

# **DEVELOPMENT OF A 6 DOF PARALLEL SERIAL HYBRID MANIPULATOR**

A Thesis Submitted in Partial Fulfilment of the  
Requirements for the Degree of

**BACHELOR OF TECHNOLOGY** in **MECHANICAL ENGINEERING**  
and  
**MASTER OF TECHNOLOGY** in **MECHATRONICS AND AUTOMATION**

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## Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgement has been made in the text.

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## CERTIFICATE

This is to certify that the thesis entitled “**Development of a 6 DOF Parallel Serial Hybrid Manipulator**”, being submitted by **Mr. Chiranjibi Sahoo**, Roll No. **710ME4087**, to the **National Institute of Technology, Rourkela** in partial fulfilment of the requirements for the degree of **Bachelor of Technology in Mechanical Engineering** and **Master of Technology in Mechatronics and Automation**, is a bona fide record of research work carried out by him under my supervision and guidance. The candidate has fulfilled all the prescribed requirements.

The thesis, which is based on candidate’s own work, has not been submitted elsewhere for the award of a degree.

To the best of my knowledge, he bears a good moral character and decent behaviour.

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## ABSTRACT

This thesis focuses on the development of a new modular 6 DOF hybrid manipulator. A hybrid manipulator consists of the synergistic combination of serial and parallel manipulator architectures. It incorporates the good performance characteristics of a serial manipulator (larger workspace and dexterity) and a parallel manipulator (higher rigidity and loading capacity/self-weight ratio). The hybrid manipulator under study includes a 3 DOF symmetric planar manipulator as a base platform over which a 3 DOF serial manipulator was placed with an appropriate end effector. The objective of the thesis was to fabricate the above-described manipulator and develop control algorithm for manipulation.

The research work started with kinematic (forward and inverse) and dynamic analysis of parallel and serial manipulators was carried analytically and computationally in MATLAB. The results of which were required for configuration selection, design optimization, motion analysis and simulation of the hybrid manipulator.

From the analysis results, the planar base and serial arm manipulator was fabricated. The prototype developed was controlled in real time through MATLAB-SimMechanics Arduino Interface. The inverse kinematics was solved by MATLAB and servo control was established via Arduino. The algorithm developed for manipulation was verified alongside computation simulation and experiments.

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# Chapter 1: Introduction

As the demands for products and services increases, new technologies develop to meet the target. In manufacturing and service operations, robots are increasingly getting stronghold because of their flexibility, automation and reduced expenses compared to special purpose machineries. These advantages have led to research and development of such robots. Robotic manipulators are extensively used in the industrial manufacturing sector, space explorations, assembly operations, remote health care etc.

Robot is a multi-disciplinary engineering device that requires combination of the design of mechanical and electrical components to sensor technology, computer systems, and artificial intelligence as represented in figure 1. The mechanical section deals with the kinematics dynamics and structural requirement of the robot. The electrical section deals in with the actuators for generating the prime motion in the joint of the robots. System design deals with perception, sensing and control methods of robots. The software technology enables the root to work autonomously or under expert supervision by incorporating algorithm and intelligence to it.

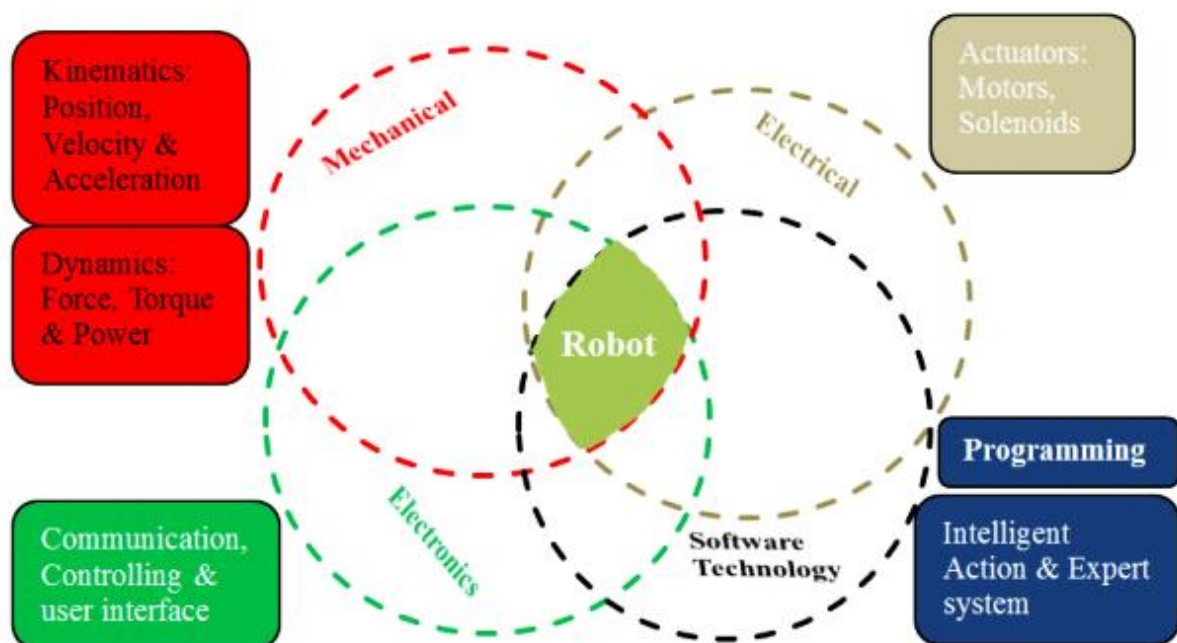


Figure 1 – Multidisciplinary nature of robotics

## 1.1 Origin of the work

A robotic manipulator or robotic arm is an electronically controlled mechanism, consisting of multiple link segments, that performs tasks by interacting with its environment. The manipulator is fixed at one or more places and has an end effector to perform various tasks as assigned. The end effector position and motion depends upon the relative motion of the attached links.

Based on the kinematic structure, the manipulators are classified primarily into three types:

[i] Open Loop Manipulator or Serial Robots

[ii] Closed Loop Manipulator or Parallel Robots

[iii] Hybrid manipulator (Consists of both open and closed loop chains) (figure 4) [1]

Figure 2 shows an example of a serial robot (KUKA 650 Industrial Manipulator) with 6 DOF. Figure 3 shows an example of a parallel robot (ABB Delta Robot) with 6 DOF. Figure 4 shows an example of a serial parallel hybrid robot [1] with 6 DOF.

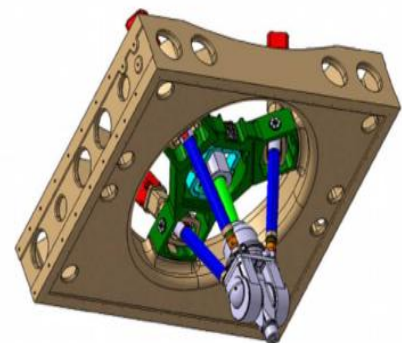
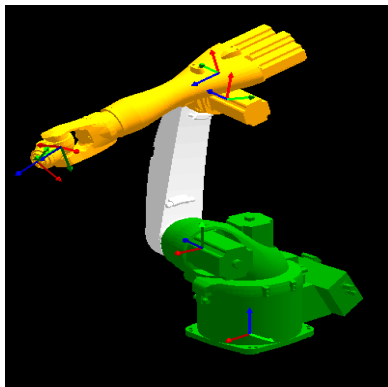


Figure 2: KUKA 650 Robot

Figure 3: ABB Delta Robot

Figure 4: Serial Parallel Robot

The serial manipulator has larger workspace and high dexterity compared to the parallel robots but lacks on rigidity and positional accuracy. While the parallel manipulator have more stiffness and lightweight, but their limited workspace and complex kinematics make them unsuitable for large work spaces.

Hybrid manipulators possess the complementary characteristics of both serial and parallel robots. Combining both types of manipulators, hybrid robotic manipulators could be constructed, which exhibited good performances inherited from both the serial and parallel manipulators. Consequently, a hybrid manipulator becomes a promising candidate to perform wide range of tasks associated with complicated geometries.

## 1.2 Objective

The objective of this project is to develop a new hybrid manipulator which could be used in diverse applications. Hybrid manipulators could be designed combining serial and parallel configurations according to design objective and performance. In the past decade, several approaches to hybrid manipulators have been applied [2], [3]. But mostly due to complex configuration and kinematics these models were restricted to mathematical models.

The new design is based using a modular approach that has a large reachable dextrous workspace along with desired rigidity and positional accuracy for diverse applications. For this purpose, a simple hybrid parallel serial manipulator is proposed after design and feasibility study. In this system, a serial arm is coupled with a parallel platform to provide the base motion. The development of the hybrid manipulator system covers mechanical system design, system dynamic modelling and simulation, design optimization, trajectory generation and control system design. The different aspects under hybrid manipulator motion control scheme are shown in figure.5. These aspects of manipulation and control include:

1. Hybrid configuration selection and kinematic feasibility
2. Forward and Inverse Kinematics of Serial, Parallel and Hybrid configuration (to solve for joint angles to reach the desired end effector position)
3. Trajectory algorithm and path generation (decision-making for path generation of both serial and parallel manipulator)
4. Motion Dynamics and Joint Motion control (path execution in workspace)



Figure 5 - Hybrid manipulator motion control scheme

The following are the objectives of the project specified:

- Forward and Inverse kinematics of the serial and parallel manipulators are analysed to enable the robot for manipulation in the workspace
- Study of feasibility and singularity in workspace. Selection of the joint parameters and configuration.

- Design Optimization after selecting the required hybrid manipulator platform. CAD modelling in SolidWorks to design and simulate the manipulator assembly.
- Kinematic and dynamic simulation of the serial and parallel modules in MATLAB and Simulink.
- Developing the control algorithms for motion planning and joint velocity control
- Combining the Serial and parallel arm to create the hybrid platform.
- Inverse Kinematics Solving in MATLAB for trajectory generation and calculation of joint angles. Control of the servo motors using Arduino microcontroller.
- Experimental Analysis of the hybrid manipulator to validate the control algorithm and simulation results.

### 1.3 Thesis Overview

The dissertation is organized as follows

- Chapter 2 presents a background in the development of hybrid manipulators. This includes literature survey on the kinematic models, performance analysis and design paradigm and control of hybrid architectures along with existing models developed over the time.
- Chapter 3 and 4 describes the development of the serial and parallel arm respectively which includes detailed analysis of manipulator configuration, kinematics, and workspace analysis.
- Chapter 5 provides the simulation and analysis of serial and parallel arm to verify independent working of the modules. The system was simulated in MATLAB Simulink and Solidworks Motion Analysis.
- Chapter 6 describes the integration of serial and parallel module to form the hybrid manipulator. The trajectory planning and path algorithm is discussed in this section. The control strategy for joint actuation was implemented.
- Chapter 7 outlines the complete process of realization of the system, i.e. CAD modeling, FEA analysis, Fabrication, Prototype Assembly, Electronics and Control module interfacing.
- Chapter 8 deals with the experimental analysis of the developed hybrid manipulator to control its motion with techniques described in the previous chapters.
- Chapter 9 addresses the results and conclusions.
- Chapter 10 lists the references and bibliography.

## Chapter 2: Literature Survey

A hybrid manipulator has multiple area of research that has been studied to improve the design, manipulation and performance characteristics. To discuss the present design, the serial, parallel and hybrid configuration were referred and studied separately.

### 2.1 Serial Manipulator

Industrial manipulators were introduced to reduce human effort in repetitive and tedious work. The manipulation system comprises of links and kinematic joints (revolute, prismatic or linear) to provide degree of freedom. Synthesis of planar and spatial mechanism with several DOF are presented in mechanism theories [4-5].

A design approach to analysis of industrial manipulator kinematic chain is described by Cubero [6]. The method generates plane mechanical structures with different DOF. The generalized solution for kinematics and dynamics of serial manipulators is presented [7] using 4\*4 homogenous transformation matrix and Jacobian matrix. Singh et al [8] presented a computational algorithm to solve robot kinematics using D-H Parameters, differential transformation matrix theory. The inverse kinematics models of a serial manipulator maps the Cartesian workspace to the joint space. The solution to inverse kinematics problems are difficult to solve since the relation between the two spaces is nonlinear and can have multiple solutions.

Pashkevich [9] developed algorithms for inverse transformation of coordinates (analytical) kinematics of robotic manipulators. The solutions obtained possess good convergence including singularity positions. The Inverse kinematics and dynamic algorithms were also presented in [10]. In this case, the robot is controlled by the joint actuation (torques and forces) to produce the end effector trajectory. The complexity of the inverse kinematics increases with increase in number of links.

Shah et al [11] developed a multi dynamic solver for serial chain manipulators capable of computation of kinematic and dynamic analysis using D-H parameters as input of tree type robotic systems [12].

### 2.2 Parallel Manipulator

A parallel robot is a closed loop mechanism which is joined to base by at least serial kinematic chain or legs [13-14]. Stewart Platform [15] is one of popular parallel configurations widely used in pilot simulators and positioning devices for precision surgical robots because of its high

rigidity, loading capacity and fine motion. Earl and Rooney [16] studied the kinematic structures for robotic applications and their interconnections for serial and parallel manipulators. Hunt [17] researched the kinematics of parallel manipulators based on screw theory.

Existing parallel manipulators suffer from limited and complicated workspace with singularities, and highly non isotropic input/output relations [18]. Hence, the performances could significantly vary over the workspace and depending on the direction of the motion. Chablat and Wenger [19] an inverse kinematic solution showing the existence of a non-singular assembly mode changing trajectory for a 3R symmetric planar platform.

Do and Yang [20] used Newton Euler approach to solve the inverse dynamics of parallel platform assuming unsymmetrical legs and frictionless joints.

Shirkhodaie and Soni [21], Gosselin and Angeles [22] and Pennock and Kassner [23] each present a kinematic study of one planar parallel manipulator. Gosselin et al [24] presents a general computation algorithm for kinematics and dynamics of planar spatial or parallel robots.

Williams and Shelly [25] presented the algebraic inverse kinematic solutions for position and velocity for planar manipulator with independent calculation for active and passive joints.

Yang et al [26] presented a new model based controller for a Stewart platform using PID with gravity compensation. The physical systems are modelled in ADAMS and the PID controller is built in Simulink to improve control and reduce the steady state error.

### 2.3 S-P Hybrid Manipulator – Architecture Study

Hybrid manipulators are used as several architectures in a combination of closed and open loop linkages. This section describes some novel implementation of hybrid architectures suited to different applications. This will help to gain insight on the world on hybrid manipulators, its scope for present and future applications.

Atia and Cartmell [27] presented a design for a 2 DOF hybrid 5 bar robotic manipulator with operation in either serial, parallel or redundant parallel modes. The design paradigm is based on singularity avoidance in specific modes, therefore versatility is increased as one manipulator could perform various modes.

Jianguo and Jianyou [28] presented a new type of universal Cartesian serial parallel manipulator with kinematic and dynamic solutions using Newton Euler method. Six DOF motion is realized through linear driving and easy control, could be implemented in surface manufacturing.



A novel dexterous 6DOF manipulator [29] serially connected by two compliant parallel stages is presented for precision task handling. The upper stage is a 3-RPS mechanism and the lower one is a 3-RRR mechanism. In virtue of the method of the physical model of the solution space, optimal design has been accomplished.

Ota et al [30] presented a six legged robot is developed with two leg bases with three legs and walks by moving each leg bases alternatively through a 6 DOF mechanism. The force, velocity and movable range of various mechanism for connecting the two legs bases were compared and it was found that good performance could be achieved by using a hybrid mechanism.

Moosavian et al [31] analysed a compounded serial parallel wheeled mobile robot a differentially-driven wheeled platform, a planar parallel manipulator, which is called here as Star-Triangle (ST) mechanism, and a serial Puma-type manipulator arm. Next, a closed-form dynamics model is derived for the whole hybrid system based on a combined Newton-Euler and Lagrange formulation.

Park et al [34] developed a robotic manipulator combined a parallel manipulator and wrist manipulator. The robot has a parallel manipulator with three linear actuators and a central axis for positional motions and a wrist manipulator with two rotary actuators for rotational motions. Kinematics, available workspace, and dexterity analysis are investigated for getting optimal design parameters to meet a desired workspace including orientation of wrist.

## 2.4 S-P Hybrid Manipulator – Kinematics Study

To design and model a hybrid manipulator, forward and inverse kinematics needs to be investigated. Waldron et al [2] studied the kinematic and dynamic analysis of 10 DOF hybrid manipulator. A closed form polynomial solution was derived for FK but not for IK.

Lee and Kim [32] proposed a projection method for kinematic analysis of 6 DOF hybrid manipulator by rate kinematics analysis. However the FK and IK displacement analysis were not discussed. Shukla and Paul [33] presented a ‘virtual link’ concept where parallel structure can be considered as a virtual link and the hybrid manipulator can be considered as an equivalent serial one, but the kinematic models are difficult to formulate.

