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Design of 6 Degrees of Freedom Robotic Manipulator for Covid-19 Vaccine Distribution Centers

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Abstract - *Robotics is an interdisciplinary branch of engineering that comprises the formation, design, building, and action of robots. This field overlays with mechanical, mechatronics, electrical engineering, computer science, electronics, AI, Nanotechnology and bio-engineering. In addition, Robotics deal with the computer systems for their control, sensory response, and information processing. These different fields knowledge is utilize to build machines that can work like human. Robots operate in different environment and can be used for various purpose where human cannot perform any task.*
"A goal-oriented machine that can sense, plan and act"
The goal is to make a 6-DOF robotic arm which is cheap to build and power-to-weight ratio. The end effector designed can be used to perform pick-and-place operation, segregation of objects etc. In recent times, Covid-19 vaccine is being supplied to various places for vaccine drive. This vaccine must be in cool environment all the time. This affordable arm can help in aseptic handling and segregation of the vaccines in extremely cold environment.

Key Words: **Robotic arm, Vaccine, Motor, Controller, End-effector, DOF, Kinematics**

1.INTRODUCTION

A robot arm has a mechanical structure that alters its form using a group of electric motors that behave like servo motors, pneumatic, or hydraulic actuators. They attempt to reproduce movement similar to a human arm. A common term that's used when a robot arm is designed is the DOF (degrees of freedom); it is related to roll, yaw, and pitch. All the complex mechanisms and circuits make these arms expensive. The economic factor is making it difficult to install the arms at vaccine distribution centres for aseptic and fast segregation and distribution. So, we decided to design a robotic arm which is competitively priced, light weight and high power to weight ratio.

2. ROBOT JOINTS & CALCULATIONS

A joint can be viewed as providing freedoms to allow one rigid body to move relative to another. It can also be viewed as providing constraints on the possible motions of the two rigid bodies it connects. For example, a revolute joint can be viewed as allowing one freedom of motion between two rigid bodies.

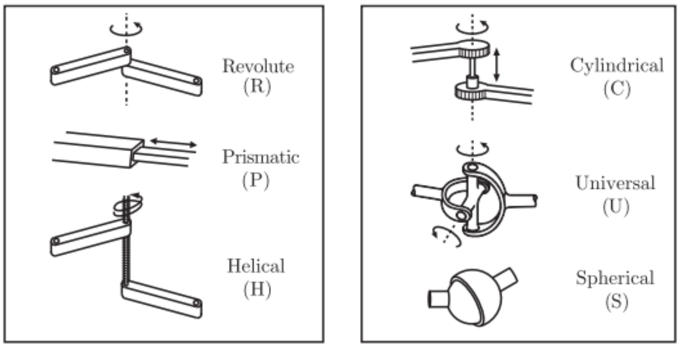

Fig 2.1: Schematic representation of different joints

Joint type	dof f	Constraints c between two planar rigid bodies	Constraints c between two spatial rigid bodies
Revolute (R)	1	2	5
Prismatic (P)	1	2	5
Helical (H)	1	N/A	5
Cylindrical (C)	2	N/A	4
Universal (U)	2	N/A	4
Spherical (S)	3	N/A	3

Fig 2.2: Details of various joints

The factors considered are the maximum load weight, the stall torques of each one of the servos, how much weight each servo must support related to its position in the arm, and the weight each frame that constitutes the arm.

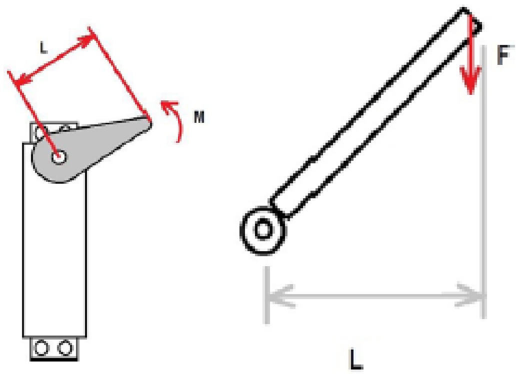

Fig 2.3: the perpendicular length to determine torque
The length is represented by L and it's the measurement of centre of the servo's shaft to the end of the arm. The letter M

represents the quantity of mass (weight) attached to the end of the arm.

