda_{max}$  as all the elements of  $x_{max}$  are either +ve or –ve.
2. Sum of elements of  $x_{max}$  is calculated

$$\alpha = \sum_{i=1}^n (x_i)_{max}$$

3. Weight vector **W** is calculated as

$$W = \frac{(x_{max})}{\alpha}$$

Such that  $\sum_{i=1}^n W_i = 1$

### e) Weighted normalized specification

To obtain weighted normalized matrix  $U$  weight information obtained from previous section is merged into the normalized matrix  $N$

$$U = W.N$$

$$U = \begin{bmatrix} w_1 n_{1,1} & w_2 n_{1,2} & \cdots & w_n n_{1,n} \\ w_1 n_{2,1} & \ddots & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ w_1 n_{m,1} & w_2 n_{m,2} & \cdots & w_n n_{m,n} \end{bmatrix}$$

$$= \begin{bmatrix} u_{1,1} & u_{1,2} & \cdots & u_{1,n} \\ u_{2,1} & \ddots & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ u_{m,1} & u_{m,2} & \cdots & u_{m,n} \end{bmatrix}$$

### f) Positive and negative benchmark

For ranking and selection matrix  $U$  is used to obtain negative and positive benchmark robots. These benchmark robots are imaginary robots, which is supposed to have superlative and vilest possible magnitude. The TOPSIS (Technique for order preferences by similarity to ideal solution) method is based on the idea that selected option should have distance closest to positive benchmark robot and far from the negative benchmark robot. The measure confirm that the top ranked robot is nearby positive benchmark robots and far from negative benchmark robots.

### g) Determination of separation measure

TOPSIS method based on an idea that selected alternative should be nearest to the positive benchmark and farthest from the negative benchmark. Now the separation of alternatives is given by

Separation of alternative from positive benchmark

$$S_i^+ = \sqrt{\sum_{j=1}^n (u_{ij} - u_1^+)^2}$$

i= 1, 2 .....m

Separation of alternative from negative benchmark

$$S_i^- = \sqrt{\sum_{j=1}^n (u_{ij} - u_1^-)^2}$$

i= 1, 2 .....m

### **h) Relative closeness to positive benchmark**

It is the degree of appropriateness of the robot for the chosen application on the basis of pertinent attribute.

$$C^* = \frac{S_i^-}{S_i^+ + S_i^-}$$

i= 1, 2 .....m

### **Ranking procedure (stage 3)**

All the alternatives can be settled in a descending value order of  $C^*$  to find the preference order of alternatives.

# CHAPTER 4

## Results and discussion

### 4.1 Module determination

Table 4.1 Components used for modular design

Components	Brand	Model number	Quantity
Spherical bearing	SKF	GEH 25 ES-2RS	6
Hydraulic cylinder	Bailey	218-306	6
Pin 1	G.L. HUYETT	CLP-1000-6000	6
Pin 2	G.L. HUYETT	CLP-1000-4000	12
Pin 3	G.L. HUYETT	CLP-1500-9000	3
Rod end (Hook)	CHIEF	276-031	6
Face plate	In-House		1
Base plate	In-house		1
Part New to the firm 1 (PNTF1)	In-House		6
Part New to the firm 2 (PNTF2)	In-House		3

Identified modules are shown in Table 4.1. This table has 4 column that is component, brand, model number, quantity. These modules are coupled together make Fanuc parallel robot modular

#### 4.1.1 Replacement parts

There are two ways by which part can be replaced

- Part from same company whose product specified and used in our design.
- Part with same specification manufactured by other companies can be used

There are thousands of company's manufacturing parts with same specification and few of them are specified in Table 4.2. This table show that availability of parts is very high so mean time to repair reduces to great extent.

**Table 4.2** Replacement part

<b>Hydraulic cylinder</b>	
<b>1. International fluids</b>	ITR-2010
<b>2. Hysec</b>	HYS-20AGU10-10
<b>3. Bailey</b>	218-306
<b>Spherical bearing</b>	
<b>1. SKF</b>	GEH 25ES-2RS
<b>2. GLT</b>	GEH 25 ES
<b>3. RBC</b>	MBH 2530
<b>PIN 1</b>	
<b>1. G.L Huyett</b>	CLP-1000-6000
<b>2. Grainger</b>	2MUU9
<b>3. ITW Bee</b>	3HK Z2
<b>PIN 2</b>	
<b>1. G.L. Huyett</b>	CLP-1000-4000
<b>2. Grainger</b>	2MUU7
<b>3. ITW Bee</b>	3HKY8
<b>PIN 3</b>	
<b>1. G.L. Huyett</b>	CLP-1500-9000
<b>HOOK</b>	
<b>1. CHIEF</b>	276-031

The modules used in this product can be added to the module library specifying its dimensions, weight, material, cost, etc. So number of links can be made and all the modules can be added to the module library and can be used before looking for new ones.

#### **4.1.1.1 Results**

Modules used for making modular robot is identified easily from internet searches and various company catalogues. Modules fit for our purpose and their replacement

parts are easily identified and MCOTS decreases the design, manufacturing time and decrease counterproductive time

### 4.1.1.2 Discussion

Searching a module fit for our purpose is very easy as all the specifications like cost material used, dimensions, weight, etc. are provided by the every manufacturer in their catalog or company broucher. Components which are fit for our purpose can be added to our module library so that they can be used for new product. Module used have number of replacement parts, so the availability of module is never a problem thus reduces mean time to repair to a large extent. The MTTR is very less so the product is available most of the time i.e. product availability increases.

## 4.2 POSSIBILITY TO CREATE MODULAR ROBOT USING MCOTS

Fanuc F-200iB is a six axis, six degree of freedom. It has UPS configuration that is universal (2 DOF) Prismatic (1 DOF) spherical (3 DOF). This is a 6 DOF parallel robot that serves the purpose of

- a. Sub-compact robot welding
- b. Pedestal welding
- c. Part loading/positioning
- d. Nut running
- e. Vehicle lift and locate
- f. Flexible/convertible fixturing
- g. Material Removal
- h. Dispense

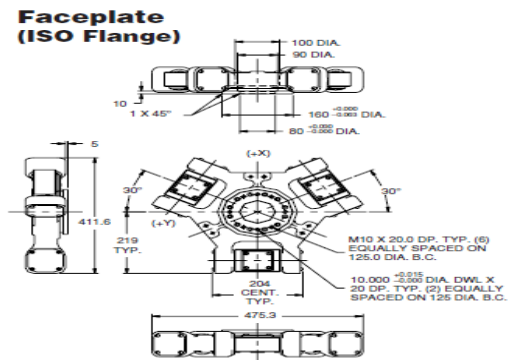
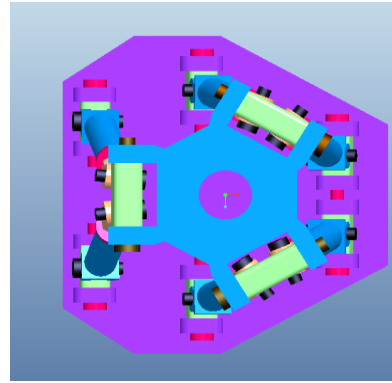
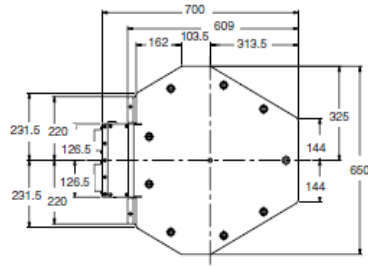


