RPVC CONTROL AND TRAJECTORY OPTIMIZATION FOR A PUMA ROBOT

Masters Project

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Abstract

In this report, I designed and implemented a Robust passivity controller for a puma robot which also accommodates energy regeneration by the use of an ultracapacitor for the purpose of energy storage.the controller is used to implement a trajectory which has been optimized by the a non-linear optimizer in matlab and the results are implemented on the robot which are then compared to the obtained theoretically predicted results.

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Chapter 1

Introduction

The rate at which the robots are replacing humans in various applications is sky rocketing as the total maintenance and electricity cost on robot in long term is way more cheaper than compared to employing humans for a similar task over a time period.For example in an assembly line, the amount of energy they consume may be huge but since they don't get bored as humans do for monotonous task like fixing a screw or removing one for the whole day they are pretty much more accepted than human workers.In the same assembly line the energy they consume on a regular basis is similar and there won't be any huge changes as the trajectory they follow while doing the task is the same with a lot of repetitions.It means the trajectories are cyclic,they start and end at the same position due to which the robotic manipulator has to gain and lose the same amount of energy in an ideal world,but due to various problems like a obstruction in the trajectory or due to friction most of this energy is dissipated as heat.

Generally the robots are back drive able as the motors when there is torque acting on them they regenerate which works by converting this excess energy at the end of trajectory back into electrical energy.Now,since the manipulators are generally powered by a grid it is quite illogical to think about storing this energy.

This can be changed if the robots are powered by a energy storing devices such an ultra capacitor why it is a best idea to use a ultra-capacitor over an battery is descried in the the section 1.0.1

1.0.1 Motivations for the using an ultra-capacitor over a battery

Even though batteries are much lighter than ultra-capacitors it is a better idea to use a ultra-capacitor for the same energy because of the following reasons:

- When a robotic manipulators is recharging the currents can reach very high values depending upon the negative torque being applied to the manipulator which is generally high in case of a very fast manipulator.
- A very rapid charge cycles can rapidly reduce the life time of battery it is a good idea to use ultra capacitor.
- In case of assembly line manipulator there is no motion hence the weight of the ultra-capacitor will not play any role in energy being consumed by the robotic manipulator.

1.1 Motive of the project

Generally a robot in an assembly line goes on and on in the same trajectory it may be a pick and place robot or welding robot as the robot has to transverse through the trajectory there are changes in its energy changes accordingly at some point it may have to lose some energy and at some points it may have to increase its total energy to follow the trajectory more precisely or it may give up due to saturation of the voltage.To make sure that the robot tracks the trajectory it has to follow it is better to consider a robust controller.

1.2 Methodology of the project

The project consists of two parts part one emphasis on the energy regeneration part as whole and the amount of energy that can be saved when there is energy regeneration and the other part considers a robot in a Assembly line is whose trajectory can be adjusted to reduced the energy being consumed.

1.2.1 Sine-wave comparison

To show the idea of regeneration and get an idea of how much energy is being stored on the ultra-capacitor or the amount of energy being used to the following tests are considered:

- Puma robot tracking a simple sine-wave where the current sensors are used to monitor the current that is going into the motors and a current sensor which tracks the current that is coming out from the ultra-capacitor.
- Placing a Diode on the ultra-capacitor so that there is no regenerated current going into the ultra-capacitor.
- Analyzing the current flow and the energy flow form the PUMA robot.

1.2.2 Trajectory optimization

Now as we know a robot in an assembly line will not follow a simple sine-wave but rather it has follow a path in case of a pick and place robot it has to pick up a object form a point let say A and place it at some point B and then go back to point A and do the same task again.Now if we optimize the trajectory so that there is energy regeneration.We may reduce the amount of energy that is being required for the complete trajectory and end up saving by huge margins.

1.3 Manipulator

The Manipulator being used for the analysis is a PUMA robot which has 6-DOF as follows:

1. Waist : Revolt around z^0.
2. Shoulder: A revolute joint around z^1.
3. Elbow: A revoulte joint around z^3.
4. Wrist: consists of 3 revolute joints around x,y and z of the wrist.

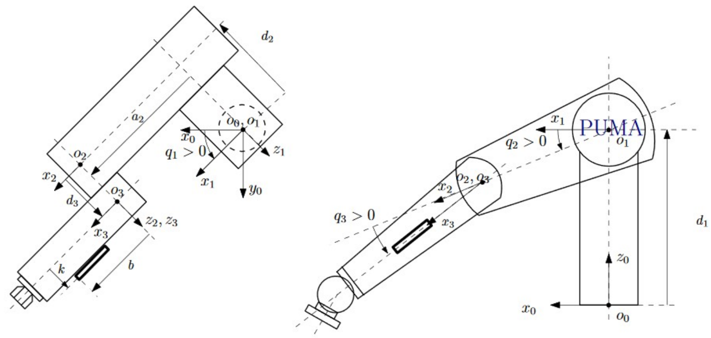

Figure 1-1: Puma Robot

Link	θ_z	d_z	d_x	θ_x
1	q_1^*	d_1	0	$-\pi/2$
1’	0	$-d_2$	0	0
2	q_2^*	0	d_3	0
3	q_3^*	0	0	0

Table 1.1: D-H convention of the given robot

The Robot can be seen in the Figure 1-1.The wrist which consists of 3-DoF can be neglected as it has next to no impact on energy regeneration as the joint lacks the energy being put into in due to its low mass.So Only the first three joints can be considered for regeneration .