The formula that defines torque can be expressed as follows:

$$T = F \times L$$

$$T = m \times g$$

$$T = F \times L = (m \times g) \times L$$

Where T means torque, L is the perpendicular length, m is the mass, and g is the gravitational acceleration. Of course, the force (F) in this case never changes since the mass is constant and subjected to the same gravitational acceleration. the worst-case scenario is when the arm is stretched out horizontally because the perpendicular length is bigger.

3. SERVO MECHANISM

It consists of three parts:

- Controlled device
- Output sensor
- Feedback system

It is a closed loop system where it uses positive feedback system to control motion and final position of the shaft. Here the device is controlled by a feedback signal generated by comparing output signal and reference input signal.

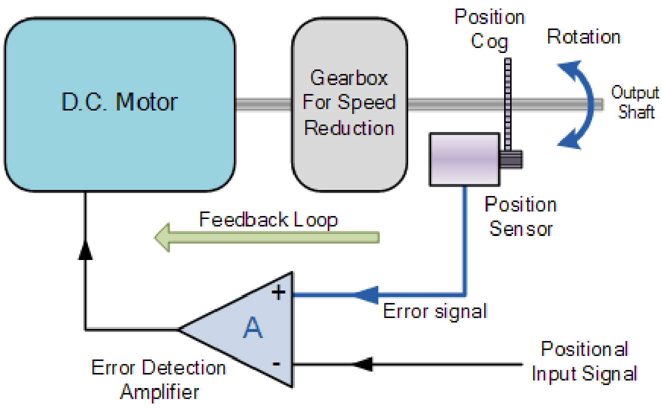

Fig 3.1: Block diagram of Servo mechanism

Here reference input signal is compared to reference output signal and the third signal is produces by feedback system. And this third signal acts as input signal to control device. This signal is present as long as feedback signal is generated or there is difference between reference input signal and reference output signal. So, the main task of servomechanism is to maintain output of a system at desired value at presence of noises. Servo motor is controlled by PWM (Pulse with Modulation) which is provided by the control wires.

4. MATERIAL SELECTION

The decision for selection of the material is based on the goals, which is to design and manufacture the parts which are strong enough to withstand all the loading conditions and also of minimum weight and cost.

To satisfy our loading conditions and durability of the part we have given each property a multiplying factor according to the importance of that property for our design. Stiffness is related to Elastic modulus whereas Yield strength is important for determining the strength to density ratio, fatigue strength decides the durability of the part as it will undergo a number of extreme loading cycles. After considering all these factors, the decision matrix was tabulated

Most commonly used materials are-

- Aluminium 7075 T6
- Stainless steel 1020
- Titanium alloy
- Grey cast iron

Sl.no	Properties	Al 7075 T6	SS 1020	Titanium alloy	Grey cast iron
1	Yield strength (MPa)	480	430	940	120
2	Elastic modulus (GPa)	70	190	110	180
3	Fatigue strength (MPa)	160	69	48	510
4	Strength to weight ratio	160	57	16	213

Table 1: Material Properties

PARAMETERS	WEIGHTAGE (W)	Al 7075 T6	SS 1020	Titanium	Grey cast iron
		(score)	(score)	(score)	(score)
Strength-to-weight ratio	3	4	1	5	1
Fatigue Strength	3	2	1	5	1

