Final Design Report

[EGH586] Decisions and Control

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1 Introduction

1.1 Project Context

The project follows on from the work done by A. McFadyen, J. Ford and P. Corke in visual servoing [1]. They provide a visual servoing simulator and control system design based on the following dynamics:

$$s(k+1) = s(k) + L(k)\, u(k)\, \Delta t \tag{1}$$

1.2 Project Report Objectives

This report aims to:

- provide a detailed overview of proposed alternative's subsystems,
- provide information about the design process of each subsystem,
- assess the viability, strengths and weakness of the new design, in contrast with the existing controller,
- provide a recommendation for future work.

1.3 Design Report Scope

The report provides an overview of the implementation, as well as insights into the process to develop subsystems that make up the new control design. It details simulated ablation studies and the resulting performance over a variety of test cases. It will outline limitations of the design, and provide recommendations for future implementation and application of the visual servoing system.

The test cases are made up of 4 initial conditions under 6 different conditions. These conditions are as follows:

1. No error, no measurement noise case
2. Measure error is ON. No other error sources.
3. Range error is ON. No other error sources.
4. Feature error is ON. No other error sources.
5. Wind error is ON. No other error sources.
6. Measurement, range, feature, Wind errors are all ON.

The project assumes that features are isolated geometries in the world, such as hovering drones in the case of a swarm application. As such, adhering to boundaries or imposed spatial is beyond the scope of this study.

Each scenario is run with a simulation length of 100 steps.

1.4 Design Project Resources

- MATLAB
- Basic Visual Servoing Simulator written by Aaron McFadyen, modified by Jason Ford.

1.5 Design Report Structure

Section 1 provides a meta overview of the design report itself.
Section 2 will discuss details of each subsystem of the final design, as well as some details around the design process.
Section 3 outlines the performance of the control design in a variety of test cases.
Section 4 provides the code changes to the Basic Visual Servoing Simulator (modified by Jason Ford) that implements the control design.

2 Part A - Description of the Final Design

2.1 Subsystem 1: PID Controller

Objective and interfaces:

The objective of this subsystem is to better control the robot based on the measured error. Ideally, this will lead to reduced control energy/effort with minimal impact on final error, and provide robustness in scenarios which contain either measurement or process noise.

Its inputs are:

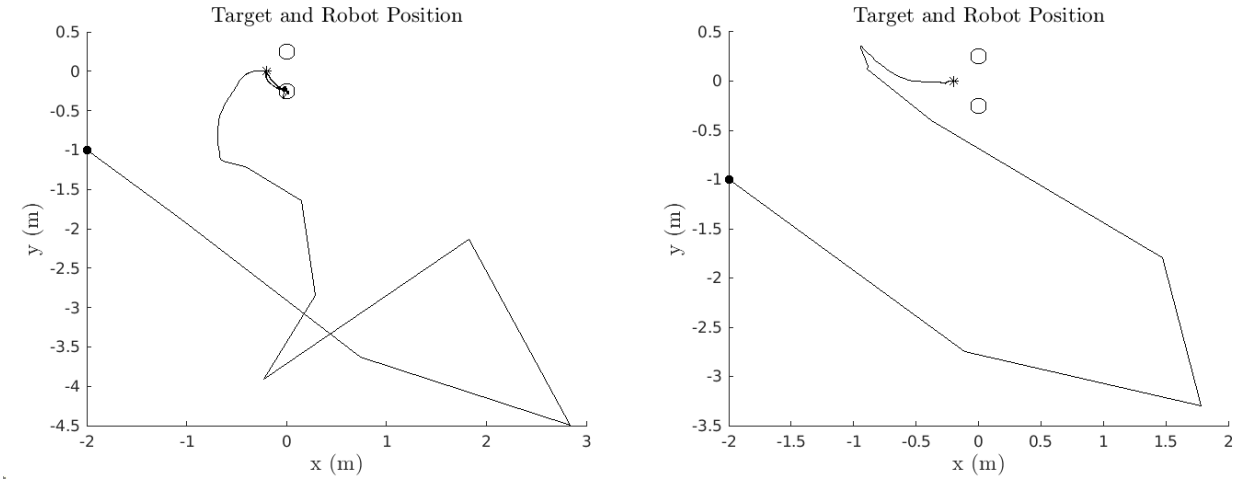
- Image Jacobian (Ja(:,control.dof))
- Previous error (error_old)

The outputs are:

- Gain (gainP, gainI & gainD)
- Control signal (uactual)

Design Justification:

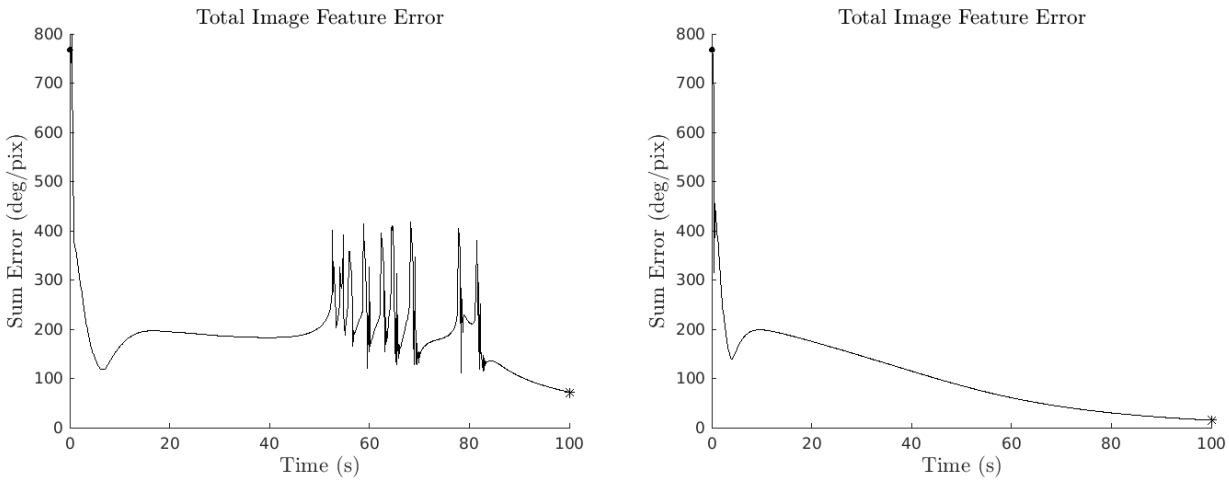
The implementation of the PID controller is based off provided unit material. The controller has been tuned through testing to improve its performance. It was found that the time for error convergence was too slow, and appropriate adjustments were made to increase the rate of approach, and minimise damping effects.



(a) Position Plot of Initial PID Gains

(b) Position Plot of Revised PID Gains

Figure 1: Comparison of initial and revised PID trajectories



(a) Feature Error Plot of Initial PID Gains

(b) Feature Error Plot of Revised PID Gains

Figure 2: Comparison of initial and revised PID errors

The resulting changes are:

- Increased $\mathrm{K}_P = 0.3$
- Increased $\mathrm{K}_I = -0.0009$
- Decreased $\mathrm{K}_D = -0.3$

Testing description:

The PID controller is intended to provide better performance in the test cases the current system falls short. This mostly involves disturbances and difficult initial conditions. The following test cases are the focus of the PID controller:

- Test Case 1-1
- Test Case 1-2
- Test Case 5-1
- Test Case 5-2
- Test Case 5-3
- Test Case 5-4
- Test Case 6-1
- Test Case 6-2
- Test Case 6-3
- Test Case 6-4

Capabilities and Limitations

The PID Controller consistently is able to reach the desired target, or is a few steps short, even in cases where the provided solution is unable to. However, the controller takes a very inefficient trajectory. There appears to be regions of linear position change which is likely a result of the larger K_P value, which accomplishes its objective but may raise concerns regarding safety of operation with the sudden and fast changes in trajectory.

2.2 Subsystem 2: Kalman Filter

Objective and interfaces:

In several test cases, forms of measurement error are introduced to the system which impact control outcomes. To that end, a Kalman filter was implemented in an attempt to provide a better estimate of the current state of the system, and mitigate issues r1elated to noise.

Its inputs are:

- Feature error (e.actual)
- Estimated feature err (kf.e_est)
- Error covariance (kf.P_prev)
- Image Jacobian (Ja(:,control.dof))
- Δt (Timing.dt)
- Previous control signal (uactual)

The outputs are:

- Estimated feature err (kf.e_est)
- Error covariance (kf.P_prev)

Design Justification:

The Kalman filter was designed around the measurements of the feature positions. However, the estimations and predictions output the feature error, as the error is given in terms of the measured feature position, and a constant reference position. The following considerations were taken as part of the design of the Kalman filter:
Servoing Dynamics: The servoing dynamics of the system can be represented as $x_{k+1} = Ax_k + B_k u_k$, where $A = I$ and $B_k = L(k)\Delta t$, as per the "Extra Support" material. This means that an initial estimate of the image Jacobian, $L_0(k)$, is required as part of the design, as well as an initial estimate for u_0.
H Matrix: The H matrix was represented by the identity, $I_{8\times 8}$, to easily conform to the shape requirements of the image Jacobian and the . This forms an assumption that the measurement of each feature depends only upon itself, which does not reflect reality but does provide an approximation.
Initial estimates B_0, u_0: To find reasonable estimates for B_0 and u_0, the simulator was run to find typical values. Each element of each term was then initialised randomly within a range of typical values for the respective terms.
Tuning Q and R: The focus of Q and R tuning was to minimise the total image feature error. Starting values were based on a previous implementation of a Kalman filter and a bi-section style approach was applied to converge on an answer, starting with transitions of an order of magnitude.

Testing description:

As with the PID controller, the Kalman filter was implemented independently to gain an understanding of its contribution to performance. As the Kalman filter was included to provide improved estimates, it is intended to perform better on tests that incorporate measurement error. No improvement is expected for test case 1 as there is no benefit to the Kalman filter in that scenario.

The following test cases are the focus for Kalman filter testing:

- Test Case 2-1
- Test Case 2-2
- Test Case 2-3
- Test Case 2-4
- Test Case 4-1
- Test Case 4-2
- Test Case 4-3

- Test Case 4-4
- Test Case 6-1
- Test Case 6-2
- Test Case 6-3
- Test Case 6-4

Capabilities and limitations:

In general, Kalman filters provide better estimations of states in the presence of noise. However, in this case, the performance of control without the filter proves to be better performing due to issues relating to model mismatch.

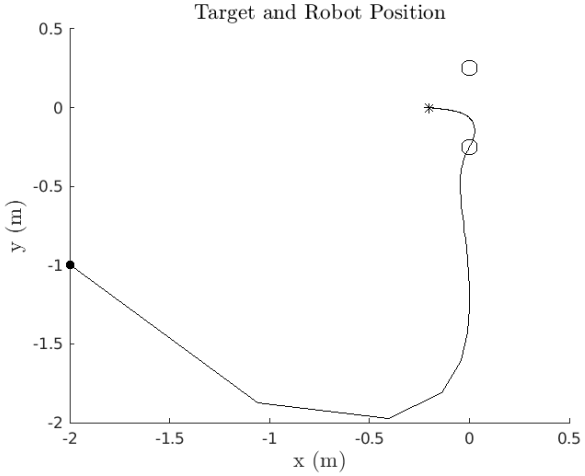
Recommendation for future investigations or improvements for this subsystem:

The Kalman filter has been modelled under the assumption that measurements are somewhat independent of each other. In reality, the feature measurements are coupled together as changes to one position cannot occur without changes to another given the fixed relative positions shared by the features. In some instances, this could be non-linear with the robot rolling. It is recommended to update and improve the existing model to prevent model mismatch, and improve the filter through the application of either an extended Kalman filter or unscented Kalman filter to account for the non-linear coupling of feature measurements, or apply a simpler filter, such as a low pass filter, which may prove more beneficial due to the ultimately simple nature of the measurements. Alternatively, due to the reasonable performance observed in the absent-filter tests, abandoning the filter altogether is a reasonable solution.