1.3.1 DH-Convection

The dh-convention of this puma robot is as shown in the table 1.1:

Chapter 2

Controller

As we know uncertainties in the model will play a role on the tracking capabilities of the robot hence it is best to know the model perfectly or go for a robust controller which will negate the uncertainties in the model.Since the second approach saves time it is better to consider a Robust passivity controller for the robot.

2.1 Puma Model

The Puma robot model can be described as follows:

$$M\ddot{x} + C\dot{x} + G = \tau$$

where, M is the Mass matrix
C is the Coriolis matrix
G is the gravity matrix. These equations can be rearranged into regressor form that is $Y\hat{\theta} = \tau$ where θ Consists of all the terms in the robot that is mass of the links,length of the link etc.The parameters and the regressor can be seen below and the code for the generation of regressor is in the github repository.The theta values for any PUMA

robot are as follows:

$$\Theta = \begin{bmatrix} (m_2+m_3)d_2^2 - 2m_3d_2d_3 + m_3d_3^2 + I_{2x} + I_{3x} + I_{1y} \\ (m_2+m_3)a_2^2 + 2m_2a_2c_{2x} + m_2c_{2x}^2 - I_{2x} + I_{2y} \\ m_3c_{3x}^2 - I_{3x} + I_{3y} \\ a_2c_{3x}m_3 \\ -c_{3x}m_3(d_2-d_3) \\ (m_2+m_3)a_2^2 + 2m_2a_2c_{2x} + m_2c_{2x}^2 + m_3c_{3x}^2 + I_{2z} + I_{3z} \\ m_3c_{3x}^2 + I_{3z} \\ -d_2m_2(a_2+c_{2x}) - a_2m_3(d_2-d_3) \\ c_{3x}gm_3 \\ gm_2(a_2+c_{2x}) + a_2gm_3 \end{bmatrix}$$

The nominal values for this PUMA are as follows:

$$\Theta_{nom} = \begin{bmatrix} 2.9625 \\ 1.5893 \\ 0.0421 \\ 0.3369 \\ -0.1171 \\ 7.6163 \\ 1.1870 \\ -0.7620 \\ 7.6547 \\ 39.6898 \end{bmatrix}$$

To make sure that the puma parameters are uncertain in simulation the controller is feed the theta values in a range of 0.5 of the original values.But this process is done only in simulation but not in real time.

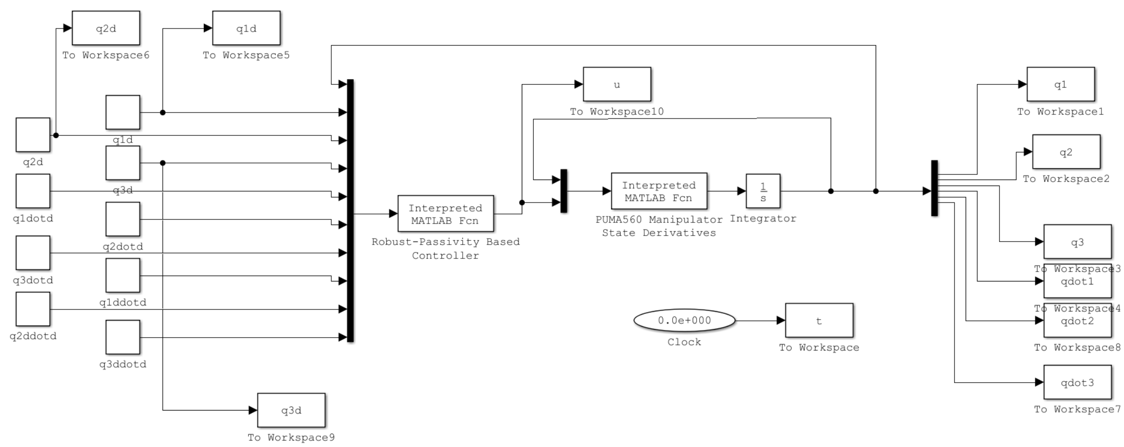

Figure 2-1: Simulink model

2.2 Simulation

The controller simulation is run in simulink,which is set up as shown in the Figure 2-1 and the code can be found in the github repository. The controller creation can be further be divided into to more categories as follows:

- Controller
- Plant

Controller

The robust passivity controller was selected to ensure the robot tries to track even though there are some uncertainties, if at a certain state the voltage of the capacitor drops below a certain point such that it is not enough to follow the trajectory until certain point in such a case a robust controller will start to track once the control voltage can be given.Consider the Plant dynamics

$$M\ddot{X} + C\dot{X} + G = \tau$$

which is then Converted into the form of $Y\Theta = \tau$,Where Θ Contains all the model parameters like Mass of the links, position of center of masses.etc where all the uncertainties in the model lie.Now the controller is given as

$$Y\Theta - Kr = u$$

where u is the control,K are controller gains. **??**. The controller code can be see in section **??**.