Yang et al [35] presented a modular approach to developing a hybrid robot for deburring application and obtained a closed form kinematic solutions verified through simulations. The developed prototype has 3RRR planar manipulator as base with RPR serial arm and end effector.

## 2.5 Summary

From the detailed review of the theory and existing architectures, it can be summarised that the hybrid manipulator should be developed in an entity basis (i.e. to develop the serial and parallel manipulators separately and assembling them to create a hybrid manipulator). Hybrid manipulators could be designed combining serial and parallel configurations according to design objective and performance. This project requires a modular reconfigurable manipulator with generalized operability, from which the following two variations are the most practical solutions to this problem.

### **Type I:**

This configuration constitutes of a 3 DOF planar parallel manipulator to which a 3 DOF serial manipulator could be fixed to form a hybrid serial & parallel mechanism [35] (Figure 6).

### **Type II:**

This configuration has 3 serial arms supporting a platform. The serial arms have two active joints and four passive joints, so the platform has 6 DOF in total. [30] (Figure 7).

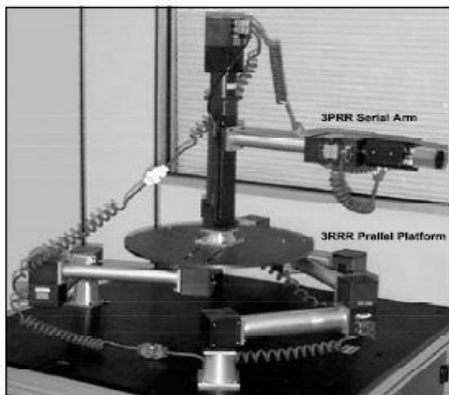


Figure 6 - Example of Type I Configuration

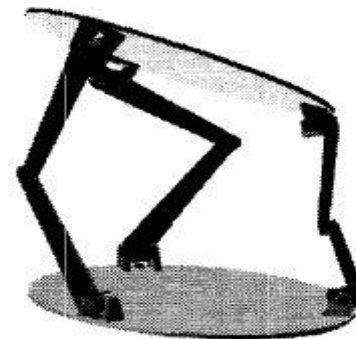


Figure 7 - Example of Type II Configuration

To use any of the above mechanisms, parameters such as stiffness, workspace range, weight balances, event of collision of links and the position of the actuators is optimized. For the manipulator configuration opted in this project, a symmetric distribution of both mass and space between the two configurations are optimum. Also, the number of linkages should be reduced to make a light-weight machine and reduce the likelihood of a linkage collision.

With detailed study of performance characteristics and kinematic complexity, the Type I manipulator is a better trade off than the later because of lower center of gravity (location of the

servo motors at or close to the structure base), higher structural rigidity and computationally easier inverse kinematics.

The proposed hybrid manipulator consists of a three DOF parallel manipulaor as a base support with a 3 RRR articulated serial arm fixed with a desired end effector. Since the parallel base has 3 DOF (planar), the serial arm could be simpler in design. The desired performance could be achieved from this manipulator. The soultion for kinematics of the above serial and parallel manipulators is simple and easy to develop the displace analysis and algorithm which is essential considering motion planning, simulation and real time direct control of the robot.

A modular design paradigm is employed while developing the project in order to implement standardized active and passive joints, configurable link and base designs along with connecting elements. This approach is helpful for

- Design modifications and maintainance at any stage of the project.
- Shorten the development or construction time
- Adjust in design parameters, actuation schemes, joint types and link lengths.

## Chapter 3: Development of Serial Manipulator

Manipulator kinematics is the study of the motion of a manipulator with respect to a fixed reference frames without seeing the forces/moments. Thus, kinematic models of robot obtain the associations between the joint-variable space and the location and alignment of the end-effector of the manipulator. Positioning is meant to carry the end-effector of the arm to a specific point within its workspace; whereas orientation is to move the end-effector to the required orientation at the specific position. The positioning and orientation are the jobs with respect the arm and wrist respectively. Sometime the positioning and alignment of the end-effector can decouple to simplify the kinematic analysis.

### 3.1 Homogeneous Transformation

The links in a serial manipulator are modeled as rigid links. The links move with respect to global and local reference frame. The position of one link B relative to another A is represented by coordinate transformation  ${}^A T_B$  between local reference frames involved to the link. The transformation matrix is used to get the position and orientation of the body frame to the global reference frame. The links are connected using mainly revolute or prismatic joints. A kinematic model is defined by individual link lengths, joint degree of freedom, joint limits and configuration hierarchy of joints and links.

Denavit and Hartenberg introduced a generalized method to represent the three-dimensional geometry of a manipulator respecting a static reference frame. This convention is known as D-H Notations. This notation gives a spatial relationship between two links using a 4\*4 homogenous transformation matrix.

### 3.2 Manipulator Forward Kinematics

The forward/direct kinematics of a 3-DOF serial robot arm is simple and direct. The example diagram sketch of the 3-DOF (RRR) serial robot arm shown in [Figure 8], where five coordinate frames has been defined. The base frame P of the RRR serial manipulator is equal with the moving platform of the 3RRR parallel platform. The joints are started by servo motors for precise joint control and there is a point for end effector to be used as per requirement.

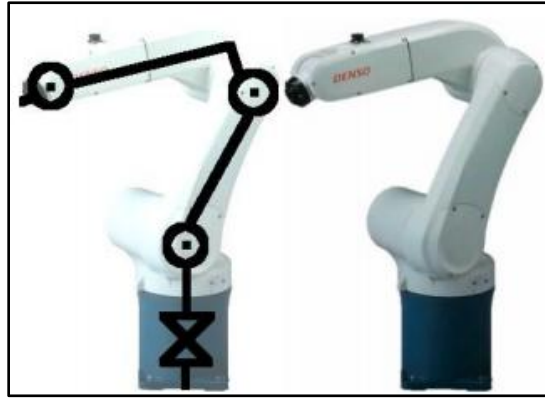


Figure 8: Example of the 3-DOF (RRR) Industrial Robotic arm

### Configuration of the Serial Arm

The serial arm is a 3 RRR Articulated type robotic arm (+1 end effector). The Denavit-Hartenberg parameters provide a generalized configuration methodology of robotic models.

Table 1: D-H Parameters for Serial Arm

$i$	$\alpha_{i-1}$	$a_{i-1}$	$d_i$	$\theta_i$
1	0	$\pi/2$	L0	$\theta_0$
2	L1	0	0	$\theta_1$
3	L2	0	0	$\theta_2$
4	L3	0	0	$\theta_3$

The link lengths are used in the analysis and implemented for prototyping are as follows:

$$L_0 = 0.05 \text{ m}, L_1 = 0.15 \text{ m}, L_2 = 0.12 \text{ m}, L_3 = 0.05 \text{ m}$$

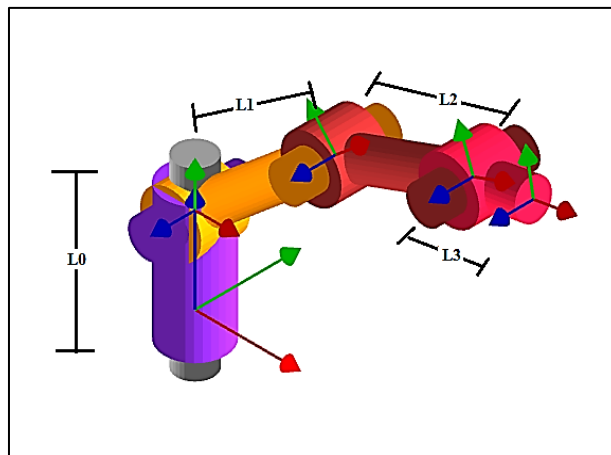


Figure 9: DH Parametric Model – RoboAnalyzer [10]

A geometrical model is created from the input D-H Parameters [Table 1] for kinematic and dynamic modelling of the robot. Figure 9 shows the different degrees of freedom of the arm. Along with D-H parameters, there is option to customise for mass, centre of gravity, joint and path trajectory, initial and final configurations of the robot which are key parameters for the analysis.

### Kinematic Analysis of Serial Arm

The kinematic analysis (figure 10) of a serial can be solved by several kinematic modelling methods. In this project, Jacobian matrix is used to for forward kinematics and geometric transformation for Inverse Kinematics (Inverse Jacobian could also be used but it is complex to solve compared to trigonometric transformations).

The local frames of the serial arm joints are defined in [Figure 9]. The end-effector pose has a fixed transformation matrix from the serial base (point P in Parallel base). The transformation matrix is calculated and shown in [Table 2]

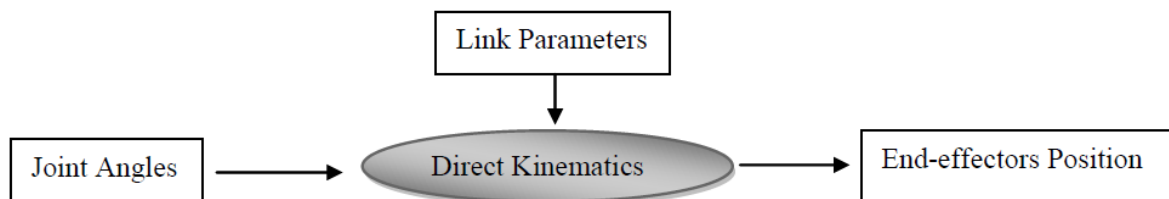


Figure 10 - Schematic diagram of direct kinematics of a manipulator

Table 2: Transformation Matrix (End effector to Base P)

0.984808	-0.173648	0	0.27691
0	0	-1	0
0.173648	0.984808	0	0.216143
0	0	0	1

The Jacobian matrix is calculated for forward kinematics that relates the joint space speed to the end effector speed in the workspace. The Jacobian matrix is shown in [Table 3].

Table 3: Jacobian (Joint velocity to End effector velocity)

$L2 \sin(\theta_2 + \theta_3) + L3 \sin(\theta_3) + L1 \sin(\theta_1 + \theta_2 + \theta_3)$	$L2 \sin(\theta_2 + \theta_3) + L3 \sin(\theta_3)$	$L3 \sin(\theta_3)$	0
$L2 \cos(\theta_2 + \theta_3) + L3 \cos(\theta_3) + L1 \cos(\theta_1 + \theta_2 + \theta_3)$	$L2 \cos(\theta_2 + \theta_3) + L3 \cos(\theta_3)$	$L3 \cos(\theta_3)$	0
0	0	0	0
0	0	0	0
0	0	0	0
1	1	1	1

### 3.3 Manipulator Inverse Kinematics

Given the end effector position (x, y, z) in workspace, the joint angles required for the achieving that configuration could be calculated. Mainly the Z coordinate (height) and additional X, Y coordinates beyond the reach of parallel base are traversed by the serial arm. Inverse kinematics (Figure 11) can be solved using various techniques such as algebraic matrix, numerical methods and geometric approaches.

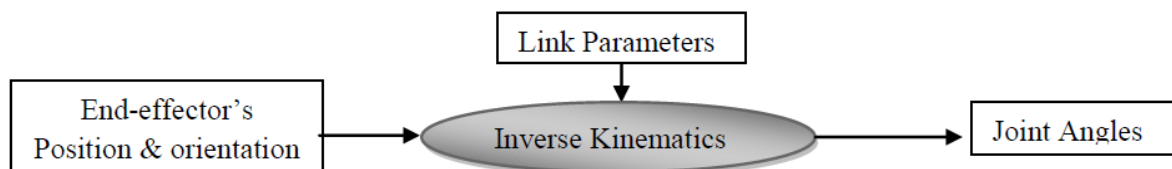


Figure 11 - Schematic diagram of inverse kinematics of a manipulator

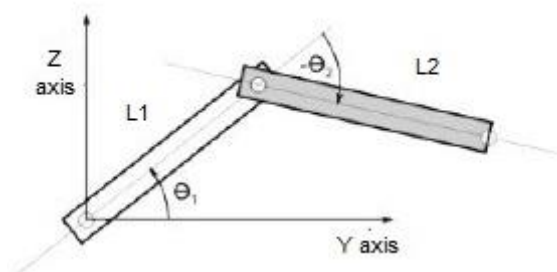


Figure 12 – Elbow down configuration of serial arm

With reference to figure 12 showing the elbow down configuration of the serial arm, the inverse kinematics for the joint angles  $\theta_0$ ,  $\theta_1$  and  $\theta_2$  are calculated as follows.

From the manipulator geometry,

$$y = l_1 \cos \theta_1 + l_2 \cos(\theta_2 + \theta_1)$$

$$z = l_1 \sin \theta_1 + l_2 \sin(\theta_2 + \theta_1)$$

$$z^2 + y^2 = l_1^2 \cos^2 \theta_1 + l_2^2 \cos^2(\theta_2 + \theta_1) + 2l_1 l_2 \cos \theta_1 \cos(\theta_2 + \theta_1) + l_1^2 \sin^2 \theta_1 \\ + l_2^2 \sin^2(\theta_2 + \theta_1) + 2l_1 l_2 \sin \theta_1 \sin(\theta_2 + \theta_1)$$

We know

$$\sin(x \pm y) = \sin x \cos y \pm \cos x \sin y \text{ and } \cos(x \pm y) = \cos x \cos y \mp \sin x \sin y$$

$$z^2 + y^2 = l_1^2 + l_2^2 + 2l_1 l_2 \cos \theta_2$$

$$\cos \theta_2 = \frac{z^2 + y^2 - (l_1^2 + l_2^2)}{2l_1 l_2}$$

$$\sin \theta_2 = \pm \sqrt{1 - \cos^2 \theta_2}$$

$$\theta_2 = \tan^{-1} \left( \pm \frac{\sqrt{1 - \cos \theta_2}}{\cos \theta_2} \right) = \tan^{-1} \left( \pm \frac{\sqrt{1 - \frac{z^2 + y^2 - (l_1^2 + l_2^2)}{2l_1 l_2}}}{\frac{z^2 + y^2 - (l_1^2 + l_2^2)}{2l_1 l_2}} \right)$$

Let  $k_1 = l_1 + l_2 \cos \theta_2$  and  $k_2 = l_2 \sin \theta_2$ , now the equation becomes

$$y = k_1 \cos \theta_1 - k_2 \sin \theta_1$$

$$z = k_1 \sin \theta_1 + k_2 \cos \theta_1$$

Upon solving we get,

$$\theta_1 = \tan^{-1} \left( \frac{z}{y} \right) - \tan^{-1} \left( \frac{k_2}{k_1} \right)$$

$$\theta_1 = \tan^{-1} \left( \frac{z}{y} \right) - \tan^{-1} \left( \frac{l_2 \sin \theta_2}{l_1 + l_2 \cos \theta_2} \right)$$

The following formula is obtained after inverse analytic computation of the serial arm geometry and substituting the design parameters.



$$\theta_2 = \tan^{-1} \left[ \frac{\sqrt{1 - \frac{(z^2 + y^2 - 225 - 144)}{2 * 15 * 12}}}{\frac{(z^2 + y^2 - 225 - 144)}{2 * 15 * 12}} \right]$$

$$\theta_1 = \tan^{-1} \left( \frac{z}{y} \right) - \tan^{-1} \left( \frac{12 \sin \theta_2}{15 + 12 \cos \theta_2} \right)$$

$$\theta_0 = \tan^{-1} \left( \frac{y - 240}{x} \right)$$

Here  $\theta_0$ ,  $\theta_1$  and  $\theta_2$  are joint angles respective to the joint 0, 1 and 2 respectively.

N.B. – The coordinate described above are local to the serial manipulator and its origin location is in the centroid P of the triangular base platform.

## Chapter 4: Development of Parallel Manipulator

The kinematics of planar, 3-RRR parallel robot, actuated with DC motors, is introduced in this section. Electric motors require minimal auxiliary support devices, which are typically a power supply and motor drive. These support devices are small and fairly portable. Secondly, the motor mass is fixed to the base frame and not part of the moving linkage mass, keeping the manipulator inertia lower. Additionally, the rotary type of actuator does not require a large base assembly and therefore the overall dimensions of the manipulator can be kept small. For these reasons, the electric motor is considered the best actuator for this parallel manipulator.

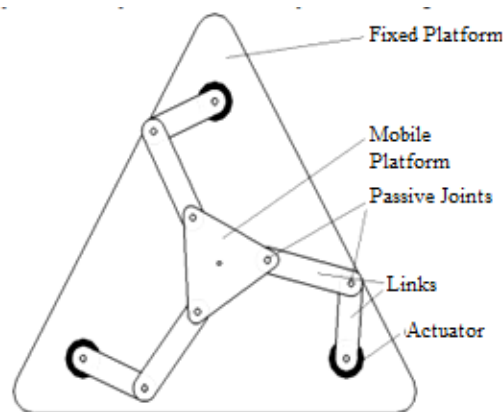


Figure 13: 3 DOF Symmetric Planar Parallel Robot

### 4.1 Configuration of Parallel Platform

As presented in the subordinate part of [Figure 6], the 3RRR parallel platform [Figure 13] has a closed-loop assembly in which the platform is linked to the base over a 3RRR kinematic chains. With the aim of getting a desired workspace, we implement a symmetric design method as recommended by Gosselin [36] i.e. the three legs are equal with one another and the initial joints and the final joints of the three legs form an equilateral triangle, respectively (symmetric design).

