# PS 9: Hybrid Force Control

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## 1 Hybrid Position/Force Controller

1. In this problem you will design and simulate a hybrid position/force controller for the same planar 2-DOF robot used in previous Problem Sets. As in PS#8, the robot is to interact with a horizontal wall at y =-0.025m, having a stiffness $k_w$. On the course website, you are provided with a Simulink template <PS9_template2023.slx>, which has Inverse Dynamics Control already implemented in operational space. The wall dynamics are included in the robot/environment subsystem. You will modify this template to simulate hybrid position/force control, where both position feedback and force feedback are used in a non-conflicting manner. The desired trajectory is to move the end-effector back and forth along the wall (x-direction) while exerting a constant force of 2 N against the wall (negative y-direction):

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 0.075\ \cos(2\pi f t) + 0.2 \\ -0.025 \end{bmatrix}$$

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \begin{bmatrix} 0 \\ -2 \end{bmatrix}$$

The desired position trajectory has been implemented for you in the Simulink template, but you will need to implement the desired force trajectory.

Design and simulate the following direct force control schemes with a speed of 0.2 circles/sec:

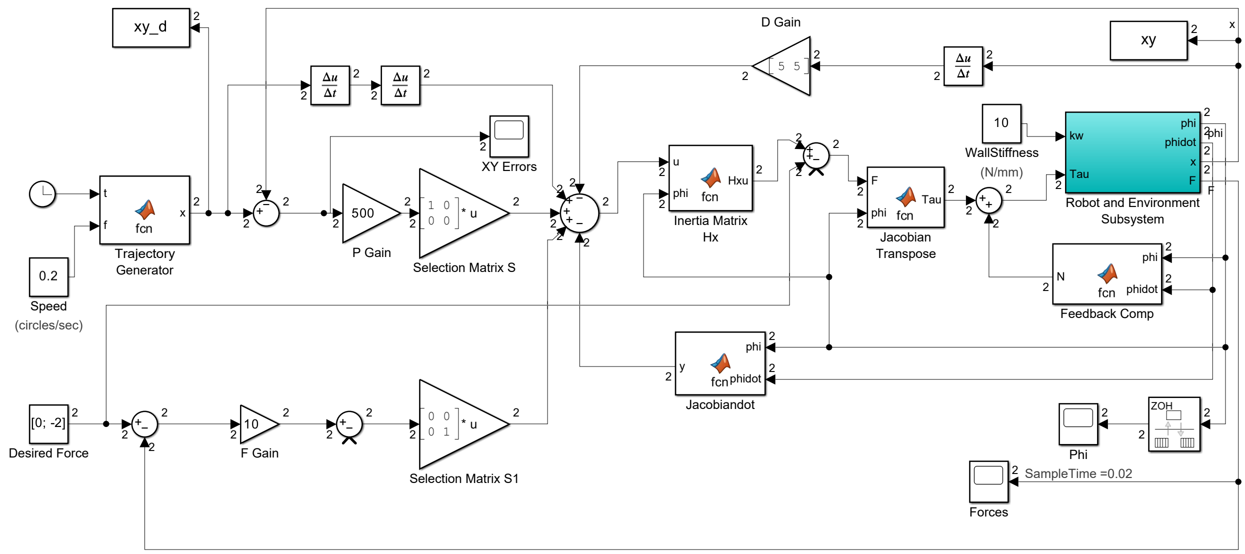
**1.1** Hybrid Position/Force Control with P force control
**1.2** Hybrid Position/Force Control with PI force control
**1.3** Add a constant disturbance force in the y-direction (i.e. just prior to the $\mathbf{J}^{\mathrm{T}}$ block) to your hybrid controller and compare the robustness of P vs. PI force control.

In each of these cases, you should also have a proportional gain on the position error, and use an inner velocity loop to add damping (instead of derivative control).

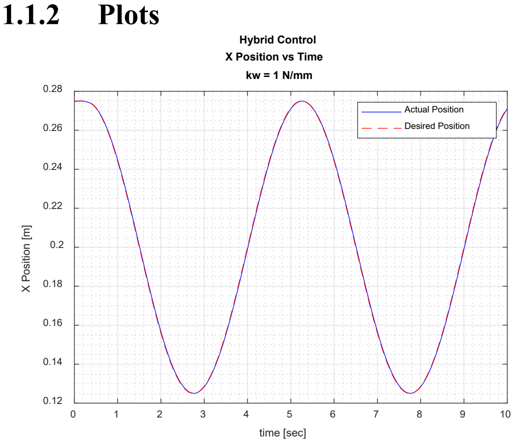
For each control scheme, simulate with a soft wall ($k_w$ = 1 N/mm) and a hard wall ($k_w$ = 10 N/mm). For each control scheme, provide an image of your Simulink model. Plot the x-position and tracking error vs. time, as well as the y-force and tracking error vs. time (for reference, plot the actual trajectories overtop of the desired trajectories). Be sure to properly title your plots and label your axes. Compare the stability and force/position tracking performance of each control scheme. As before, you can control your simulations with the *RobotApp*, which has an option to display the wall and modify the wall stiffness.