Plant

The Plant is given by

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau$$

.Where τ can replaced by $aV - B_e$.In which B_e is a column vector with the back emf values. Now that the Plant and Controller layout for voltage mode is obtained we can go further by introducing a error of 50 percent is selected in the parameters of the plant.

2.2.1 The input trajectories for the links are as follows

The Figures 2-2,2-3 and 2-4 show tracking capabilities of the RPC controller the trajectories followed by each joint are as follows.

$$Waist = sin(2t)$$

$$Shoulder = 0.25sin(2t)$$

$$Elbow = 0.5sin(2t) - \frac{\pi}{2}$$

2.3 Simulation Results

It can be seen form the Figures that the controller works decently to track the given trajectories even though its parameters are misplaced by 50 percent of its original value. It can also be understood that the control inputs are with in bounds expect

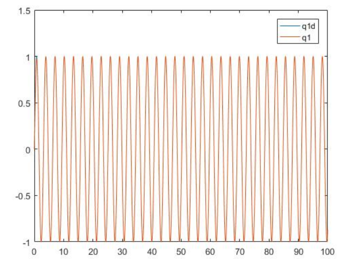

Figure 2-2: Tracking:Waist

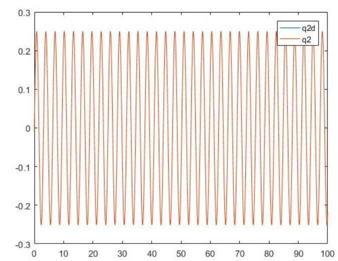

Figure 2-3: Tracking:Shoulder

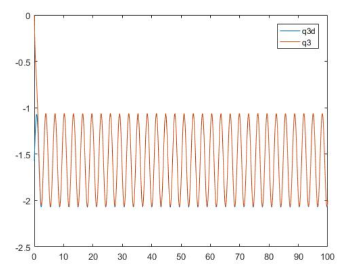

Figure 2-4: Tracking:Elbow

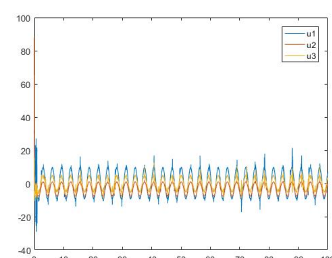

Figure 2-5: Control efforts

the initial phase where the controller tries to start tracking.

Chapter 3

Setup

In this chapter there will be explanation of the way the experiment has been setup and the about the various components used.The components used are as follows :

- PUMA robot.
- Motor Driver(syren-25).
- D-space.
- Simulink.
- Voltage Divider.
- Current Sensors.

3.1 components used

The Description of the various components used.

3.1.1 PUMA robot

As Described earlier the PUMA robot is R-R-R-R-R configuration robot for the case of simplicity only the first three degrees are considered.The Puma robot can be seen in the Figure 1-1

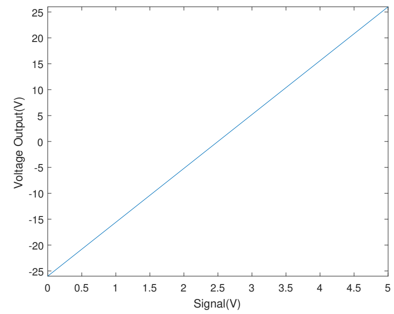

Figure 3-1: signal input Vs Output voltage

3.1.2 Motor driver

The motor drivers used for this experiment are syren-25 which are regenerative and can be seen in the Figure 3-1.The absolute maximum that can be given as input into the syren-25 is 30V to make sure that the bounds are always meet we take the input voltage at 26V-27V for most of the experiment.The signal input and the voltage output can be seen in the Figure 3-1.

3.1.3 D-space

The robot communicates with simulink through the Dspace Board which is R1103 on which the simulink compiled file is loaded, It comes with a control desk software which helps to further control the robot.

Control Desk

The software used is Control 10.3.It is basically a software interface for the Dspace board.

Dspace Board

This is the Hardware board used for communication between the PC and the robot .