Since each leg consists of three rotary joints (one active joint and two passive joints), we can obtain three different actuation schemes as depicted in [Fig. 14 (a), (b) and (c)], where the active joints are located at the initial, intermediate and final (last) joint positions of the legs, respectively. Any alteration of the actuation arrangements does not affect disparagingly the kinematics of the robot. Nonetheless, it has huge influence on the assumption of setup singularities exclusive of the workspace, which is a serious basis to evaluate the implementation of the parallel stage.

Specifically, if a parallel robot has less configuration singularities, it will have bigger effective workspace and hence signifies an improved proposal.

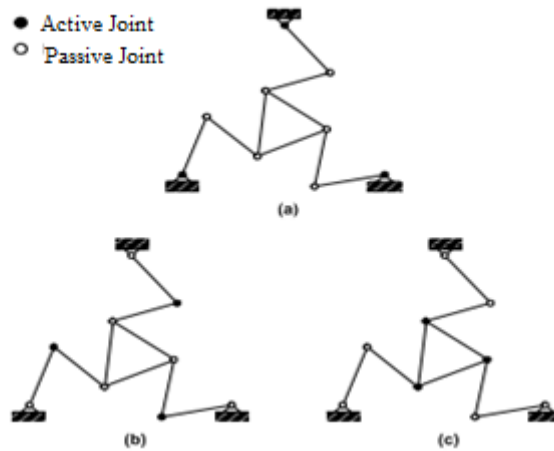


Figure 14: Various Actuation Architecture of Parallel Base

Using the singularity study process proposed by the authors, we realised that the 3RRR parallel platform has the minimum configuration singularities when the initially joint on each of the legs is an active joint (Figure 14(a)). Such an actuation system, is consequently, adopted in our design. Another advantage from such an actuation system is that the closed-form forward displacement solutions could be resulting in a symbolic form, which will considerably streamline the kinematic analysis.

## 4.2 Kinematics Analysis of Parallel Platform

The resolve of kinematic analysis is to decide the end-effector pose once the six active-joint angles are identified (Forward kinematics) and vice versa (Inverse Kinematics). Established on the kinematic arrangement of the 6-DOF hybrid parallel-serial manipulator, we share the forward displacement analysis into two sections: the forward displacement analysis of the 3RRR planar platform and that of the 3-DOF RRR serial robot arm.

The kinematic analysis of a common 3RRR planar platform was well calculated by Gosselin and Sefrioui [37] in which a closed-form polynomial answer was derived. Nevertheless, since the closed-form solution leads to a polynomial of order six, no symbolic form of the solution can be derived. Even though this solution approach is general adequate to cope with any 3RRR planar parallel robots, it is not much computationally efficient.

For the 3RRR planar parallel platform with a symmetric design and the precise actuation system, symbolic closed-form solutions are derived, as we only require solving a simple quadratic polynomial equation [38].

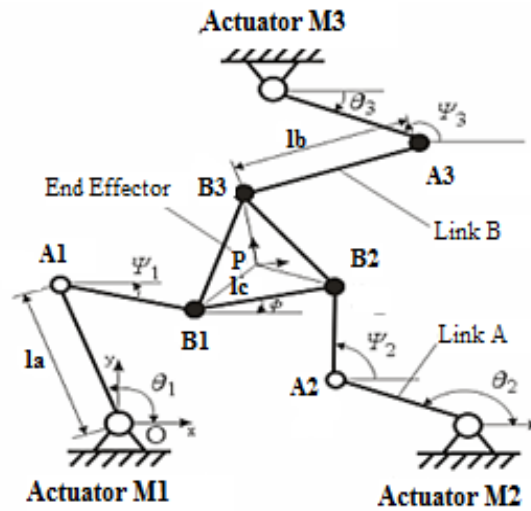


Figure 15: Kinematic schematic of the 3RRR planar platform

The symbolic solution is computationally effective and can aid us to have a clear vision into the solution organization. The schematic sketch of the 3RRR planar platform is presented in figure 15.

$M_i$ ,  $A_i$ , and  $B_i$  ( $i = 1, 2, 3$ ) represent the initial, intermediate and final (last) joints of leg  $i$  respectively. Among the nine revolute joints,  $M_1$ ,  $M_2$ , and  $M_3$  are active joints, whereas others are all passive joints. For of the symmetric scheme, both triangles  $B_1B_2B_3$  and  $M_1M_2M_3$  are equilateral triangles.

The locus of the end effector is given by  $P$ ; this is the center of mass of the moving platform.  $P$  is also the  $x$ - $y$  coordinates of the manipulator in global coordinates.

The orientation of the end effector is given by the angle  $\phi$ , measured from the  $x$ -axis.  $l_a$  is the length of Link A,  $l_b$  is the length of Link B, and  $l_c$  is the distance from point  $P$  to  $B_i$ .  $\theta_i$  is the joint angle measured from the  $x$ -axis. The angle given by  $\psi_i$  is the angle of Link B measured from the  $x$ -axis.  $\gamma_i$  is the angle of the line from point  $P$  to the joint at  $B_i$  - it is measured from the line connecting  $B_1$  and  $B_2$  on the moving platform.

The derivation of the inverse kinematics comes from the loop closure equation for the 3-RRR parallel robot:

$$OP = OM_i + M_iA_i + A_iB_i + B_iP$$

Writing the equations in component form:

$$x_p = l_a \cos(\theta_1) + l_b \cos(\psi_1) + l_c \cos(\varphi + \gamma_1) + x_{M1} \quad (1)$$

$$y_p = l_a \sin(\theta_1) + l_b \sin(\psi_1) + l_c \sin(\varphi + \gamma_1) + y_{M1} \quad (2)$$

Rewriting equations (1) and (2)

$$l_b \cos(\psi_1) = x_p - l_a \cos(\theta_1) - l_c \cos(\varphi + \gamma_1) - x_{M1} \quad (3)$$

$$l_b \sin(\psi_1) = y_p - l_a \sin(\theta_1) - l_c \sin(\varphi + \gamma_1) - y_{M1} \quad (4)$$

Squaring equations (3) and (4) and summing both we get:

$$\begin{aligned} l_b^2 = & x_p^2 + y_p^2 + l_a^2 + l_c^2 + x_{M1}^2 + y_{M1}^2 - 2x_p l_a \cos\theta_1 - 2x_p l_c \cos(\varphi + \gamma_1) - 2x_p x_{M1} + 2l_a l_c \cos(\theta_1) \cos(\varphi + \gamma_1) \\ & + 2l_a x_{M1} \cos(\theta_1) + 2l_c x_{M1} \cos(\varphi + \gamma_1) - 2y_p l_a \sin\theta_1 - 2y_p l_c \sin(\varphi + \gamma_1) - 2y_p y_{M1} + 2l_a l_c \sin(\theta_1) \sin(\varphi + \gamma_1) + \\ & 2l_a y_{M1} \sin(\theta_1) + 2l_c y_{M1} \sin(\varphi + \gamma_1) \end{aligned} \quad (5)$$

Now combining terms in equation (5) so that all terms with  $\sin\theta_i$  are grouped together, and similarly, terms with  $\cos\theta_i$  are grouped.

$$e_1 \sin \theta_i + e_2 \cos \theta_i + e_3 = 0 \quad (6)$$

$$\begin{aligned} e_3 = & x_p^2 + y_p^2 + l_a^2 + l_c^2 + x_{M1}^2 + y_{M1}^2 - 2x_p l_c \cos(\varphi + \gamma_1) - 2x_p x_{M1} + 2l_c x_{M1} \cos(\varphi + \gamma_1) - 2y_p l_c \sin(\varphi + \gamma_1) - \\ & 2y_p y_{M1} + 2l_c y_{M1} \sin(\varphi + \gamma_1) \end{aligned} \quad (7)$$

$$e_2 = -2x_p l_a + 2l_a l_c \cos(\varphi + \gamma_1) + 2l_a x_{M1} \quad (8)$$

$$e_1 = -2y_p l_a + 2l_a l_c \sin(\varphi + \gamma_1) + 2l_a y_{M1} \quad (9)$$

Using the cosine-sine solution method suggested as in Lipkin Duffy [39] in order to avoid algebraic indeterminacy which occurs when  $e_3 - e_2 = 0$ . In fact, numerical round off can cause significant error even when  $e_2 e_3 \cong 0$ .

Dividing equation (6) by  $\sqrt{e_1^2 + e_2^2}$

$$\frac{e_1 \sin \theta_i}{\sqrt{e_1^2 + e_2^2}} + \frac{e_2 \cos \theta_i}{\sqrt{e_1^2 + e_2^2}} + \frac{e_3}{\sqrt{e_1^2 + e_2^2}} \quad (10)$$

Now, rearranging equation (7) and using the trigonometric identity and yeild

$$\cos(\alpha - \beta) = \cos \alpha \cos \beta + \sin \alpha \sin \beta \quad (11)$$

$$\cos(\theta - \rho) = -\frac{e_3}{\sqrt{e_1^2 + e_2^2}} \quad (12)$$

Where

$$\cos(\rho) = \frac{e_1}{\sqrt{e_1^2 + e_2^2}}, \sin(\rho) = \frac{e_2}{\sqrt{e_1^2 + e_2^2}} \quad (13)$$

Using the identity  $\cos^2 \alpha + \sin^2 \alpha = 1$ , and equation (12) gives:

$$\sin(\theta - \rho) = \pm \frac{\sqrt{e_1^2 + e_2^2 - e_3^2}}{\sqrt{e_1^2 + e_2^2}} \quad (14)$$

$$\text{Let } \sigma \text{ be such that; } \theta^\pm = \sigma^\pm + \rho \quad (15)$$

Applying the identity of equation (12)

$$\cos(\theta^\pm) = \cos \sigma \cos \rho + \sin \sigma \sin \rho \quad (16)$$

$$\cos(\theta^\pm) = \frac{-e_1 e_2 \mp e_2 \sqrt{e_1^2 + e_2^2 - e_3^2}}{\sqrt{e_1^2 + e_2^2}} \quad (17)$$

$$\sin(\theta^\pm) = \frac{-e_2 e_3 \mp e_1 \sqrt{e_1^2 + e_2^2 - e_3^2}}{\sqrt{e_1^2 + e_2^2}} \quad (18)$$

For the particular robot there are two possible solutions given by the equations (17) and (18). The two solutions are called elbow left and elbow right corresponding to the solutions  $\theta^+$  and  $\theta^-$  (Figure 16). In practice, the atan2 command is used to find the solution in the proper quadrant. When the roots are imaginary (i.e. there is no real solution) for some given pose, it means that the position/orientation of that configuration is outside the reachable workspace.

In this project, the  $\theta^-$  orientation is chosen. The joint actuation is limited in that region and since the shift from  $\theta^-$  to  $\theta^+$  requires to pass through a serial singularity, this assumption is useful for simplifying the inverse kinematics

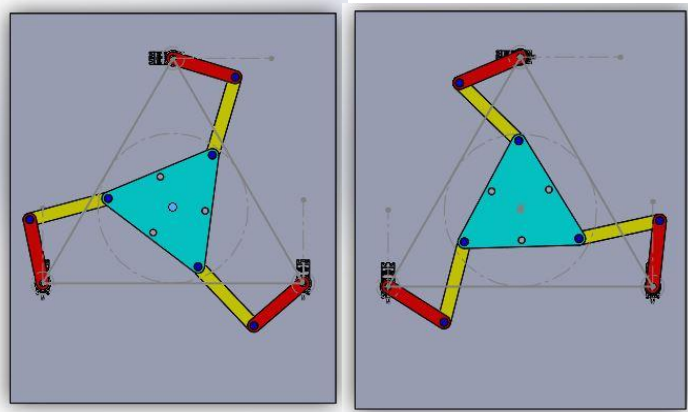


Figure 16: Solutions to Inverse Kinematics Problem Orientation ( $\theta^+$  and  $\theta^-$ )

### 4.3 Singularity and Workspace Analysis

For the planar manipulator studied, such singularity configurations are reached whenever the axes  $A_1B_1$ ,  $A_2B_2$  and  $A_3B_3$  intersect (possibly at infinity), as described in figure 17(a). In the incidence of such configurations, the manipulator cannot struggle any torque applied at the joining point I [19].

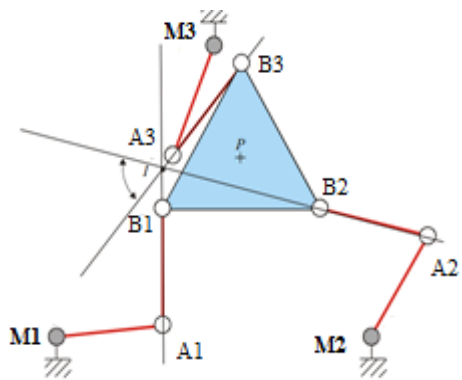


Figure 17(a): Example of parallel singularity

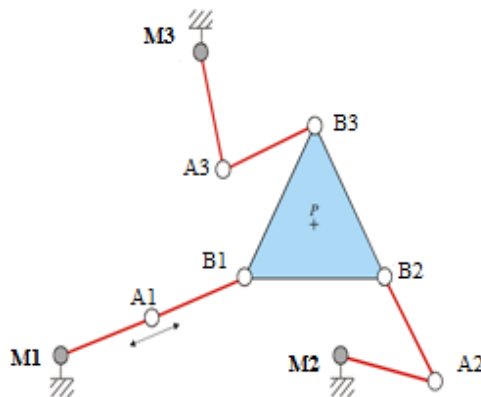


Figure 17(b): Example of serial singularity

For the manipulator under study, the serial singularities occur whenever the points  $A_i$ ,  $B_i$ , and  $M_i$  are aligned. [Figure 17(b)]

Workspace can be determined by using discretization method. There were identified several cases of workspace. The workspace of the platform in the current working mode (a) [40] was computed in MATLAB.

The 3 DOF in a planar platform are  $x$ ,  $y$  and twist  $\theta$ , the workspace analysis is plotted in figure.18 and 19 using two cases of the link lengths.

Case I: Equal link lengths ( $l_a = l_b = 10 \text{ cm}$ )

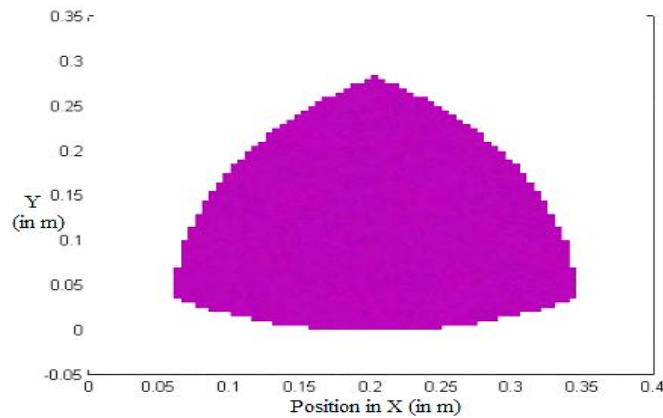


Figure 18: Workspace of the 3-RRR parallel platform for Case I

Case II: Equal link lengths ( $l_a = 10 \text{ cm}$ ,  $l_b = 15 \text{ cm}$ )

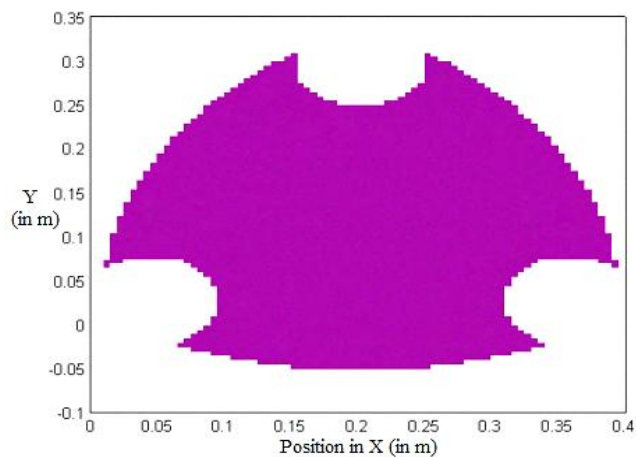


Figure 19: Workspace of 3-RRR parallel platform for Case II

From figure 18 and 19, we get the information relating link lengths to workspace and singularities present within. For Case I with equal link lengths there is no presence of parallel singularity and the workspace is limited by effect of serial singularity and joint constraints. While in Case II, the work space is larger compared to Case I with parallel singularity present near the actuated joints  $M_i$ . Due to the modular configuration of links, the link length of link B ( $l_b$ ) could be adjusted.