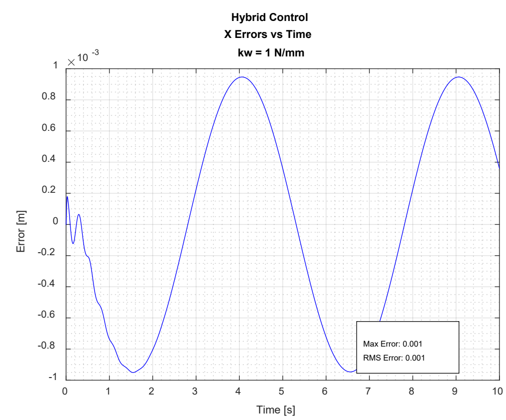
## 1.1 P Force Control

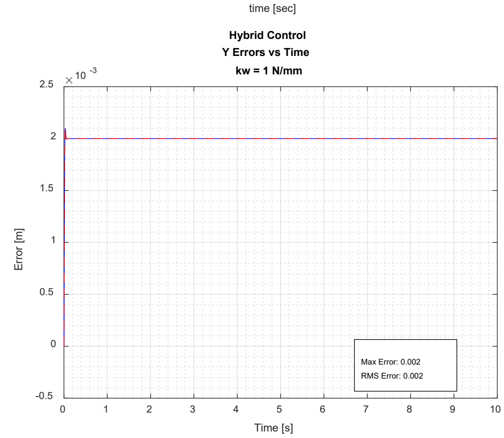
### 1.1.1 Simulink Model

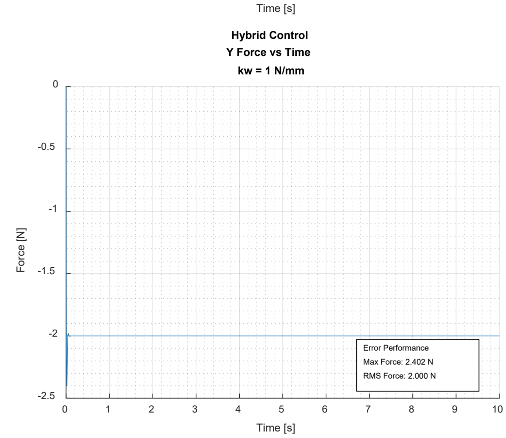


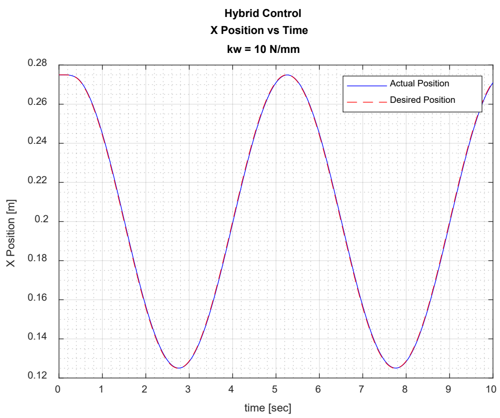

### 1.1.2 Plots

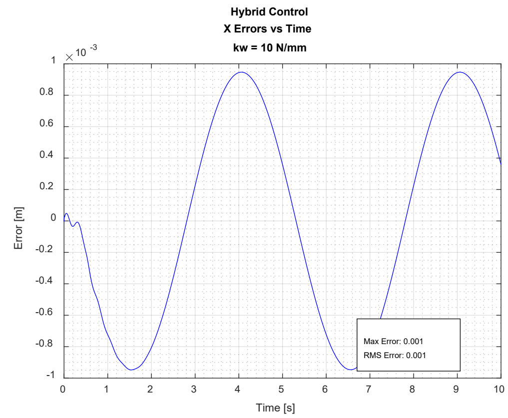


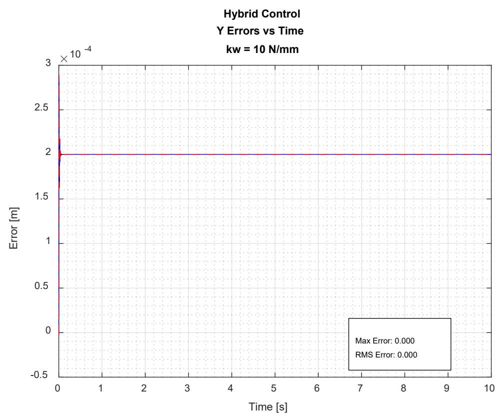



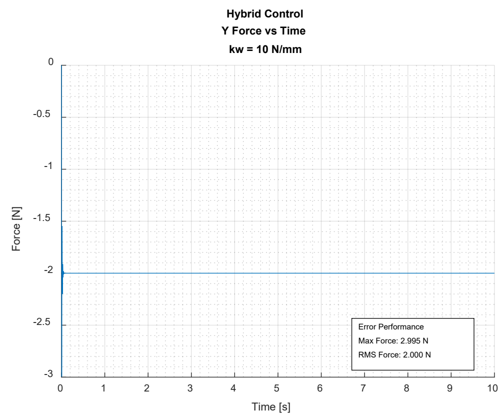