3.1.4 Simulink

The simulink model for the experiment is as shown in the Figure **??**

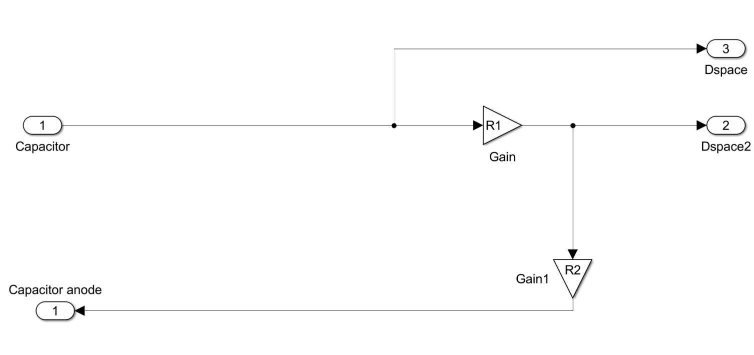

Figure 3-2: Voltage Divider Circuit diagram

3.1.5 Sensors

The following sensor where used:

Voltage Divider

The Dspace can only take an input analog voltage of -10V-10V but the problem is that the operating voltage of 27V for the Ultra-Capacitor .To Over come this a voltage divider is used whose circuit diagram can be seen in the Figure 3-2.

Current Sensors

The current is further measured to make sure how much energy is being utilized and how much energy is being regenerated.Total of 6 current sensor where used one for each side of the servo driver to get a complete picture of how the energy is being transferred.The current sensor is shown in the figure 3-3

3.1.6 Complete Schematic

The complete schematic is as shown in the Figure 3-3.

3.2 Procedure to run the Experiment

The procedure to run the experiment is as follows:

1. Start up the PC and navigate,Open up matlab and navigate to "C:\DspaceProjects\RPBC"

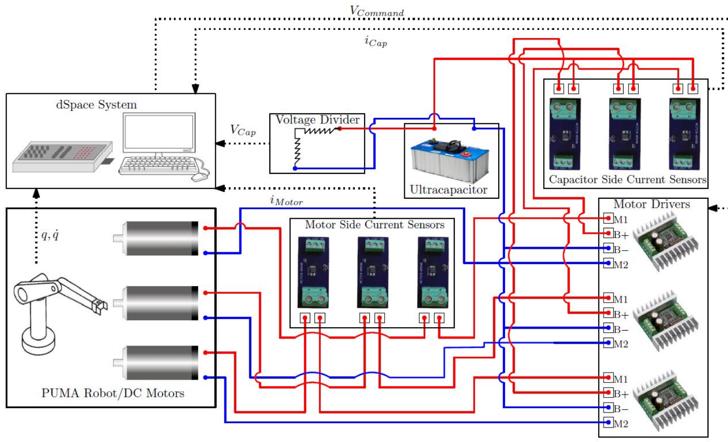

Figure 3-3: Complete Schematic

2. Run parameters.m
3. Open up model.slx.
4. compile the model in simulink.
5. Open Control Desk
6. select the experiment.
7. In the Layout on the bottom right conner you will see radio buttons for the 3 links namely shoulder, elbow and waist.
8. select the links you want to run.
9. on the right side you will see a radio button where you can select whether to run a sine-wave experiment or a trajectory based control
10. Select run
11. Wait for the experiment to finish.

Chapter 4

Sine-wave experiment

To run the trajectory optimization in the next part it is necessary to know how much of energy is being consumed by the servos and how much of it is being used by the robot.The data form this experiment has been used to generate a better model for the puma robot to so that optimization algorithm could be feed with a better model to make sure it predicts the optimal trajectory in a better way.

4.1 Trajectories

The Figure 4-1, 4-2 and 4-3 show the waist,shoulder and elbow trajectory which it was given to follow and the tracking capabilities of the controller.As it can be seen the robust passivity controller works pretty perfectly except for the the Shoulder which is mainly due to the fact that the voltage of the ultra capacitor reached 23Volts due to which it is not able to supply enough power to the joint to makes it saturate.

4.2 Power

The Figure to 4-4, 4-5 and 4-6 show the waist,shoulder and elbow's power being consumed and amount of power being send into the capacitor.