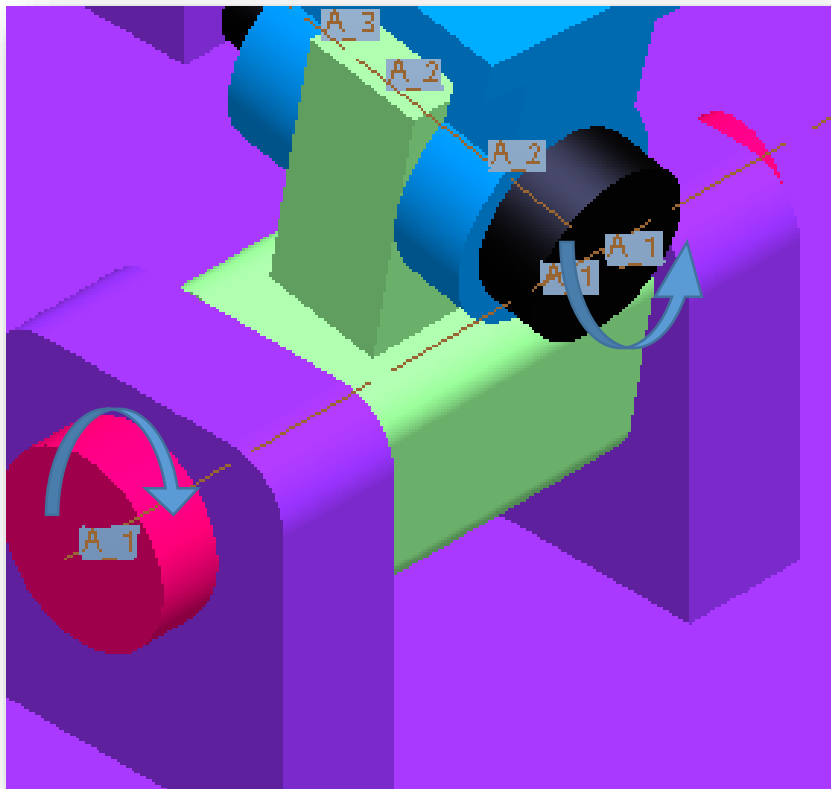
Figure 4.1 Fanuc F-200iB (left) and Face plate (Right)

**Baseplate**



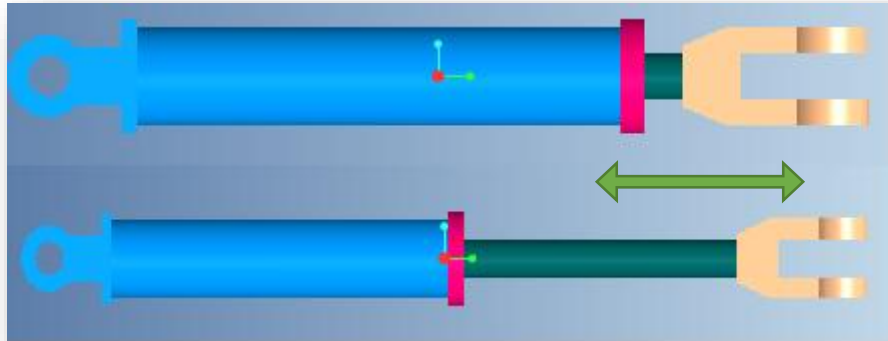
**Figure 4.2** Base plate (left) and Assembly top view (Right)

Figure 4.1, is the picture of Fanuc F-200iB and faceplate and Figure 4.2 shows Base plate of Fanuc robot and assembly of modular robot created in pro-engineer CAD software. Where various identified modules are coupled together to construct a modular parallel robot.



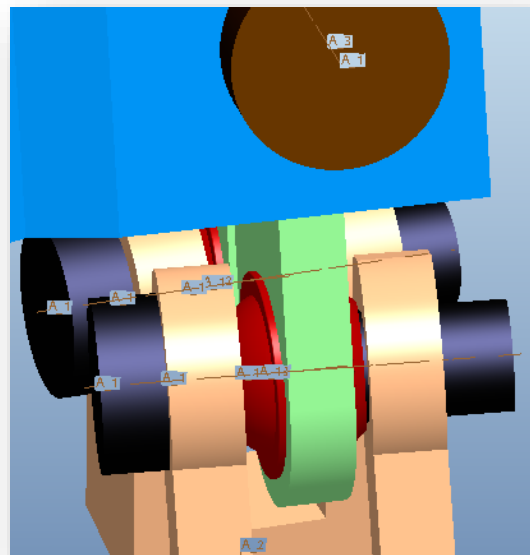
**Figure 4.3** Shows connectivity of five modules

Figure 4.3 shows the connectivity of five modules i.e. Base plate, PNTF1, Hydraulic cylinder, Pin1, Pin2 that provide 2 DOF



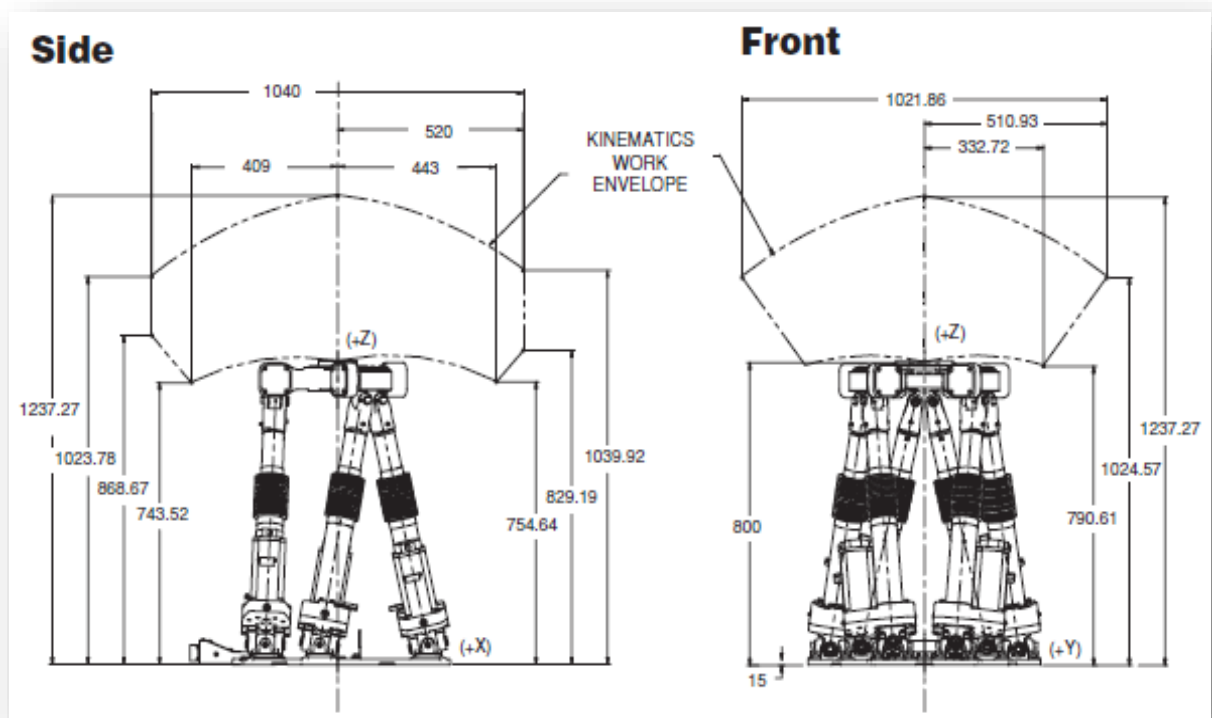
**Figure 4.4** Hydraulic cylinder and hook connectivity

Figure 4.4 shows connection of Hydraulic cylinder and hook connection and its retracted and extended position this joint provide 1 DOF

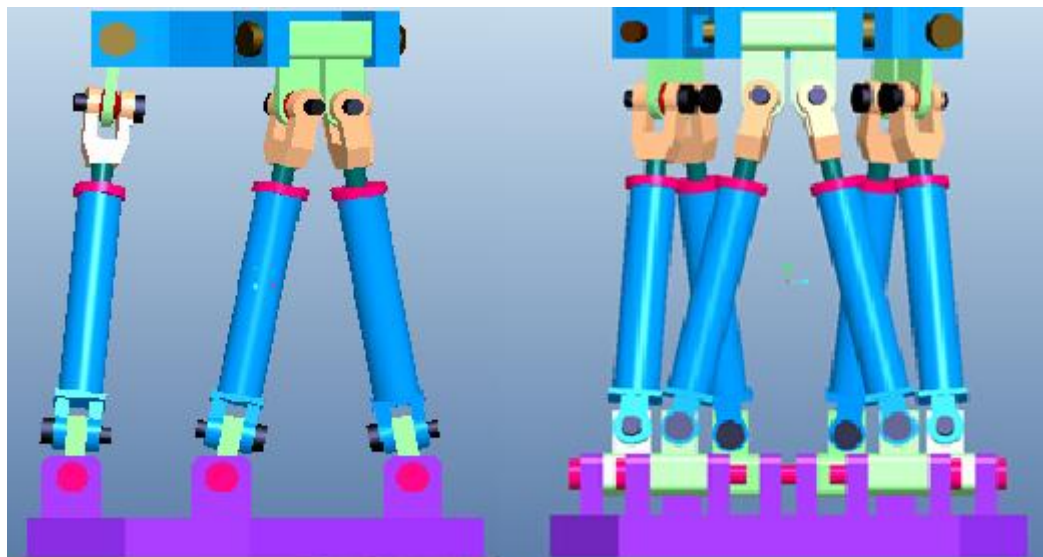


**Figure 4.5** connectivity of 6 modules

Figure 4.5 shows connectivity of six modules i.e. hook, pin2, PNTF2, spherical bearing, pin3, face plate. This connectivity provide 3 DOF.