The final configuration chosen is  $l_a = 10 \text{ cm}$  and  $l_b = 12.5 \text{ cm}$  in order to have a larger workspace and keep the parallel singularity to minimum. The region of parallel singularity is near to the actuator (servo motors) which needs to be secured from collision. So, there is no significant loss in workspace range.



# Chapter 5: Kinematic and Dynamic Analysis Simulation

## 5.1 Kinematic Analysis Simulation

Kinematic Analysis is an important section of the project since it verifies the feasibility of the proposed model and provides essential parameters for research. The Forward Kinematics and the Inverse Kinematics of the serial arm and parallel base is computed using MATLAB and Roboanalyzer through DH conventions adopted in the design of serial arm [Figure 20(a)].

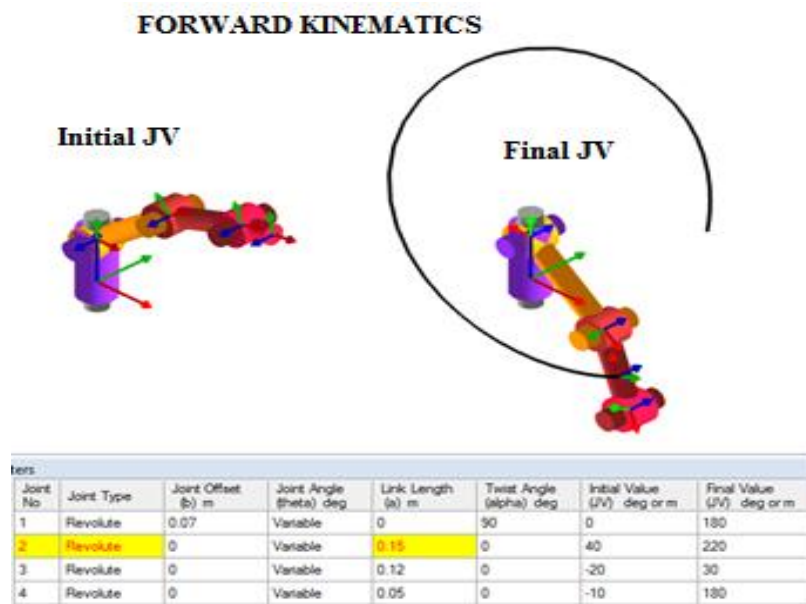


Figure 20(a): Serial Arm- Forward Kinematics Parameters

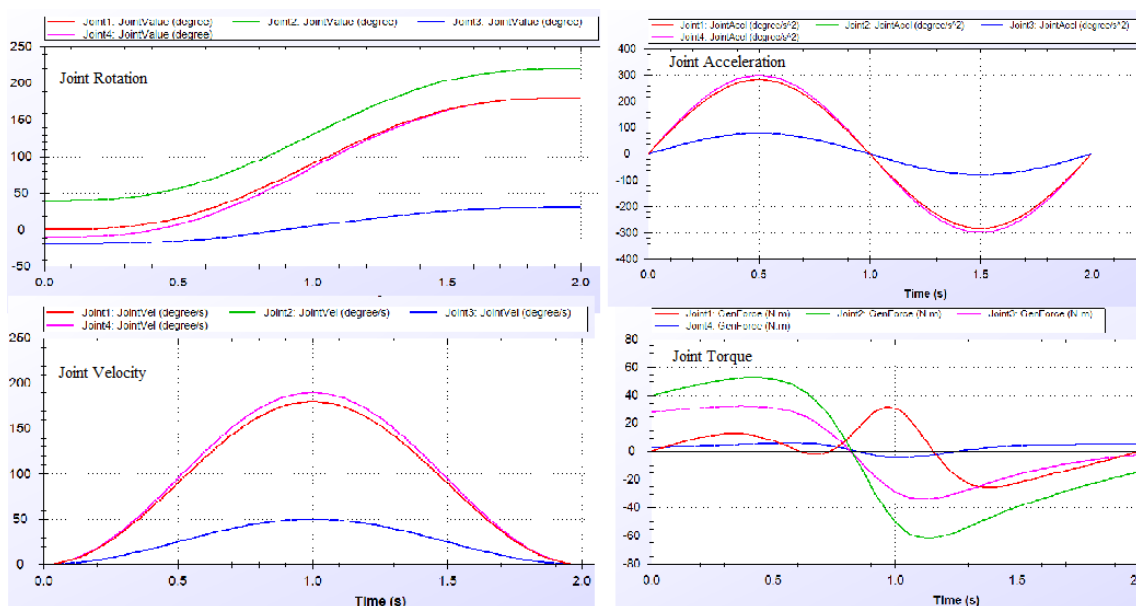


Figure 20(b): Serial Arm- Forward Kinematics Results

The link lengths, DH configuration, workspace positions/orientation and material properties of the model were taken as input. The joint displacement, velocity, acceleration and torques were found from the study [Fig. 20(b)]. The trajectory was of a cycloidal type with linear acceleration profile (which amounts to much vibration in system). The torque required at each joint for this motion was maximum for joint 2 which bears most structural and inertial loads in Z axis. The maximum acceleration and velocity are kept under limits.

Similar, study was carried out for parallel platform in SimMechanics Toolbox of MATLAB [26]. The joint relations defined in the Solidworks CAD model were exported to MATLAB through SimMechanics Import Interface [Figure 21]. The forward and inverse kinematics of the parallel manipulator were computed on a defined trajectory.

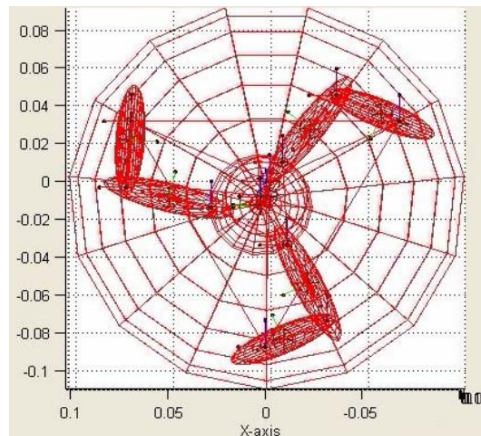


Figure 21: Imported 3R planar model in SimMechanics

The Sim mechanics interface takes the model parameters as inputs (link lengths, joint type, inertia from link weight, assembly mating constraints). The applied load or velocity is defined in from the Simulink control blocks and the output parameters are monitored via scopes and graphs.

In the simulation, parameters such as joint angles, velocities and torques were calculated. The results of the simulation are presented in [Figure 22 and 23].

From the Forward Kinematics of the Parallel Platform using MATLAB Robotics Toolkit [Figure 22] , the simulation was computed for time  $t = 2$  sec with time increasing joint speeds at actuator. It was observed that the joints face increasing torque values with joint velocity and the outer joint face a large torque and force compared to the non-actuated joints. The model is simulated to estimate the planar torque requirement which comes around 8 kg-cm for the motion [Figure 23].

The motion simulation is presented in the animation window.

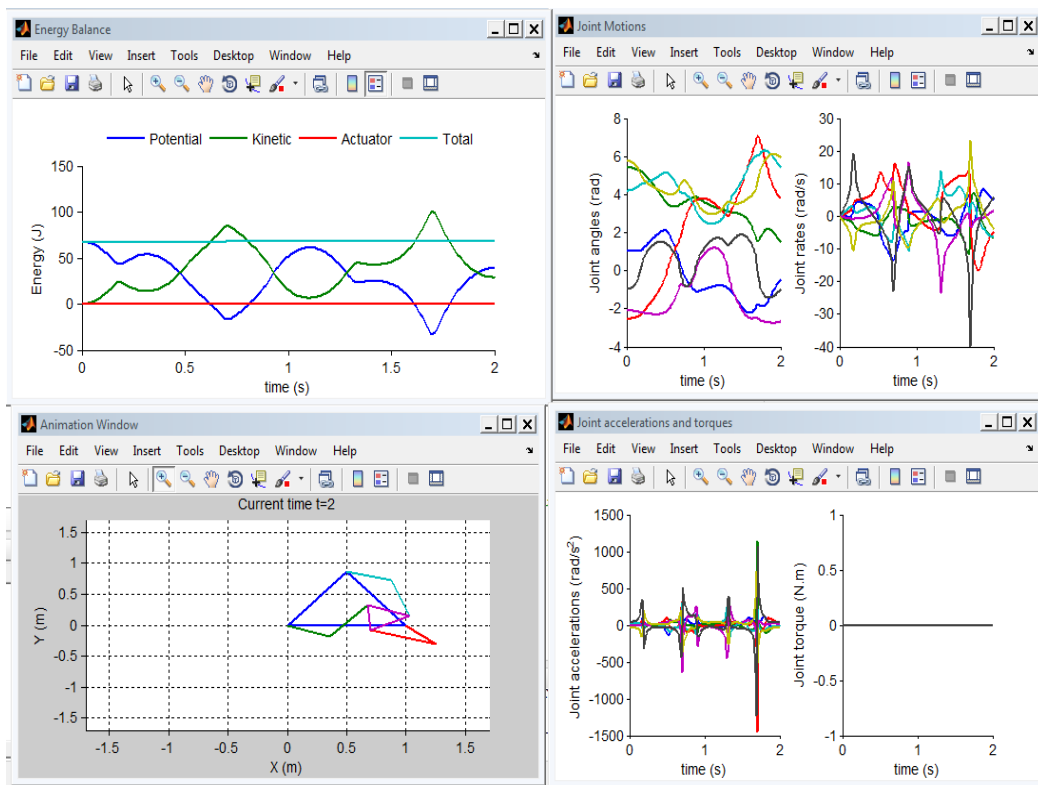


Figure 22 – Forward kinematics Parallel Base

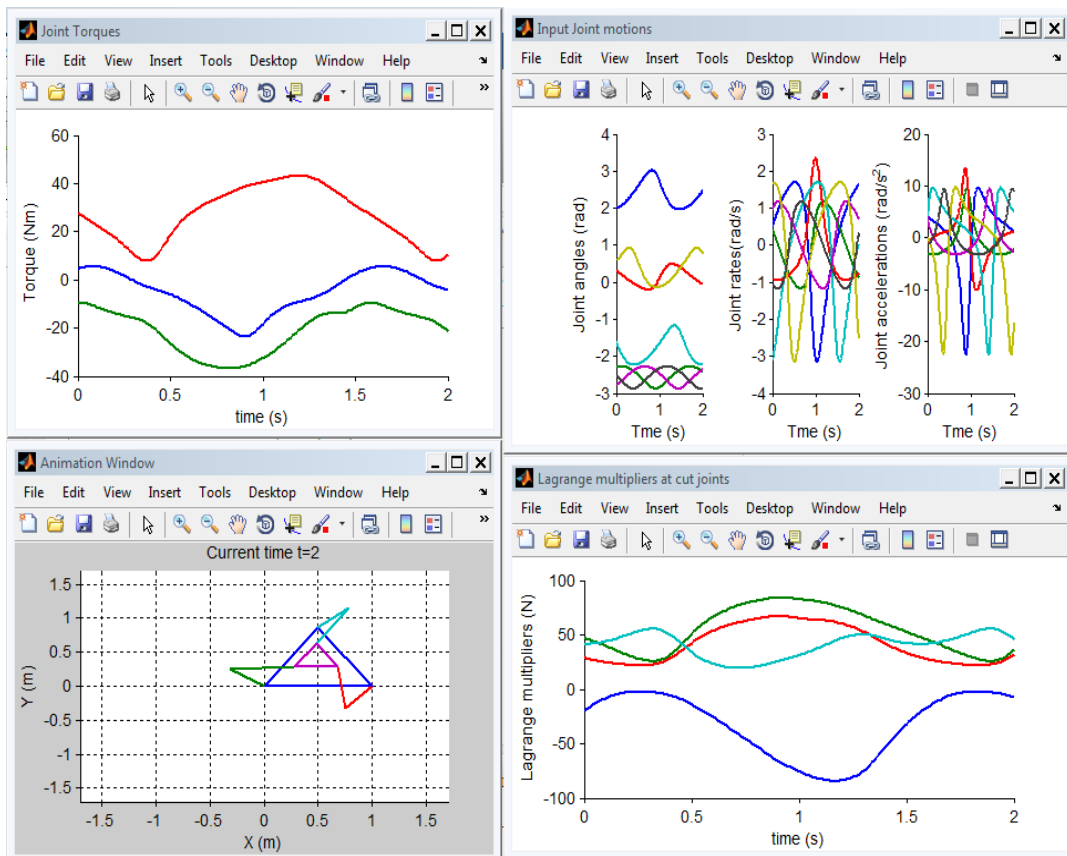


Figure 23 – Inverse kinematics Parallel Base

## 5.2 Dynamic Analysis

The torque and speed which every joint's actuator ought to create in a standard position and stance so as to deliver a yield constrain and speed in the Z heading of solidarity is computed, and this is known as the standard torque  $T$  and standard speed  $\omega$ . The purpose behind considering the Z bearing is that the biggest power is fundamental for supporting the robot weight itself. The torque  $T$  and speed  $\omega$  which every actuator ought to create in a subjective position and stance when the yield compel and speed in that heading is equivalent to solidarity is ascertained.

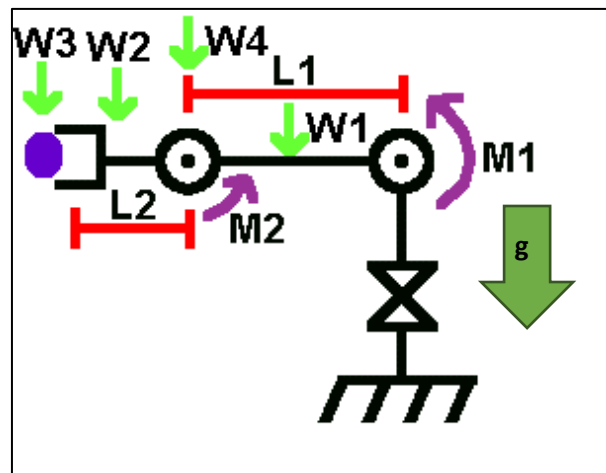


Figure 24: Forces acting on the serial arm including gravity

A minute arm computation ought to be finished by reproducing descending power times the linkage lengths. This estimation must be defeated every lifting actuator. This specific outline has only two DOF that obliges lifting, and the focal point of gravity of every linkage is thought to be  $(\text{length}/2)$ . [Table 4] describes the components and units involved in Dynamic parameters of the serial arm [Figure 24].

Table 4: Component Description and Quantity

Part Name	Unit Quantity	Description
W1	0.060 kg	Weight of link 1
W2	0.045 kg	Weight of link 2
W3	0.300 kg	Weight of end effector
W4	0.040 kg	Weight of Joint 3
L1	0.15 m	Length of link 1
L2	0.12 m	Length of Link2

In the serial arm, the major load at base joint (Joint 0) is axial because of the overhanging links and it is supported with the help of the axial- radial bearings. Hence, the torque requirement for joint M0 is reduced. [Table 5] provides the Joint requirement and available torque from the servo units.

Table 5: Joint Torque Mapping

Joint	Torque Required	Torque Available
<b>M0</b>	1.5 kg-cm	3.4 kg-cm
<b>M1</b>	3.5 kg-cm	3.7 kg-cm
<b>M2</b>	2.5 kg-cm	3.7 kg-cm

#### Servo Motors Used

- Futaba S3003 – 3.7 kg-cm @ 6V (At M1, M2)
- GS-3630BB – 3.4 kg-cm @ 6V (At M0)

For Parallel platform, the torque requirement is uniform around 8 kg-cm. Three uniform servo motors (FeeTech FS5115M – 15 kg-cm @ 6V) are used at the three joints to overcome the inertial and torque load of entire assembly.

## Chapter 6: Control of Hybrid Manipulator

The S/P Hybrid Platform has, as mentioned above, three parallel linked arms, composed of two links each, equally spaced 120 degrees apart on each body segment providing a total of 3 DOF along with the coupled serial arm having 3 DOF. The total system can be analysed by combining each arm system. The overall kinematics of the entire 6-DOF hybrid manipulator can be readily derived from the product of individual transformation matrix obtained from both parallel & serial arms.

The maximum X and Y traversal limits of the parallel base is computed along with singularity (to avoid near singular positions). The serial arm is required to traverse the Z and the X, Y positions (if required).

Mechatronics systems often require control mechanisms and algorithms for effective and smooth operation of the system. This manipulator inherently have vibrations induced due to motion of motors and flexible structure which need to be controlled and compensated.

The following control strategies are implemented in this project are as follows:

### 6.1 Joint Motion and Position Control

It is important to note that DOF has its limitations, known as the configuration space [32]. Since not all joints can revolve 360 degrees, each joint has a max angle restriction. Limitations could be from wire wrapping, actuator capabilities, servo max angle or other design restrictions. The analog servo used in this project has max.  $180^\circ$  of motion. It is very important to avoid near singular positions and high static torques.