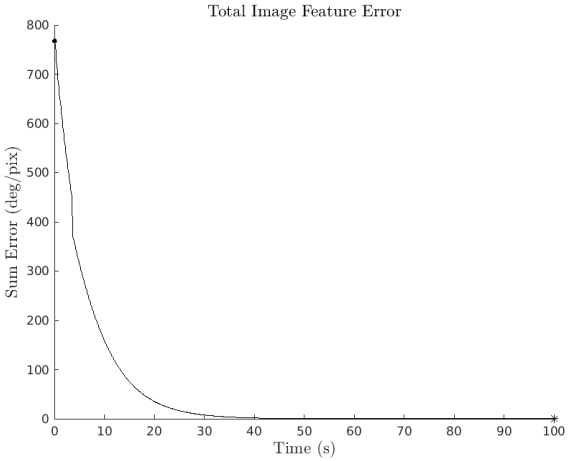
3 Part B - System Performance

3.1 Test Case 1 - No Error

3.1.1 Provided Solution Performance

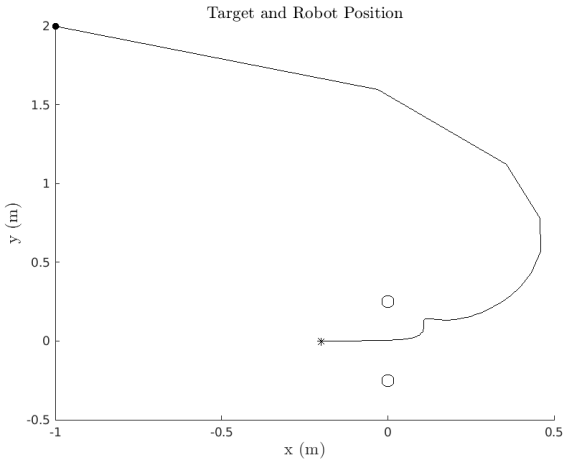


(a) 1-1 Provided Solution Trajectory

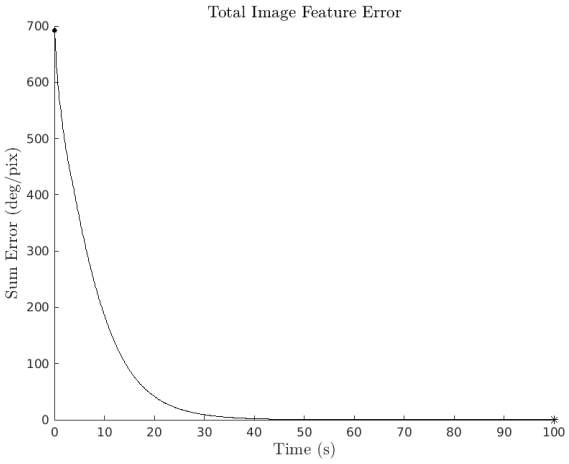


(b) 1-1 Provided Solution Error

Figure 3: Test Case 1, Initial Condition 1: Provided Solution

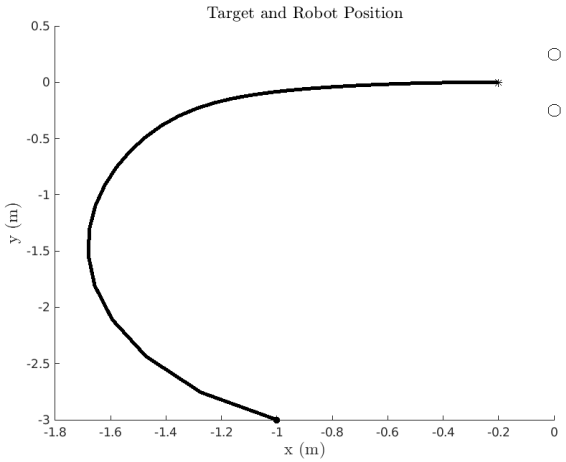


(a) 1-2 Provided Solution Trajectory

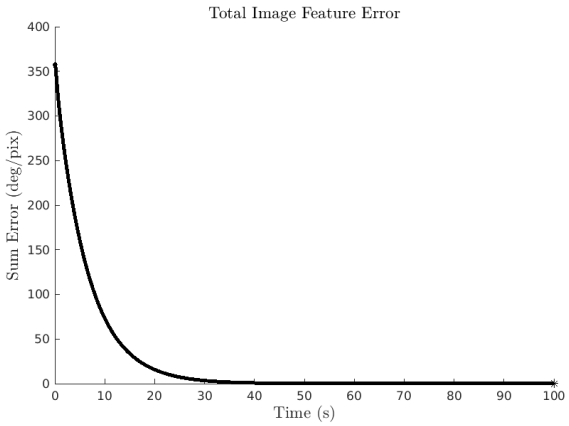


(b) 1-2 Provided Solution Error

Figure 4: Test Case 1, Initial Condition 2: Provided Solution

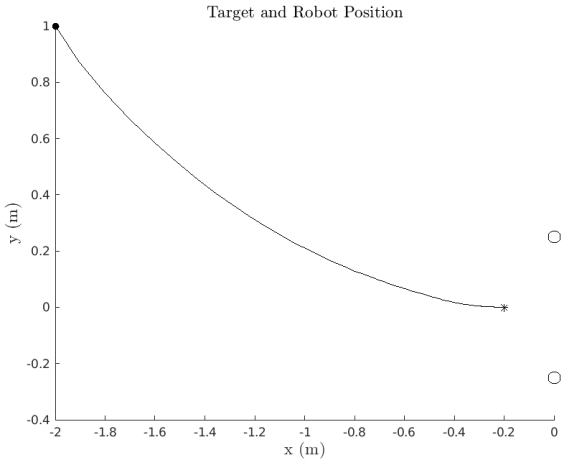


(a) 1-3 Provided Solution Trajectory

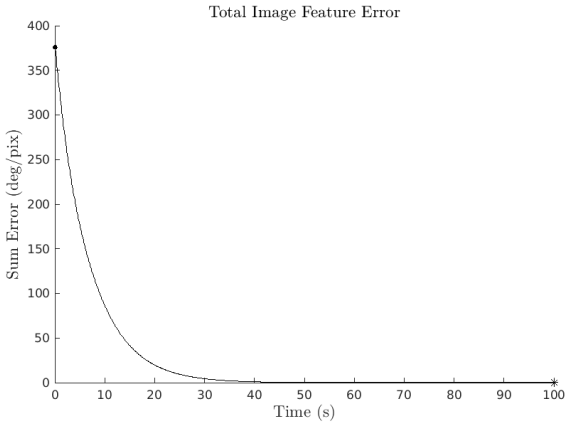


(b) 1-3 Provided Solution Error

Figure 5: Test Case 1, Initial Condition 3: Provided Solution



(a) 1-4 Provided Solution Trajectory



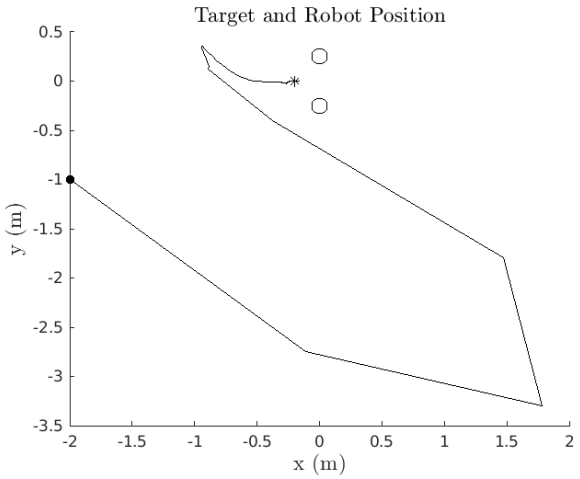
(b) 1-4 Provided Solution Error

Figure 6: Test Case 1, Initial Condition 4: Provided Solution

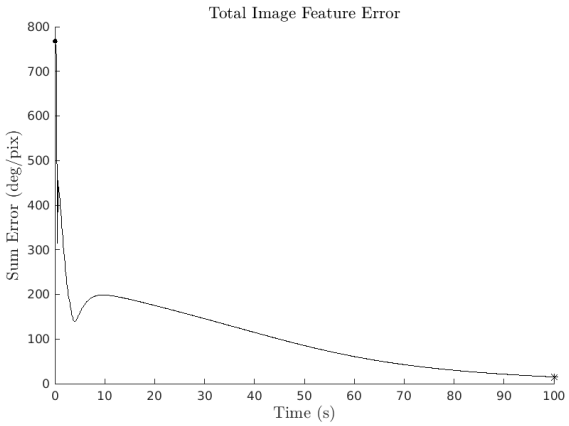
	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	170.2261	1.3837e-07	0.00019657
Start Case 2	96.2538	1.628e-07	0.0002306
Start Case 3	54.1759	7.0003e-08	8.7361e-05
Start Case 4	19.528	9.4745e-08	0.00011181

Table 1: Test Case 1 Provided System Performance

3.1.2 PID Control Performance

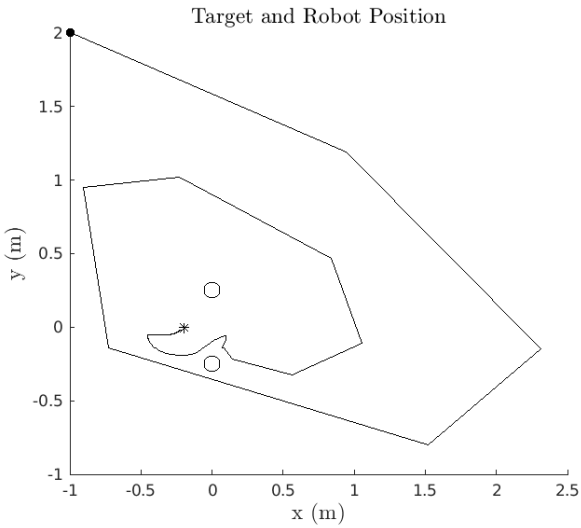


(a) 1-1 PID Controller Trajectory

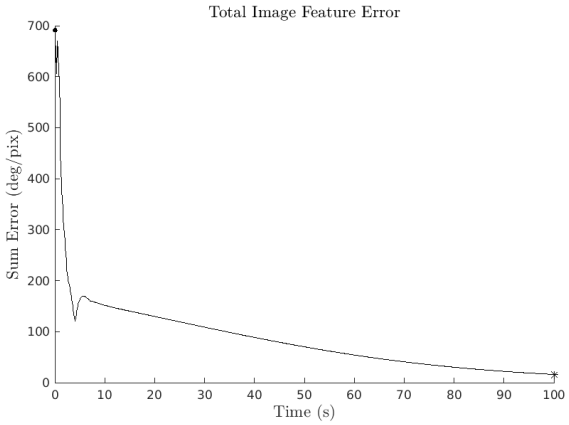


(b) 1-1 PID Controller Error

Figure 7: Test Case 1, Initial Condition 1: PID Controller

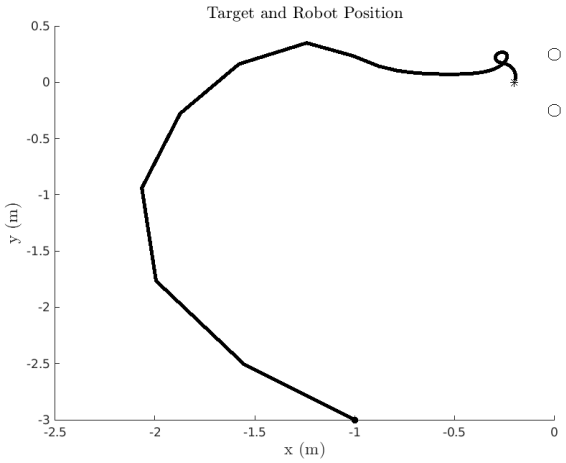


(a) 1-2 PID Controller Trajectory

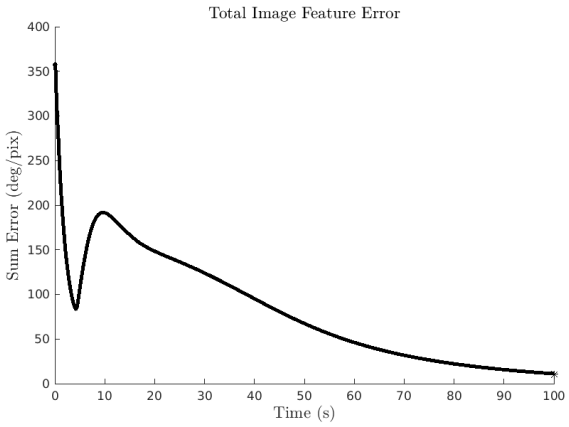


(b) 1-2 PID Controller Error

Figure 8: Test Case 1, Initial Condition 2: PID Controller

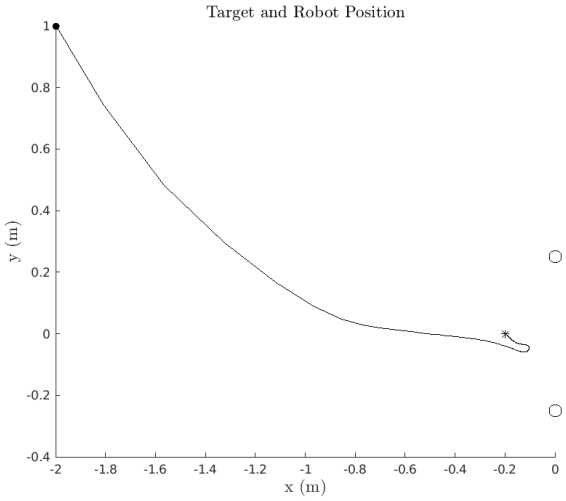


(a) 1-3 PID Controller Trajectory

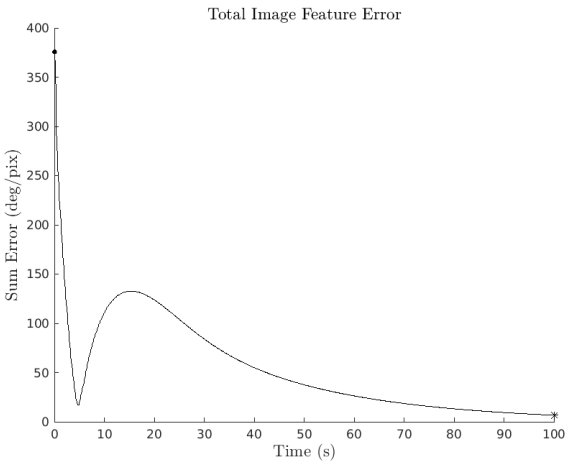


(b) 1-3 PID Controller Error

Figure 9: Test Case 1, Initial Condition 3: PID Controller



(a) 1-4 PID Controller Trajectory



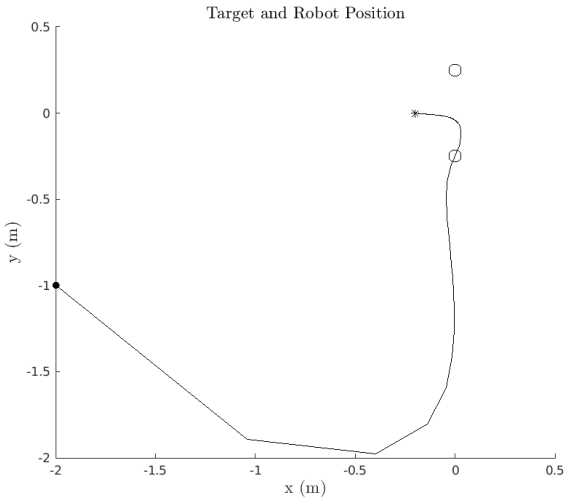
(b) 1-4 PID Controller Error

Figure 10: Test Case 1, Initial Condition 4: PID Controller

	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	1268.1647	0.015306	15.0611
Start Case 2	1132.8613	0.014529	16.0546
Start Case 3	192.4635	0.0095517	11.1168
Start Case 4	63.642	0.005909	6.6974