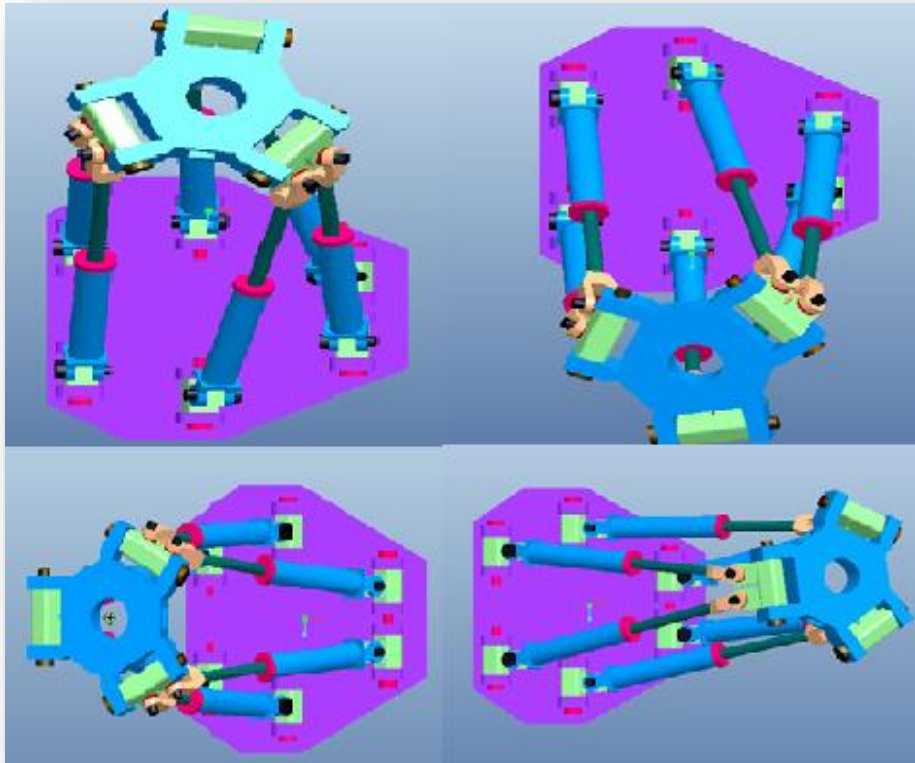


**Figure 4.6** Side view (Left) and Front view (Right) of Fanuc F-200iB robot

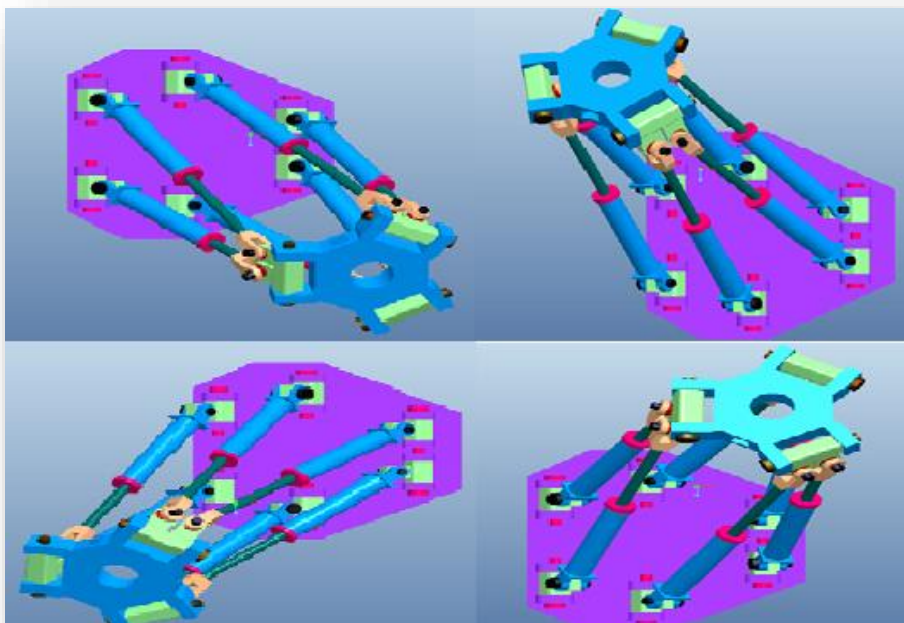


**Figure 4.7** Side view (Left) and Front view (Right)

Figure 4.6 shows the front and side view of Fanuc F-200iB robot and Figure 4.7 shows side view and front view robot constructed in CAD software.



**Figure 4.8** Movement of face plate 1



**Figure 4.9** Movement of face plate 2

Figure 4.8, 4.9 shows the various position achieved by the robot which is constructed by joining the modules which are taken commercially of the shelf.

### 4.2.1 Result

It is possible to construct robot using MCOTS. As the various position attained by the face plate is shown in figure 4.8 and figure 4.9.

### 4.2.2 Discussion

Main purpose of this section is to show the possibility of creating a modular robot using MCOTS. In this section Fanuc F-220iB is turned from integral to modular structure. The possibility is shown by creating a CAD model. The components identified in previous section are coupled together to form a parallel robot and is shown in figure 4.6 (side view,Front view). Thus a modular robot is possible to construct using MCOTS.

## 4.3 Modularity

### 4.3.1 Product modularity

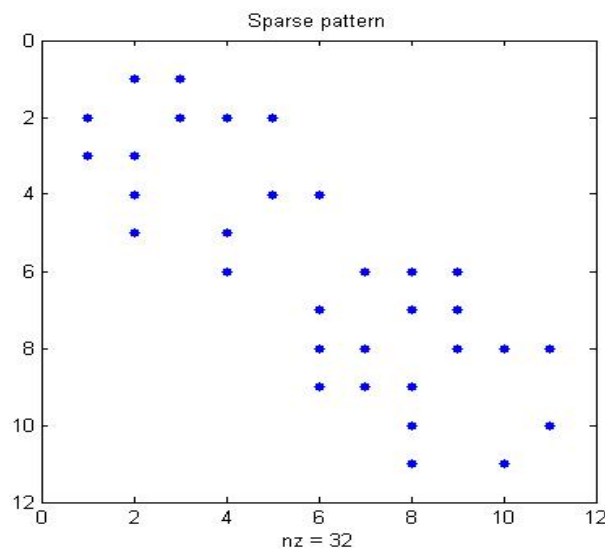
Table 4.3 shows a design structure matrix (DSM). This matrix is made by using Table 3.1 where connectivity is shown by 1 and 0 for no connection.