Stiffness	4	2	5	3	5
Availability	2	3	4	-2	3
Cost	2	2	3	-3	3
	Sum	42	40	32	38

Table 2: Decision matrix for material selection

5. COMPUTER AIDED DESIGN(CAD) AND FINITE ELEMENT ANALYSIS(FEA)

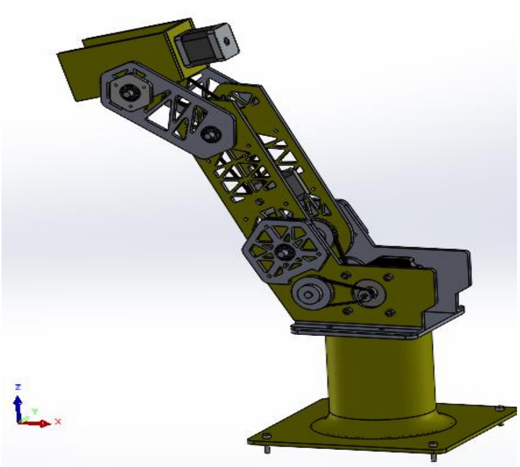

Fig 5.1: Overview of the arm assembly

We proceeded to mechanical design of the components of robotic arm after evaluating all the forces acting on all the links. We started with the base of the arm and proceeded further to the upper components of the arm. The base houses a motor which allows the arm to yaw about its base. The mounting can be seen in the below picture attached. Four flanges are given to mount the motor. The arm sits on the base with 4 bolts holding it in place.

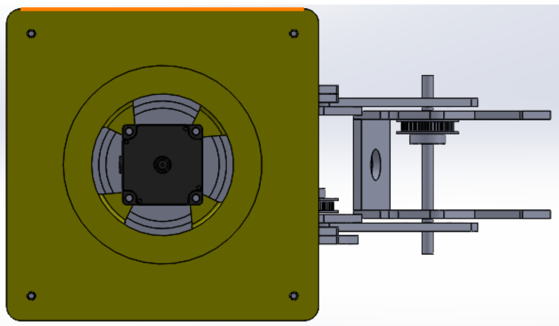

Fig 5.2: Bottom view of the arm assembly

The end-effector(gripper) is designed for pick and place operations (picture below). The end shape of the gripper can be altered according to the specific shape and dimensions of the object to be handled.

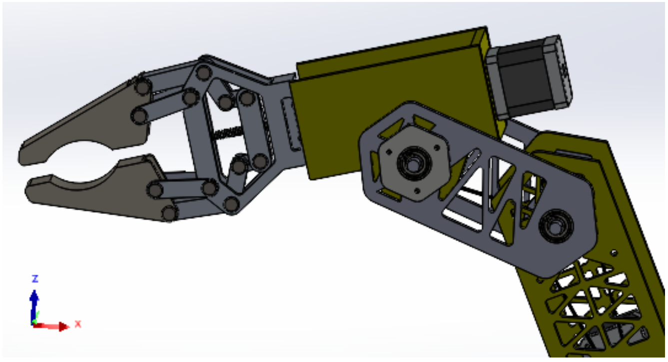

Fig 5.3: End effector(gripper)

After designing all the joints, we proceeded to FEA (Finite Element Analysis) to check for the failure of various links and joints and to optimize them for reduced weight which is one of the key goals of the project. The part is meshed first using the meshing tool. Tetrahedral mesh is used for all the parts considering the low complexity of the parts and stress appeared in the part being the key focus.

5.1 FEA of link 1(between elbow and shoulder)

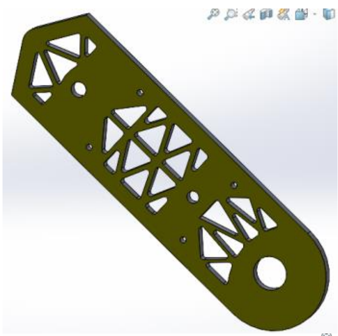

Fig 5.4: Model with weight reduction. Many iterations were performed to achieve this final design. Fillets are given to reduce the formation of stress concentration.

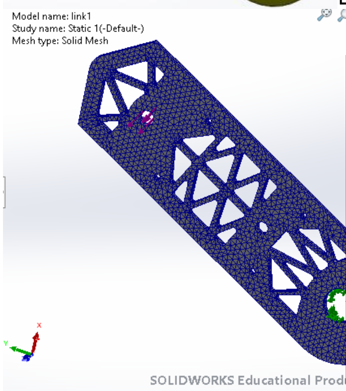

Fig 5.5: Meshing is performed for the stress analysis. Tetrahedral mesh is used to accurately determine the formation of any stress concentration