The velocity and servo position could be easily controlled through PWM signals and proper programming.

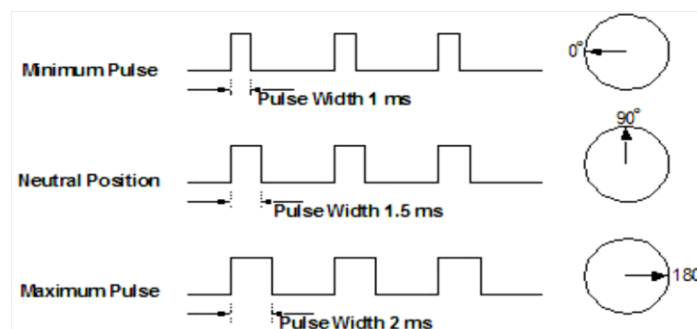


Figure 25: PWM signal for servo joint control

### *Serial Arm:*

From Base Reference (Point P)

- Base =  $0^\circ$  to  $180^\circ$
- Shoulder =  $40^\circ$  to  $140^\circ$
- Elbow =  $45^\circ$  to  $140^\circ$

The overshooting angles are saturated to the limiting values. The servo positions are incremented by  $\pm 1^\circ$  in the elbow & shoulder;  $\pm 5^\circ$  in the base angle.

### *Parallel Base:*

The servo positions are incremented by  $\pm 1^\circ$  in the joints from their initial configuration for smooth motion. Each servo only has 132 degrees range of actuated motion. 25 deg - 157 deg. (157 = servo angle zero, 25 = servo angle 132)

## 6.2 Joint Velocity Control

The motor presents a constraint in maximum acceleration and velocity due to technical limitations. S profiling is adopted for Forward and Inverse Kinematics path planning. The angular acceleration of motors is done using step functions [Figure 26] to generate a smooth motion and reduction in jerk/vibration.

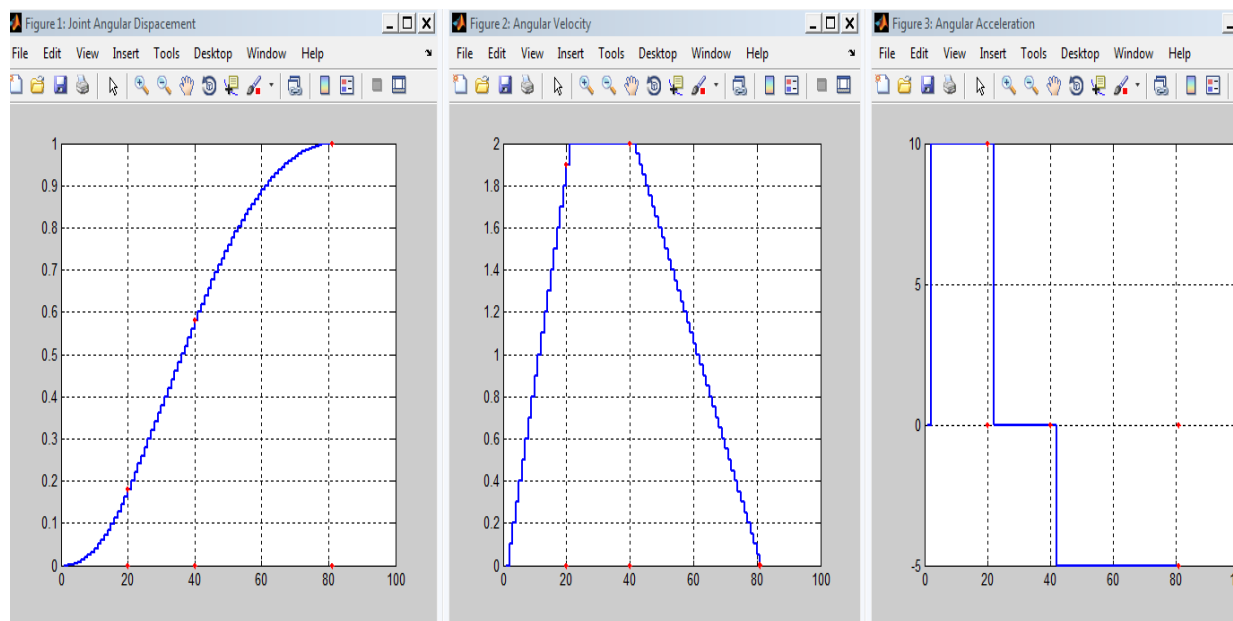


Figure 26: S Profile- Angular Displacement, Velocity and Acceleration

### 6.3 PID Control

Numerous control techniques are available for serial manipulators. Because parallel manipulators result in a loss of full constraint at singular configurations, any control applied to a parallel manipulator must avoid such configurations.

Simple independent joint control is a practical approach to robot control. Linear PID is a reliable source for this purpose. Control scheme describes the mechanical structure of the robot together three controllers of type PID.

The PID Control is implemented in SimMechanics Control block [Figure 27]. Driving joints are actuated by rotation actuators. To each joint it is attached a position sensor.

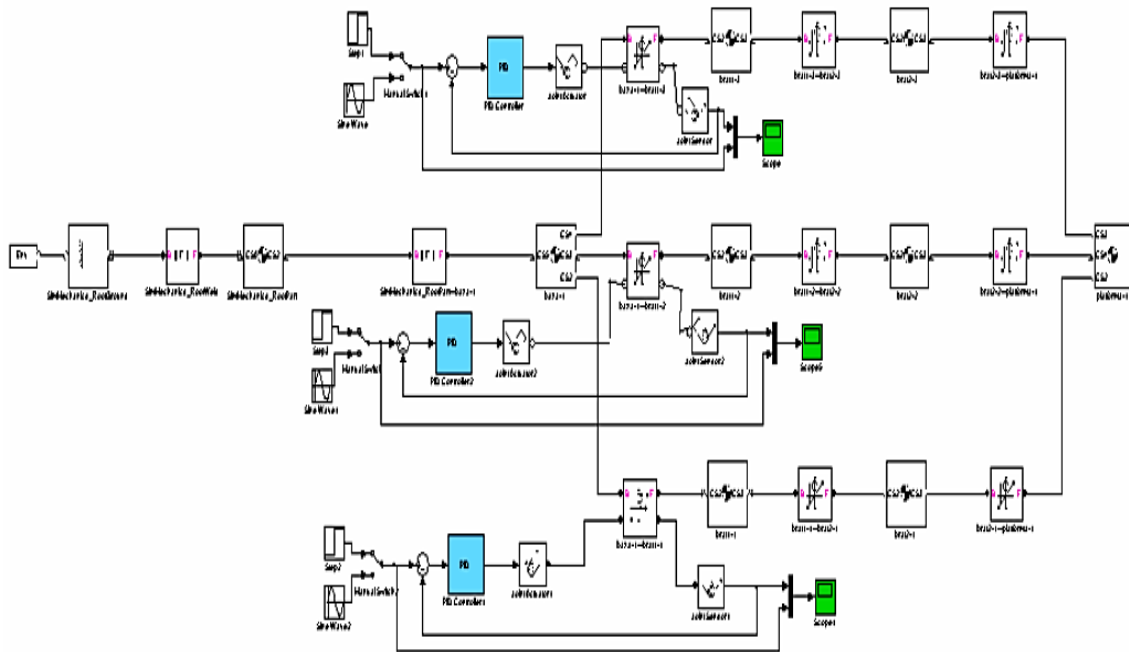


Figure 27: SimMechanics PID Control block

The parameters  $K_p$ ,  $K_d$  and  $K_i$  are tuned to reduce the error in the desired and actual joint angle values. [Figure 28 (a)]

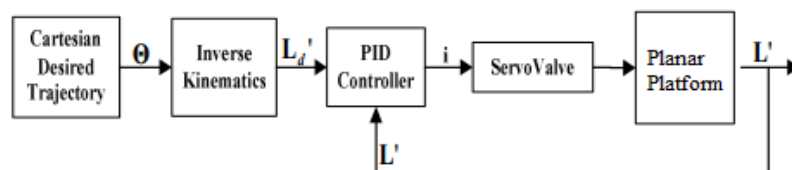


Figure 28 (a): Working of a PID Servo Controller



The PID simulation results are for  $K_p = 2500$ ,  $K_d = 35$ , and  $K_i = 1500$ . [Figure 28(b)]

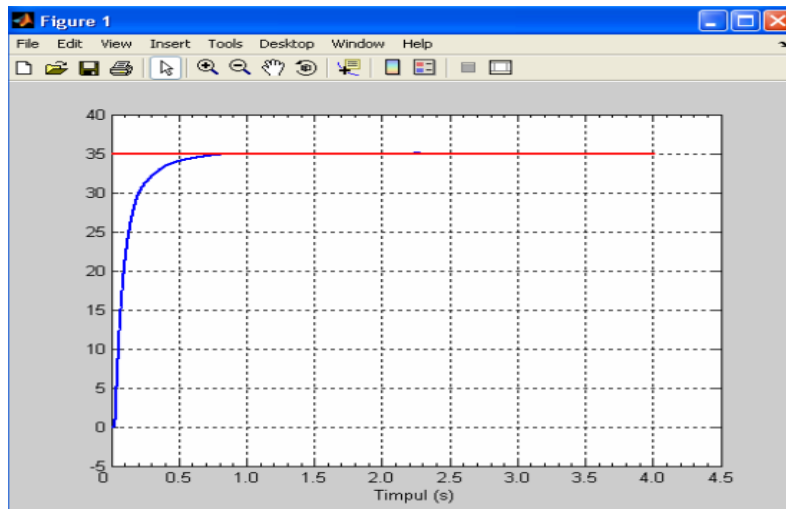


Figure 28 (b): PID Simulation Results

# Chapter 7: Realization of the Hybrid Manipulator

## 7.1 Mechanical Design, CAD and FEA

The CAD [Fig 29 (a) and (b)] and FEA structural analysis for the prototype was done in SolidWorks. The link dimensions were optimized for reduction in weight and efficient load bearing. The servo motor and fixtures were placed with preliminary motion analysis.



Figure 29(a): CAD Model of Serial Arm

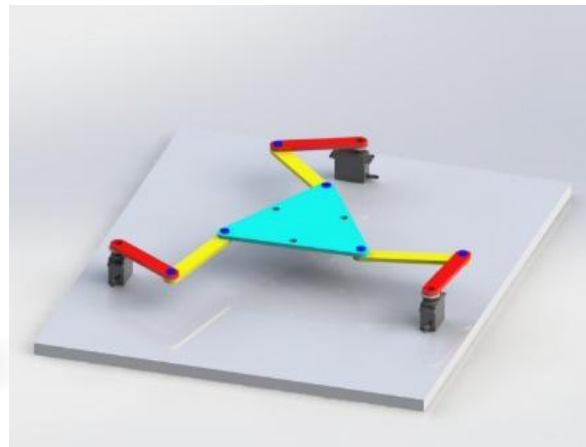


Figure 29(b): CAD Model of Parallel Platform

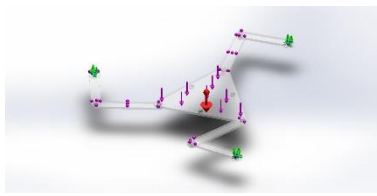
The material selected for the links is Acrylic (Medium impact) due to its high strength to weight ratio and ease of manufacture of small components. The fixtures used in the prototype for assembly are made of stainless steel, plastic and rubber types.

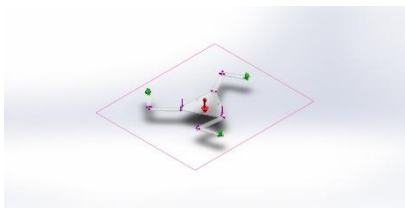
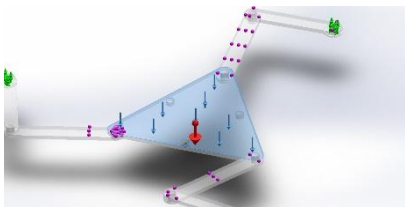
The physical parameters of link material Acrylic are

<b>Yield strength:</b>	4.5e+007 N/m <sup>2</sup>
<b>Tensile strength:</b>	7.3e+007 N/m <sup>2</sup>
<b>Elastic modulus:</b>	3e+009 N/m <sup>2</sup>
<b>Poisson's ratio:</b>	0.35
<b>Mass density:</b>	1200 kg/m <sup>3</sup>

The Inertial loads, joint torques along with the gravity are considered for structural analysis. The material satisfies the required design strength and properties. The deformation induced in the joints and platform is under controllable limits as verified from the FEA Analysis shown above in [Table 6 and 7] with associated figures.

**FEA Analysis: Loads and Fixtures** [Table 6: FEA Load, Fixtures and Mesh Parameters]

Fixture name	Fixture Image	Fixture Details		
Fixed Hinge-1		Entities:	3 face(s)	
		Type:	Fixed Hinge	
Resultant Forces				
Components	X	Y	Z	Resultant
Reaction force(N)	0.00496531	12.037	-0.00833583	12.037
Reaction Moment(N-m)	0	0	0	0

Load name	Load Image	Load Details	
Gravity-1		Reference:	Top Plane
		Values:	0 0 -9.81
		Units:	SI
Force-1		Entities:	1 face(s)
		Type:	Apply normal force
		Value:	20 N

Mesh Control Name	Mesh Control Image	Mesh Control Details	
Control-1		Entities:	6 face(s)
		Units:	mm
		Size:	2.963
		Ratio:	1.5

## FEA Results: Parallel Link

Table 7(a): Von Mises Stress FEA Results

Min	Max
3192.43 N/m <sup>2</sup>	4.89895e+006 N/m <sup>2</sup>
Node: 1111	Node: 28259

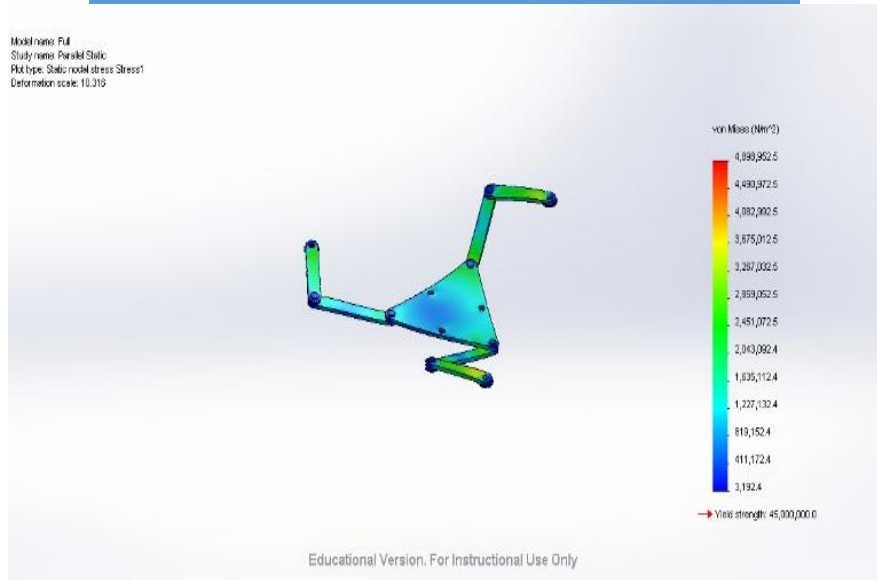
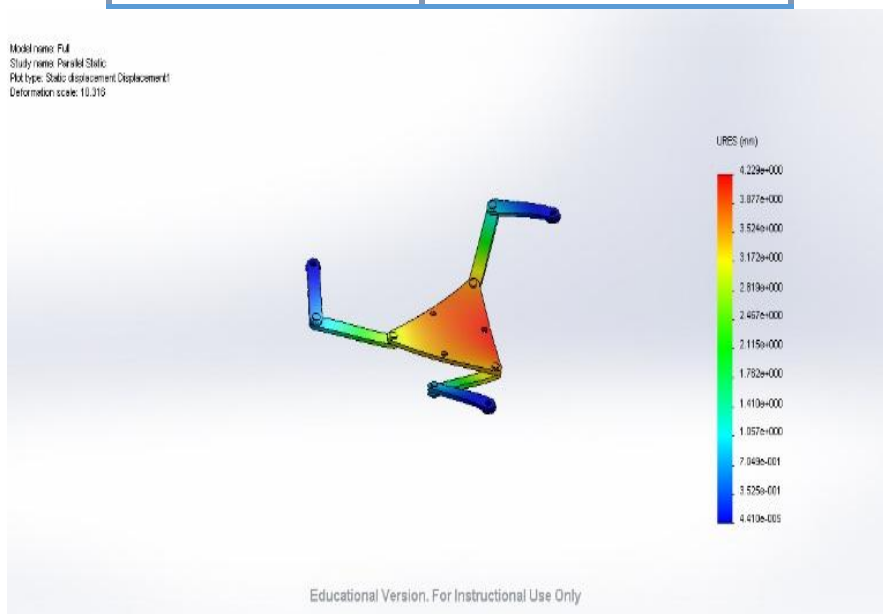


Table 7(b): Resultant Displacement FEA Results

Min	Max
4.4102e-005 mm	4.22912 mm
Node: 27049	Node: 56198



## 7.2 Mechanical Assembly

The manipulator is fabricated from Medium impact Acrylic sheet. The holes and profiles is cut intricately reduce the weight of the moving parts. Standard fasteners are used and some support link is custom made using rapid prototyping. The serial arm is connected to the parallel base [Figure 30] via bearing platform that supports serial arm and bears major part of the structural load.