**Table 4.3** Design structure matrix

0	1	1	0	0	0	0	0	0	0	0
1	0	1	1	1	0	0	0	0	0	0
1	1	0	0	0	0	0	0	0	0	0
0	1	0	0	1	1	0	0	0	0	0
0	1	0	1	0	0	0	0	0	0	0
0	0	0	1	0	0	1	1	1	0	0
0	0	0	0	0	1	0	1	1	0	0
0	0	0	0	0	1	1	0	1	1	1
0	0	0	0	0	1	1	1	0	0	0
0	0	0	0	0	0	0	1	0	0	1
0	0	0	0	0	0	0	1	0	1	0

For a case if there are 150 attribute the matrix formed will be 150 X 150. Means there are 22500 elements in the matrix and it became very complicated to calculate number of connection between modules. So to make things easier DSM is visualized in a sparse pattern.

From Table 3.1 the first row belongs to base plate and is showing connection with other modules. 0 shows there is no connection between modules and 1 shows a connection between these modules. First row shows connection of base plate with pin1 and component which is new to the firm (PNTF1).



**Figure 4.10** Sparse pattern

$$modularity (M) = 1 - \frac{\sum_{i=1}^N \sum_{j=1}^N DSM_{ij}}{N(N - 1)}$$

Number of nonzero (nz) =32

N= total number of modules used = 11

$$modularity (M) = 1 - \frac{32}{11(11 - 1)}$$

$$modularity (M) = 0.709$$

Value of modularity M= 0.709 shows the degree of modularity. If this value reaches M=0 then system is said to be completely integral and as value approaches M=1 the system is said to be fully modular.

$$0 \leq M \leq 1$$

The value of modularity always lies between 0 and 1

### 4.3.1.1 Result

Value of  $m=0.709$  shows that product is 70.9% modular. As value of 'm' increases, product modularity increases. With a down fall in value of 'm' product modularity decreases

### 4.3.2 Component Modularity

**Table 4.4** Component modularity

<i>components</i>	<b>In-degree</b>	<b>M(ID)</b>	<b>Out-degree</b>	<b>M(OD)</b>
<b>Base plate</b>	2	0.80	2	0.80
<b>New to the firm 1</b>	4	0.60	4	0.60
<b>Pin 1</b>	2	0.80	2	0.80
<b>Hydraulic</b>	3	0.70	3	0.70
<b>Pin 2</b>	2	0.80	2	0.80
<b>Rod end</b>	4	0.60	4	0.60
<b>Spherical bearing</b>	3	0.70	3	0.70
<b>New to the firm 2</b>	5	0.50	5	0.50
<b>Pin 3</b>	3	0.70	3	0.70
<b>Face plate</b>	2	0.80	2	0.80
<b>Pin 4</b>	2	0.80	2	0.80

Table 4.4 shows component modularity. The component modularity is measure using formula

$$component\ modularity = \frac{actual\ component\ disconnectivity}{maximum\ possible\ connectivity\ possible}$$

This table consist of 5 columns first column belongs to components, second belong to In-degree, third column belongs to In-degree modularity, fourth column belongs to out-degree and last column is modularity of out-degree.

#### 4.3.2.1 Result

Component which is new to the firm (PNTF2) is very less modular as compared to other modules. And due to this component modularity of the product decreases. No component of a system is 100 percent modular.

### 4.3.2.2 Discussion

Using the formula for modularity, we can check whether the product is modular or not. Also a component present in system is modular and upto what level. Modularity of our modular product made in previous section is calculated and results shows that this product is 70.9 % modular. According to our concept for modularity 100 percent modularity is impossible to achieve because each component have minimum one connection with other component.

## 4.4 Multiple attribute decision making (MADM)

Suppose a use approaches a robot manufacturing company to purchase a parallel robot for loading and positioning operation, user specify his requirement and now its designer job to fulfill his requirement. For fulfilling customer need the designer have to select optimum leg from large number of legs from their inventory that matches the specification provided. So the minimum requirement for robot leg is

**Table 4.5** Requirement specifications

1. Force output	3500 lbs
2. Type of actuator	Hydraulic only
3. Reach	800 mm
4. Cycle time	5 seconds
5. Weight	23 lbs
6. Degree of freedom	At least 3

### Stage 1 Elimination search

In this stage the manageable number of alternatives are find out. From the above table the information gained is that requirement is Hydraulic cylinder so from number of legs a manageable number of legs that suits are requirement are found i.e. Leg 1, Leg 2 and Leg 3. Now ranking for these three legs is done and optimum one is selected out of three.

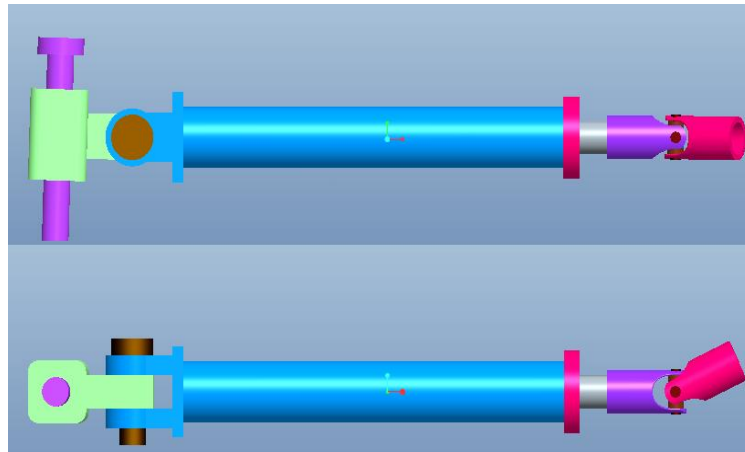
### Stage 2 Evaluation Procedure

Database is generated and after elimination stage a manageable number of robot legs are gained and their pertinent attributes are tabulated in Table 4.6. A pertinent attribute that is “modularity” is not specified by the user but this attribute is taken default by the designer.

**Table 4.6** Attribute for the shortlisted legs

	Force output (lbs)	Reach (mm)	Cycle time (seconds)	Modularity	Weight (lbs)
LEG 1	3451	877	4.6	0.60	25.37
LEG 2	3648	1129	7.5	0.68	25.52
LEG 3	3451	955	5.4	0.62	30.199

a) Leg 1 (UPU)



**Figure 4.11** Leg 1

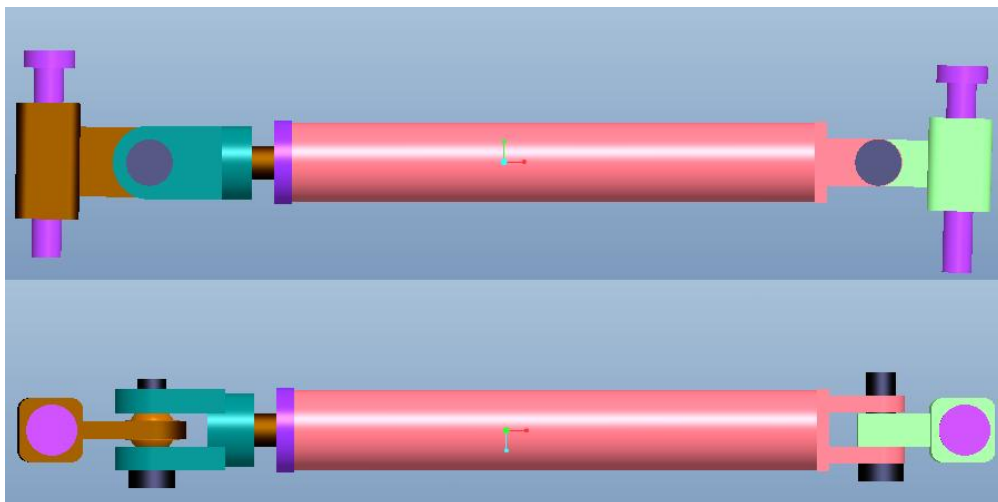
Leg 1 is a UPU joint sequence leg and can be used in the same base plate designed in previous chapter. Information regarding leg 1 is shown below

### **Modules and their specifications**

1. Hydraulic cylinder used- Bailey
  - Working pressure 2500psi
  - Bore size 2 inches
  - Stroke 10 inches
  - Rod diameter 1.125 inches
  - GPM 3
2. Universal Joint- Lovjoy D-type
  - Bore diameter 1.125 inches

3. Pin1 used- G.L HUYETT
  - Bore diameter 1 inches
4. Pin2 used- G.L HUYETT
  - Pin2 diameter 1 inches
5. PNTF1

b) Leg 2 (UPS)