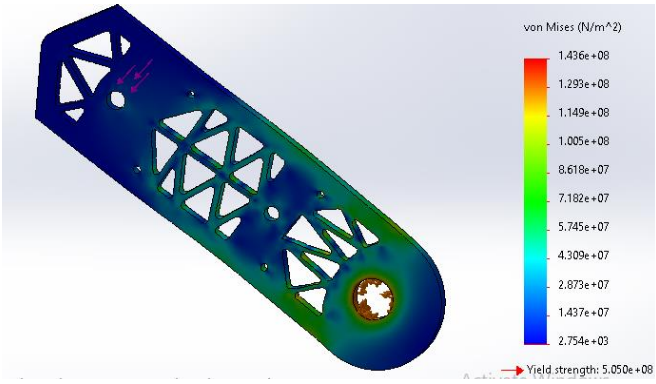

Fig 5.6: Stress analysis of link 1 upon applying a bending load of 2000N; Max stress = 1.4e+08 N/m2

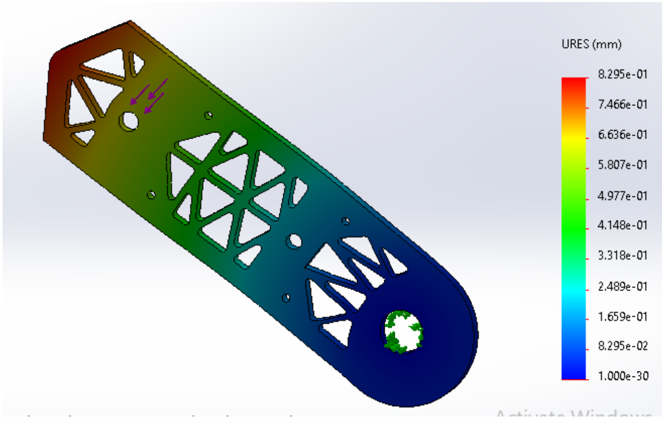

Fig 5.7: Displacement analysis of link 1; Max displacement = 0.02mm

6. MOTOR SELECTION

The power system of the arm has many components among which motor is the main driving force for the movement of the arm. The motor selection procedure starts with determining the requirement of the robotic arm and motor control which includes-

- Application
- Payload
- Operating range
- Speed
- Operation control

Based on the above parameters we have three options on the type of motors which can be used for driving different links.

- DC Motor
- Stepper Motor
- Servo motor

After considering the requirement, continuous motion servo motor provides the desired torques at required speed as well as the position control so that we can define the position of different links in the space while operating the robotic arm such as the end effector(gripper) open or close position. But when looking at hybrid stepper motor we get the closed loop feedback which gives us the orientation of the motor.

After looking at the torque and RPM requirement (https://www.orientalmotor.com/motor-sizing/arm-sizing.html) we were able to find to find out the required motor power and the peak torque required to operate the robotic arm. As NEMA hybrid stepper motor was widely available and operating complexity is also very less compared to continuous servo motor hence NEMA 17 & NEMA 23 hybrid stepper motor was chosen as per the base and arm torque requirement.

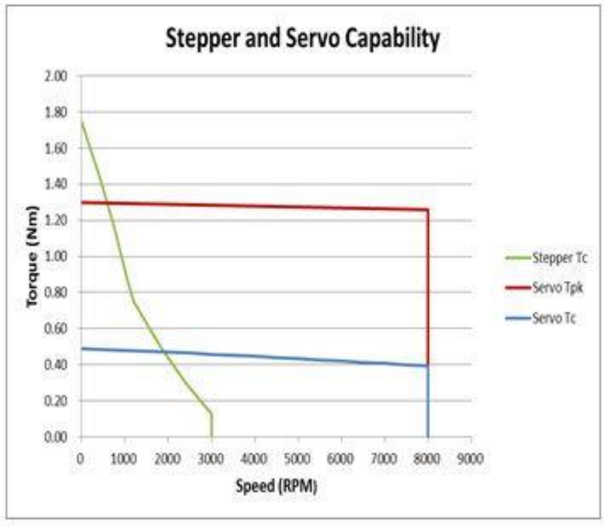

Fig 6.1: Stepper and servo characteristics

7. GEAR RATIOS

- Torque output from NEMA 23 stepper motor = 0.19 kg-m
- Drive ratio 1= 3.57; Drive ratio 2= 2.08
- Final torque output from base drive system is