Table 2: Test Case 1 PID-only Performance

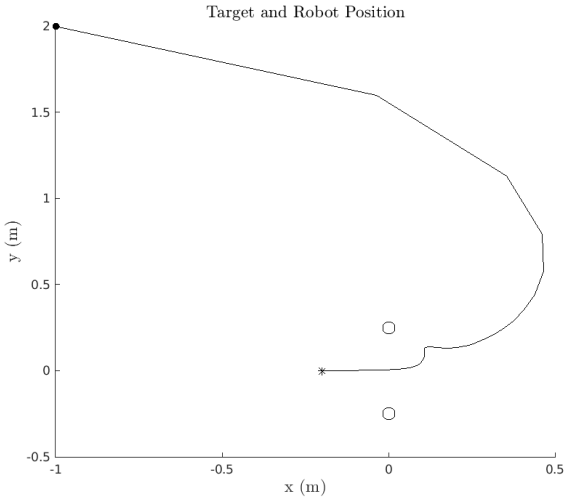
3.1.3 Kalman Filter Performance



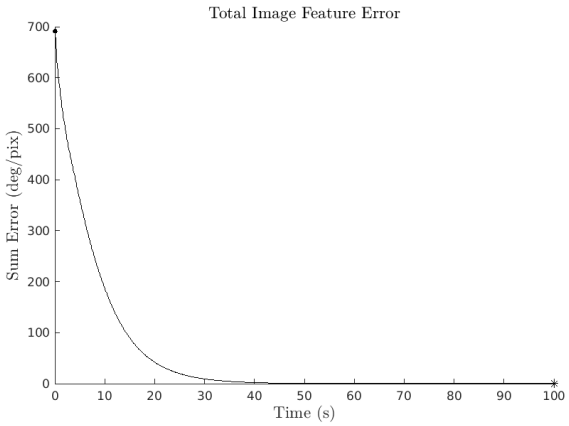
(a) 1-1 Kalman Filter Trajectory

(b) 1-1 Kalman Filter Error

Figure 11: Test Case 1, Initial Condition 1: Kalman Filter

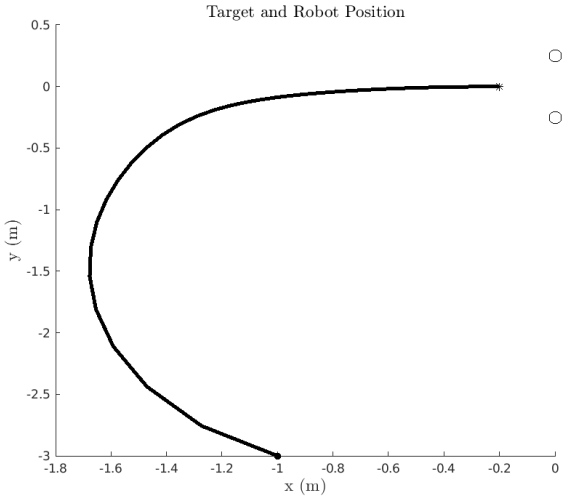


(a) 1-2 Kalman Filter Trajectory

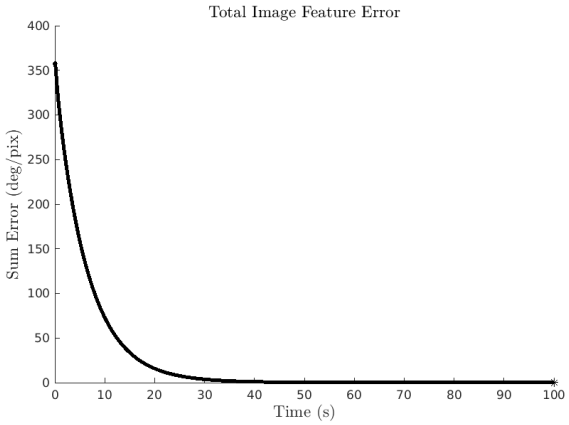


(b) 1-2 Kalman Filter Error

Figure 12: Test Case 1, Initial Condition 2: Kalman Filter

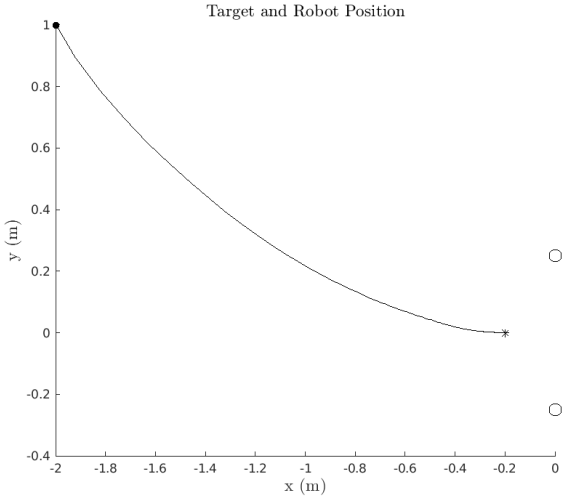


(a) 1-3 Kalman Filter Trajectory

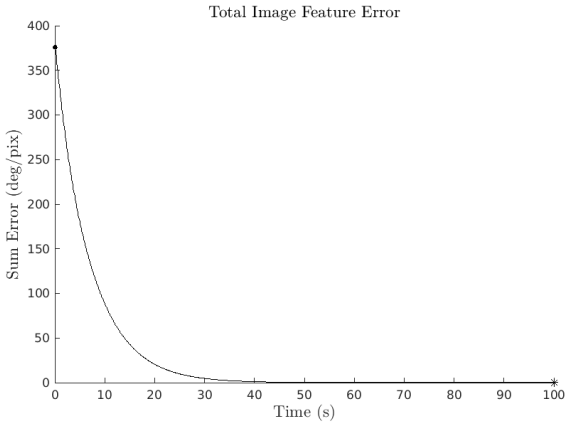


(b) 1-3 Kalman Filter Error

Figure 13: Test Case 1, Initial Condition 3: Kalman Filter



(a) 1-4 Kalman Filter Trajectory



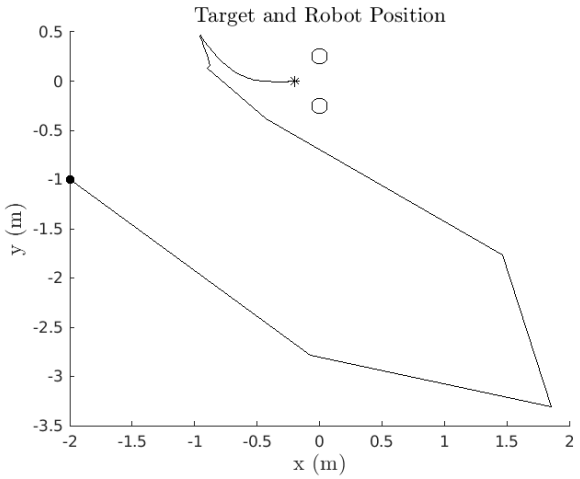
(b) 1-4 Kalman Filter Error

Figure 14: Test Case 1, Initial Condition 4: Kalman Filter

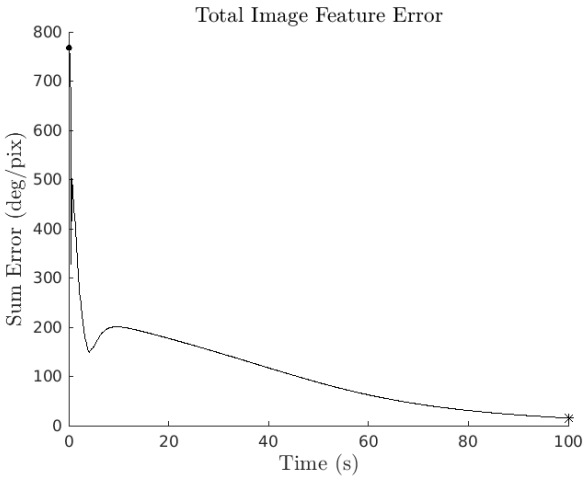
	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	174.1013	0.00011726	0.18196
Start Case 2	95.6084	1.5437e-06	0.0023358
Start Case 3	53.8423	4.4557e-06	0.0068299
Start Case 4	19.2171	2.3142e-06	0.0035573

Table 3: Test Case 1 Kalman Filter-only Performance

3.1.4 Full System Performance

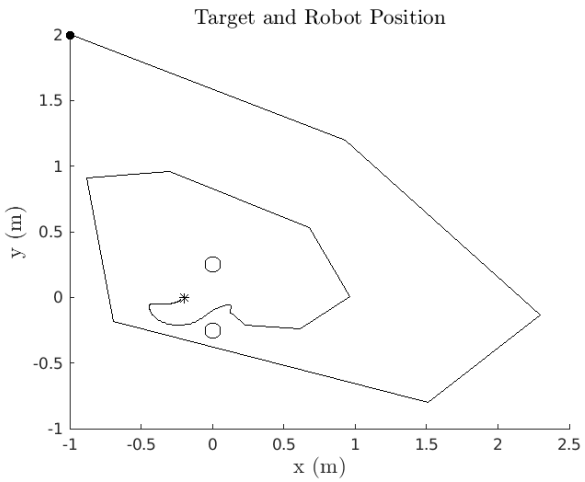


(a) 1-1 Full Solution Trajectory

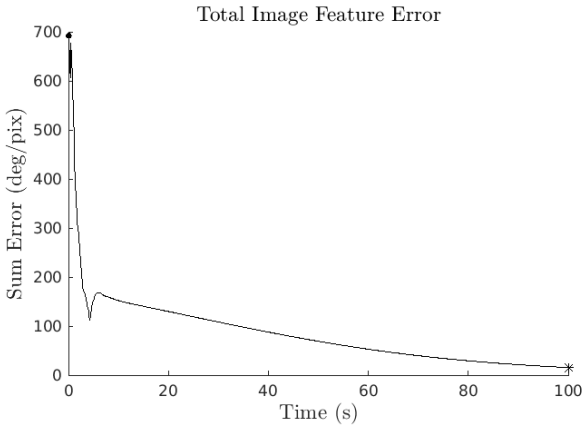


(b) 1-1 Full Solution Error

Figure 15: Test Case 1, Initial Condition 1: Full Solution

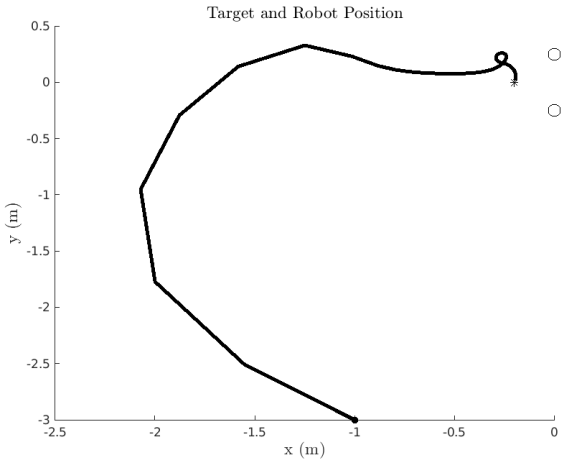


(a) 1-2 Full Solution Trajectory

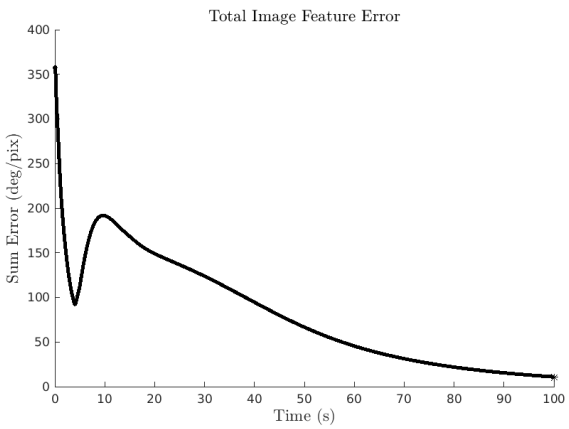


(b) 1-2 Full Solution Error

Figure 16: Test Case 1, Initial Condition 2: Full Solution

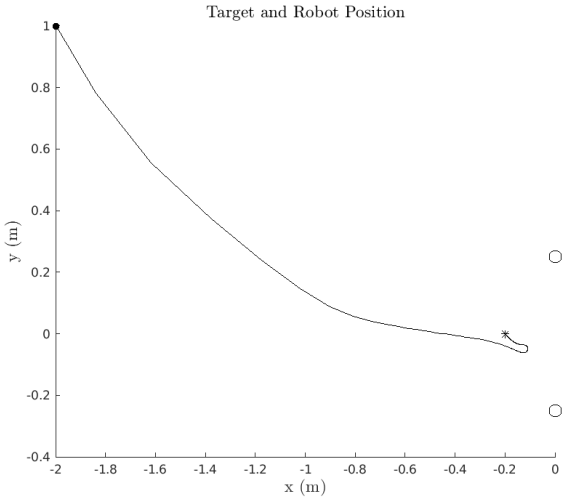


(a) 1-3 Full Solution Trajectory

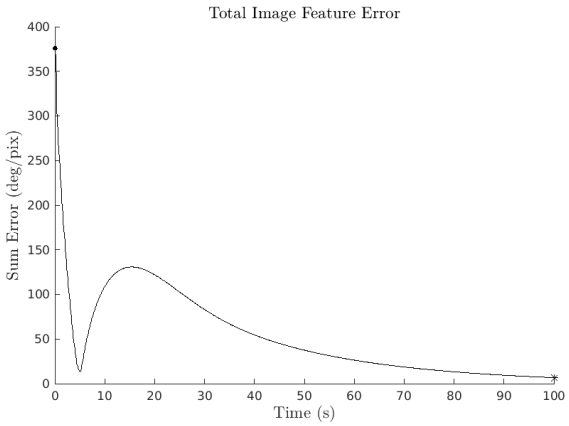


(b) 1-3 Full Solution Error

Figure 17: Test Case 3, Initial Condition 1: Full Solution



(a) 1-4 Full Solution Trajectory



(b) 1-4 Full Solution Error

Figure 18: Test Case 1, Initial Condition 4: Full Solution

	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	1327.144	0.015755	15.4446
Start Case 2	1065.3355	0.014037	15.4345
Start Case 3	190.871	0.0095045	10.9481
Start Case 4	61.5739	0.0060487	6.741

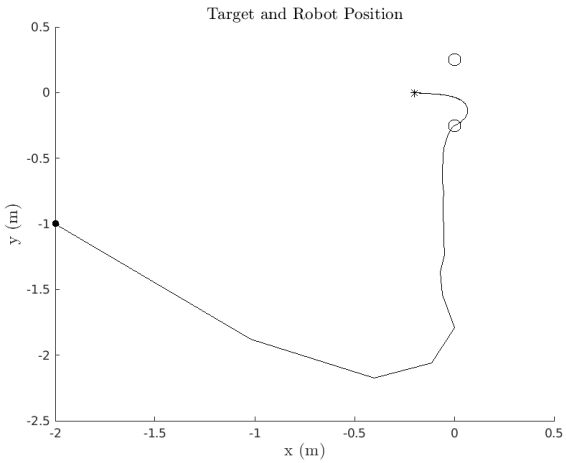
Table 4: Test Case 1 Full System Performance

3.1.5 Test Case 1 Summary and Observations

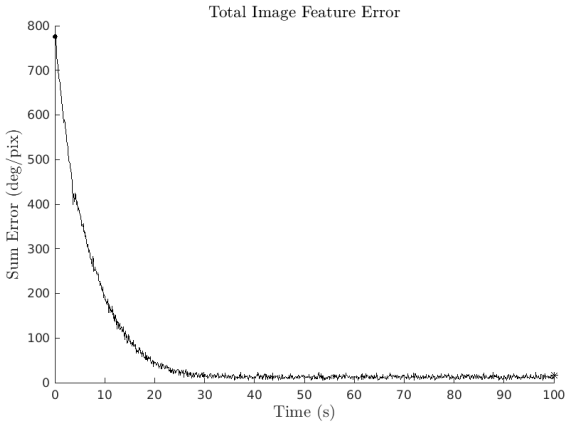
In the no-error case neither the Kalman filter or PID controller provide any benefit for the system. The provided solution vastly outperforms PID in terms of control energy and error. The Kalman filter, though not expected to improve the performance in this scenario, degrades the final error when it is applied, though the consistency indicates the Kalman filter, at a base level, has been implemented correctly.

3.2 Test Case 2 - Measurement Error

3.2.1 Provided Solution Performance

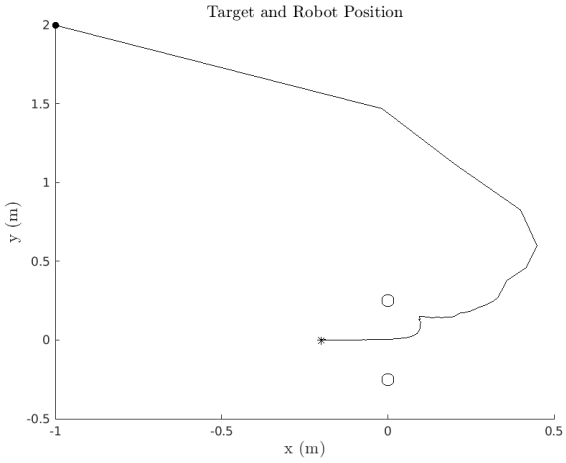


(a) 2-1 Provided Solution Trajectory

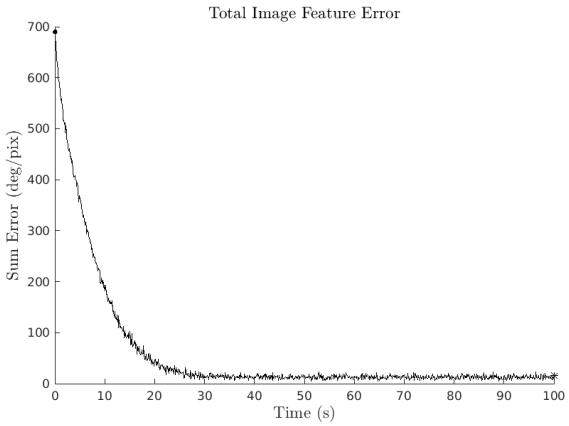


(b) 2-1 Provided Solution Error

Figure 19: Test Case 2, Initial Condition 1: Provided Solution

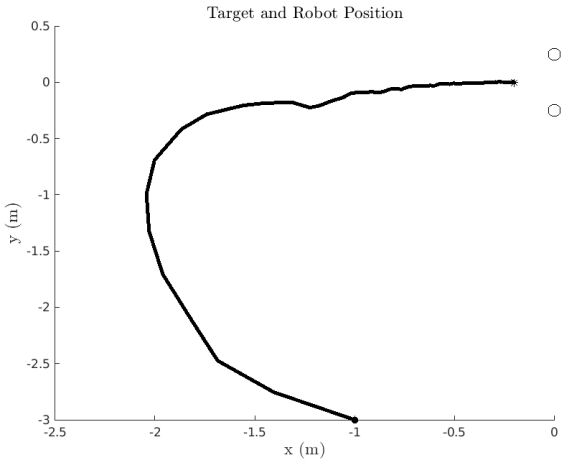


(a) 1-2 Provided Solution Trajectory

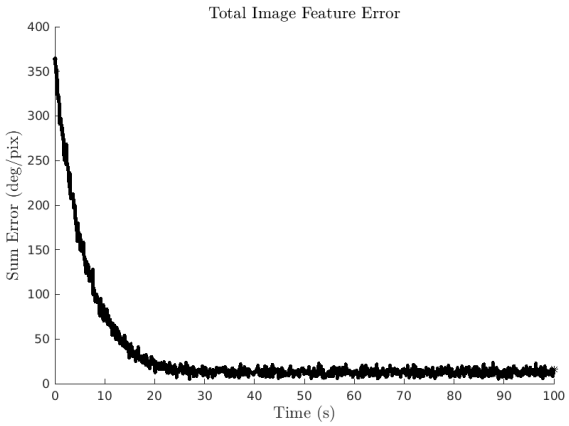


(b) 1-2 Provided Solution Error

Figure 20: Test Case 2, Initial Condition 2: Provided Solution

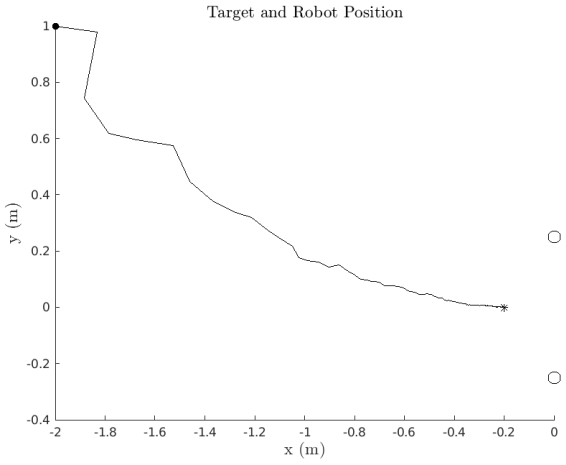


(a) 2-3 Provided Solution Trajectory

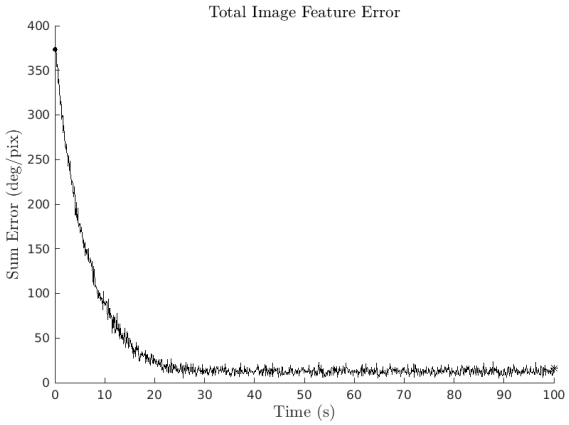


(b) 2-3 Provided Solution Error

Figure 21: Test Case 2, Initial Condition 3: Provided Solution



(a) 1-4 Provided Solution Trajectory



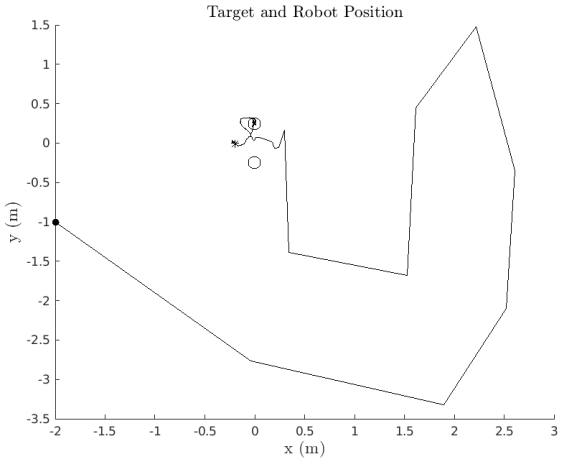
(b) 1-4 Provided Solution Error

Figure 22: Test Case 2, Initial Condition 4: Provided Solution

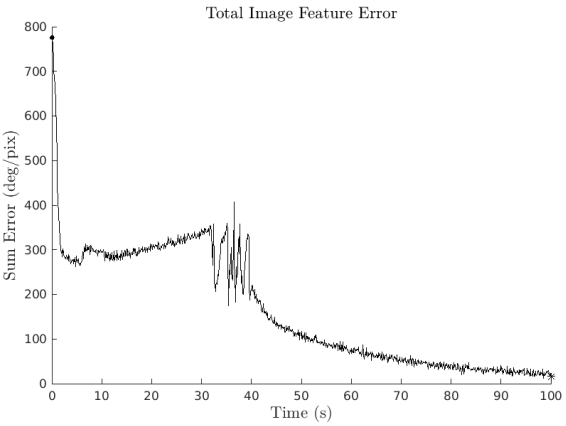
	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	180.063	0.0050248	16.3357
Start Case 2	95.1837	0.005025	16.3356
Start Case 3	92.4306	0.0050249	16.3358
Start Case 4	23.9756	0.0050249	16.3358