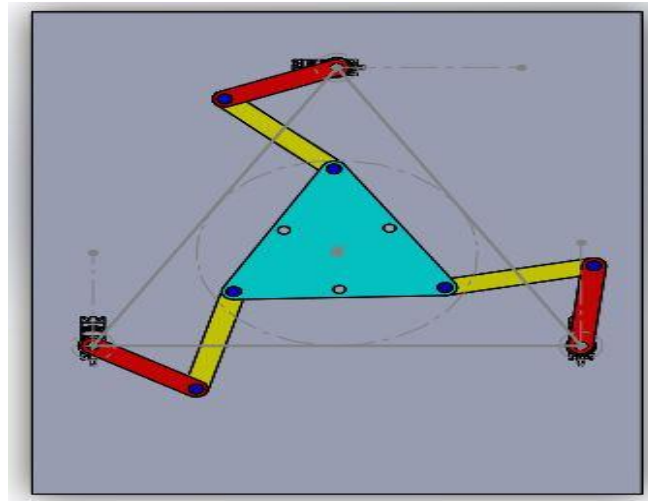


Figure 30: Parallel Base Design

To reduce the bending moment on the parallel links, three omnidirectional caster wheels were attached underneath the parallel platform to support the weight of the parallel platform and serial arm.

## 7.3 Electronics

The electronic components used in the prototype are shown in [Table 8]. Seven Standard Analog servo motors of varying torque rating are used in this project. A SMPS is used to provide power to the entire servo assembly (3.5 amps @ 6V) while the controls are handled by the microcontroller. The power is distributed via a circuit [Fig. 31] designed on a general purpose PCB. The cables are safely harnessed and constrained to avoid interference with manipulator motion.

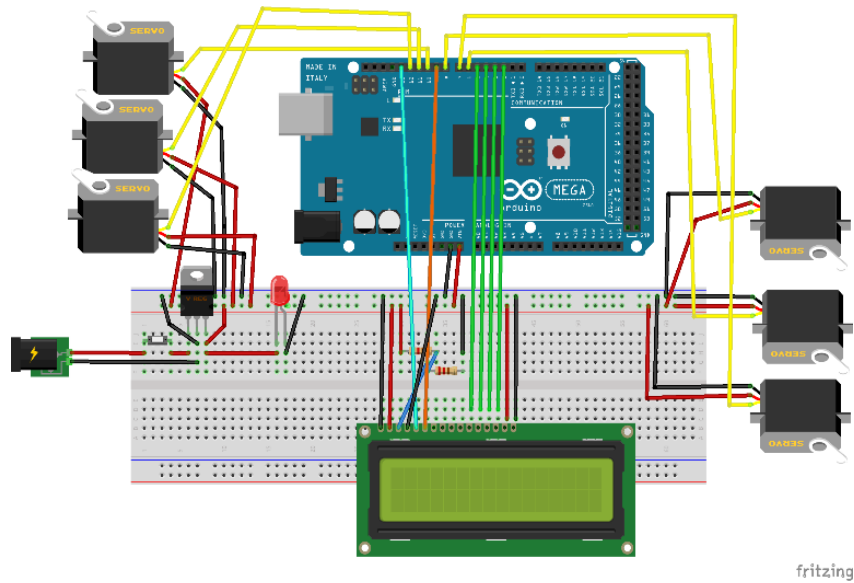


Figure 31: Electronics Component Layout

Table 8: Electronics Component BOM

Part Name	Amount	Properties
Servo Motor	6 (+1)	Analog 180 deg
LCD screen	1	type Character; pins 16
Red LED	1	5 mm [THT]
Arduino Mega 2560	1	
SMPS	1	12 V, 5 A
Voltage Regulator	2	7805, 7808
Switch	1	SPST, Normally Open
USB Cable	1	
Jumper Wires	Vary	
General PCB	3" * 3"	

## 7.4 Communication and Software

Arduino Mega 2560 with Atmel ATmega2560 processor is used for low level hardware, running custom made firmware. It takes care of sending PWM and direction signals to the motor drivers, supplying power to encoders and reading encoder increment interrupts and external digital hardware. It receives input signals over USB serial communication line, of which the protocol has been custom defined.

The joint angles are stored in a buffer array & character commands are sent to the Arduino. Depending on the case of incoming serial data from the buffer array, the orientation of arm changes in response.

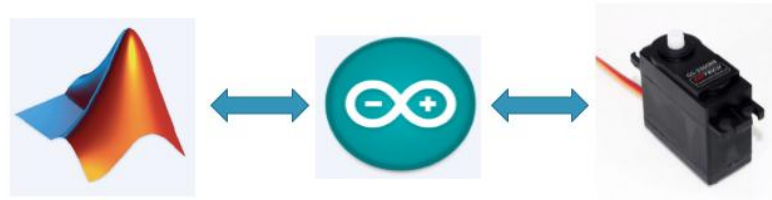


Figure 32: USB SPI Interfacing in the Prototype

The high level hardware comprises of a PC running MATLAB program to compute the kinematics and send the servo commands to Arduino. The setup is established via the MATLAB-Arduino add-in and used in continuous serial mode as the presented in [Fig 32]. A feedback is established between the components and control units to keep track of the system. The servo motors have inbuilt encoders that provide joint angle data to Arduino and MATLAB which is helpful for implementing PID control.

## 7.5 The Prototype



Figure 33: Top View of the Hybrid Manipulator Prototype

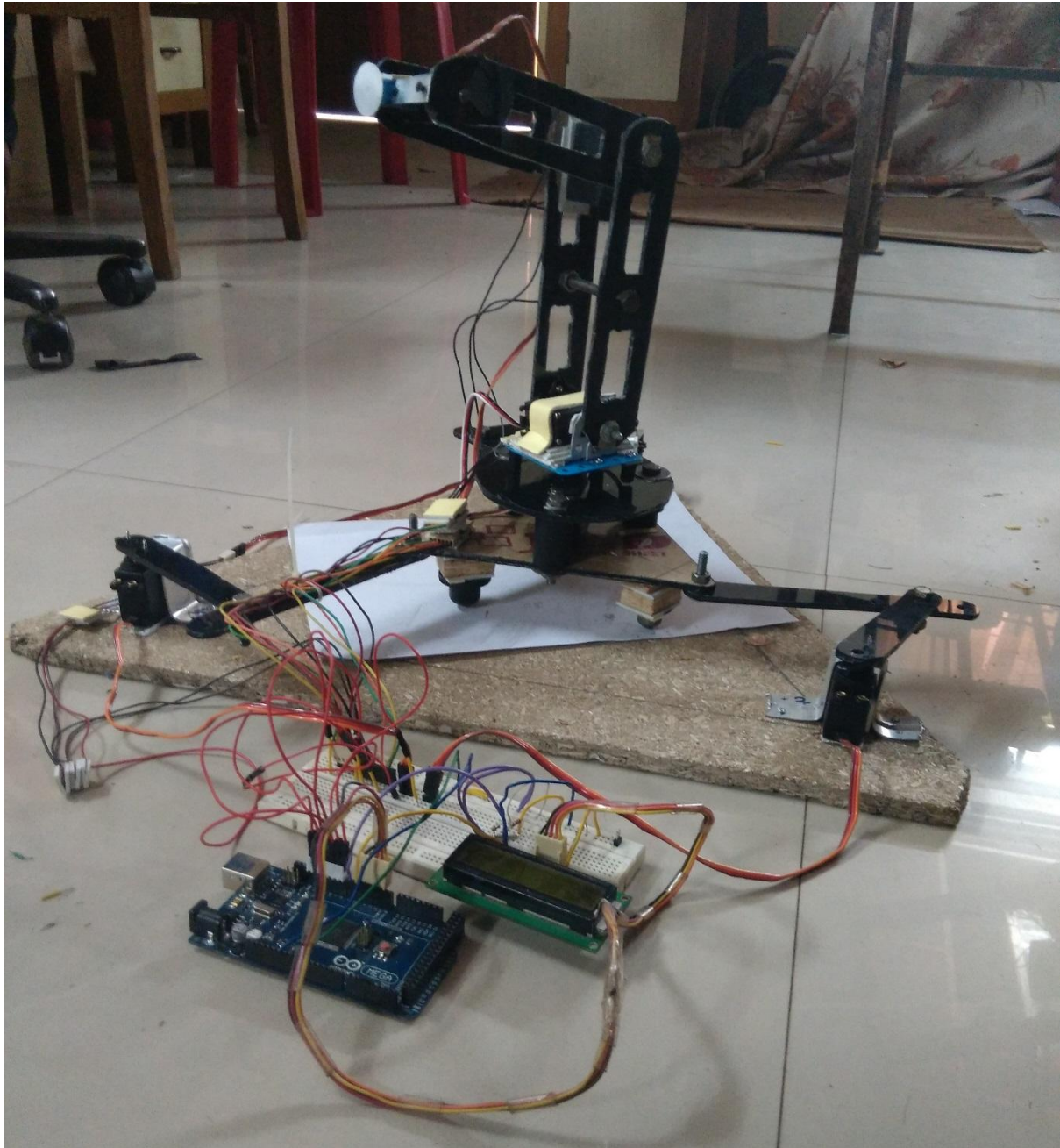


Figure 34: Isometric View of the Hybrid Manipulator

The end effector as seen in figure 34 is a 360 degrees continuous servo motor. The manipulator has a cardboard ground base as a support with parallel base servo motors rigidly fixed to it. The support structures are made from aluminum profiles. The passive joints are 8 mm small steel nut and bolts which allow a smooth relative motion between the links. The parallel platform is attached with 3 omnidirectional caster wheels arranged in a circular manner which supports the weight of serial arm and parallel platform, thereby reducing the bending moment on the parallel links and servo shafts. The cables were routed properly to not hinder the motion of the assembly. The LCD shows the current joint angles and coordinate of the parallel manipulator.



# Chapter 8: Experimental Results and Discussions

The Serial Arm prototype [Figure 36] is tested with an object tracking approach (Open CV Image Processing) to gather the workspace coordinates (with base position at P) for Inverse Kinematics and the algorithm is verified with inverse kinematics operation tracking the object [Figure 35] whilst the object is in motion.

Due to this tracking unit, the joint limits and workspace limits of the serial arm are verified which is used for algorithm definition.

## 8.1 Serial Manipulator Results

This image processing application was implemented to test the inverse kinematics of the serial arm in real situations where the object (red circle) is in motion and its position in workspace is variable. To achieve the object detection, a CMOS camera system was mounted as an end effector in the serial arm such that the camera capture the object in the frame. This camera is connected to a computer which captures the video and analyses the frames. A program is written in C++ language using standard OpenCV library functions which runs in Microsoft Visual Studio environment. This program identifies the location of ball in real time. The program also calculates the joint angles of the robotic arm. These angles are sent to the controller of the robotic arm via USB serial port at a baud rate of 57600 bps. The microcontroller used for driving the actuators is Arduino Mega development platform.

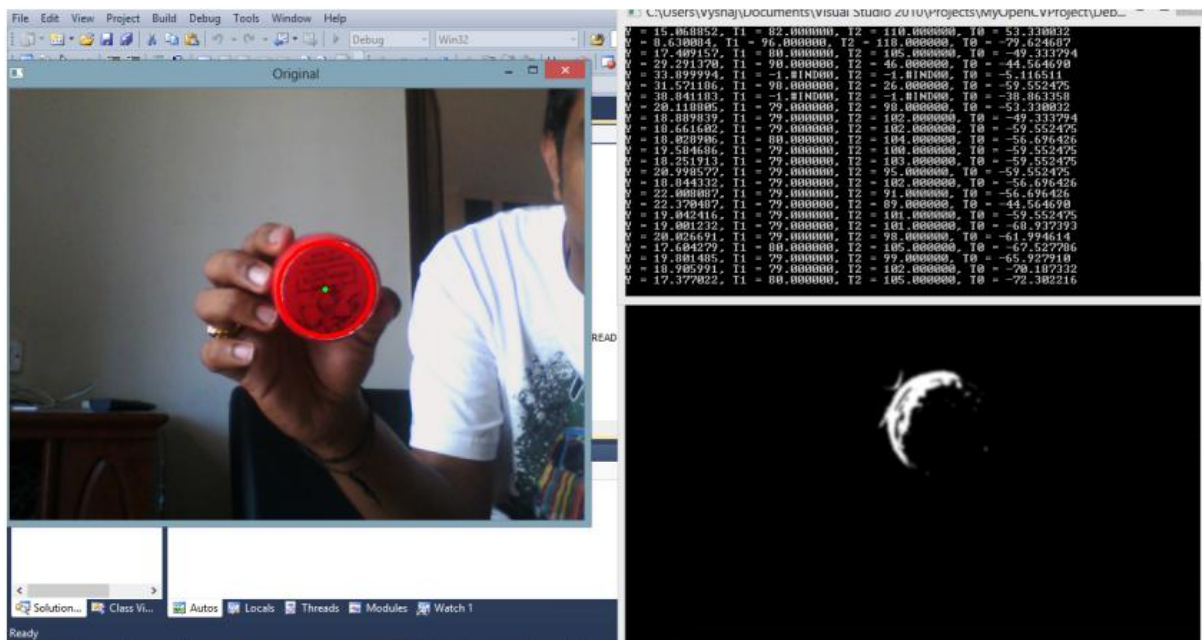


Figure 35: Image processing operation tracking the Object

## Functions used to get images from the webcam and do the set-up:

**cvCaptureFromCAM()** - This function associates the cvCapture struct to our webcam

**cvNamedWindow()** - declares a window(does not automatically show the window)

**cvCreateImage()** - creates a blank image(we only call this once because the other image is from the webcam)

**cvQueryFrame()** - gets a frame from the webcam

## Image Processing Functions:

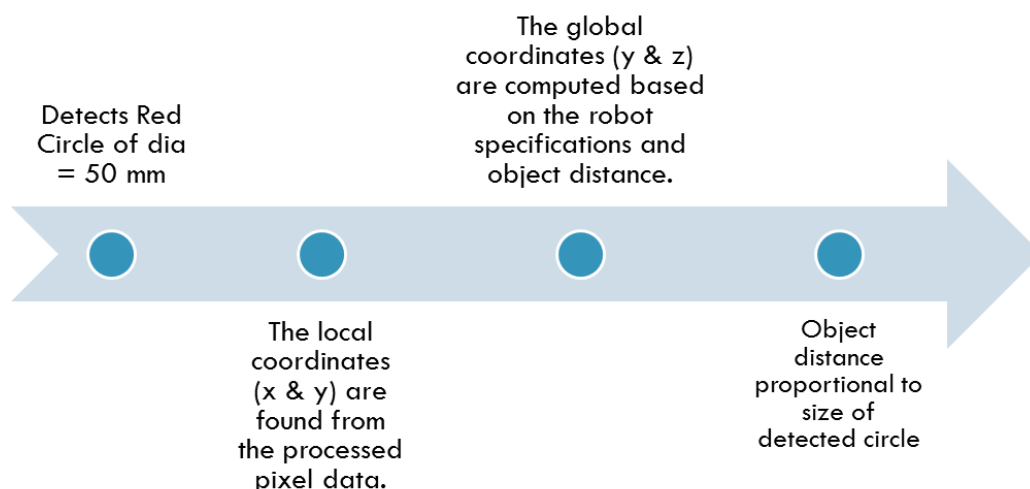
**cvInRangeS()** - Takes an input and an output image(outputs pass by reference), and also two CvScalar structs, we will use the Cv RGB macro to simplify the function call. The first CvScalar struct(entered via the RGB macro for simplicity is the minimum filtering value, and the second CvScalar struct (CV RGB macro) is the maximum "filtering value. For each pixel in the input image the output image (at the same pixel location) will be set to a white pixel if within the min and max filtering value, and a black pixel if not in the min to max range. This the output image is a black and white image, where everything that matched the color in the original way, image that we were looking for will be white, everything else will be black.

**cvSmooth()**-Perform a Gaussian Bur on the resulting image from cvInRangeS (we will call this the processed image) before we look for circles in the processed mage.

**cvHoughCircles()** - This is the function that actually locates the circles in the processed image and returns a pointer to CvSeq struct that is a list of the circles found.