  18.6*3.57*2.08= 138.11 N-m

- The maximum load the base drive system can hold is, we know that torque= Force/distance (radius) =138.11/0.24= 575.45N

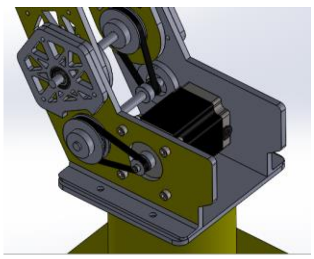

Fig 7.1: CAD model of two stage belt drive reduction

8. BEARING SELECTION

The process of selection of bearings is followed from 'Design of Machine Elements by V.B Bhandari".
First the all the maximum axial and radial forces acting on the joint were evaluated with the help of free body diagrams. From these forces, we decided that deep groove ball bearings would be the optimal bearing for the application. An equivalent dynamic load is calculated from axial and radial loads to help determine the bearing size.

- $P_e=S[XVF_r+YF_a]$

Where, S = Service factor/Shock factor; V = Race rotation factor; X = Radial load factor; Y = Axial load factor; Fr = Radial load; Fa = Axial load

- Also bearing life is calculated
  $L_{90}=(C/P_e)^k$

Where, C = Dynamic load capacity; K = 3 for ball bearing; K = (10/3) for roller bearing; C/P_e = loading ratio.
F_r= 1000 N; F_a=0
Pe= 1000 N;
Based on the calculation data and the dimensions of various bearings 608ZZ bearing is selected.

9. ARM LENGTH AND WORKSPACE

The workspace of a robot, known as work envelope, expresses a robot's ability to reach specific area. The lengths of the arms are set such that the end effector can reach all the points i.e., part of the workspace to perform the operation. Range of Motion (ROM) of joints of the robotic arm is the maximum angle that can be achieved between the links to perform the operation. With the ROM information and link lengths of the robotic arm, workspace of that respective arm can be determined.

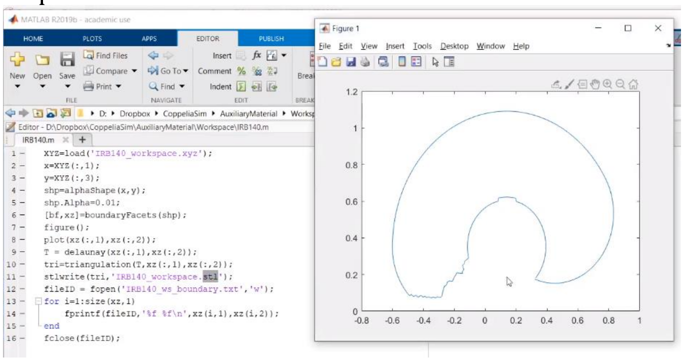

Fig 9.1: MATLAB code with the plot obtained

A maximum radius is obtained inside which the end effector can be moved. There will be some part of the circle where the end effector cannot be reached because of the joint angles and their restrictions. A rough "V" can be observed in the above plot with the region where the end effector cannot be reached.
A MATLAB code is used to determine the workspace, using Range of motion information and initially assumed link lengths. Later it is verified with CoppeliaSim software if the required motion is achievable and the reach of the robot is as required.