Table 5: Test Case 2 Provided System Performance

3.2.2 PID Control Performance

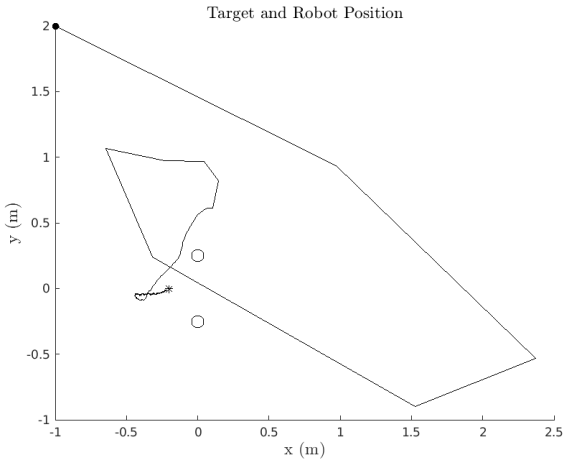


(a) 2-1 PID Controller Trajectory

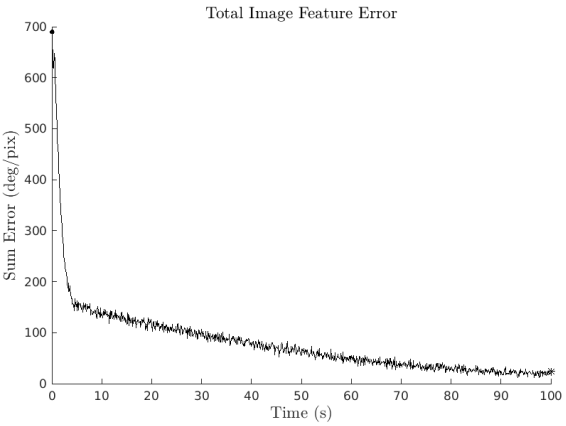


(b) 2-1 PID Controller Error

Figure 23: Test Case 2, Initial Condition 1: PID Controller

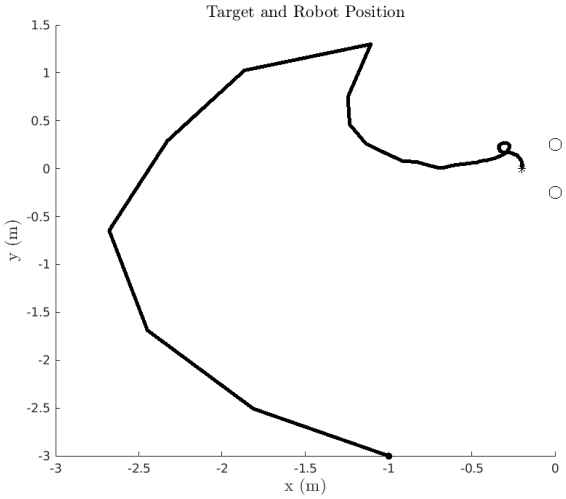


(a) 2-2 PID Controller Trajectory

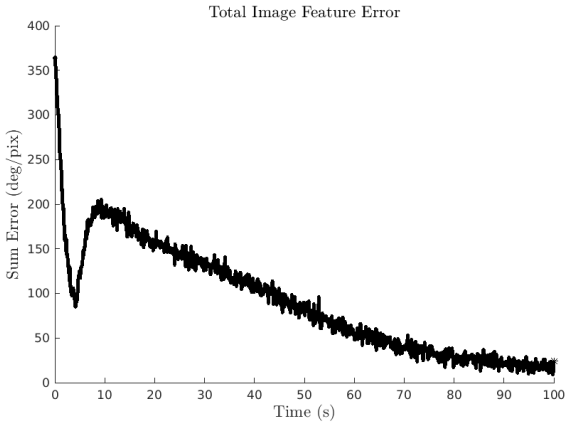


(b) 2-2 PID Controller Error

Figure 24: Test Case 2, Initial Condition 2: PID Controller

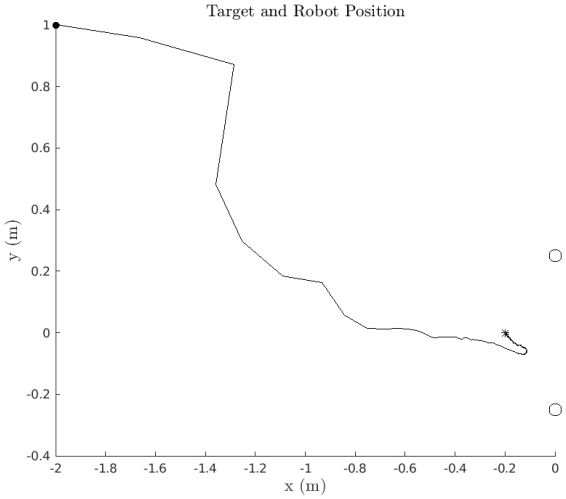


(a) 2-3 PID Controller Trajectory

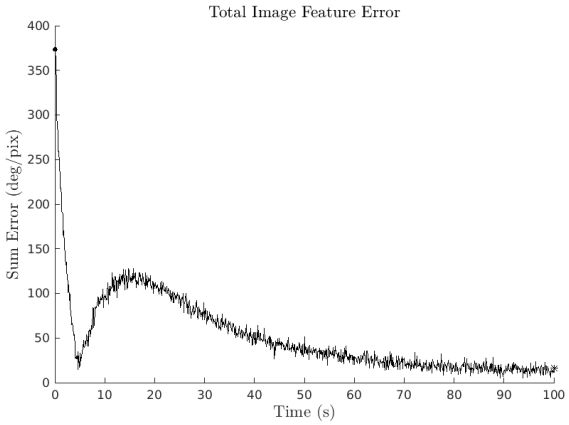


(b) 2-3 PID Controller Error

Figure 25: Test Case 2, Initial Condition 3: PID Controller



(a) 2-4 PID Controller Trajectory



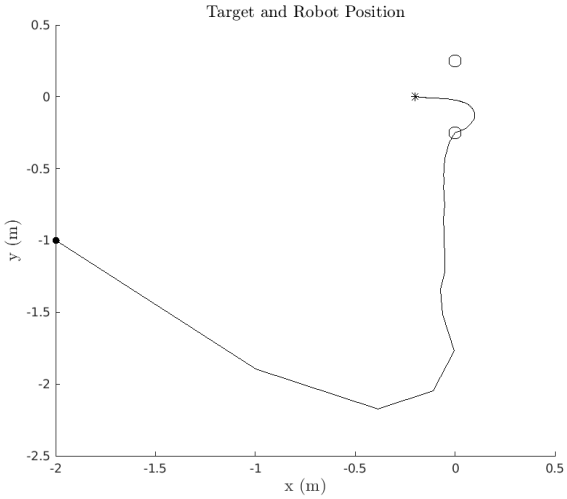
(b) 2-4 PID Controller Error

Figure 26: Test Case 2, Initial Condition 4: PID Controller

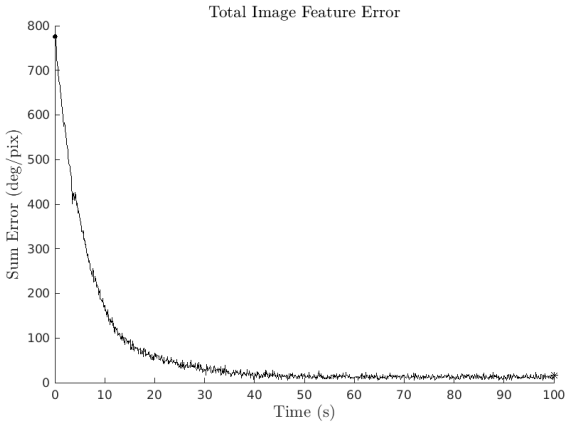
	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	1832.684	0.021011	16.7763
Start Case 2	915.644	0.011813	24.797
Start Case 3	374.702	0.012475	24.0083
Start Case 4	77.0497	0.0040368	16.6449

Table 6: Test Case 2 PID-only Performance

3.2.3 Kalman Filter Performance

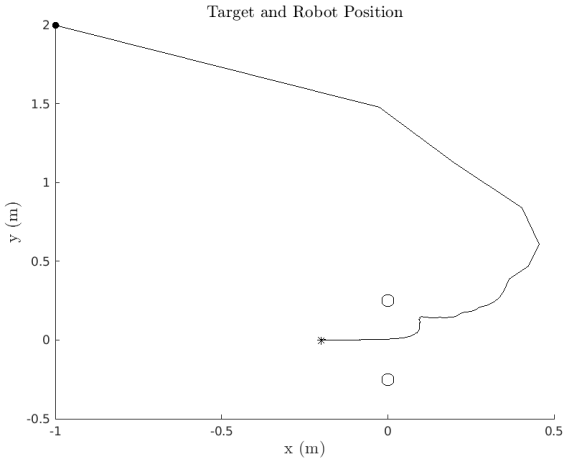


(a) 2-1 Kalman Filter Trajectory

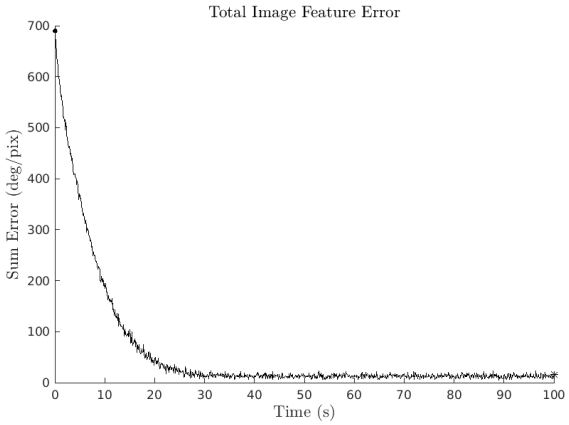


(b) 2-1 Kalman Filter Error

Figure 27: Test Case 2, Initial Condition 1: Kalman Filter

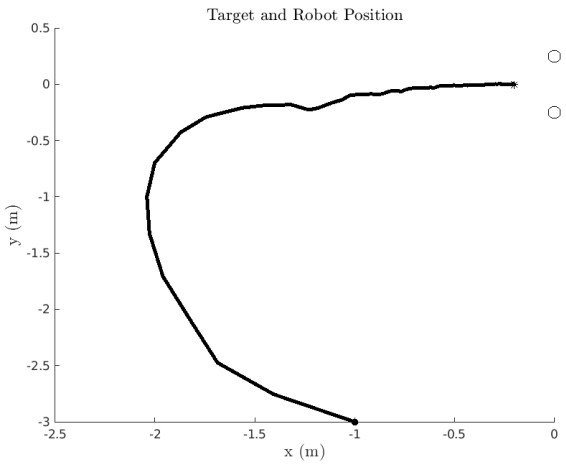


(a) 2-2 Kalman Filter Trajectory

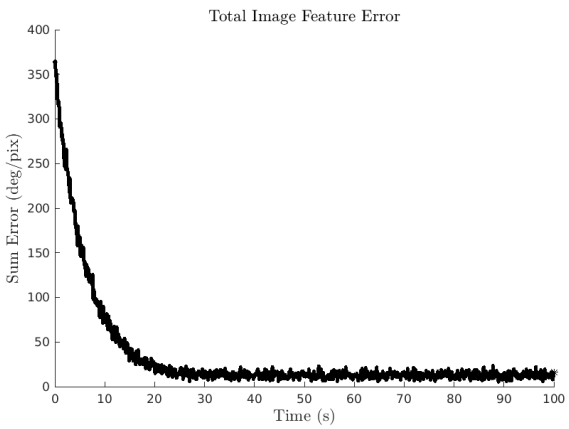


(b) 2-2 Kalman Filter Error

Figure 28: Test Case 2, Initial Condition 2: Kalman Filter

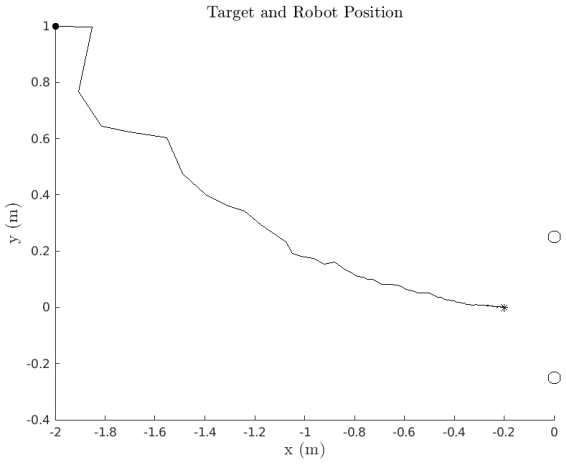


(a) 2-3 Kalman Filter Trajectory

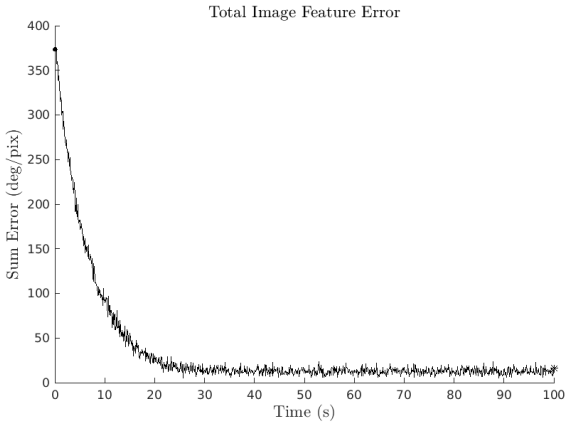


(b) 2-3 Kalman Filter Error

Figure 29: Test Case 2, Initial Condition 3: Kalman Filter



(a) 2-4 Kalman Filter Trajectory



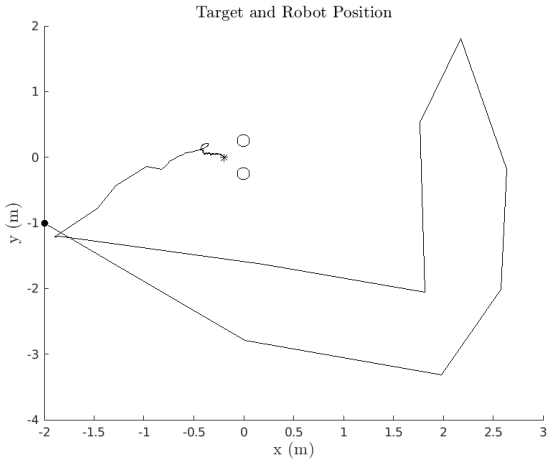
(b) 2-4 Kalman Filter Error

Figure 30: Test Case 2, Initial Condition 4: Kalman Filter

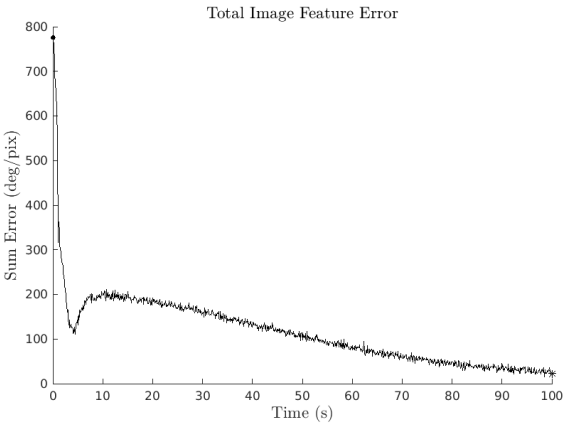
	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	183.8961	0.0056205	16.057
Start Case 2	94.3981	0.0054807	16.1138
Start Case 3	91.9945	0.005498	16.1069
Start Case 4	23.8046	0.005494	16.1085