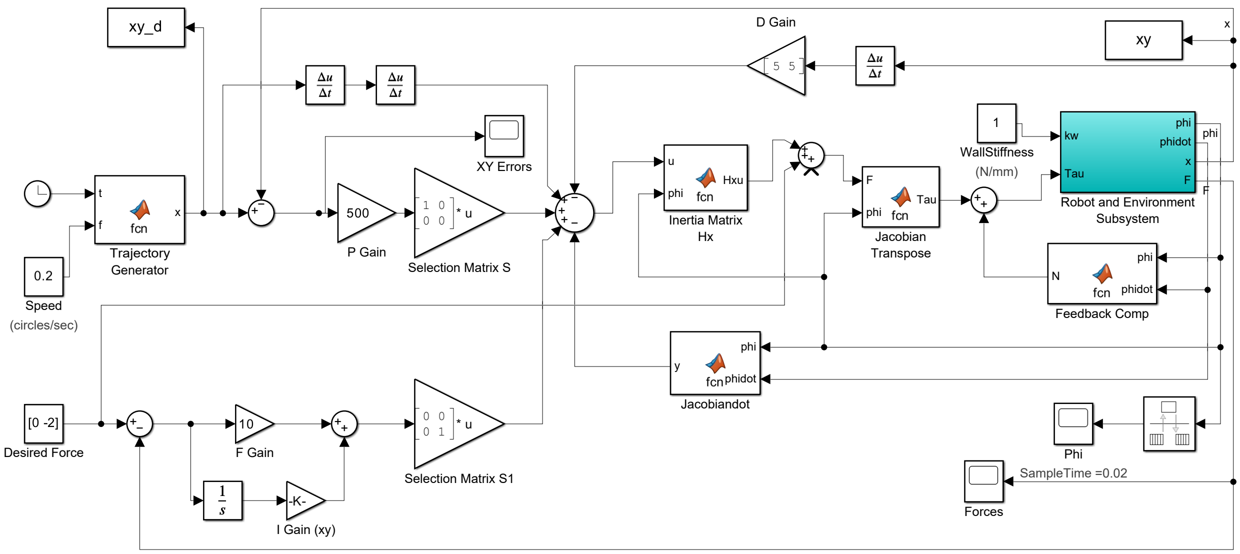




### 1.1.3 Analysis

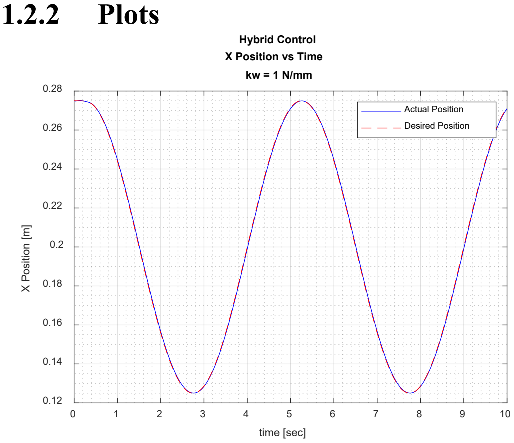
The controller performs well, with zero to little error in the force, and small errors in the x direction. There's nearly perfect tracking, but there is a high maximum initial force. There was better y direction tracking with a stiffer environment but came at the cost of high initial impact force.