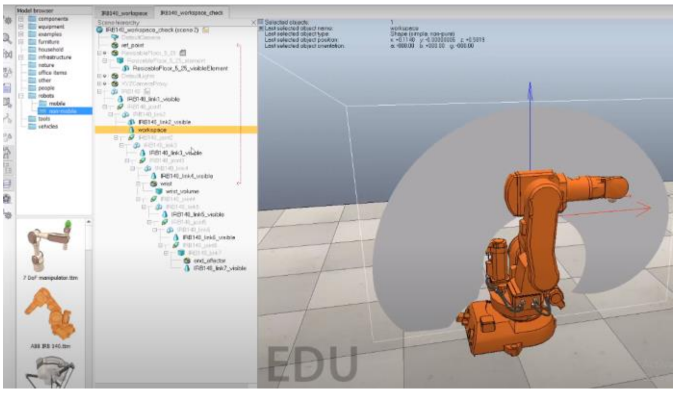

Fig 9.2: Simulation in CoppeliaSim Edu

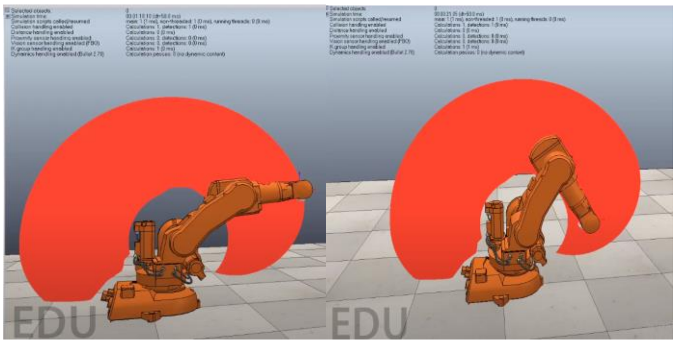

Fig 9.3: A sweep is created by the model to determine the workspace

10. ELECTRONICS

10.1 Controller

With so many controllers available in the market, it was more of a case of compatibility, cost effectiveness and familiarity with the microcontrollers. While keeping these things in mind we decided to use Tiva-C tm4c123gxl Launch Pads which features an ARM cortex-M4F 32-bit CPU operating at 80 to120 MHz, made by Texas Instruments. For programming, we decided to use Code Composer Studio. For GUI interface, Visual Studio due to its compatibility with C++ will be used to communicate data through serial communication.

Fig 10.1: Controller

10.2 Motor Driver

For the control of motors, it was decided to use L298 bridge driver. It is a high-power motor driver which has five different resolutions: full-step, haft-step, quarter-step, eight-step and sixteenth step. Also, it has a potentiometer for adjusting the current output, over-temperature thermal shutdown and crossover-current protection.

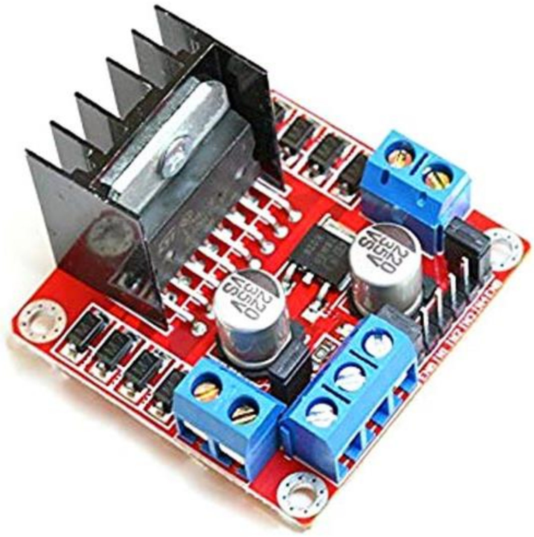

Fig 10.2: Motor Driver

10.3 CIRCUIT DIAGRAMS

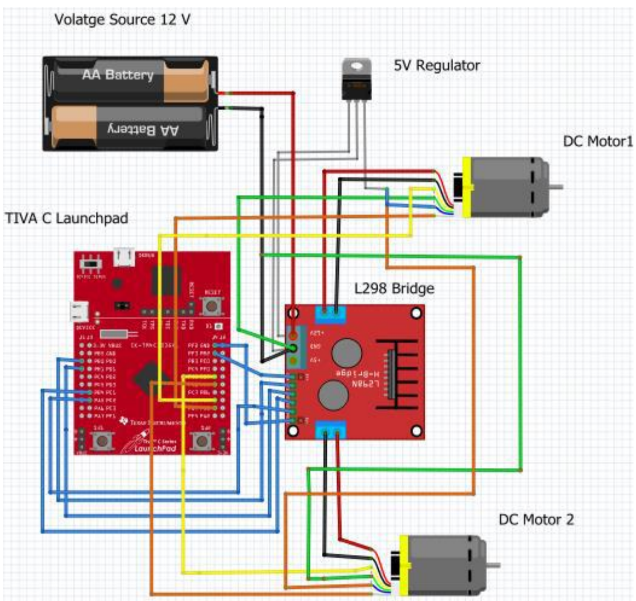

Fig 10.3: connection between the motors and controller through a motor driver.