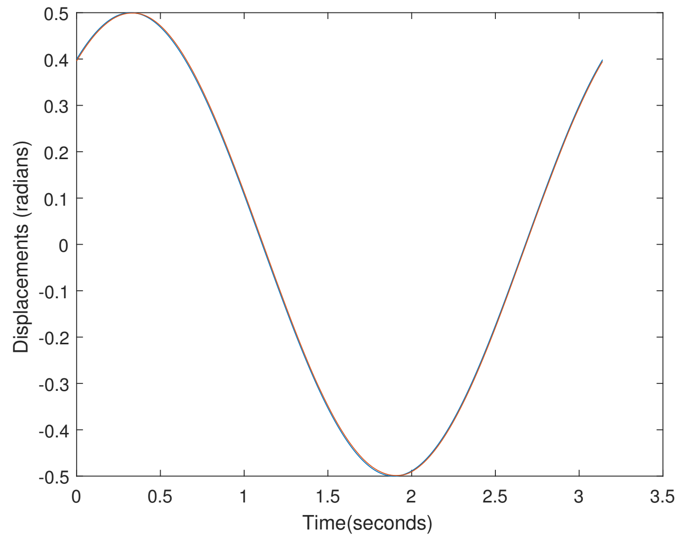

Figure 4-1: Waist Trajectory

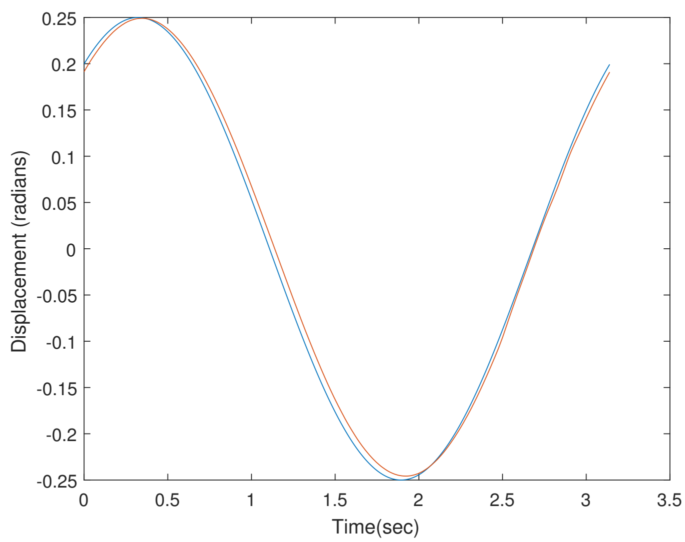

Figure 4-2: Shoulder Trajectory

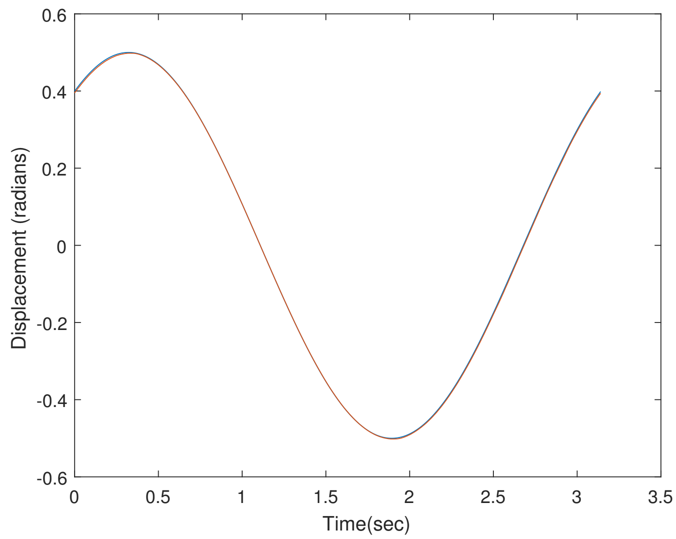

Figure 4-3: Elbow Trajectory

4.2.1 Waist

It can be seen in the Figure 4-4 that power being transferred into the waist and power being sent from the capacitor are almost the same but this is not up to the mark when compared when power being sent from the waist this is because of the servo driver being not as efficient in the fourth quadrant.

4.2.2 Shoulder

As discussed earlier it can be clearly seen loss in the fourth quadrant this is because of the servo drivers but there is regeneration compared to the other joint because of the fact that this joint has more mass and is acting in the vertical direction due to which there a gain and loss of the potential energy through the trajectory which is being followed.

4.2.3 Elbow

As explained before the energy being transferred in when the power is in the fourth quadrant is quite low but there some which is due to the fact that as Shoulder the elbow acts in the fourth quadrant and there is a lot of change in the potential energy