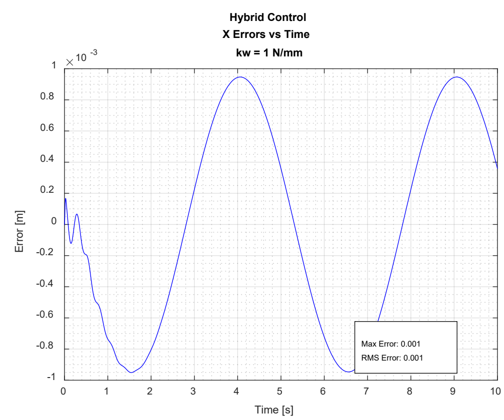
## 1.2 PI Force Control

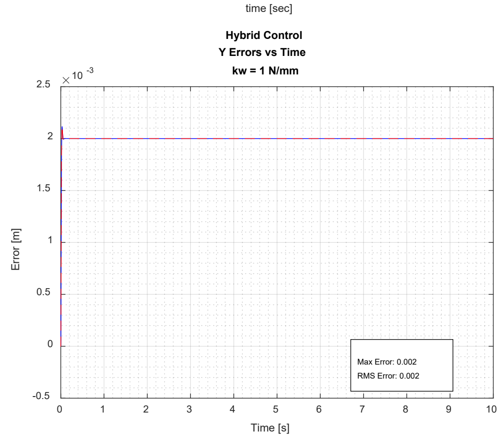
### 1.2.1 Simulink Model

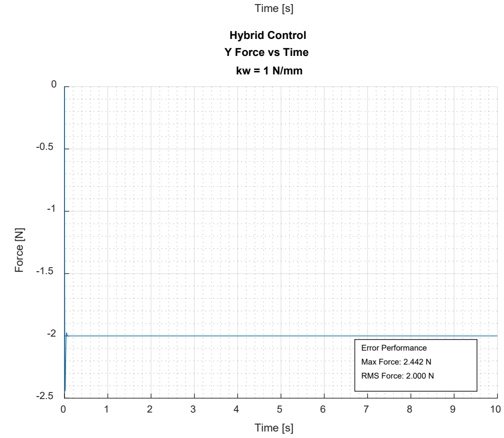


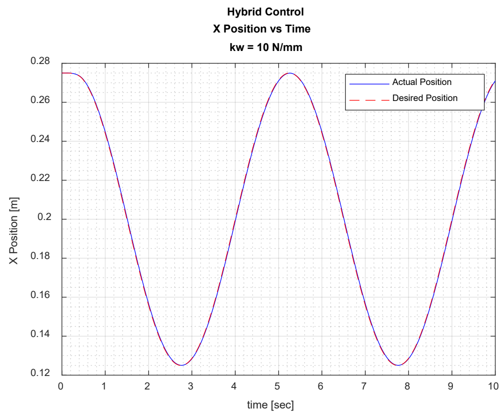

### 1.2.2 Plots

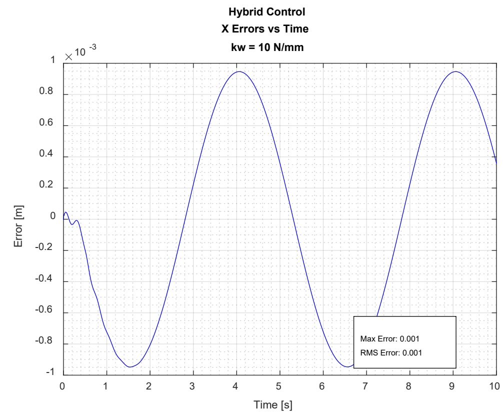


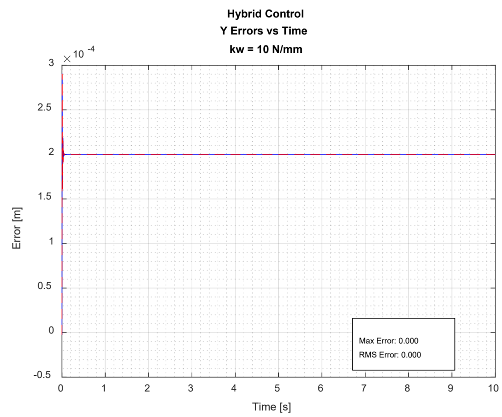



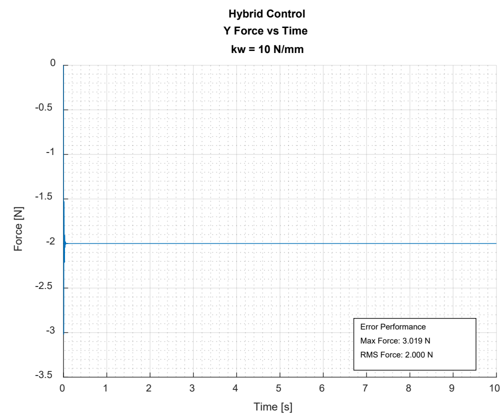