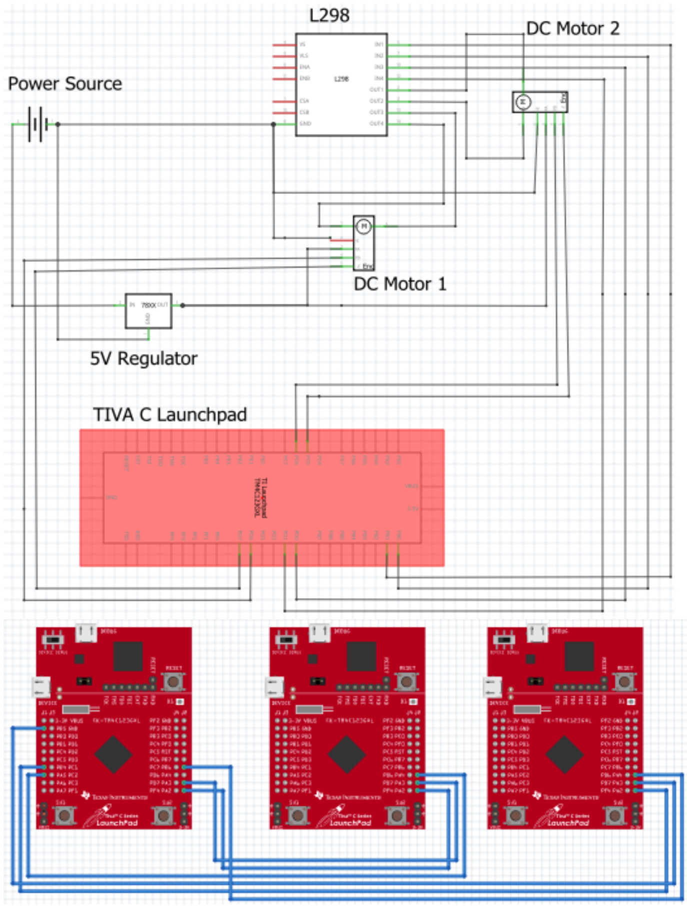

Fig 10.4: Circuit diagram representing interconnection between different controller boards

11. SIMULATIONS

In order to interface between different hardware modules like motors, sensors, and controllers we will be implementing PID controller through MATLAB PID tuner.

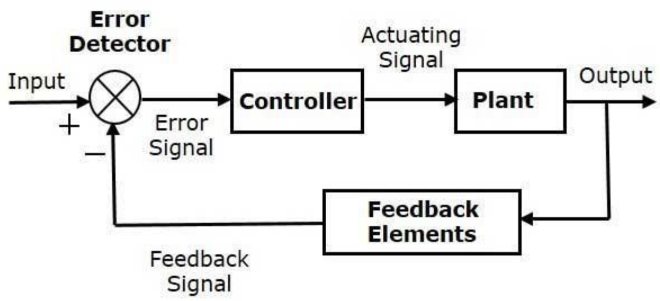

Fig 11.1: Block diagram

As represented in the above block diagram, it is a closed loop feedback system comprising of proportional, integral and derivative responses of the sensors output for computing the desired output.

11.1 Motor transfer function

In the PID tuner toolbox of MATLAB, a system identification tool using estimated data and validation data creates a motor transfer function.