**cvGetSeqElem()** - Gets one of the circles found from the cvSeq struct, based on the index passed in (just like an array, the index can be 0, 1, 2, etc), and returns a pointer to float(same as float array since this is in C), which contains 3 elements, the circle center point x location, circle center point y location, and the circle radius.

**cvCircle()** - This function draws a circle on an image. We will call this twice, both times on the original image. The first time we will draw a 3 pixel radius green circle at the center point of the located object, the second time we will draw a draw a red circle around the located object.



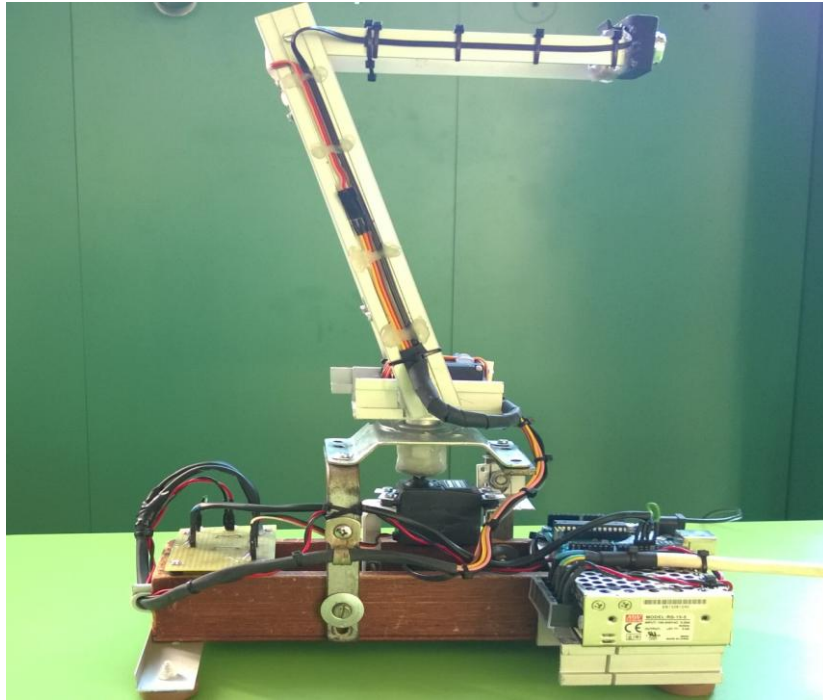


Figure 36: Prototype of the Serial Arm with a camera at end effector  
(Positioned at idle configuration)

The serial arm prototype was tested subjected to various position of tracking object and the observations were noted for open loop and PID closed loop control [Table 9]. The variations were noted as error %. The PID control approaches the simulation result by a greater extent to that of open loop control. This is due to the transient dynamics of serial arm and unsmooth servo motion in open loop. The gravity adds up time required by motion vs. simulation.

Table 9: Results of Serial Arm: Simulation vs Experiment

Test run	Coordinate	Simulation	Experiment (open loop)	Error	PID closed loop	Error
1	(10, 10,10)	1.8 sec	1.5 sec	16.7%	1.7 sec	6 %
2	(10,10,15)	2 sec	1.5 sec	20 %	1.8 sec	10 %
3	(10,10,20)	2.3 sec	1.8 sec	22 %	2.1 sec	8.5 %
4	(10, 15, 10)	2.3 sec	1.7 sec	26 %	1.9 sec	17 %
5	(10, 20, 10)	2.8 sec	2 sec	28 %	2.4 sec	14 %
6	(10,20,20)	Workspace Not feasible	Indeterminate	N/A	Indeterminate	N/A

## 8.2 Parallel Manipulator Results

The Parallel base kinematics was implemented via MATLAB Arduino Interface. For forward kinematics, the servo motors were given specific angles and the platform position was noted. Various combination of servo angles were tested to estimate the workspace and singularity limits. The results were tested against the workspace analysis done in MATLAB. The actual workspace was less than the estimated (about 30-35 %) because of joint constraints implemented in algorithm (for simpler inverse kinematics), effect of singularity positions and physical constraints from links and platform.

For the Inverse Kinematics, the position (x and y coordinates of the platform) is taken as input in the code and the inverse kinematics is computed to find the joint angles. The orientation of the platform was fixed at  $\phi = 0^\circ$  for the experiment, however it can be easily changed in the code. The feasible workspace was determined and the platform moved to that position. Trajectory shapes are sent as position arrays and functions to run the inverse kinematics that showed proper results. The infeasible workspace positions were displayed as error.

## 8.3 Future Work

The immediate future works includes combing the serial and parallel robots and implement the combined transformation. The flowchart for workspace division in Parallel and Serial Manipulator and for the motion control is presented in figure 37 and 38 respectively.

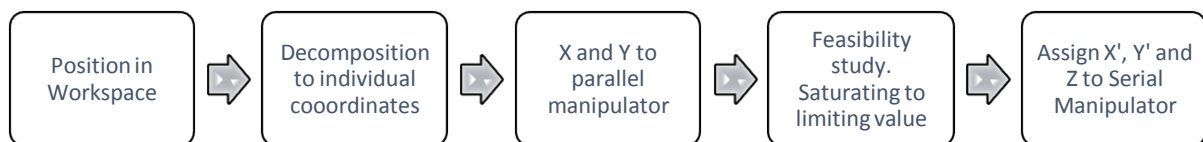


Figure 37: Workspace Division Algorithm

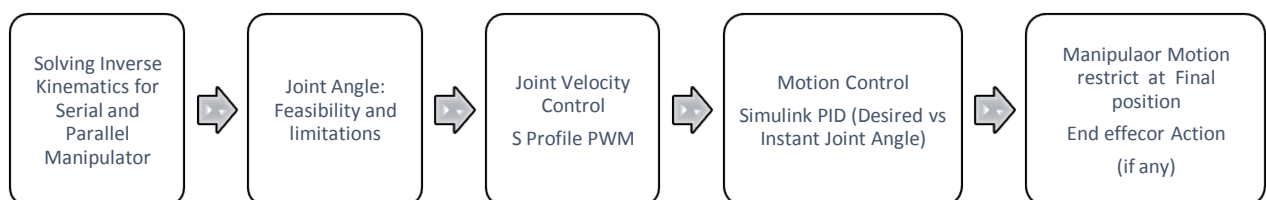


Figure 38: Motion Control Algorithm in Hybrid Manipulator

## Chapter 9: Conclusion

The hybrid manipulator is developed using the above described paradigm. Kinematic and Dynamic Analysis was carried out in computational software (MATLAB, Roboanalyzer) and the algorithm was successfully tested in a fabricated prototype.

To improve the performance of the manipulator closed loop PID control was used through Sim Mechanics-Arduino interface and motion constraints were implemented through algorithm and mechanical constraints. The PID control approaches the simulation result by a greater extent to that of open loop control. This is due to the transient dynamics of serial arm and unsmooth servo motion in open loop. The gravity adds up time required by motion vs. simulation.

The future scope will be to create a transformation matrix and algorithm for the complete hybrid manipulator.

## Chapter 10: References

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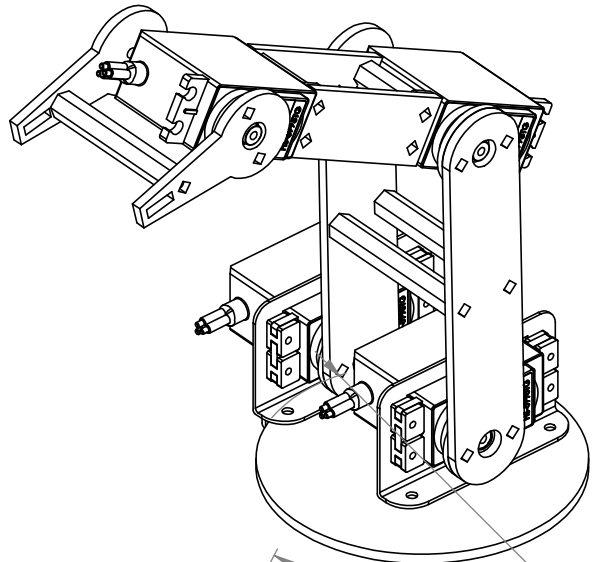
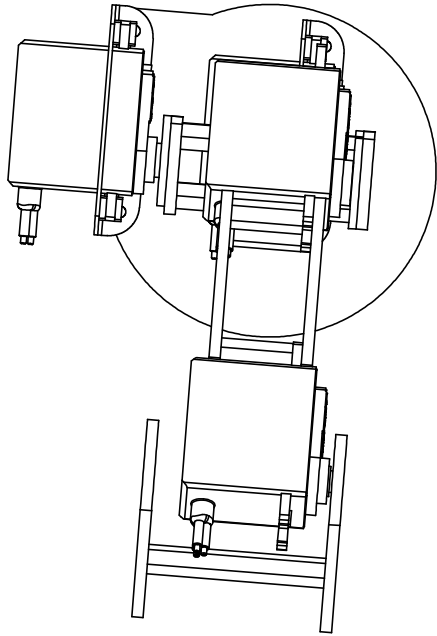
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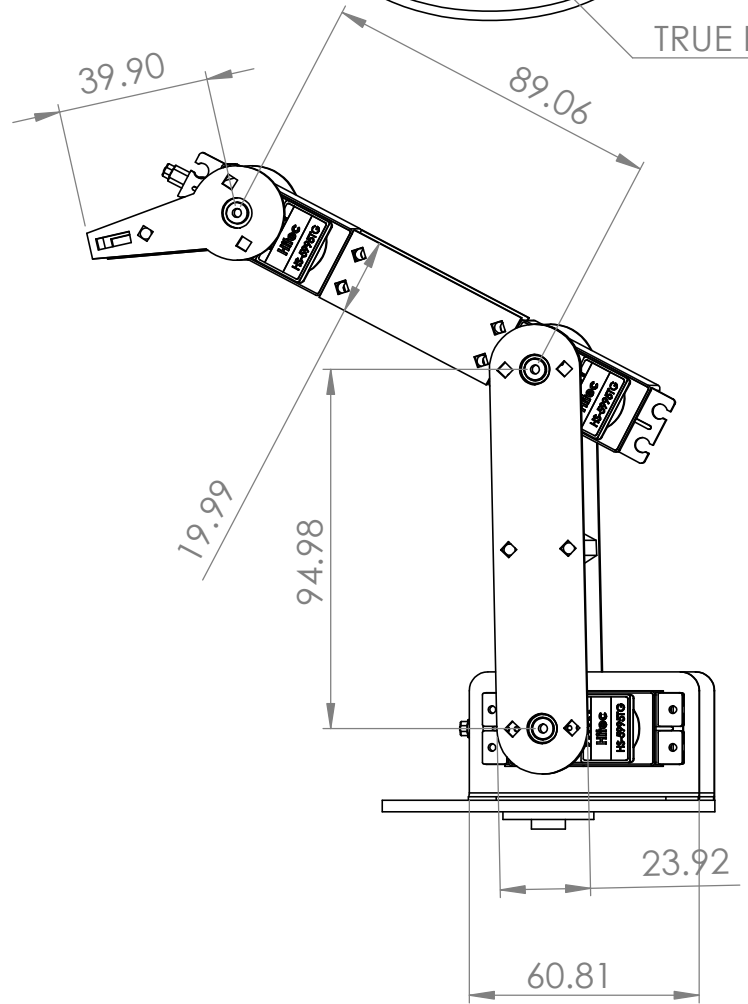
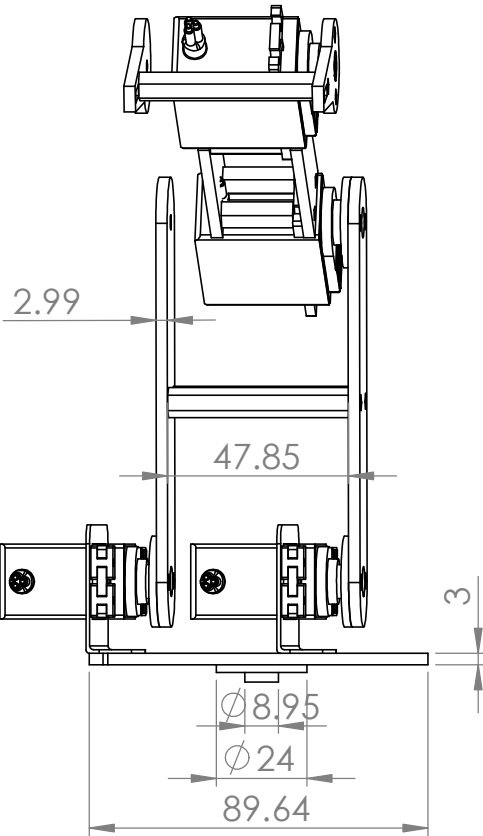


## Appendix A: Technical Drawings

1. Serial Arm CAD
2. Parallel Base CAD
3. Platform Design CAD
4. Planar Link CAD
5. Hybrid Manipulator CAD



TRUE R44



UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN MILLIMETERS  
SURFACE FINISH: N/A  
TOLERANCES:  
LINEAR: 1 mm  
ANGULAR:

FINISH:

DEBUR AND  
BREAK SHARP  
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	Chiranjibi Sahoo		
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: Acrylic Hard Medium

TITLE: Serial Arm (Links with Servo)

DWG NO.