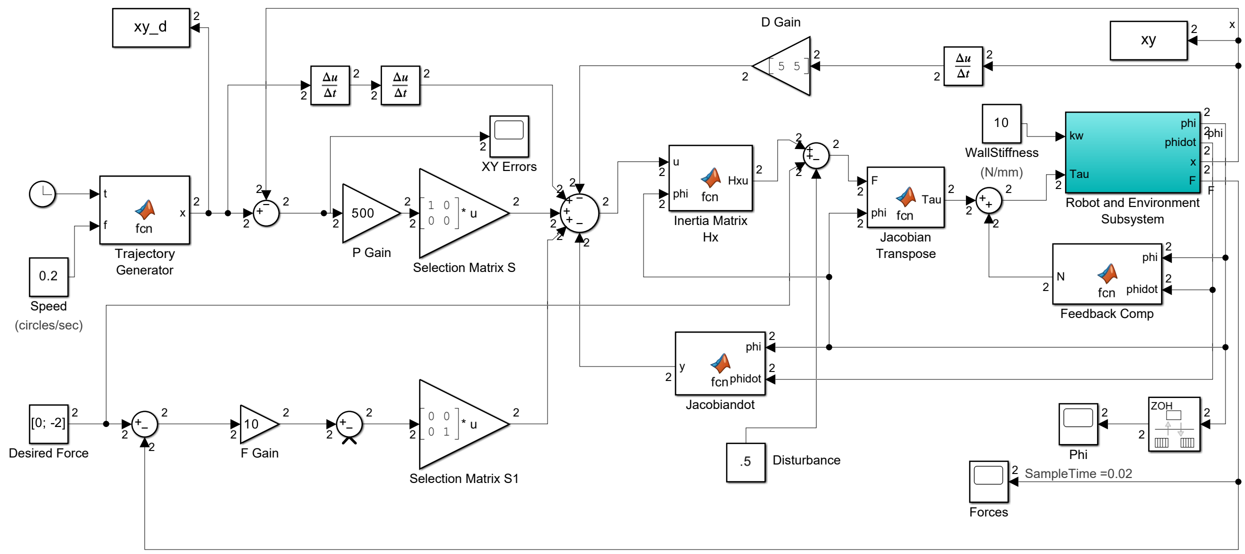



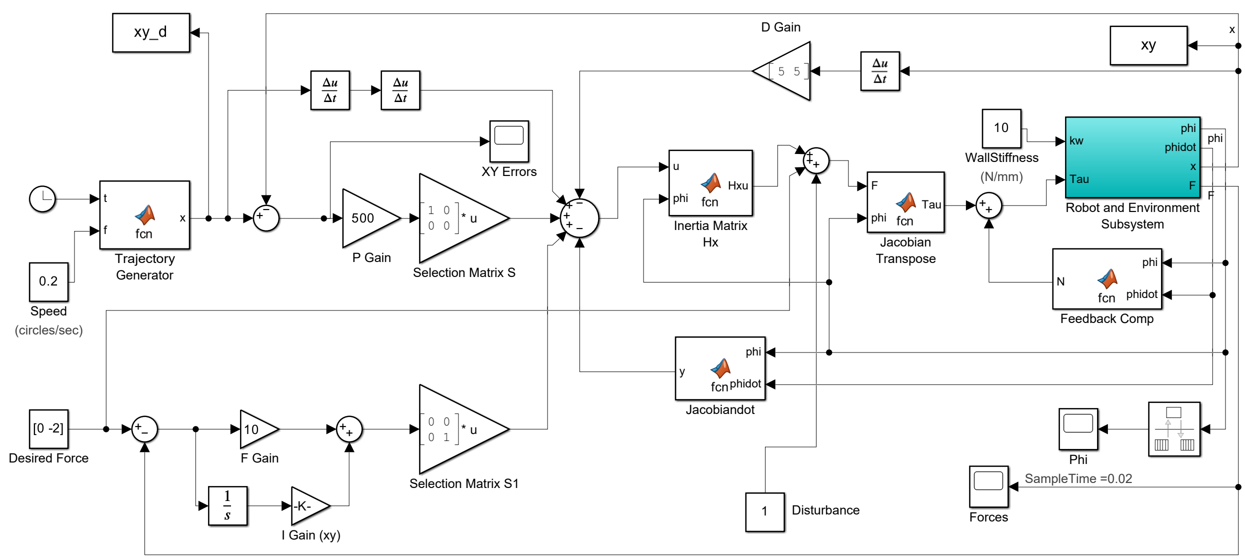

### 1.2.3 Analysis

Again, this has good simulation values. Unfortunately, the initial maximum force is higher with integration control. The integral control had lower X and Y error. The integral control had the same patterns with higher stiffness environments having better tracking with higher impact.