Table 7: Test Case 2 Kalman Filter-only Performance

3.2.4 Full System Performance

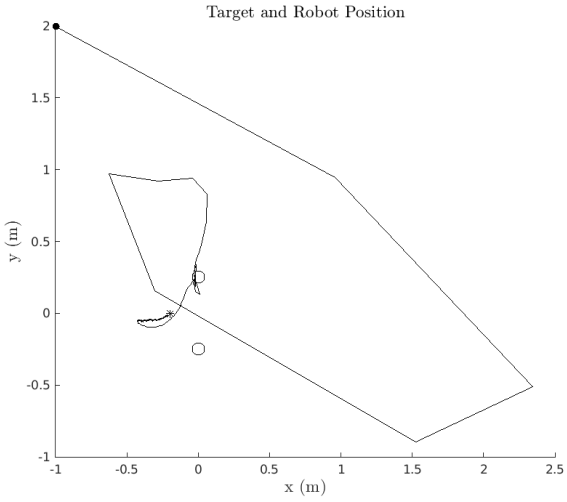


(a) 2-1 Full Solution Trajectory

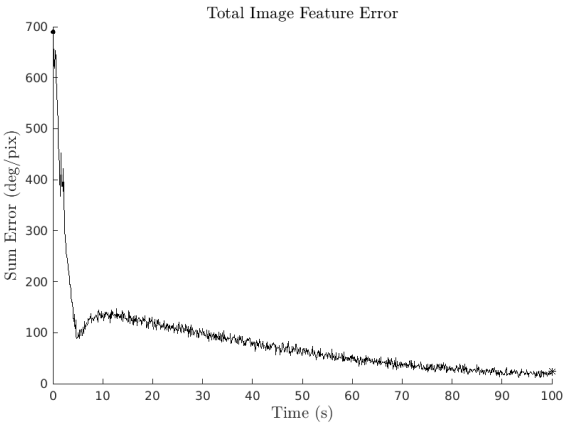


(b) 2-1 Full Solution Error

Figure 31: Test Case 2, Initial Condition 1: Full Solution

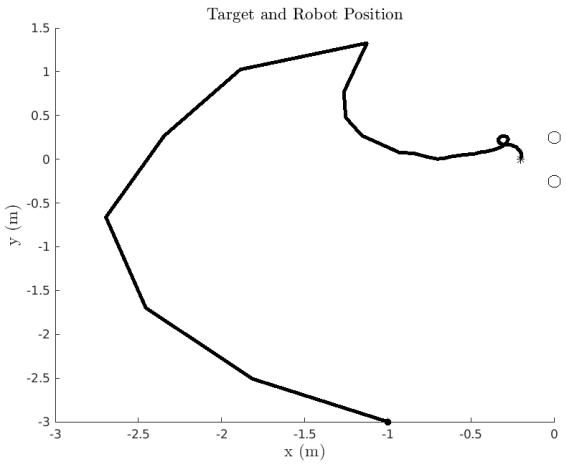


(a) 2-2 Full Solution Trajectory

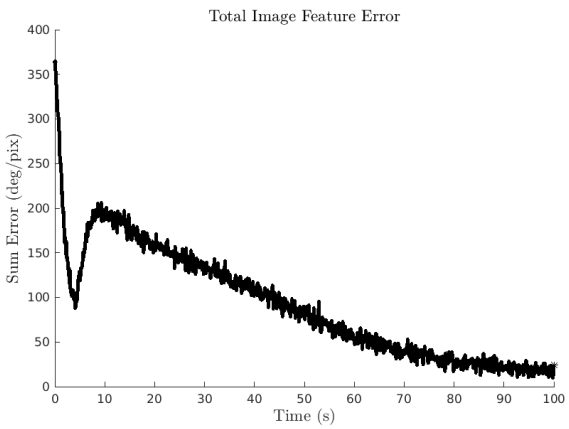


(b) 2-2 Full Solution Error

Figure 32: Test Case 2, Initial Condition 2: Full Solution

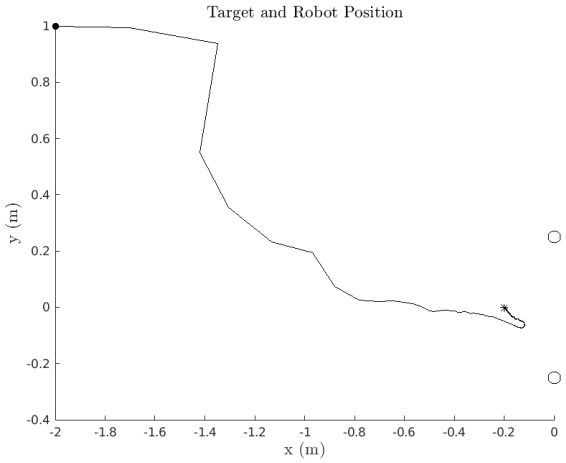


(a) 2-3 Full Solution Trajectory

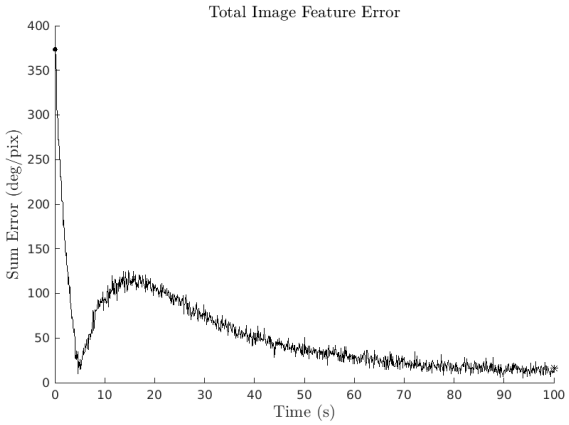


(b) 2-3 Full Solution Error

Figure 33: Test Case 2, Initial Condition 3: Full Solution



(a) 2-4 Full Solution Trajectory



(b) 2-4 Full Solution Error

Figure 34: Test Case 2, Initial Condition 4: Full Solution

	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	2494.1255	0.025186	23.68
Start Case 2	877.7686	0.011315	24.3959
Start Case 3	377.2159	0.012475	24.3089
Start Case 4	76.1943	0.0041518	16.0461

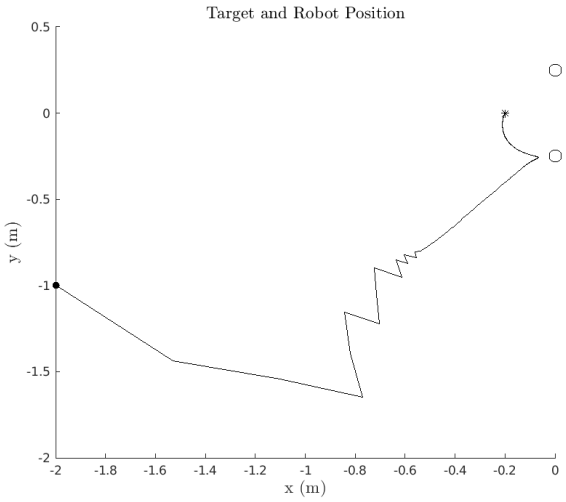
Table 8: Test Case 2 Full System Performance

3.2.5 Test Case 2 Summary and Observations

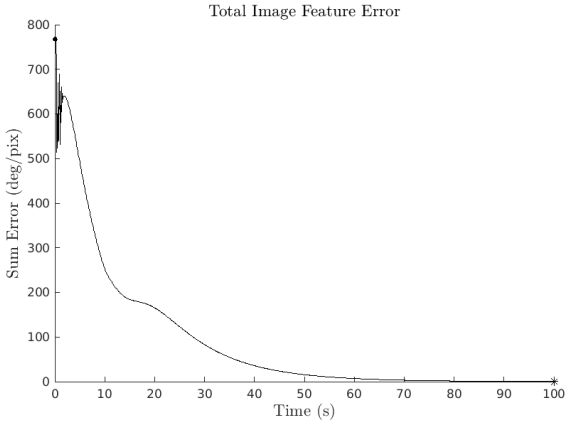
With the addition of measurement error, we see some marginal total image feature error improvement with the incorporation of a Kalman filter. While the energy and final position error are slightly degraded, they are still comparable. However, the gain in image feature error is not sufficient to justify it over the base case. As with the first case, the PID has huge increases in control energy, and significant increases to the final position error. The trajectories are significantly more chatoic than the provided solution, particularly in initial condition 1. The image feature error does become comparable, however, though there is still some distance to the existing controller's performance. Interestingly, though the Kalman filter provides marginal benefit to the base case, the full system performance has worse performance in the first starting position than the PID-only test.

3.3 Test Case 3 - Range Error

3.3.1 Provided Solution Performance

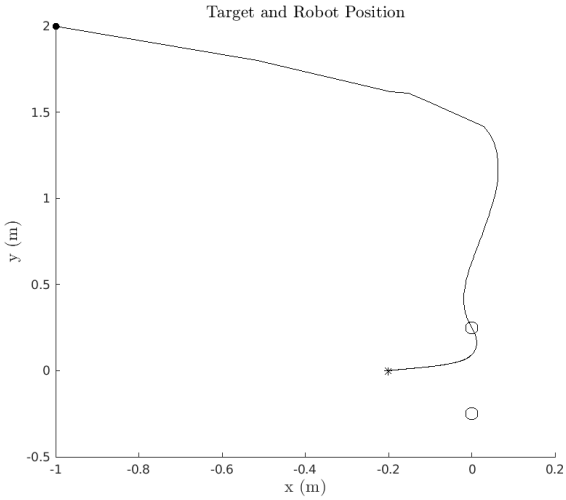


(a) 3-1 Provided Solution Trajectory

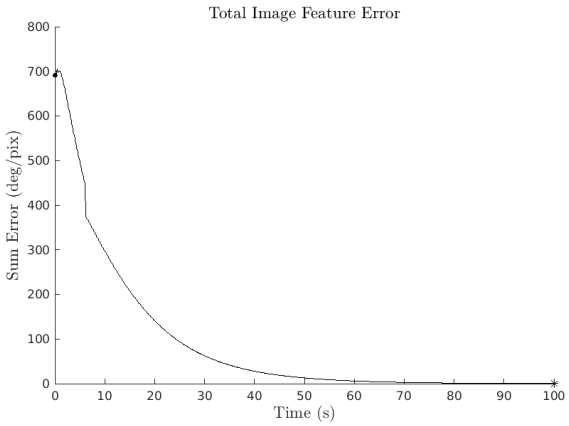


(b) 3-1 Provided Solution Error

Figure 35: Test Case 3, Initial Condition 1: Provided Solution

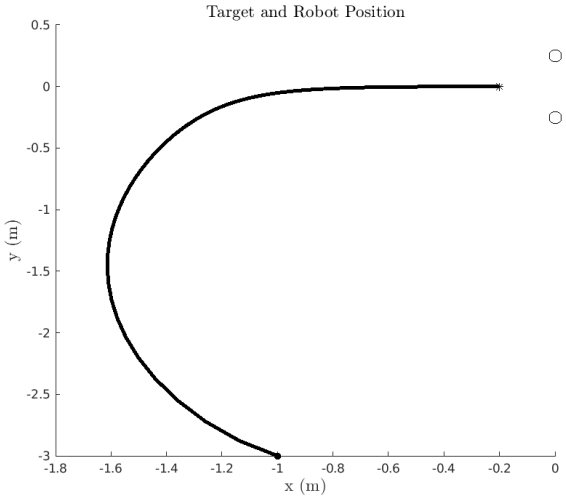


(a) 3-2 Provided Solution Trajectory

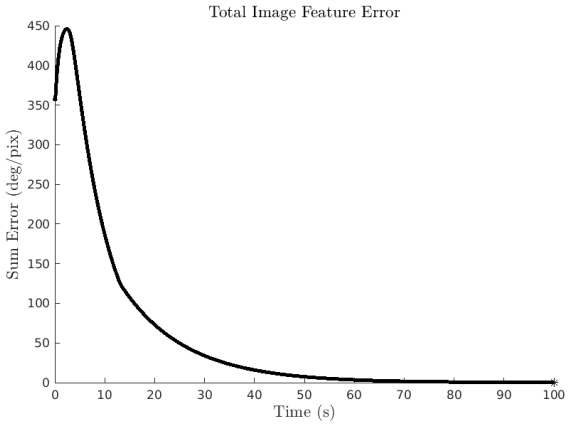


(b) 3-2 Provided Solution Error

Figure 36: Test Case 3, Initial Condition 2: Provided Solution

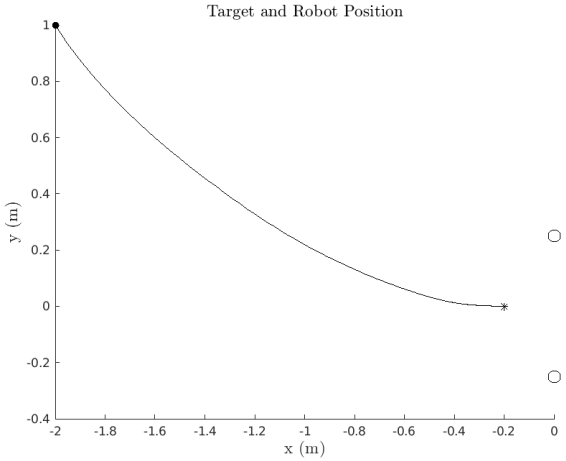


(a) 3-3 Provided Solution Trajectory

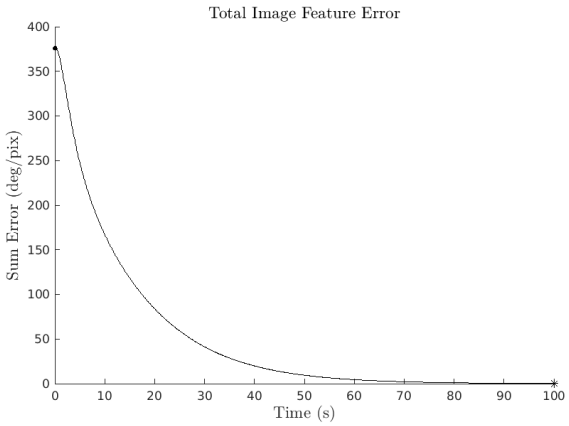


(b) 3-3 Provided Solution Error

Figure 37: Test Case 3, Initial Condition 3: Provided Solution



(a) 3-4 Provided Solution Trajectory



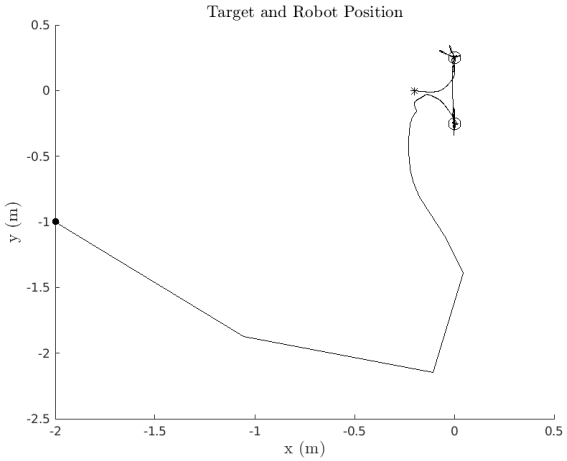
(b) 3-4 Provided Solution Error

Figure 38: Test Case 3, Initial Condition 4: Provided Solution

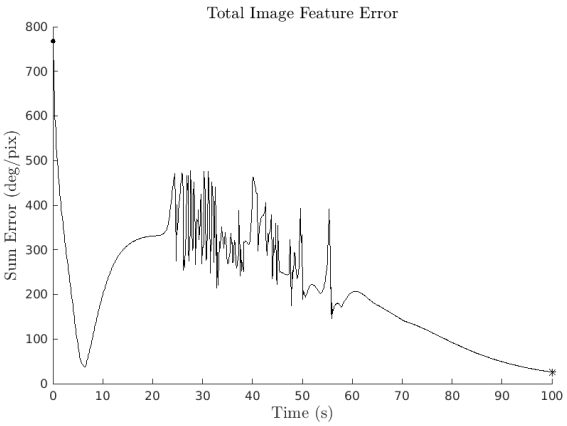
	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	66.162	0.00031049	0.32857
Start Case 2	35.4883	0.00023727	0.29359
Start Case 3	24.7377	0.00012756	0.17225
Start Case 4	9.0954	0.00018078	0.22087