**Figure 4.12** Leg 2 UPS

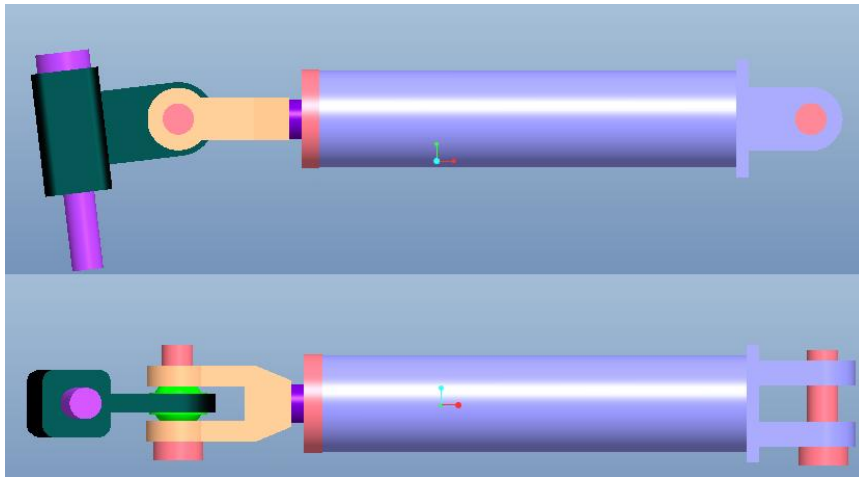
Leg 2 is a UPS joint sequence leg and can be used in the same base plate designed in previous chapter and is used to create CAD model in previous section 4.2. Information regarding leg 2 is shown below

### **Modules and their specifications**

1. Hydraulic cylinder used- Energy
  - Working pressure 1450psi
  - Cylinder bore- 2.5 inches
  - Stroke- 10 inches
  - Rod diameter 1.125 inches
  - GPM 3
2. PNTF1
3. PNTF2

4. Hook used- Bailey
  - a. Bore diameter 1.125 inches
5. Spherical bearing used- SKF
  - Working angle- 17 degree
6. Pin1 used (2)- G.L HUYETT
  - Bore diameter 1 inches
7. Pin2 used (2)- G.L HUYETT
  - Pin2 diameter 1 inches

c) Leg 3 (RPS)



**Figure 4.13** Leg 3 RPS

Leg 3 is a RPS joint sequence leg and can be used in the same base plate designed in previous chapter. Information regarding leg 3 is shown below

### **Modules and their specifications**

1. Hydraulic cylinder used- Bailey
  - Working pressure 2500 psi
  - Cylinder bore- 2 inches
  - Stroke- 12 inches
  - Rod diameter 1.125 inches
  - GPM 3

2. PNTF2
3. Hook used- Bailey
  - Bore diameter- 1.125 inches
4. Spherical bearing used- SKF
  - Working angle- 17 degree
5. Pin 1 used (1)- G.L HUYETT
  - Bore diameter 1 inches
6. Pin 2 used (2)- G.L HUYETT
  - Pin2 diameter 1 inches

### Step by step calculations

#### Step 1 Formation of decision matrix 'D'

$$D = \begin{bmatrix} 3451 & 877 & 0.2170 & 0.60 & 0.0394 \\ 3648 & 1129 & 0.1330 & 0.68 & 0.0390 \\ 3451 & 955 & 0.1850 & 0.62 & 0.0330 \end{bmatrix}$$

Matrix 'D' contain all magnitude of different specification of all specifications. The rows of the matrix are legs and attributes of these legs in column. In this decision matrix minimum magnitude of cycle time and minimum magnitude of weight is required hence the reciprocal of magnitude of these attributes are allocated in matrix 'D'

#### Step 2 Normalization of matrix 'N'

In this matrix is normalized and brings magnitude of all values on scale of 0 to 1

$$N = \begin{bmatrix} 0.5664 & 0.5101 & 0.6897 & 0.5462 & 0.6107 \\ 0.5987 & 0.6567 & 0.4227 & 0.6190 & 0.6045 \\ 0.5664 & 0.5555 & 0.5880 & 0.5644 & 0.5115 \end{bmatrix}$$

**Step 3** Relative importance matrix ‘**R**’

This matrix is n x n matrix and  $a_{ij}$  hold relative importance of  $i$ th attribute over the  $j$ th attribute. All the diagonal term of this matrix is unity.

$$R = \begin{bmatrix} 1 & 0.5 & 0.33 & 0.25 & 0.2 \\ 2 & 1 & 0.66 & 0.50 & 0.4 \\ 3 & 1.50 & 1 & 0.75 & 0.6 \\ 4 & 2 & 1.33 & 1 & 0.8 \\ 5 & 2.50 & 1.66 & 1.25 & 1 \end{bmatrix}$$

**Step 4** Find maximum Eigen value of relative importance matrix ‘**R**’

$$(A - \lambda_{max}I) = \begin{bmatrix} 1 - \lambda & 0.5 & 0.33 & 0.25 & 0.2 \\ 2 & 1 - \lambda & 0.66 & 0.50 & 0.4 \\ 3 & 1.50 & 1 - \lambda & 0.75 & 0.6 \\ 4 & 2 & 1.33 & 1 - \lambda & 0.8 \\ 5 & 2.50 & 1.66 & 1.25 & 1 - \lambda \end{bmatrix}$$

Eigen values = 4.9947, -0.0000, 0.0053, -0.0000, 0.0000

$$\lambda_{max} = 4.9947$$

$$(A - \lambda_{max}I) = \begin{bmatrix} -3.9947 & 0.5 & 0.33 & 0.25 & 0.2 \\ 2 & -3.9947 & 0.66 & 0.50 & 0.4 \\ 3 & 1.50 & -3.9947 & 0.75 & 0.6 \\ 4 & 2 & 1.33 & -3.9947 & 0.8 \\ 5 & 2.50 & 1.66 & 1.25 & -3.9947 \end{bmatrix}$$

**Step 5** Calculate weight for every attribute using Eigen vector linked with maximum Eigen values.

$$(A - \lambda_{max}I)w = 0$$

$$\begin{bmatrix} -3.9947 & 0.5 & 0.33 & 0.25 & 0.2 \\ 2 & -3.9947 & 0.66 & 0.50 & 0.4 \\ 3 & 1.50 & -3.9947 & 0.75 & 0.6 \\ 4 & 2 & 1.33 & -3.9947 & 0.8 \\ 5 & 2.50 & 1.66 & 1.25 & -3.9947 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \\ w_5 \end{bmatrix} = 0$$

$$w_1 + w_2 + w_3 + w_4 + w_5 = 1$$

$$w_1 = 0.0666$$

$$w_2 = 0.1332$$

$$w_3 = 0.2002$$

$$w_4 = 0.2667$$

$$w_5 = 0.3333$$

**Step 6** Calculate weighted normalized matrix ‘U’

This matrix is the combination of relative weight and normalized specification of the robots legs and is denoted by ‘U’. It will provide the true comparable values of the attributes.

$$U = W.N$$

$$U = \begin{bmatrix} 0.0377 & 0.0679 & 0.1380 & 0.1457 & 0.2036 \\ 0.0399 & 0.0875 & 0.0846 & 0.1651 & 0.2015 \\ 0.0377 & 0.0740 & 0.1177 & 0.1505 & 0.1705 \end{bmatrix}$$

**Step 7** Find positive and negative benchmark

$$U^+ = (0.0399, 0.0875, 0.1380, 0.1651, 0.2036)$$

$$U^- = (0.0377, 0.0679, 0.0846, 0.1457, 0.1705)$$

**Step 8** Find positive and negative separation measure ‘S’

$$\begin{aligned} S^+_1 &= 0.0276 & S^-_1 &= 0.0628 \\ S^+_2 &= 0.0535 & S^-_2 &= 0.0415 \\ S^+_3 &= 0.0437 & S^-_3 &= 0.0340 \end{aligned}$$

**Step 9** Find relative closeness to the ideal solution ‘C’

$$\begin{aligned} C^+_1 &= 0.6946 \\ C^+_2 &= 0.4371 \\ C^+_3 &= 0.4376 \end{aligned}$$

$$C^+_1 = 0.6946, C^+_3 = 0.4376, C^+_2 = 0.4371$$

#### **4.4.1 Result**

Ranking of the three robot legs is done in descending values of  $C^+$  i.e. most preferred Robot leg has maximum  $C^+$  value. A robotic leg with largest value of  $C^+_1$  is preferable, i.e. leg 1 is preferable for loading and positioning application.