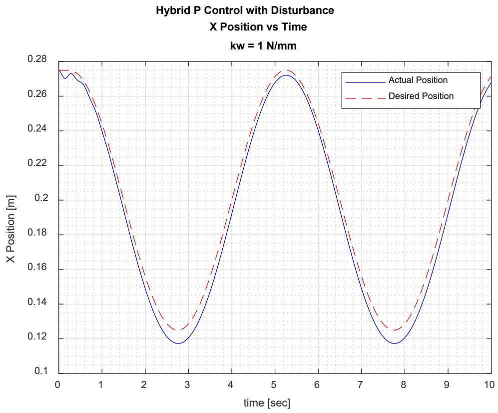
## 1.3 Disturbance

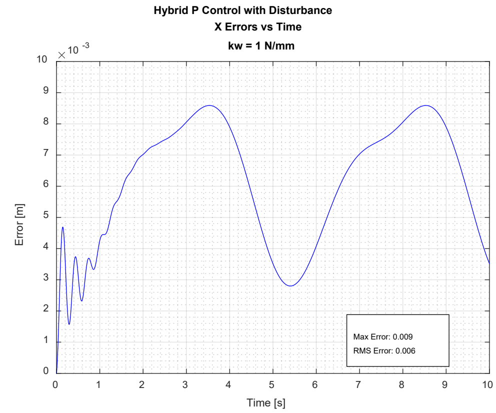
### 1.3.1 Simulink Models

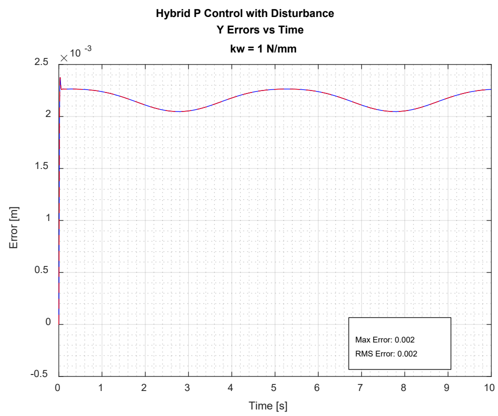


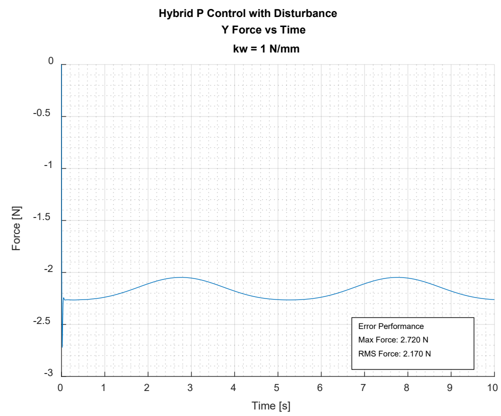



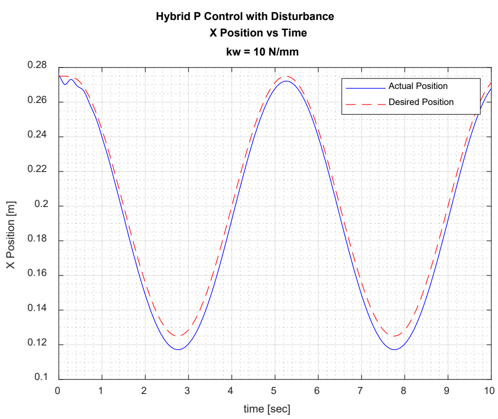
### 1.3.2 P Control Plots

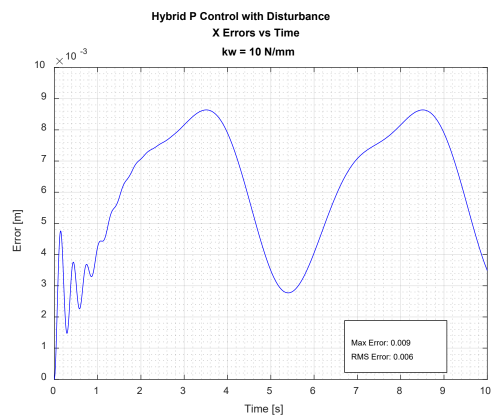


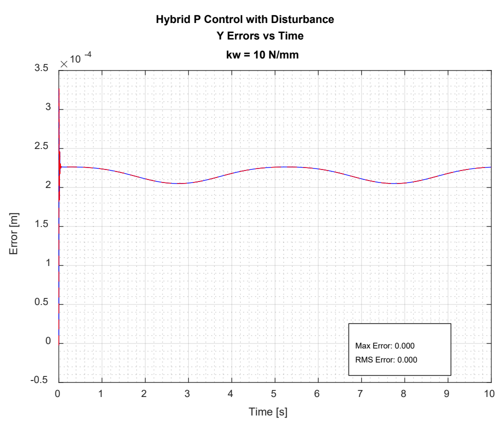



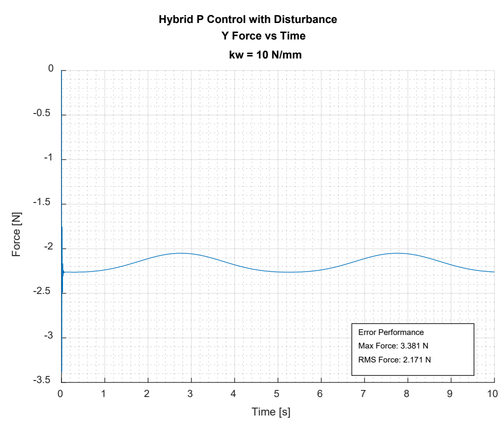



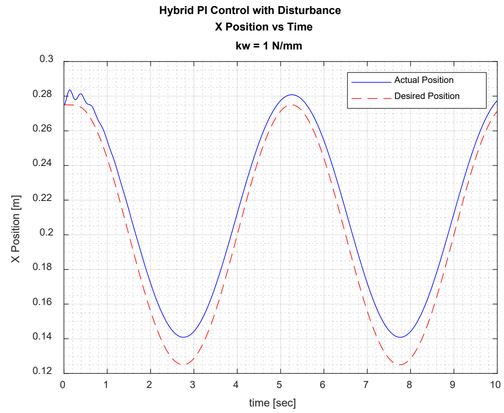



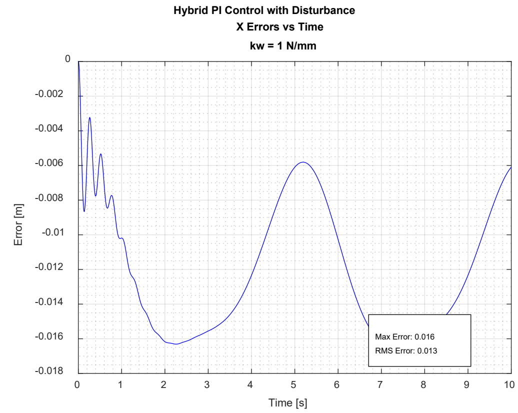



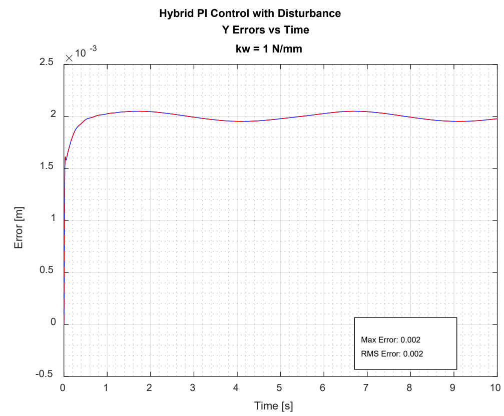



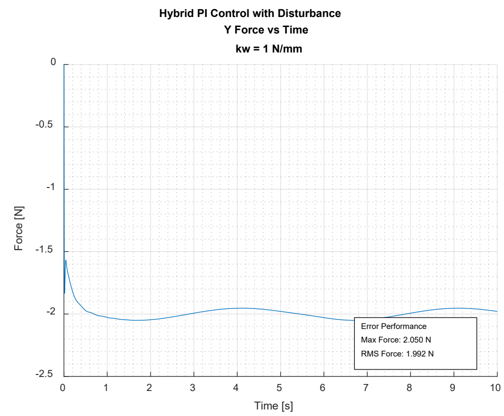