Table 9: Test Case 3 Provided System Performance

3.3.2 PID Control Performance

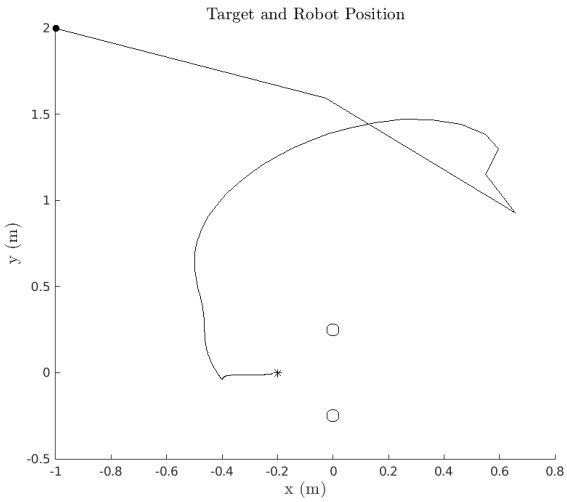


(a) 3-1 PID Controller Trajectory

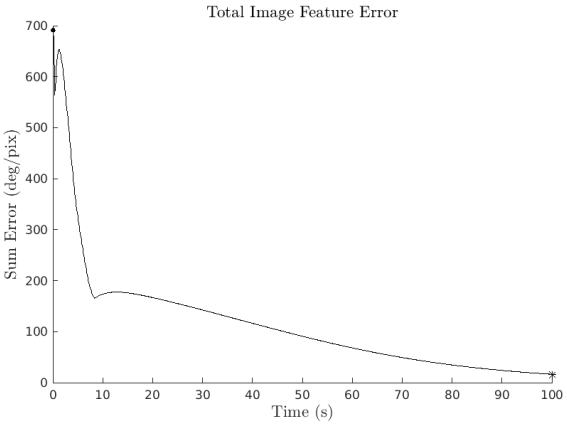


(b) 3-1 PID Controller Error

Figure 39: Test Case 3, Initial Condition 1: PID Controller

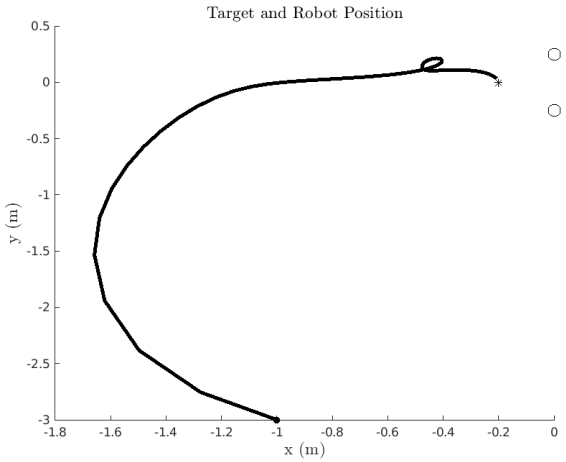


(a) 3-2 PID Controller Trajectory

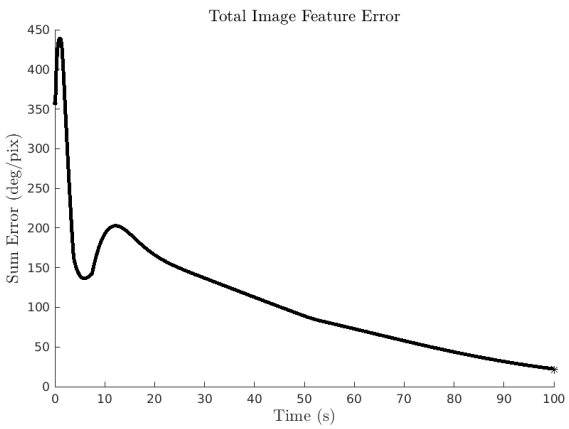


(b) 3-2 PID Controller Error

Figure 40: Test Case 3, Initial Condition 2: PID Controller

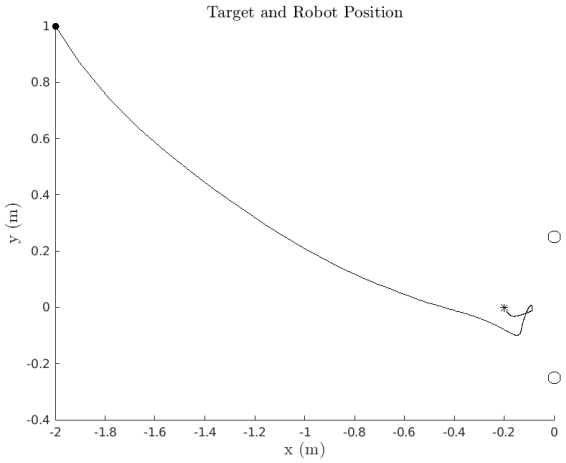


(a) 3-3 PID Controller Trajectory

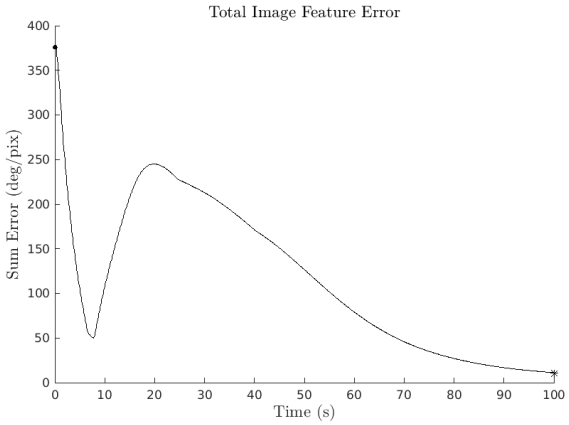


(b) 3-3 PID Controller Error

Figure 41: Test Case 3, Initial Condition 1: PID Controller



(a) 3-4 PID Controller Trajectory



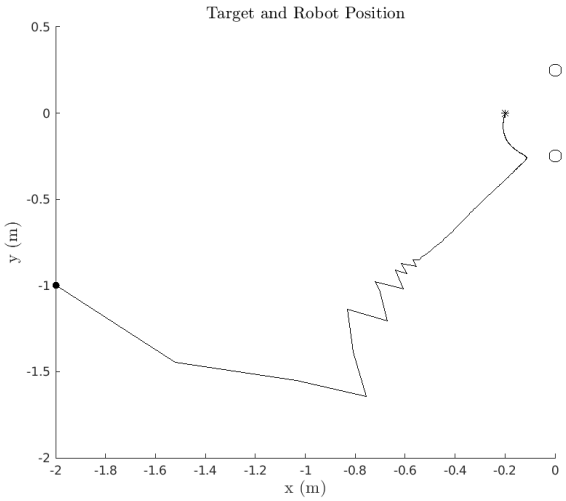
(b) 3-4 PID Controller Error

Figure 42: Test Case 3, Initial Condition 4: PID Controller

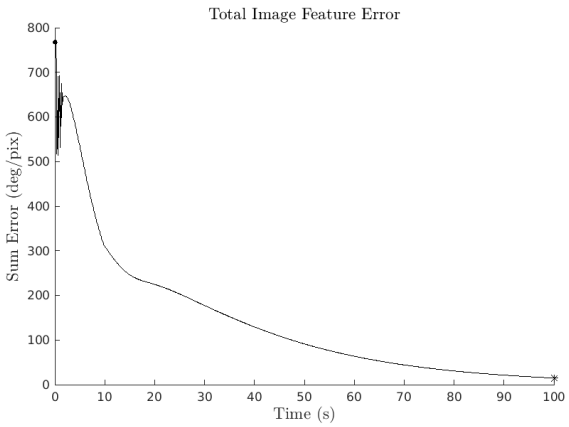
	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	236.9774	0.024346	25.9236
Start Case 2	140.1258	0.013866	16.4307
Start Case 3	63.8522	0.018676	22.2782
Start Case 4	23.572	0.011455	11.1232

Table 10: Test Case 3 PID-only Performance

3.3.3 Kalman Filter Performance

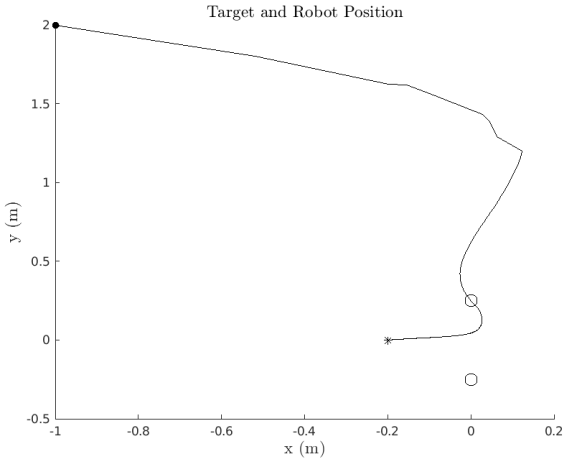


(a) 3-1 Kalman Filter Trajectory

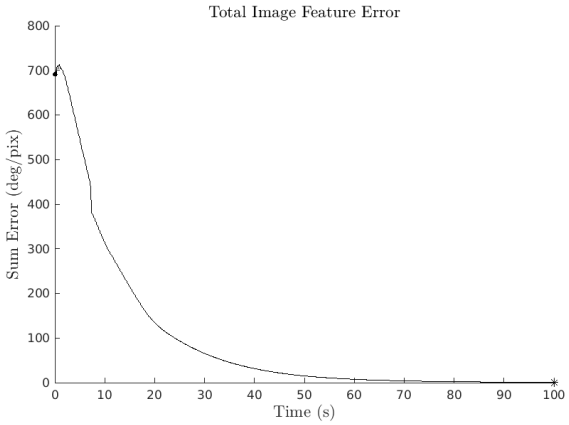


(b) 3-1 Kalman Filter Error

Figure 43: Test Case 3, Initial Condition 1: Kalman Filter

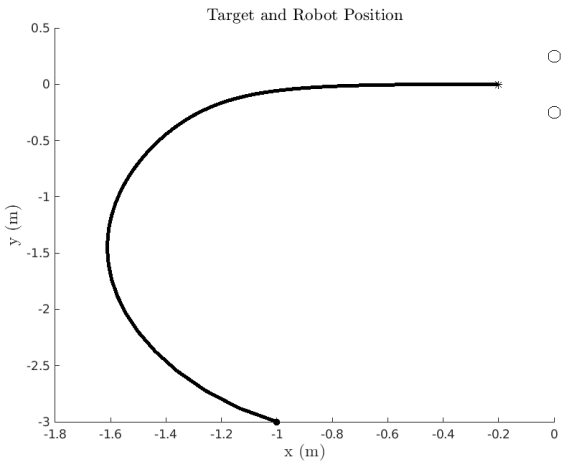


(a) 3-2 Kalman Filter Trajectory

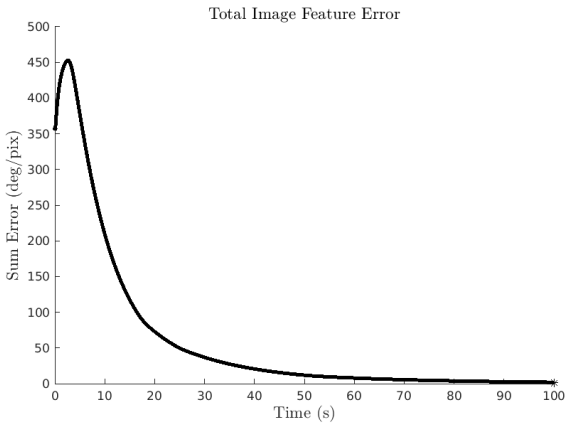


(b) 3-2 Kalman Filter Error

Figure 44: Test Case 3, Initial Condition 2: Kalman Filter

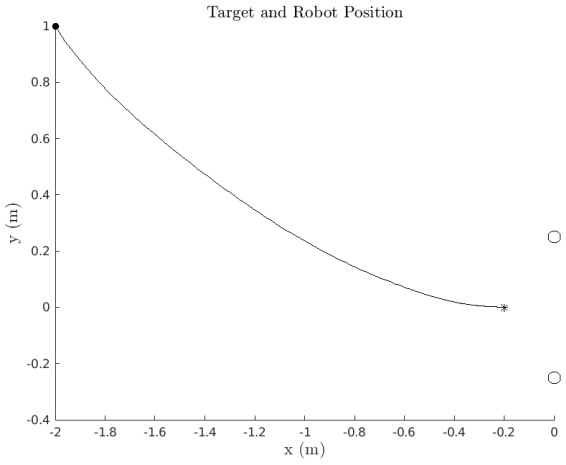


(a) 3-3 Kalman Filter Trajectory

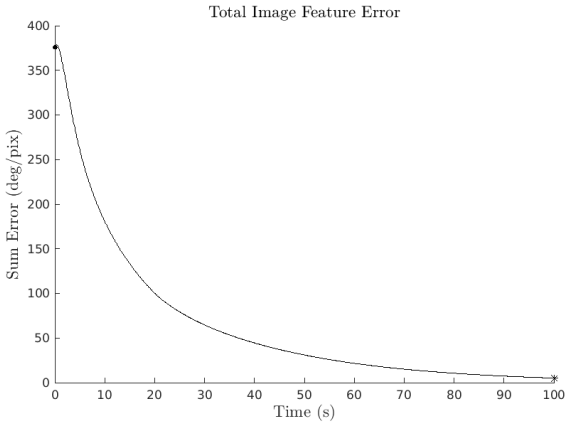


(b) 3-3 Kalman Filter Error

Figure 45: Test Case 3, Initial Condition 3: Kalman Filter



(a) 3-4 Kalman Filter Trajectory



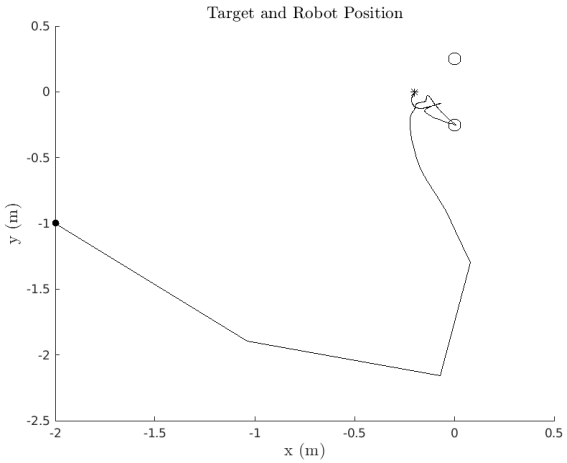
(b) 3-4 Kalman Filter Error

Figure 46: Test Case 3, Initial Condition 4: Kalman Filter

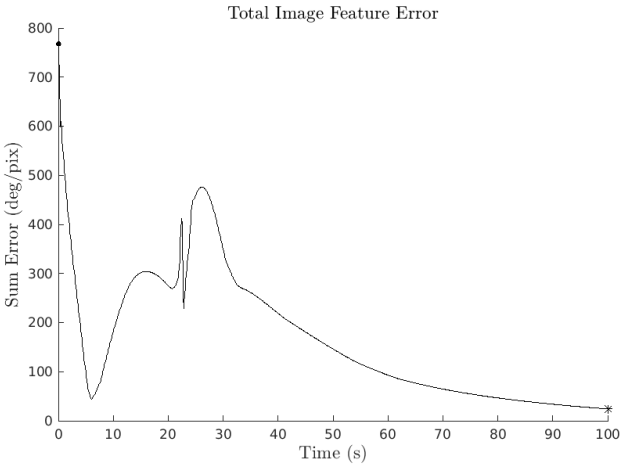
	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	67.1709	0.011158	14.8509
Start Case 2	34.8971	0.00065305	0.7208
Start Case 3	24.724	0.0014181	1.8391
Start Case 4	8.857	0.0039333	5.1219