#### **4.4.2 Discussion**

Multiple attribute decision making technique (MADM) for the selection of robotic leg for a parallel robot is oftenly not used so far. This approach recognizes various attribute required to be considered for optimum selection of robotic leg. It delivers a coding system for parallel manipulator illustrating various attributes. This approach helps to create generate a database of globally available parallel robots. This database is very much helpful for the individuals linked with the product i.e. manufacturer, designer, user.

# CHAPTER 5

## Conclusion

---

In **section 4.1** various modules required for making Fanuc F-200iB are identified that are commercially available and 2 new modules are designed which are shared by Leg1, Leg 2 and Leg3. These modules are easy to identify as information related to the components is provided by the companies in their catalogues. There are various websites like Indiamart from where identified modules are easy to order from different companies as cost and other features are specified along with them. As these modules are produced in mass and cost of component is produced in mass is produce at low cost because of no setup required and thus reduces the overall cost of the product.

In **section 4.2** Fanuc parallel robot which is 6 DOF parallel robot with all specifications provided along with it i.e. payload capacity, weight, motion speed in x-direction, motion speed in y-direction, etc. is taken as an example to prove the possibility of making robot modular. The modules identified are assembled to make Fanuc F-200iB robot modular and showing the possibility of making a robot using MCOTS. The different joints and position achieved by this robot is shown in this section.

In **section 4.3** Modularity of the modular robot assembled in previous section is measured. Modularity is measured by making a design structure matrix that shows connection between each module. And in this section it is concluded that 100 percent modularity cannot to achieved but degree of modularity can be improved.

In **section 4.4** for the optimum selection of parallel robot leg multiple attribute decision making (MADM) is used and TOPSIS for ranking, evaluation and selection of leg for a particular application as per customer requirement. This approach is used to determine which leg out of 3 best suits our need.

## REFERENCES

---

- Tolouei-Rad, M; Dhull, A. (2012) Design of modular robotic joints for achieving various robot configurations. *World academy of science*, 72:207-211.
- Acaccia, G; Bruzzone, L; Razzoli, R. (2008) A modular robotic system for industrial application *Assembly automation*, 28:151-162.
- Dash, A.K.; Chen, I.M.; Yeo, S.H.; Yang, G. (2005) Task oriented configurable design for Reconfigurable parallel manipulator systems. *International Journal of Computer Integrated Manufacturing*, 18: 615-634.
- Jose, A; Tollenaere, M. (2005) Modular and platform methods for product family design. *Journal of intelligent manufacturing*, 16: 371-390.
- Dahmus, J.B.; Javier, P; Juagsti, G; Otto, K.N. (2001) Modular product architecture. *Design study*, 22: 410-424.
- Pozna, C. (2007) The Modular robotics kinematics. *Acta Polytechnica Hungarica*, 4: 5-18.
- Huang, chun-che; Kuisak, A. (1988) modularity in design of products and systems. *IEEE transactions on systems, man, and cybernetics—part a: systems and humans*, 28: 66-77.
- Yang, J; Chen, I-Ming; Lim, W.K.; Yeo, S.H. (2001) kinematic design of modular reconfigurable in parallel robots. *Autonomous robots*, 10: 83-89.
- Agrawal, A. (2008) Product networks, component Modularity and Sourcing. *Journal of technology management and innovation*, 4: 59-81
- Gershenson, J.K.; Prasad, G.J.; Allamneni, S. (1999) Modular product design: a life-cycle view. *Journal of Integrated Design and Process Science*, 3: 13–26.
- Stryker, A.C.; Jacques, D.R. (2009) Modularity versus Functionality -a Survey and Application. *7th Annual Conference on Systems Engineering Research (CSER 2009)*
- Höltkä-Otto, K; de Weck, O. (2007) Degree of Modularity in Engineering Systems and Products with Technical and Business Constraint., *Concurrent Engineering*, 15: 113-126.
- Sosa, M.E.; Eppinger, S.D.; Rowles, C.M. (2007) A Network Approach to Define Modularity of Components in Complex Products. *Journal of Mechanical Design*, 129: 1118-1129.
- Rao, R.V; Padmanabhan, K.K. (2006) Selection, identification and comparison of industrial robots using digraph and matrix methods, *Robotics and computer-integrated manufacturing*, 22: 373-383.

Agrawal, V.P.; Kohli, V; Gupta, S; (1991) Computer aided robot selection: the multiple attribute decision making approach, *International Journal of Production Research*, 29: 1629–1644.

Bhangale, P.P.; Agrawal, V.P.; Saha, S.K. (2004) Attribute based specification, comparison and selection of a robot. *Mechanism and Machine Theory*, 39: 1345–1366.

Moubarak, P; Ben-Tzvi, P. (2012) Modular and reconfigurable mobile robot. *Robotics and autonomous system*, 60: 1648-1663.

Fisher, R; Podhorodeski, R.P.; Nokleby, S.B; (2004) design of a reconfigurable planar parallel manipulator. *Journal of robotic system*, 21: Page-665-675.

Stechi, R.M; Lagos, N. (Cardiff 2004) Reconfigurability and reconfigurable manufacturing systems-state of art review. *Manufacturing engineering center*, 529-535

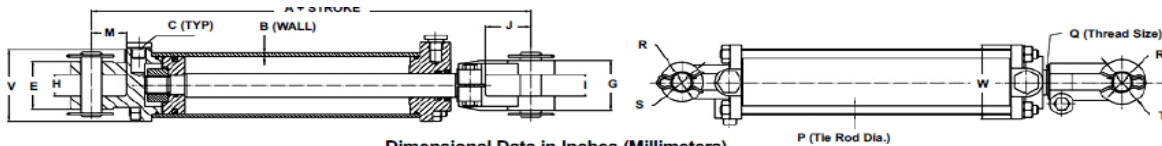
Wang, X; Baron, L; Cloutier, G. (2008) Topology of serial and parallel manipulators and Topological diagrams. *Mechanism and Machine Theory*, 43: 754-77

Table A1- Fanuc F-200iB

## F-200iB Specifications

Items	
Degrees of freedom	Six
Payload (kg)	100 (Higher payloads permissible with FANUC approval)
Allowable load moment at faceplate (kgf-m)	60
Allowable load inertia at faceplate (kgf-cm-s <sup>2</sup> )	367
Motion range (degrees)	As noted (pitch, yaw and roll vary depending upon the position of the faceplate within the envelope)
Motion speed (mm/s)	
Vertical (Z)	300
Horizontal (X & Y)	1500
Repeatability (mm)	± 0.1
Mounting method	Floor and inverted. Wall mount permissible with FANUC approval.
Installation environment	
Ambient temperature °C	0 to 45
Humidity	Normally: 75% or less Short term (within a month): 95% or less. No condensation
Vibration (m/s <sup>2</sup> )	0.5G or less
Mechanical brakes	All actuator legs
Mechanical weight (kg)	190
Controller	R-J3iB
Level of protection:	
Mechanical	IP54
Electrical	IP54
Controller	IP54