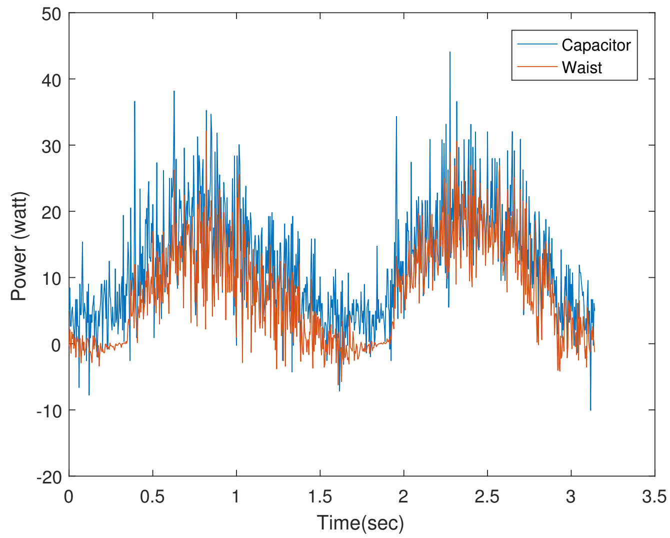

Figure 4-4: Waist Trajectory

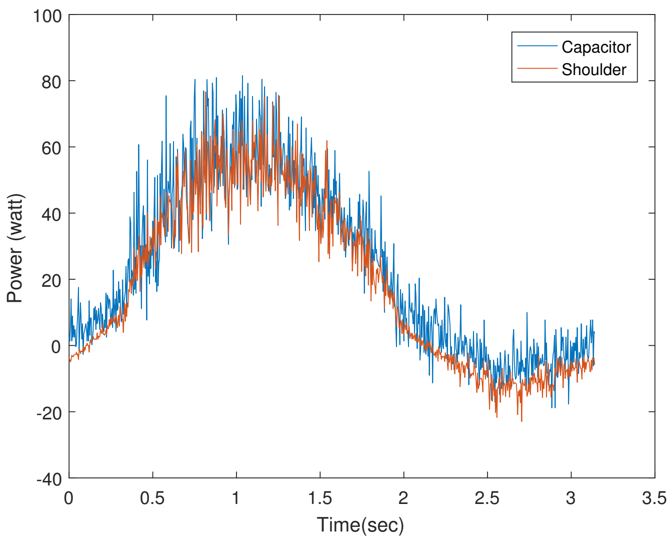

Figure 4-5: Shoulder Trajectory

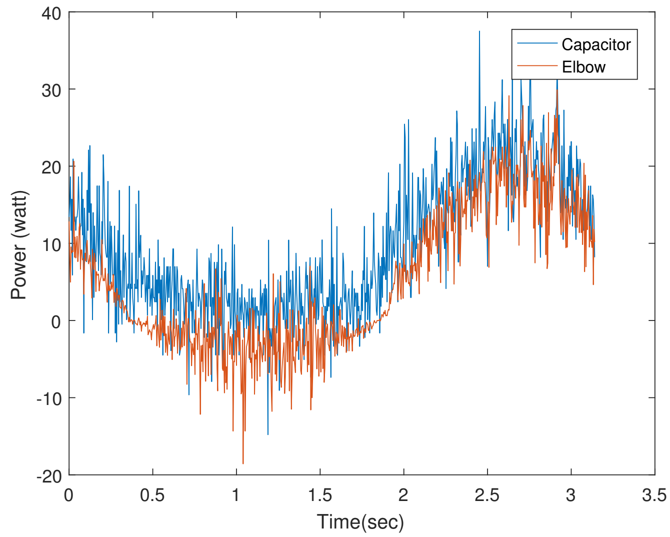

Figure 4-6: Elbow Trajectory

which can be seen.

4.3 Conclusion

It can finally be concluded the efficiency of the servo driver is not up to the mark in case of regeneration which actually depends upon various factors like control voltage to ultra-capacitor ratio frequency of the control voltage.Since all the variables are attained now the puma model can be modified and can be feed into a optimizer to find the optimal trajectory.

Chapter 5

Trajectory Optimization

This part of the report deals with the problem formulation, optimization and predicted results by simulation.The Puma robot is given a cyclic trajectory to follow which is optimized part by part that is for example lets say the robot has start at point A and end at A and has to reach point B at a particular time.The problem is formulated such that the part 1 that is getting from point A to B is treated as problem 1 and making the robot reach point A from B is treated as problem 2.
The better model obtained from the previous section is feed into the optimizer to predict a better trajectory.

5.1 Problem Formulation

The aim is to maximize the vector of optimal trajectories$(q(t), \dot{q}(t), \ddot{q}(t))$ and a vector of optimal controls (τ_d) that maximize Eq. 5.1

$$max(J) = \int_{t_1}^{t_2} \Sigma_{j=1}^{e} (\tau_j^d \dot{q}_j - \frac{R_j \tau_j^{d^2}}{\alpha_j^2}) \tag{5.1}$$

While under the influence of constraints like upper bounds on control voltage and starting and ending points of the trajectory. The problem is solved by the use of direct collocation which will be described in the next section.

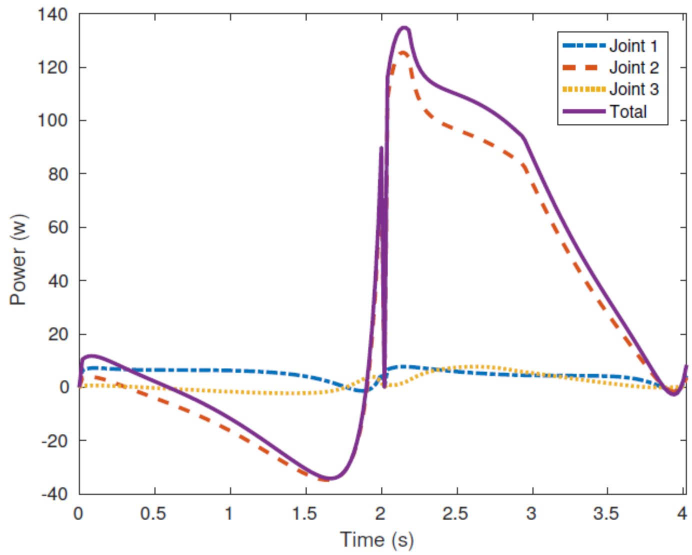

Figure 5-1: The predicted power flows of the three joints

5.2 Optimization

The problem as described in the earlier section is solved by using IPOPT(interior point optimizer) numerical solver.It generally tries to finds the global optimum if the function is concave or convex but in real world scenarios this is not the case hence the solver is run several times from randomly generated initial positions to make sure that it ends up finding global optimum.