Table 11: Test Case 3 Kalman Filter-only Performance

3.3.4 Full System Performance

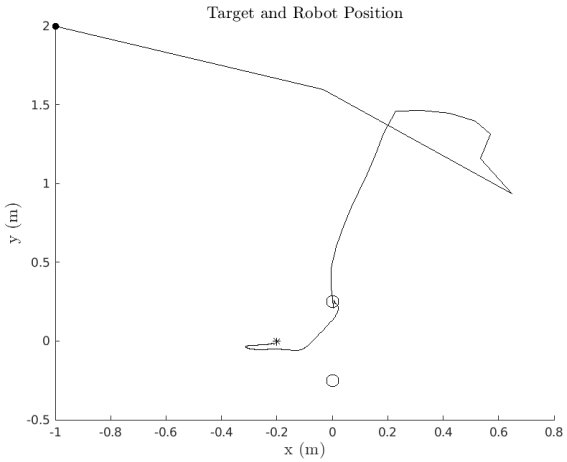


(a) 3-1 Full Solution Trajectory

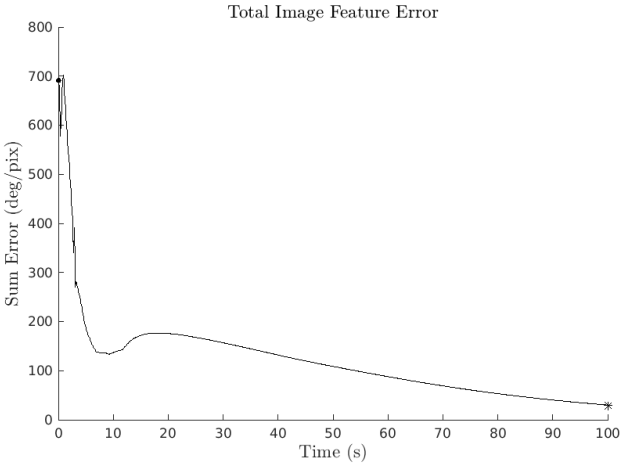


(b) 3-1 Full Solution Error

Figure 47: Test Case 3, Initial Condition 1: Full Solution

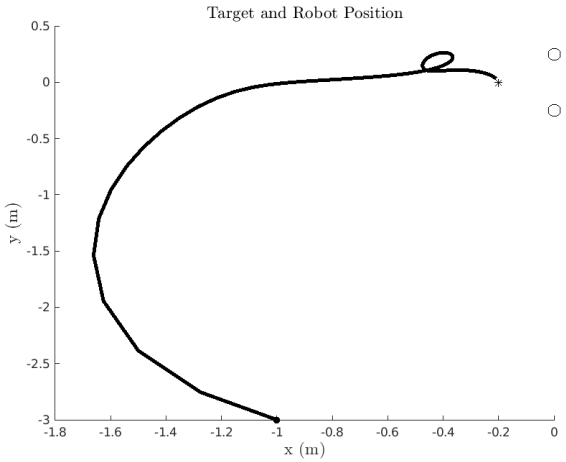


(a) 3-2 Full Solution Trajectory

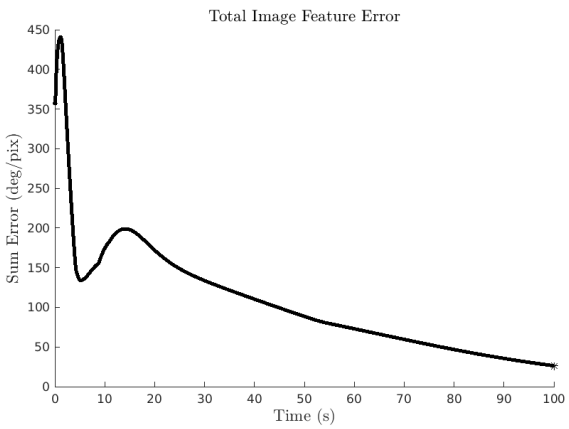


(b) 3-2 Full Solution Error

Figure 48: Test Case 3, Initial Condition 2: Full Solution

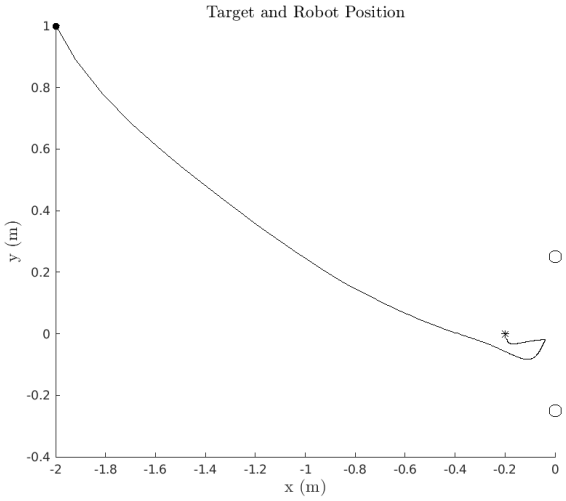


(a) 3-3 Full Solution Trajectory

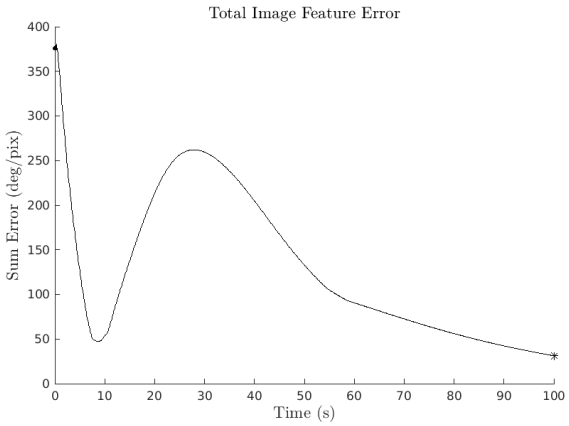


(b) 3-3 Full Solution Error

Figure 49: Test Case 3, Initial Condition 3: Full Solution



(a) 3-4 Full Solution Trajectory



(b) 3-4 Full Solution Error

Figure 50: Test Case 3, Initial Condition 4: Full Solution

	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	241.6366	0.024417	24.2283
Start Case 2	139.3364	0.023449	30.0324
Start Case 3	63.8594	0.019575	26.3178
Start Case 4	22.5317	0.02232	31.2741

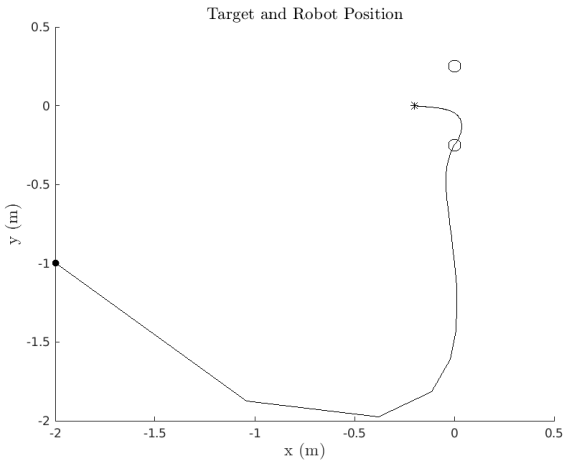
Table 12: Test Case 3 Full System Performance

3.3.5 Test Case 3 Summary and Observations

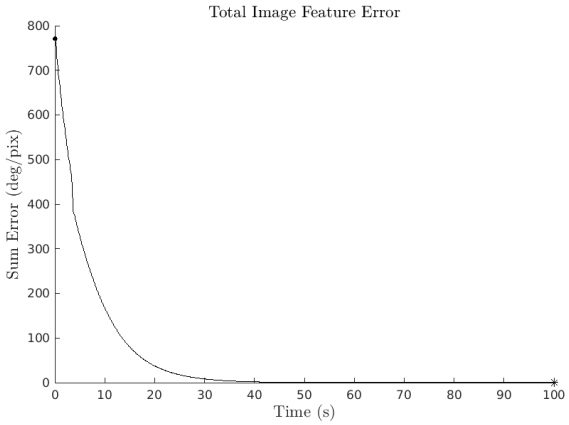
Whilst the range error has not been considered much within the context of the design of the proposed control system, its important to note the performance, especially given the poor performance of the PID controller in scenario 3-1. The Kalman filter continues to provide little benefit to the provided solution, however, it greatly improves the response of the PID controller.

3.4 Test Case 4 - Feature Error

3.4.1 Provided Solution Performance

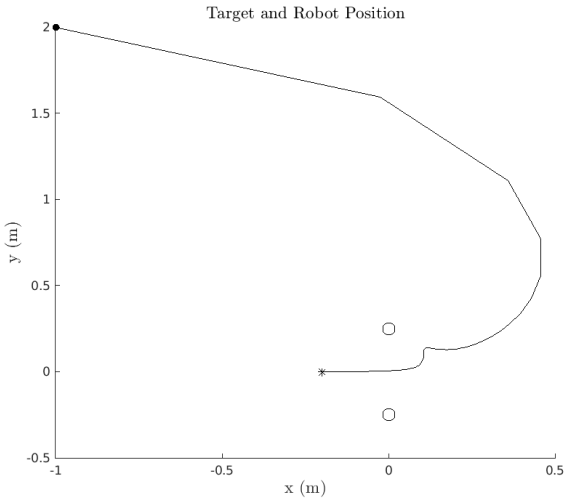


(a) 4-1 Provided Solution Trajectory



(b) 4-1 Provided Solution Error

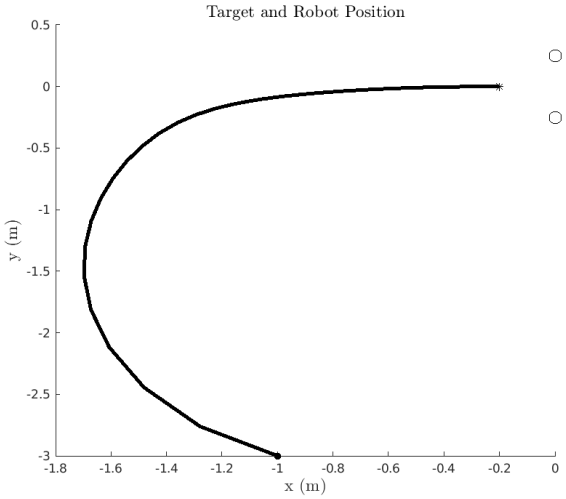
Figure 51: Test Case 4, Initial Condition 1: Provided Solution



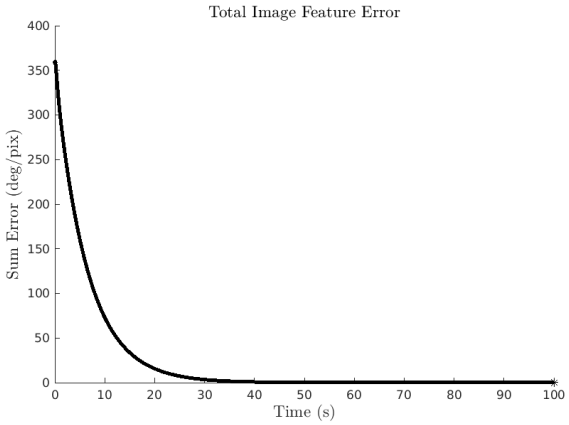
(a) 4-2 Provided Solution Trajectory

(b) 4-2 Provided Solution Error

Figure 52: Test Case 4, Initial Condition 2: Provided Solution

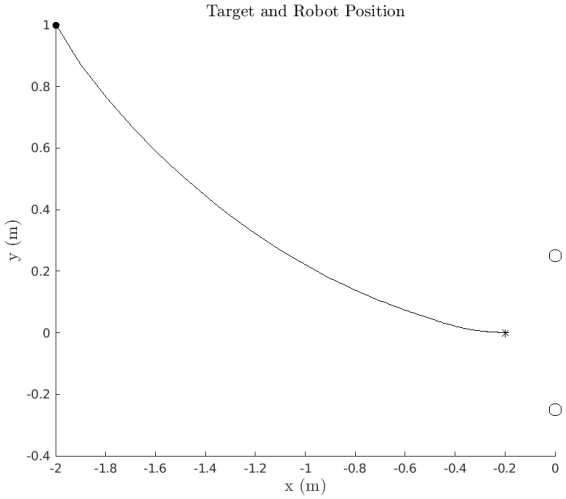


(a) 4-3 Provided Solution Trajectory

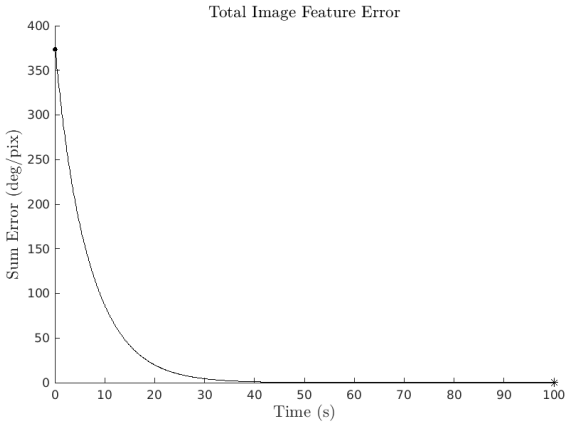


(b) 4-3 Provided Solution Error

Figure 53: Test Case 4, Initial Condition 3: Provided Solution



(a) 4-4 Provided Solution Trajectory



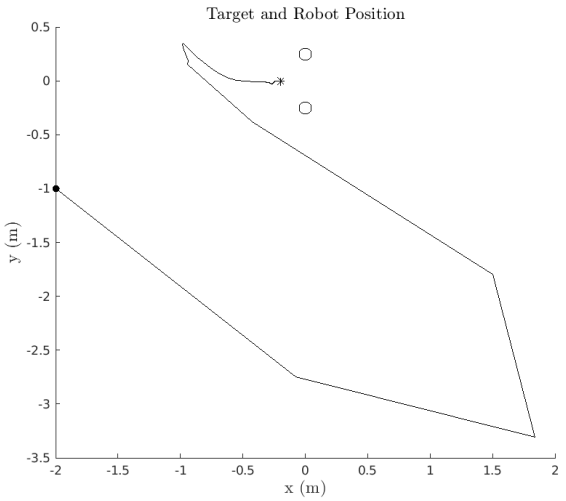
(b) 4-4 Provided Solution Error

Figure 54: Test Case 4, Initial Condition 4: Provided Solution

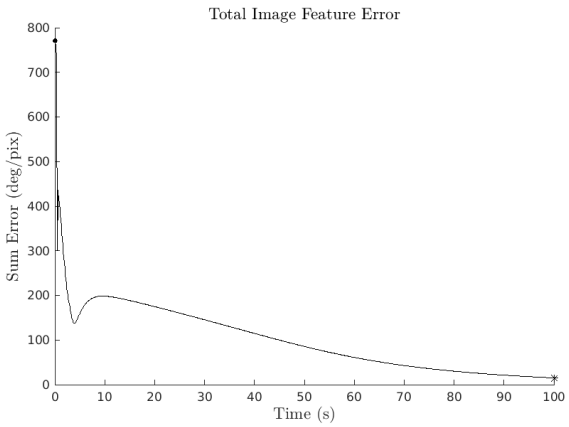
	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	173.1097	0.002975	0.021663
Start Case 2	97.0589	0.0029752	0.021672
Start Case 3	54.9008	0.0029751	0.021548
Start Case 4	19.4063	0.0029752	0.021554