Table A2- Bailey Hydraulic cylinder specification 2 inches 2500psi



**Dimensional Data in Inches (Millimeters)**

BORE	DIMENSIONS															
	A*	B	C	E	G	H	I	J	M	P	Q	R**	S	T	V	W
2.000 (50.8)	10.250 (260.4)	0.189 (4.80)	3/8" NPT	2.500 (63.5)	2.500 (63.5)	1.125 (28.6)	1.125 (28.6)	2.125 (54.0)	1.50 (38.1)	0.394 (10)	1 1/8-12 UNF	1.000 (25.4)	2.000 (50.8)	2.000 (50.8)	2.795 (71.0)	2.835 (72.0)
2.500 (63.5)	10.250 (260.4)	0.189 (4.80)	3/8" NPT	2.500 (63.5)	2.500 (63.5)	1.125 (28.6)	1.125 (28.6)	2.125 (54.0)	1.50 (38.1)	0.394 (10)	1 1/8-12 UNF	1.000 (25.4)	2.000 (50.8)	2.000 (50.8)	3.110 (79.0)	3.150 (80.0)
3.000 (76.2)	10.250 (260.4)	0.189 (4.80)	1/2" NPT	2.500 (63.5)	2.625 (66.7)	1.125 (28.6)	1.125 (28.6)	2.125 (54.0)	1.50 (38.1)	0.472 (12)	1 1/4-12 UNF	1.000 (25.4)	2.000 (50.8)	2.250 (57.2)	3.740 (95.0)	3.780 (96.0)
3.500 (88.9)	10.250 (260.4)	0.218 (5.53)	1/2" NPT	2.500 (63.5)	2.625 (66.7)	1.125 (28.6)	1.125 (28.6)	2.125 (54.0)	1.50 (38.1)	0.551 (14)	1 1/4-12 UNF	1.000 (25.4)	2.250 (57.2)	2.500 (63.5)	4.213 (107.0)	4.250 (108.0)
4.000 (101.6)	10.250 (260.4)	0.244 (6.20)	1/2" NPT	2.625 (66.7)	2.625 (66.7)	1.125 (28.6)	1.125 (28.6)	2.125 (54.0)	1.50 (38.1)	0.630 (16)	1 1/4-12 UNF	1.000 (25.4)	2.250 (57.2)	2.500 (63.5)	4.882 (124.0)	4.920 (125.0)

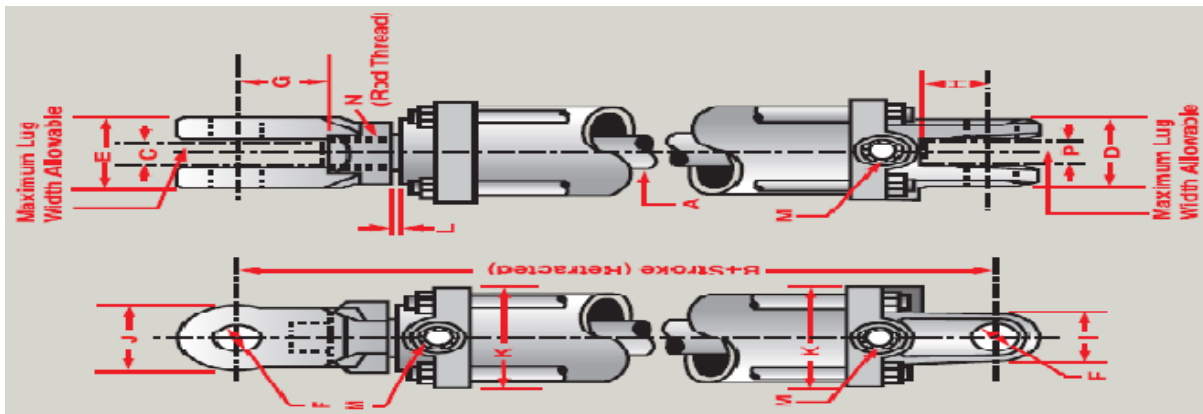
A\* 12.25" (311.2) for 8" (203.2) stroke ASAE cylinders and 15.50" (393.7) for 16" (406.4) stroke ASAE cylinders. \*\* (Pin diameter): 1.25 (31.75) for 16" (406.4) stroke ASAE cylinders from 3" to 4" bore.

BAILEY NO.	STROKE	ROD DIAMETER	DIMENSIONS		COLUMN LOAD	PORT SIZE	PIN DIAMETER	SHIP WT.	PRICE EACH	
			RETRACTED	EXTENDED					1-9	10-UP
<b>2" Bore • 2500 PSI</b>										
218-297	4"	1 1/8"	14 1/4"	18 1/4"	7,850 lbs.	3/8" NPTF	1"	16	54.00	51.00
218-298	6"	1 1/8"	16 1/4"	22 1/4"	7,850 lbs.	3/8" NPTF	1"	17	59.00	56.00
218-296	8"	1 1/8"	18 1/4"	26 1/4"	7,850 lbs.	3/8" NPTF	1"	18	60.00	57.00
218-299	8"	1 1/8"	18 1/4"	26 1/4"	7,850 lbs.	3/8" NPTF	1"	18	60.00	57.00
218-300	8" ASAE	1 1/8"	20 1/4"	28 1/4"	7,850 lbs.	3/8" NPTF	1"	19	59.00	59.00
218-306	10"	1 1/8"	20 1/4"	30 1/4"	7,850 lbs.	3/8" NPTF	1"	20	68.00	63.00
218-307	12"	1 1/8"	22 1/4"	34 1/4"	7,850 lbs.	3/8" NPTF	1"	22	70.00	65.00
218-308	14"	1 1/8"	24 1/4"	38 1/4"	7,850 lbs.	3/8" NPTF	1"	23	74.00	70.00
218-309	16"	1 1/8"	26 1/4"	42 1/4"	7,850 lbs.	3/8" NPTF	1"	25	75.00	71.00
218-310	18"	1 1/8"	28 1/4"	46 1/4"	7,850 lbs.	3/8" NPTF	1"	26	81.00	75.00
218-311	20"	1 1/8"	30 1/4"	50 1/4"	6,950 lbs.	3/8" NPTF	1"	28	85.00	79.00
218-312	24"	1 1/8"	34 1/4"	58 1/4"	5,180 lbs.	3/8" NPTF	1"	31	92.00	86.00
218-313	30"	1 1/8"	40 1/4"	70 1/4"	3,570 lbs.	3/8" NPTF	1"	35	110.00	109.00
218-314	36"	1 1/8"	46 1/4"	82 1/4"	2,610 lbs.	3/8" NPTF	1"	41	126.00	124.00
218-315	48"	1 1/8"	58 1/4"	106 1/4"	1,570 lbs.	3/8" NPTF	1"	59	163.00	161.00
204-500		1 1/8"	Packing Kit						17.00	-