5.3 Predicted Results

The predicted results by the simulation are as show in the Figure 5-1.As discussed in the earlier sections it can be clearly be seen that the shoulder and elbow are regenerating the most comparatively to the other three waist which can be attributed to the fact that the elbow and shoulder work on the plane where gravity comes in the picture.

Chapter 6

Results and Discussion

With the same setup as for the sine-wave experiment the optimized trajectories trajectories are set to run on the PUMA robot the results are discussed in this Chapter.

6.1 Experimental results

In the Figure 6-1 it can be seen that the robust passivity controller tracks the given trajectories almost perfectly for the waist and the elbow but it can be seen that the there is a problem in the shoulder when it is coming from point B to A this can be attributed to the fact that there is some saturation in the control due to the fact that the capacitor voltage is not 27Volts any more as seen in the Figure **??**, but this error in tracking is very small 0.12 radians to be precise so it can be considered to work along. In the Figure 6-2 the control in N-m can be seen where the saturation in the control torque in the shoulder is clearly visible as discussed earlier. The power results of all the joints can be seen in the Figure 6-2.It an clearly be seen that the shoulder regenerates more compared to the rest and the power consumption by the same is very high compared to the rest this is due to the fact that the given trajectory works in the plane perpendicular to gravity vector. It can also be seen that the motor side power are actually very near to the predicted values by optimization.