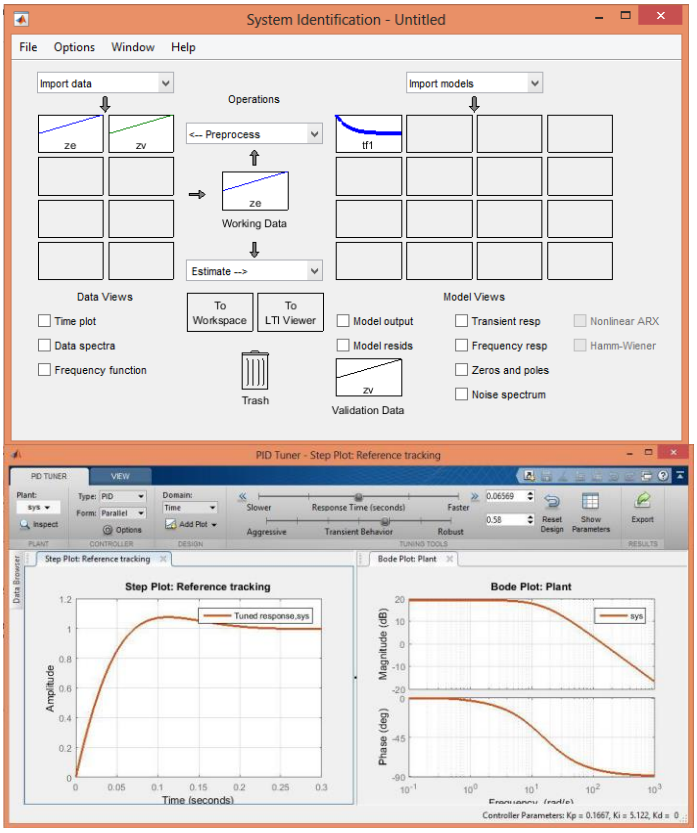

Fig 11.2: The PID tuner shows step responses as well as the bode plot of the controlled system.

12. ALGORITHMS

System Identification Toolbox:

```
Clc
Clear all
Close all
vol=[1:1:100]'; % Applied Voltage
rpm=[3.555 12.54 21.525 ...... 100 ]
ts=0.1; % Sampling Time
z = iddata(rpm,vol,ts) % Create identification variable
ze=z(1:50); % first half is use for estimation
zv=z(51:100);% Second half is use for validation
ident % command for Toolbox

%%%%% Base Motor %%%%%
num=[100 45.65];
den=[12 22 65];
sys=tf(num,den);
rlocus(sys)
%%%%% Shoulder Motor %%%%%
num=[75 58.025];
den=[1 14.29 78.065];
sys2=tf(num,den);
rlocus(sys2)
%%%%% Elbow Motor %%%%%
num=[13 12];
den=[10 12 8];
sys3=tf(num,den);
rlocus(sys3)
%%%%%% Wrist 2nd Motor %%%%%
num=[53 16.52];
den=[4.64 25.256 35];
sys4=tf(num,den);
rlocus(sys4)
%%%%%% Wrist 3rd Motor %%%%%
num=[100 45.65];
den=[12 22 65];
sys5=tf(num,den);
rlocus(sys5)

Clc
Clear all
Close all
u=pi/2; w=pi/1.09; e=pi/6+pi; r=-pi/1.6363+pi/7.2;
a=10; b=6; c=6; d=6;
%syms a b c d u w e r t1 t2 t3 t4 t5 t6
L(1)=Link([0 a 0 u 0]);
L(2) = Link('revolute', 'd', 0, 'a', b, 'alpha', 0,'offset',w);
L(3) = Link('revolute', 'd', 0, 'a', 0, 'alpha', -u,'offset',- e);
L(4) = Link('revolute', 'd', c, 'a', 0, 'alpha', u,'offset',0);
L(5) = Link('revolute', 'd', 0, 'a', 0, 'alpha', -u,'offset',r);
L(6)=Link([0 d 0 0 0]);
Rob=SerialLink(L,'name','Articulated');
T=Rob.fkine([0 0 0 0 0 0])
Rob.plot([0 0 0 0 0 0])
```

13. CONCLUSIONS

This paper presents the design, development and simulations of 6 DOF robotic arm for the purpose of vaccine distribution. The goals of the project were achieved, that are light weight and economical robotic arm. Effort was put into optimizing every part to reduce the overall weight of the assembly. Cost factor was also considered during selection of motors and controllers. Thus, this robotic arm can help pick and place the vaccines with good accuracy and low time consumption.

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