Serial Arm CAD

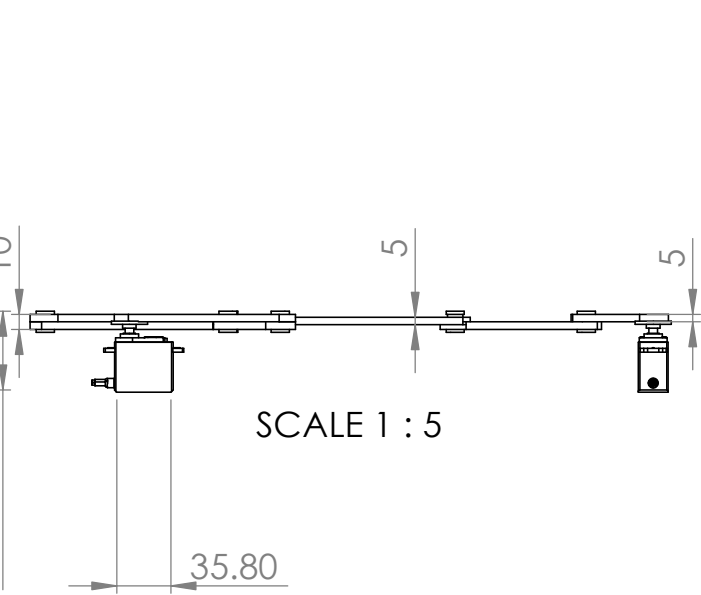
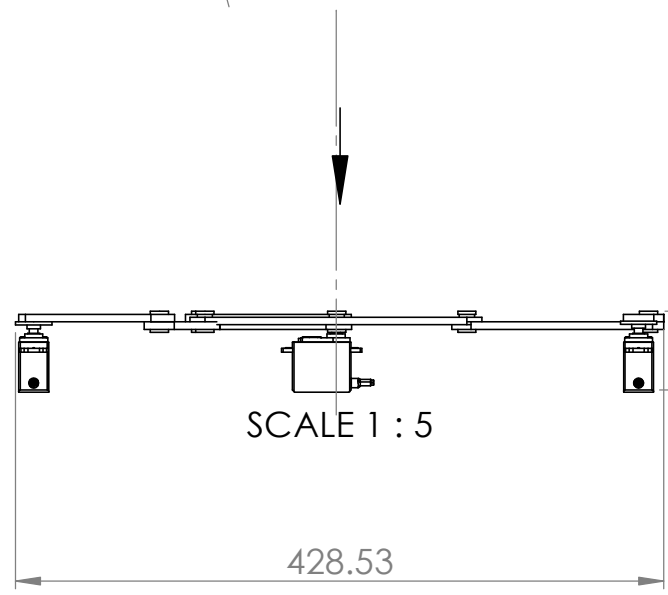
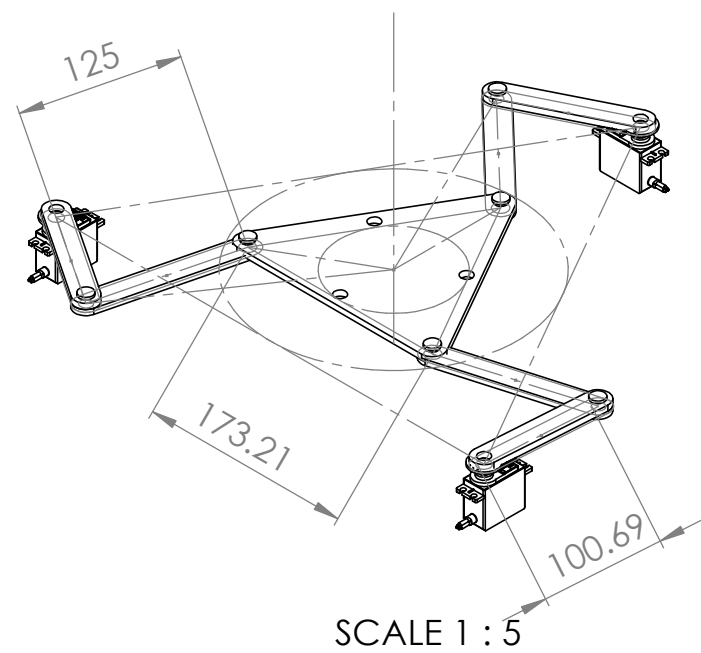
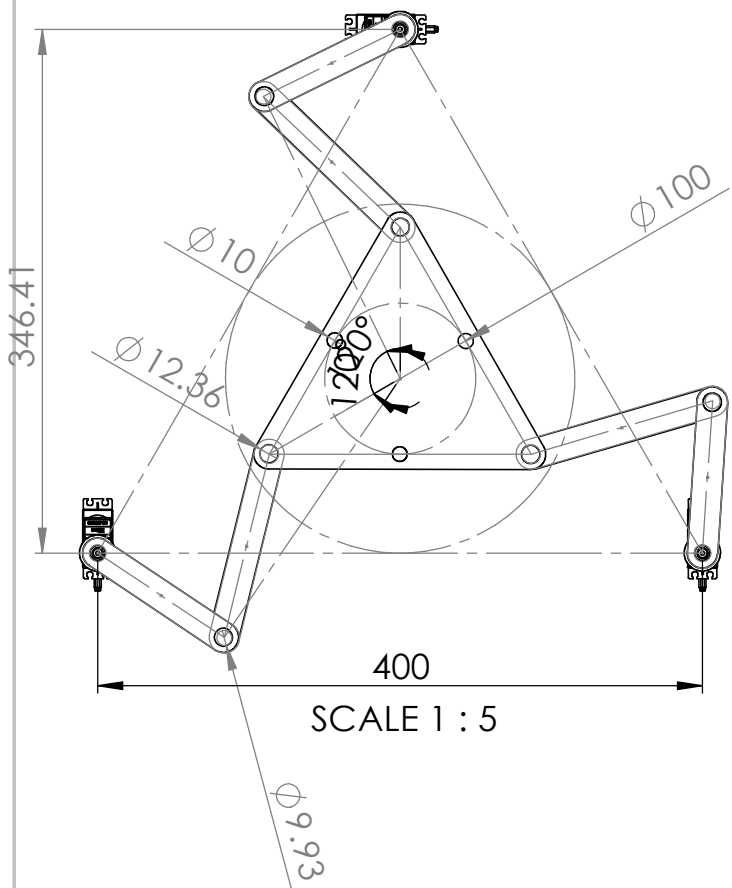
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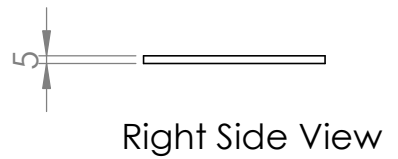
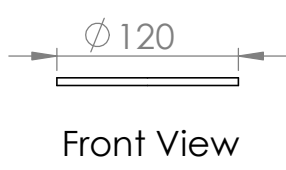
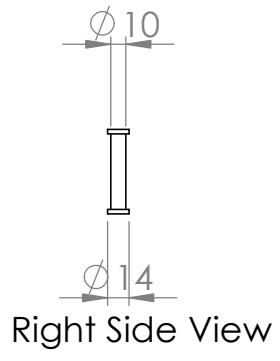
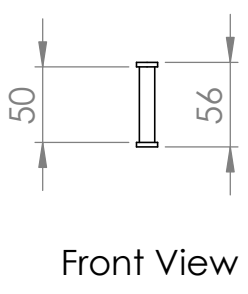
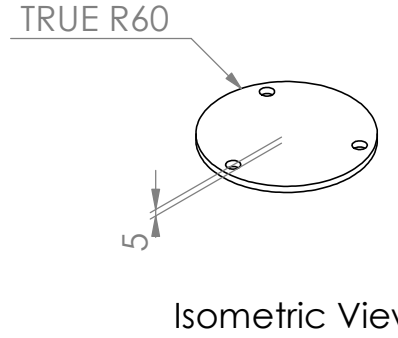
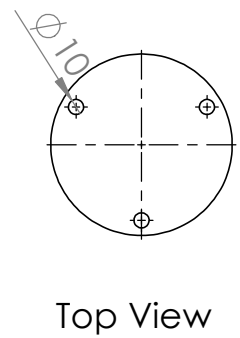
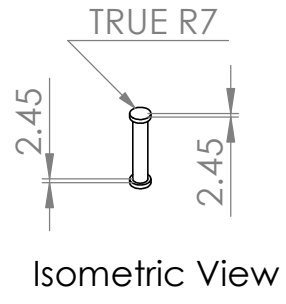
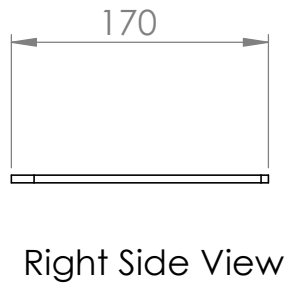
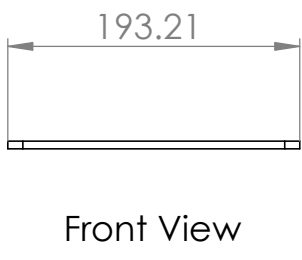
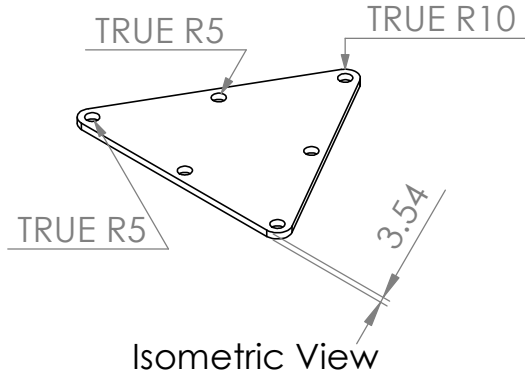
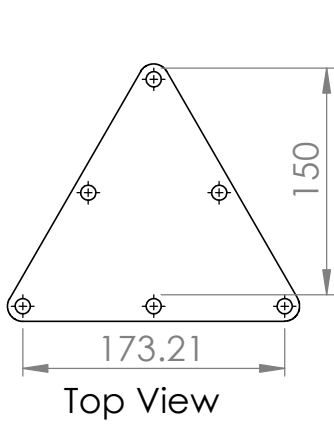
WEIGHT: 1.5 kg

SCALE:1:5

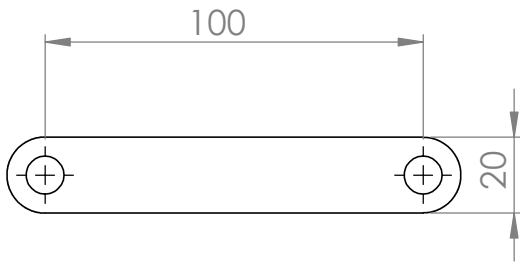
SHEET 1 OF 1



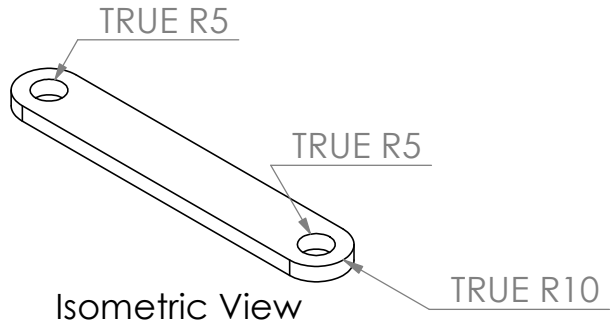
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: N/A TOLERANCES: LINEAR: ANGULAR:			FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
NAME	SIGNATURE	DATE			TITLE: Parallel Base Assembly (links with servo Attached)	
DRAWN Chiranjibi Sahoo						
CHK'D						
APPV'D						
MFG						
Q.A			MATERIAL: ACRYLIC HARD MEDIUM	DWG NO.	Parallel Base	A4
SolidWorks Educational License Instructional Use Only				WEIGHT: 0.3 kg		SCALE: 1:5



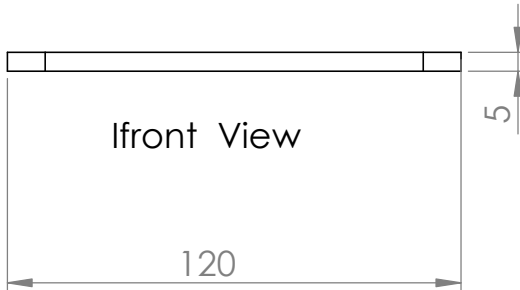
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: N/A TOLERANCES: LINEAR: ANGULAR:			FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
NAME	SIGNATURE	DATE			TITLE: Upper and Lower Platform, Base Attachment	
DRAWN Chiranjibi Sahoo						
CHK'D						
APPV'D						
MFG						
Q.A			MATERIAL: ACRYLIC HARD MEDIUM	DWG NO.	<b>Platform Design</b>	A4
<b>SolidWorks Educational License</b> <b>Instructional Use Only</b>				WEIGHT: 0.15 kg	SCALE: 1:5	SHEET 1 OF 1



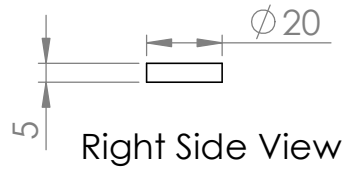
Top View



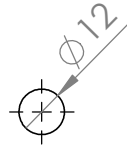
Isometric View



Front View



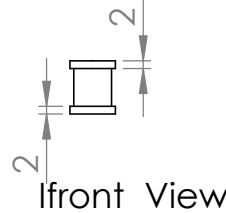
Right Side View



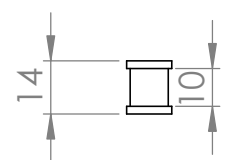
Top View



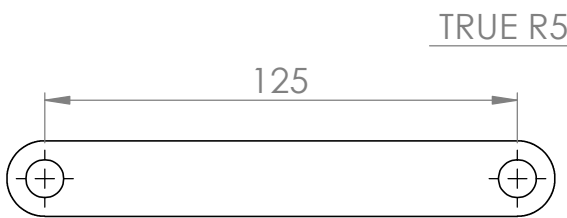
Isometric View



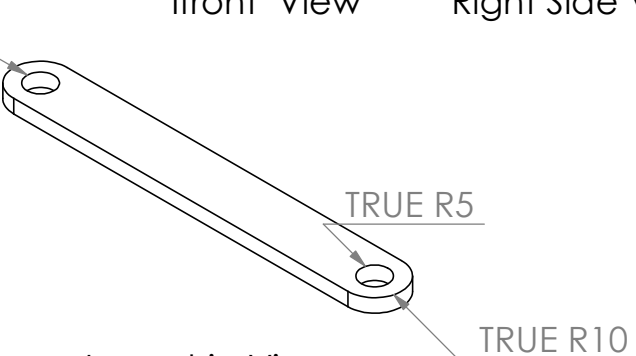
Front View



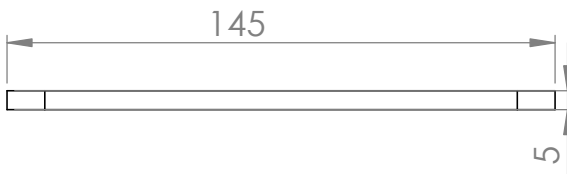
Right Side View



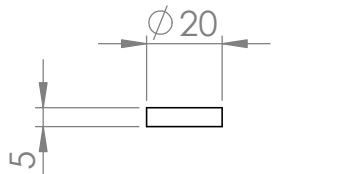
Top View



Isometric View



Front View



Right Side View

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN MILLIMETERS  
SURFACE FINISH: N/A  
TOLERANCES:  
LINEAR:  
ANGULAR:

FINISH:

DEBUR AND  
BREAK SHARP  
EDGES

DO NOT SCALE DRAWING

REVISION

NAME	SIGNATURE	DATE
DRAWN Chiranjibi Sahoo		
CHK'D		
APPV'D		
MFG		
Q.A		

TITLE: Planar link (Short and long)  
and passive revolute joint

MATERIAL: ACRYLIC HARD MEDIUM and MILD  
STEEL

DWG NO.

Planar Links

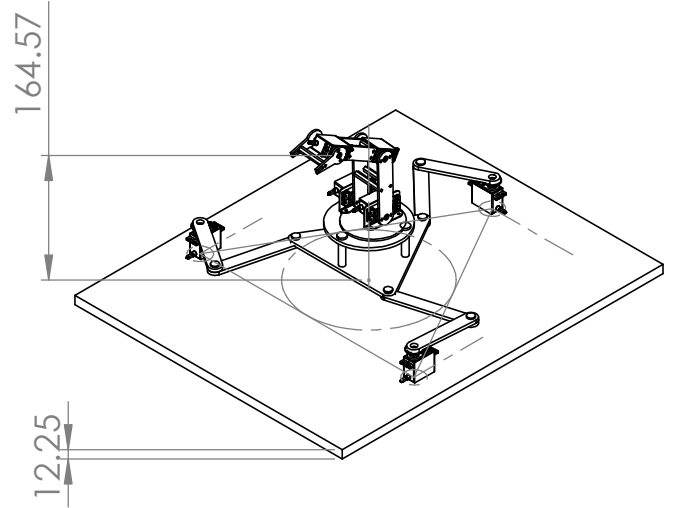
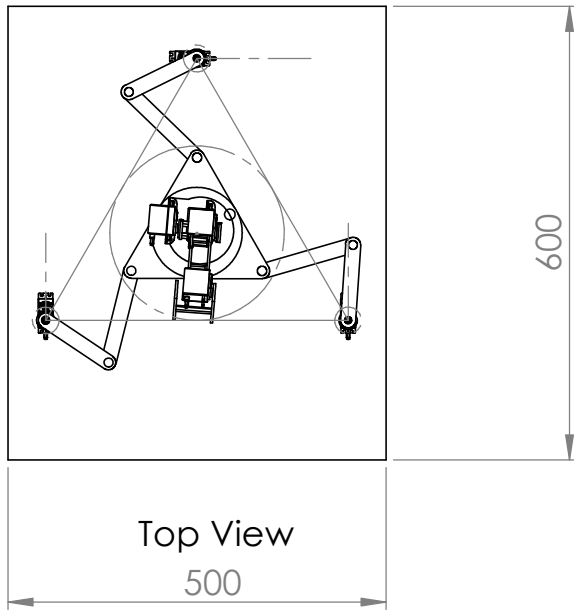
A4

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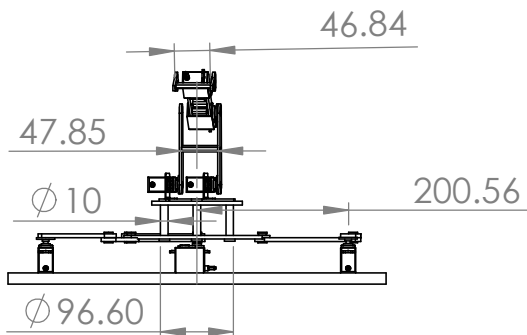
WEIGHT: 0.15 kg

SCALE:1:2

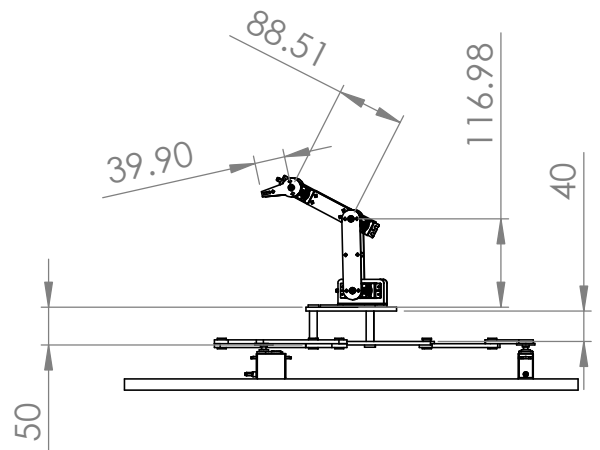
SHEET 1 OF 1



Isometric View



Front view



Right Side View

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN MILLIMETERS  
SURFACE FINISH: N/A  
TOLERANCES:  
LINEAR:  
ANGULAR:

FINISH:

DEBUR AND  
BREAK SHARP  
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	Chiranjibi Sahoo		
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: Full Hybrid Robot Assembly  
(links with servo Attached)

MATERIAL: ACRYLIC HARD MEDIUM

DWG NO.

Hybrid Manipulator

A4

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WEIGHT: 2.1 kg

SCALE: 1:5

SHEET 1 OF 1