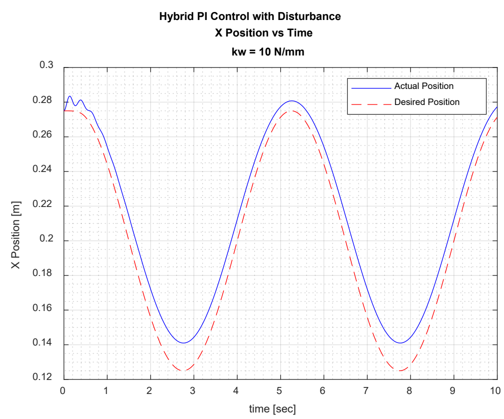
### 1.3.3 PI Control Plots

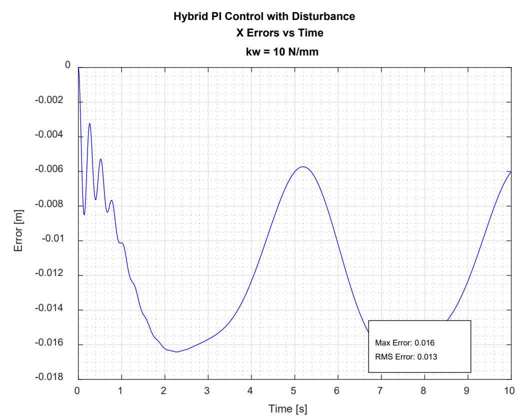


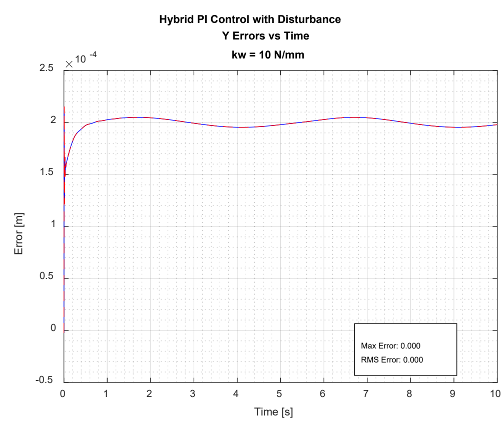



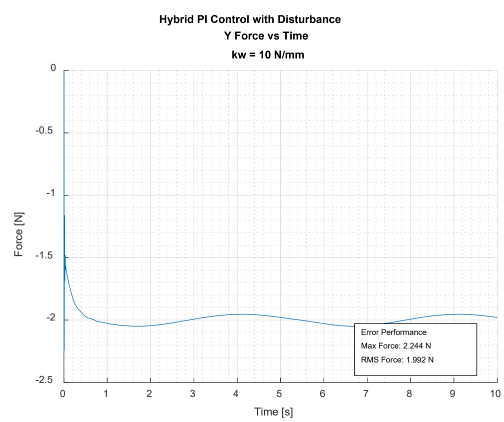



### 1.3.4 Disturbance Results Table

| | Max X Error | X RMS Error | Max Y Error | Y RMS Error | Max Y Force vs Time |
|---|---|---|---|---|---|
| P Control kw = 1 N/mm | 0.009 | 0.006 | 0.002 | 0.002 | 2.720 N |
| P Control kw = 10 N/mm | 0.009 | 0.006 | 0.000 | 0.000 | 3.381 N |
| PI Control kw = 1 N/mm | 0.016 | 0.013 | 0.002 | 0.002 | 2.050 N |
| PI Control kw = 10 N/mm | 0.016 | 0.013 | 0.000 | 0.000 | 2.244 N |