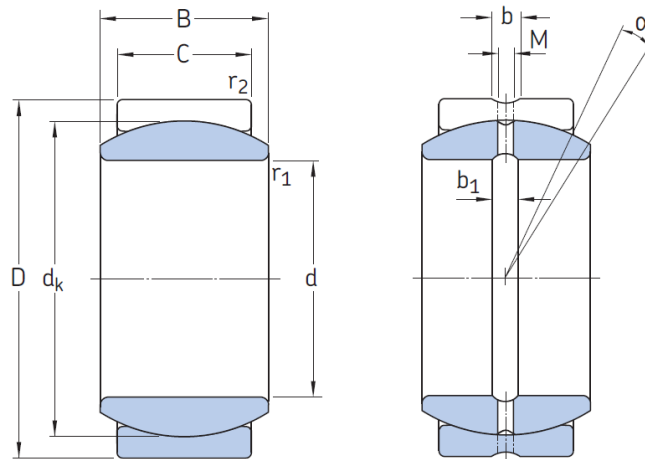
FOR LARGER VOLUME CALL FOR A QUOTE

Table A3 – Energy Hydraulic cylinder 2.5 inches 1450 psi



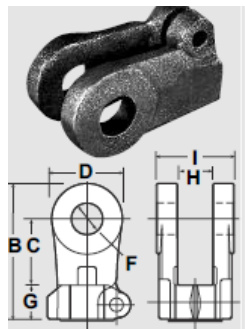
Custom Stroke Lengths															
Bore Diameter	A	B (Retracted)	C	D	E	F (Pin Dia.)	G	H	I	J	K (Approx.)	L	M	N (Rod Thrd)	P
2" (50,8 mm)	1,125" (28,6 mm)	10,25" (26,04 cm)	1,125" (28,6 mm)	2,375" (60,3 mm)	2,75" (69,9 mm)	1" (25,4 mm)	1,875" (47,6 mm)	1,75" (44,5 mm)	1,625" (41,3 mm)	2,5" (63,5 mm)	3" (76,2 mm)	.187" (4,7 mm)	9/16-18 UNF (SAE-6 ORB)	1-1/8-12 UNF	1,25" (31,8 mm)
2.5" (63,5 mm)	1,125" (28,6 mm)	10,25" (26,04 cm)	1,125" (28,6 mm)	2,625" (66,7 mm)	2,75" (69,9 mm)	1" (25,4 mm)	1,875" (47,6 mm)	1,625" (41,3 mm)	1,875" (47,6 mm)	2,5" (63,5 mm)	3,5" (88,9 mm)	.187" (4,7 mm)	3/4-16 UNF (SAE-8 ORB)	1-1/8-12 UNF	1,25" (31,8 mm)
3" (76,2 mm)	1,25" (31,8 mm)	10,25" (26,04 cm)	1,125" (28,6 mm)	2,593" (65,9 mm)	2,75" (69,9 mm)	1" (25,4 mm)	1,875" (47,6 mm)	1,562" (39,7 mm)	1,875" (47,6 mm)	2,5" (63,5 mm)	3,75" (95,3 mm)	.187" (4,7 mm)	3/4-16 UNF (SAE-8 ORB)	1-1/4-12 UNF	1" (25,4 mm)
3.5" (88,9 mm)	1,5" (38,1 mm)	10,25" (26,04 cm)	1,125" (28,6 mm)	2,718" (69 mm)	2,75" (69,9 mm)	1" (25,4 mm)	1,875" (47,6 mm)	2,062" (52,4 mm)	2,25" (57,2 mm)	2,5" (63,5 mm)	4,25" (108 mm)	.187" (4,7 mm)	3/4-16 UNF (SAE-8 ORB)	1-1/2-12 UNF	1" (25,4 mm)
4" (101,6 mm)	2" (50,8 mm)	10,25" (26,04 cm)	1,125" (28,6 mm)	2,718" (69 mm)	2,75" (69,9 mm)	1" (25,4 mm)	1,875" (47,6 mm)	2,062" (52,4 mm)	2,5" (63,5 mm)	2,5" (63,5 mm)	4,75" (120,7 mm)	.187" (4,7 mm)	3/4-16 UNF (SAE-8 ORB)	1-1/2-12 UNF	1" (25,4 mm)

Table A4- Spherical bearing SKF 25 mm bore



d	D	B	C	$\alpha$	C	C <sub>0</sub>		with standard US seats	heavy-duty seats
mm				degrees	kN		kg	—	—
4	12	5	3	16	2,04	10,2	0,003	GE 4 E	—
5	14	6	4	13	3,4	17	0,004	GE 5 E	—
6	14	6	4	13	3,4	17	0,004	GE 6 E	—
8	16	8	5	15	5,5	27,5	0,008	GE 8 E	—
10	19	9	6	12	8,15	40,5	0,012	GE 10 E	—
12	22	10	7	10	10,8	54	0,017	GE 12 E	—
15	26	12	9	8	17	85	0,032	GE 15 ES	—
	26	12	9	8	17	85	0,032	GE 15 ES-2RS	—
17	30	14	10	10	21,2	106	0,050	GE 17 ES	—
	30	14	10	10	21,2	106	0,050	GE 17 ES-2RS	—
20	35	16	12	9	30	146	0,065	GE 20 ES	—
	35	16	12	9	30	146	0,065	GE 20 ES-2RS	-2LS
	42	25	16	17	48	240	0,16	GEH 20 ES-2RS	-2LS
25	42	20	16	7	48	240	0,12	GE 25 ES	—
	42	20	16	7	48	240	0,12	GE 25 ES-2RS	-2LS
	47	28	18	17	62	310	0,20	GEH 25 ES-2RS	-2LS
30	47	22	18	6	62	310	0,16	GE 30 ES	—
	47	22	18	6	62	310	0,16	GE 30 ES-2RS	-2LS
	55	32	20	17	80	400	0,35	GEH 30 ES-2RS	-2LS
35	55	25	20	6	80	400	0,23	GE 35 ES	—
	55	25	20	6	80	400	0,23	GE 35 ES-2RS	-2LS
	62	35	22	15	100	500	0,47	GEH 35 ES-2RS	-2LS
40	62	28	22	7	100	500	0,32	GE 40 ES	—

Table A5- Hook



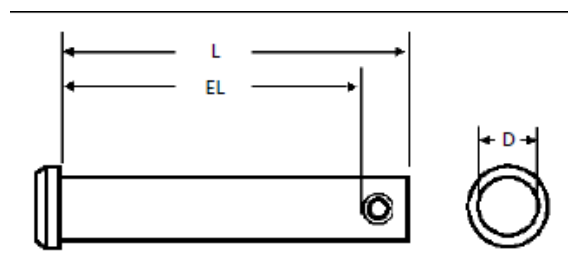
**Rod End Clevises • TC2 & TC3 Series**

• Universal ends to fit many 2", 2 1/2", 3", 3 1/2", 4" bore cylinders • 80-55-12 ductile iron

BAILEY NO.	DIMENSIONS							THREAD SIZE	MATERIAL	PRICE EACH
	B	C	D	F	G*	H	I			
276-000	4.22"	2.125"	2"	1.015"	1.1"	1.165"	2.500"	1 1/8"-12 UNF	80-55-6	23.00
276-031	4.36"	2.125"	2.25"	1.015"	1.5"	1.125"	2.500"	1 1/8"-12 UNF	80-55-6	28.00
276-001	4.36"	2.125"	2.25"	1.015"	1.1"	1.165"	2.717"	1 1/4"-12 UNF	80-55-6	26.00
276-028	4.36"	2.125"	2.25"	1.265"	1.1"	1.165"	2.717"	1 1/4"-12 UNF	80-55-6	29.00
276-002	5.00"	2.125"	2.75"	1.265"	1.5"	1.203"	2.953"	1 1/2"-12 UNF	80-55-6	31.00

\* Thread Length

Table A6- Pin G.L. HUYETT



CLP	Nominal (D)		Length (L)	Effective Length (EL)	WEIGHT		
	DIAMETER		LENGTH		Lbs. per 100 Pieces		
-0750-3750	3/4	.741/.746	3-3/4	3.515	50.63		
-0750-4000			4	3.765	53.75		
-0750-4500			4-1/2	4.265	60.00		
-0750-5000			5	4.765	65.25		
-0750-5500			5-1/2	5.265	72.65		
-0750-6000			6	5.765	78.80		
-0750-6500	7/8	.866/.871	6-1/2	6.265	85.00		
-0875-2000			2	1.703	38.13		
-0875-2500			2-1/2	2.203	47.50		
-0875-2750			2-3/4	2.453	52.50		
-0875-3000			3	2.703	55.25		
-0875-3500			3-1/2	3.203	65.63		
-0875-4000			4	3.703	73.75		
-0875-4500			4-1/2	4.203	82.13		
-0875-5000			5	4.703	90.50		
-0875-6000			6	5.703	105.25		
-1000-2000			1	.991/.996	2	1.703	53.00
-1000-2250					2-1/4	1.953	58.75
-1000-2500	2-1/2	2.203			63.00		
-1000-2625	2-5/8	2.312			67.50		
-1000-2750	2-3/4	2.453			70.00		
-1000-3000	3	2.703			75.63		
-1000-3250	3-1/4	2.953			81.00		
-1000-3500	3-1/2	3.203			86.88		
-1000-4000	4	3.703			97.50		
-1000-4500	4-1/2	4.203			108.12		
-1000-5000	5	4.703			119.69		
-1000-5500	5-1/2	5.203			130.78		
-1000-6000	6	5.703			141.88		
-1000-7000	7	6.703			165.35		
-1000-8000	8	7.703			188.82		
-1000-9000	9	8.703			212.31		
-1125-3000	1-1/8	1.105/1.125			3	2.375	100.00
-1125-4000					4	3.375	130.00
-1125-5000			5	4.375	160.00		
-1125-6000			6	5.375	190.00		
-1125-8000			8	7.375	250.00		
-1125-9000			9	8.375	280.00		

+ .020/- .000