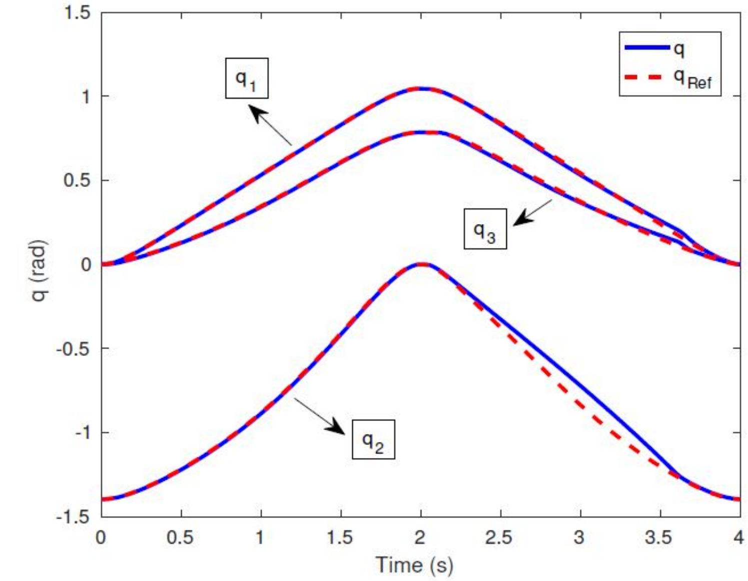

Figure 6-1: Trajectories Followed by the Robot and the Optimal trajectories

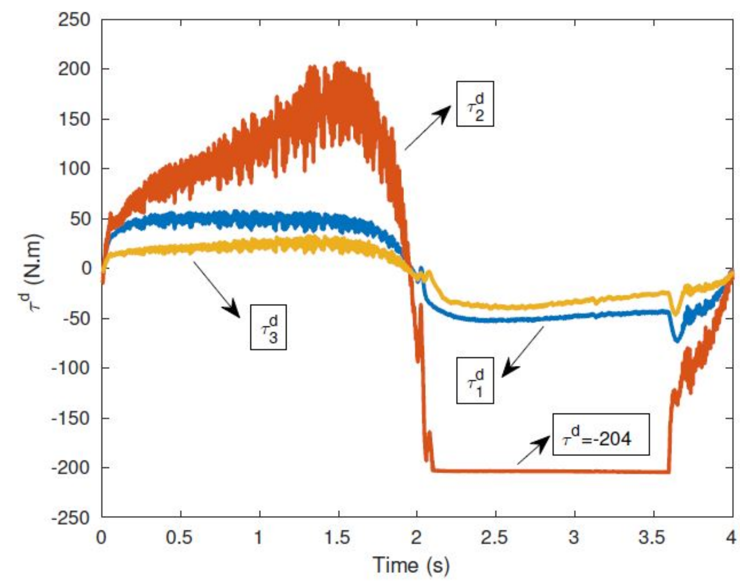

Figure 6-2: Control torques for the joints

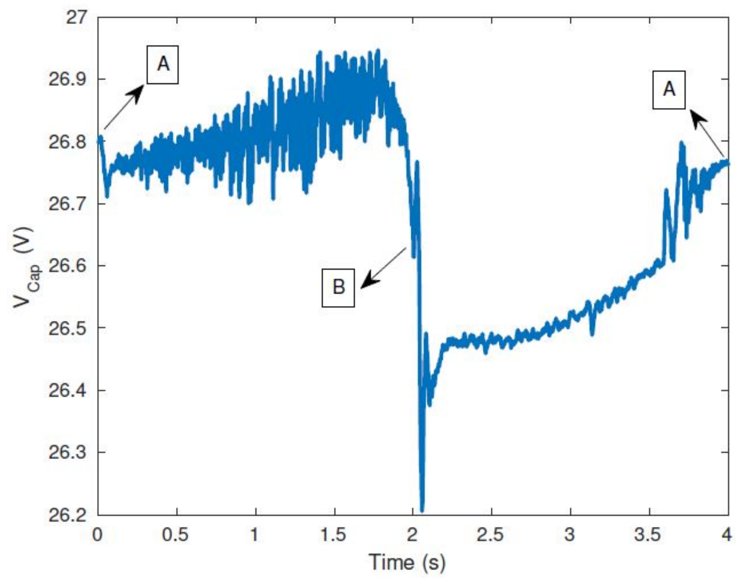

Figure 6-3: Caption

Joint	E_{AB}	E_{BA}
Waist	12.04	12.36
Shoulder	-28.18	106.18
Elbow	-1.31	12.01

Table 6.1: Energy analysis

6.2 Analysis of the results

The attained powers as analyzed by integrating by time to produce the energy outputs and the results are as shown in the Table 6.1.As discussed earlier energy regenerated by the the first joint is equivalent to nothing due to the fact of that the servo driver have mediocre performance in regeneration when the power flowing back is not up to a certain threshold value.

6.3 Future Work

Since only one of the configurations can be for the setup has been used it may be further improved by the use of a different configuration like connecting each joint to separate capacitor so that the efficiency of the servo driver may be improved as it has been observed that the servos provided best performance in regeneration when the

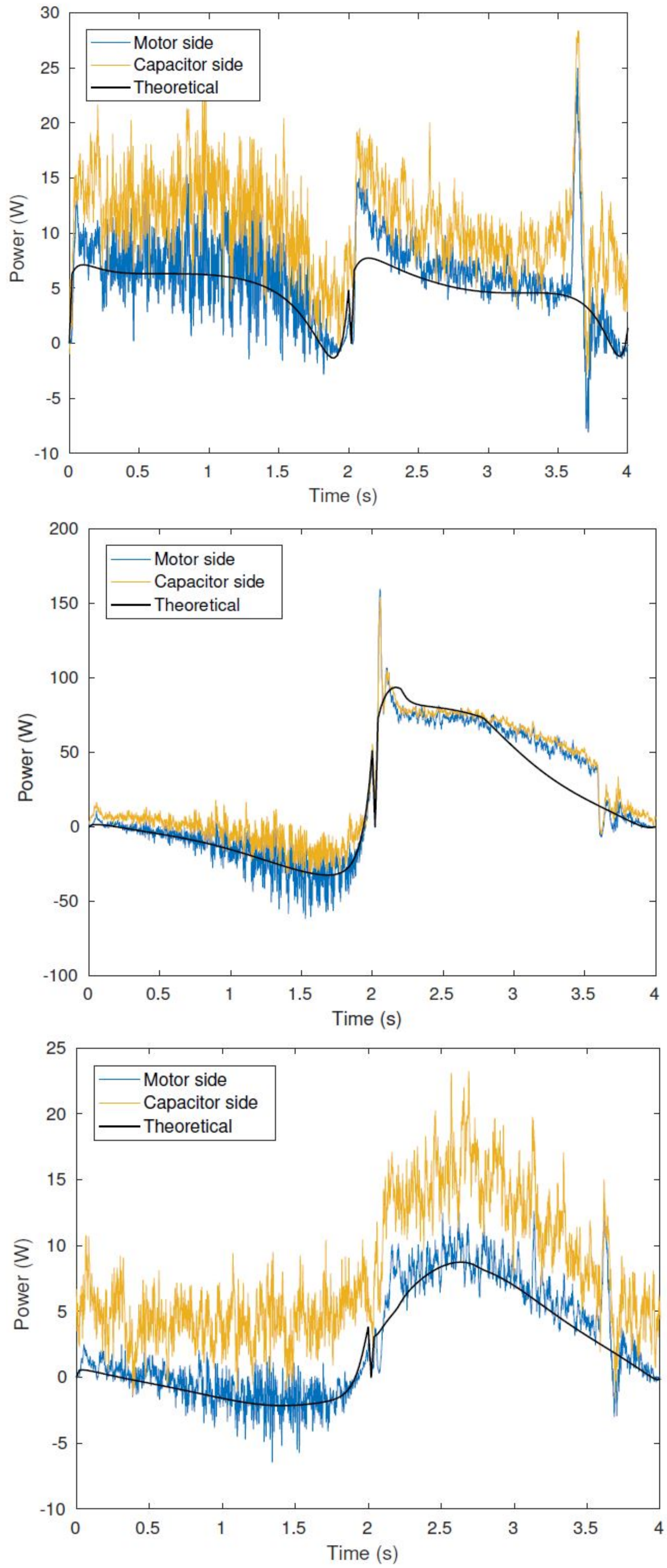

Figure 6-4: Powers of all the three joints

the r is near to 1 or the servos can be replaced by better ones.