### 1.3.5 Analysis

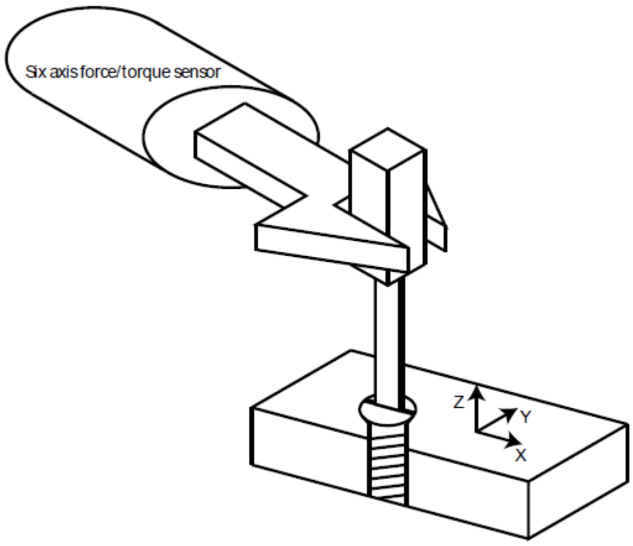
The disturbance results clearly show that integral control will lower the maximum Y force, but has slightly worse trajectory tracking. Stiffer environments again had much better trajectory tracking with higher initial force values.

**2.** Suppose you want to design a hybrid position/force controller for the task illustrated below, where a 6-DOF robot is screwing a screw into a block using a flat-head screwdriver. For the purposes of control design, assume that the contact between the tool and the screw is frictionless.

**2.1** Set up a table of natural and artificial constraints for hybrid control and find the selection matrix.

**2.2** Sketch a block diagram for the hybrid control. Also write the control law.

**2.3** Should the constraint frame be rotating with the tool? If the force/torque sensor is located in the wrist of the robot, what frame will the measured force/torque be in? Show how you handle these coordinate transformations in your controller.




2.1)

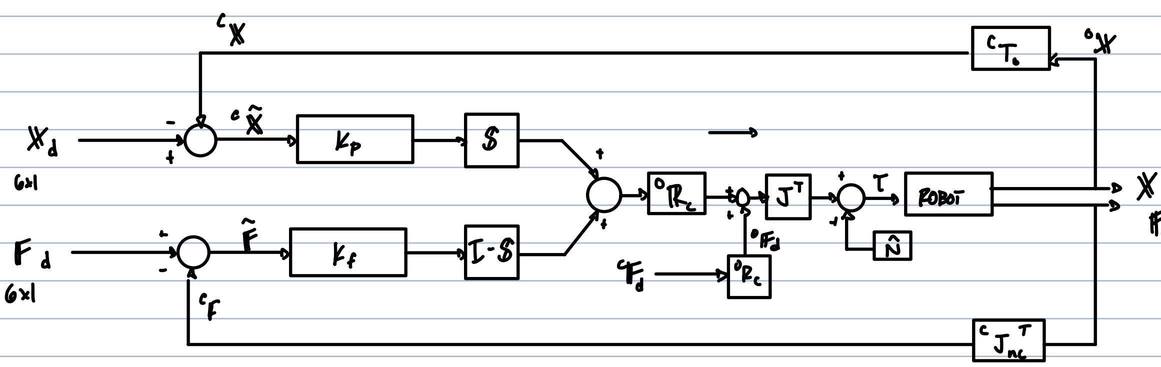
| | KINEMATIC | STATIC |
| --- | --- | --- |
| NATURAL | $V_y=0$, $V_z=0$, $\omega_x=0$, $\omega_y=0$ | $f_x=0$, $\tau_z=0$ |
| ARTIFICIAL | $V_z=V_{z,d}=0$, $\omega_z=\omega_{z,d}$ | $f_z=f_{z,d}$, $f_y=f_{y,d}=0$, $\omega_x=\omega_{x,d}=0$, $\omega_y=\omega_{y,d}=0$ |

ASSUME: NO FRICTION IN SCREW

$$\sigma = [1\ 0\ 0\ 0\ 0\ 1]$$

$$S = \mathrm{diag}(\sigma)$$

2.2)




$\omega_z=\omega_{z,d}$

$V_z=V_{z,d}$

$f_x=f_{x,d}=0$ $f_y=f_{y,d}=0$

$\omega_x=\omega_{x,d}=0$ $\omega_y=\omega_{y,d}=0$

$$u = K_{P,z}\tilde{V}_z + K_{P,\omega_z}\tilde{\omega}_z + K_{P,fx}\tilde{f}_x + K_{P,fy}\tilde{f}_y + K_{P,\tau x}\tilde{\tau}_x + K_{P,\tau y}\tilde{\tau}_y$$

2.3) THE ABOVE DIAGRAM SHOWS HOW TO DEAL WITH ROTATING THE END EFFECTOR. BELOW ARE EQUATIONS USED FOR ROTATIONS. IF A WRENCH IS FED BACK, USE THE JACOBIAN TRANSPOSE

$${}^cX = {}^cR_0\,{}^0X$$

$${}^cX = {}^cT_0\,{}^0X$$