Table 13: Test Case 4 Provided System Performance

3.4.2 PID Control Performance

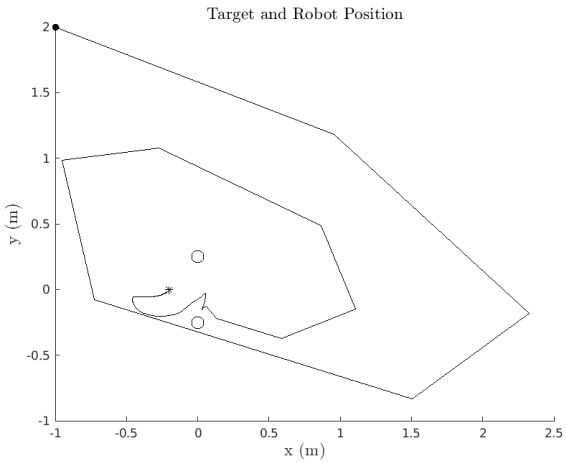


(a) 4-1 PID Controller Trajectory

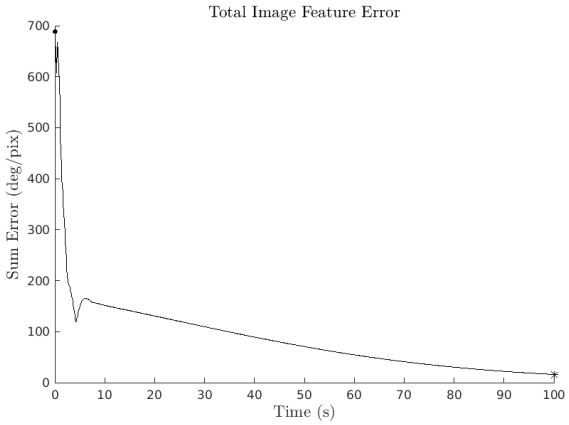


(b) 4-1 PID Controller Error

Figure 55: Test Case 4, Initial Condition 1: PID Controller

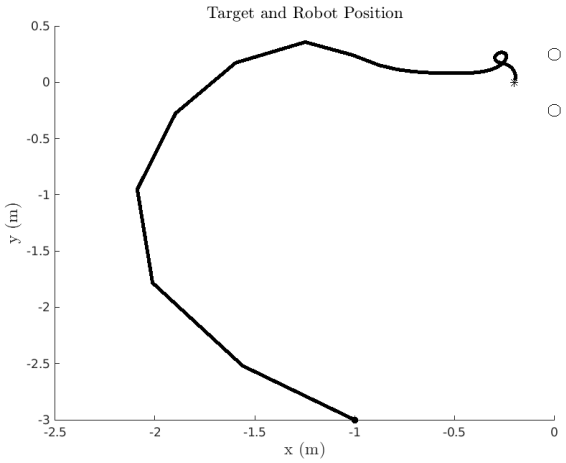


(a) 4-2 PID Controller Trajectory

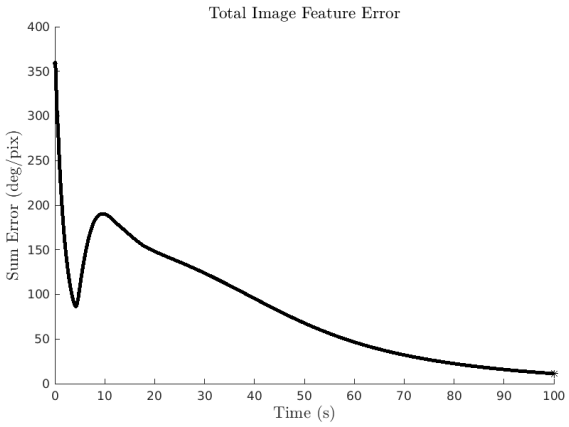


(b) 4-2 PID Controller Error

Figure 56: Test Case 4, Initial Condition 2: PID Controller

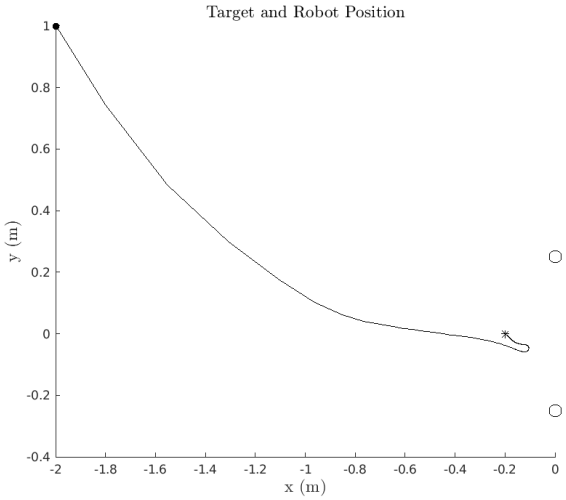


(a) 4-3 PID Controller Trajectory

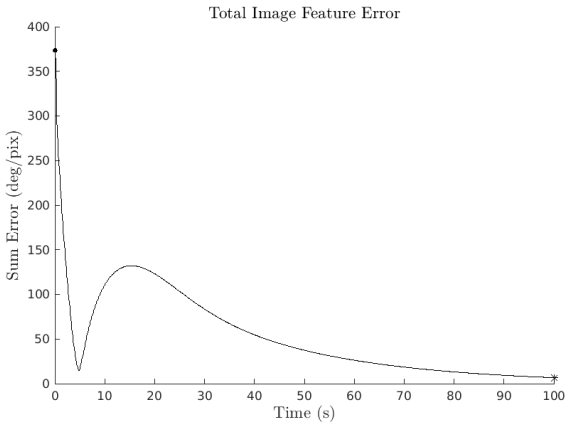


(b) 4-3 PID Controller Error

Figure 57: Test Case 4, Initial Condition 3: PID Controller



(a) 4-4 PID Controller Trajectory



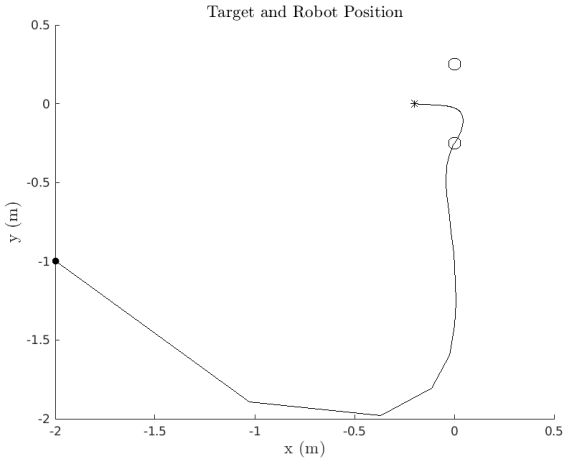
(b) 4-4 PID Controller Error

Figure 58: Test Case 4, Initial Condition 4: PID Controller

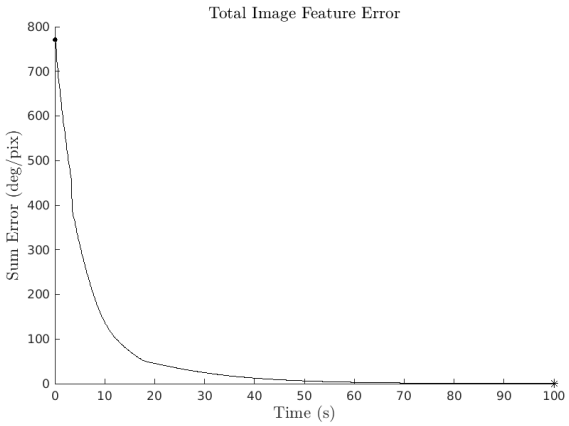
	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	1300.583	0.018362	15.1368
Start Case 2	1158.9343	0.013959	16.0412
Start Case 3	195.4008	0.0095488	11.2275
Start Case 4	63.2339	0.004209	6.6823

Table 14: Test Case 4 PID-only Performance

3.4.3 Kalman Filter Performance

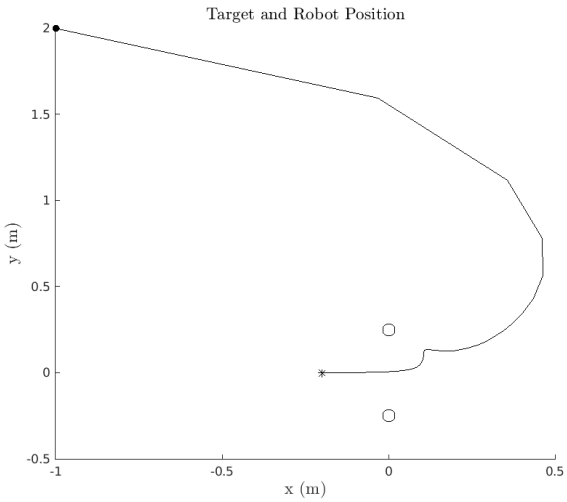


(a) 4-1 Kalman Filter Trajectory

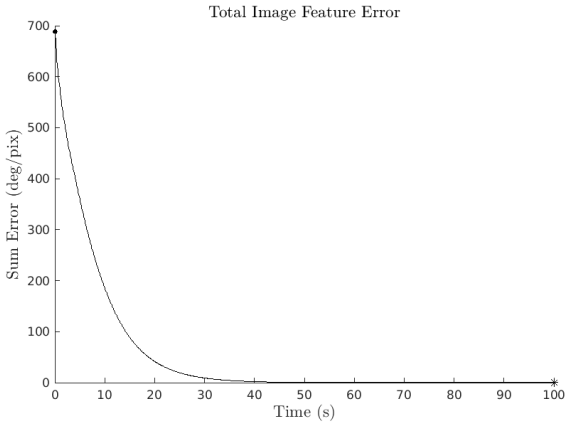


(b) 4-1 Kalman Filter Error

Figure 59: Test Case 4, Initial Condition 1: Kalman Filter

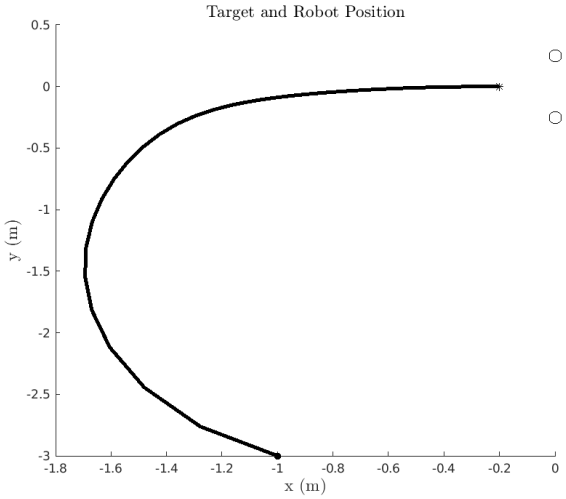


(a) 4-2 Kalman Filter Trajectory

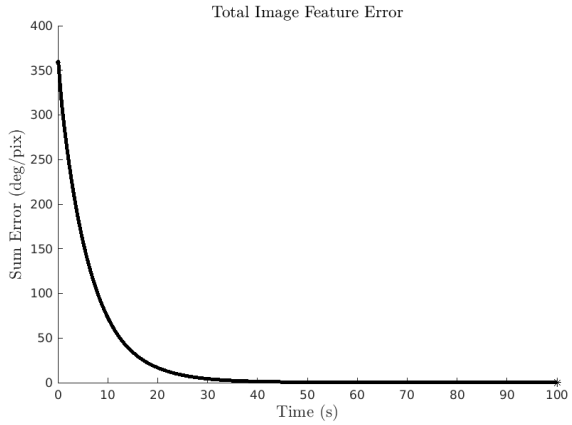


(b) 4-2 Kalman Filter Error

Figure 60: Test Case 4, Initial Condition 2: Kalman Filter

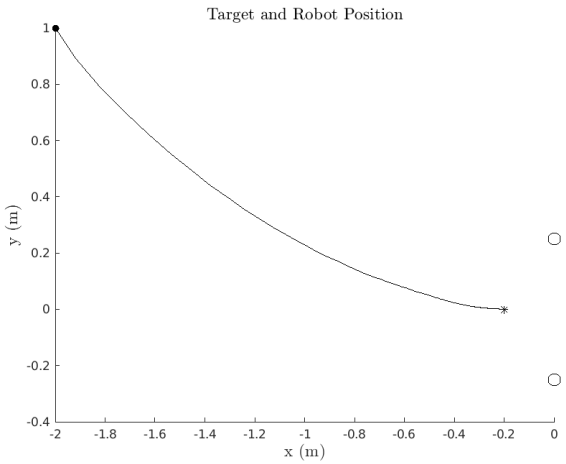


(a) 4-3 Kalman Filter Trajectory

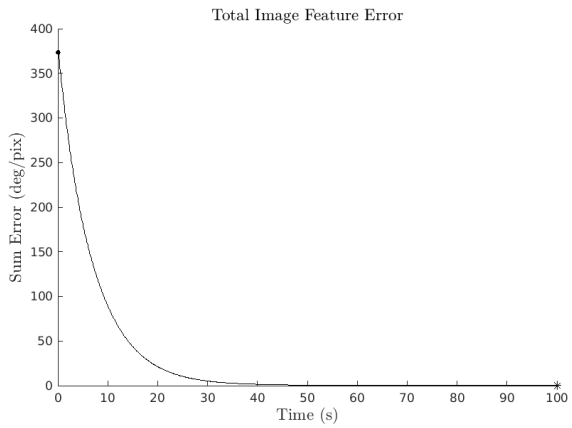


(b) 4-3 Kalman Filter Error

Figure 61: Test Case 4, Initial Condition 3: Kalman Filter



(a) 4-4 Kalman Filter Trajectory



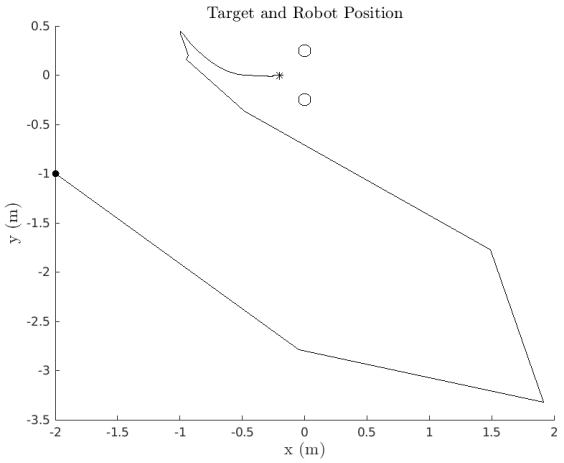
(b) 4-4 Kalman Filter Error

Figure 62: Test Case 4, Initial Condition 4: Kalman Filter

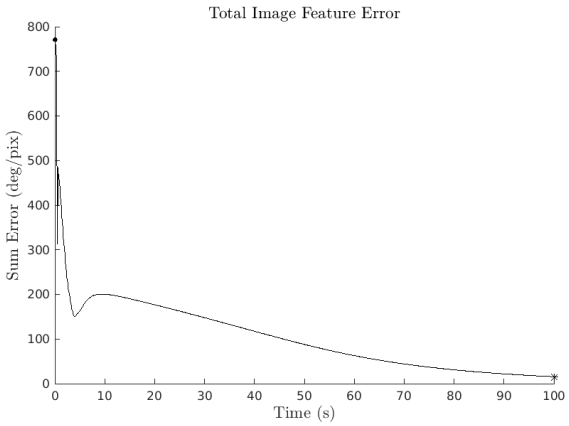
	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	177.0428	0.0030911	0.17992
Start Case 2	96.4188	0.002975	0.021668
Start Case 3	54.5592	0.0029856	0.023783
Start Case 4	19.0964	0.0029824	0.021668

Table 15: Test Case 4 Kalman Filter-only Performance

3.4.4 Full System Performance

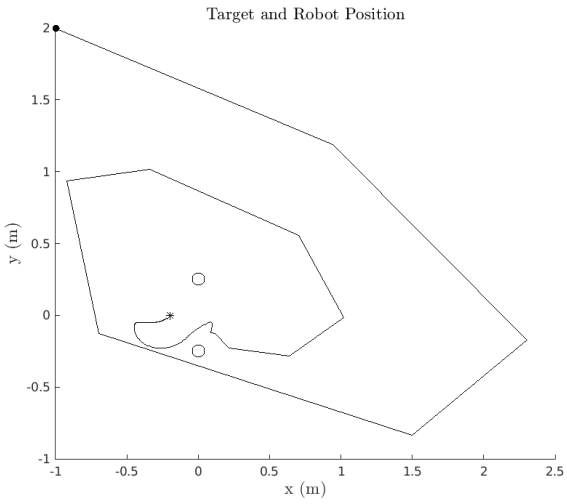


(a) 4-1 Full Solution Trajectory

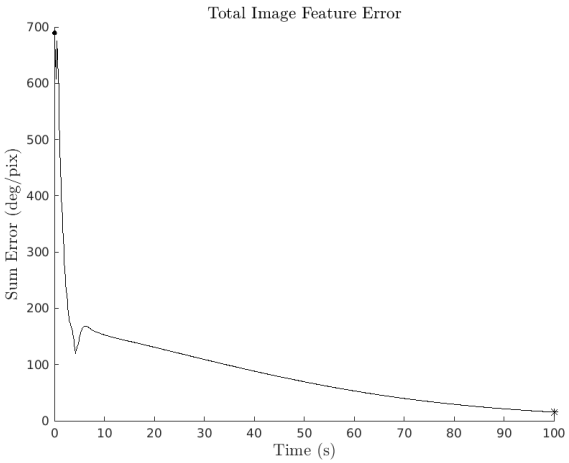


(b) 4-1 Full Solution Error

Figure 63: Test Case 4, Initial Condition 1: Full Solution

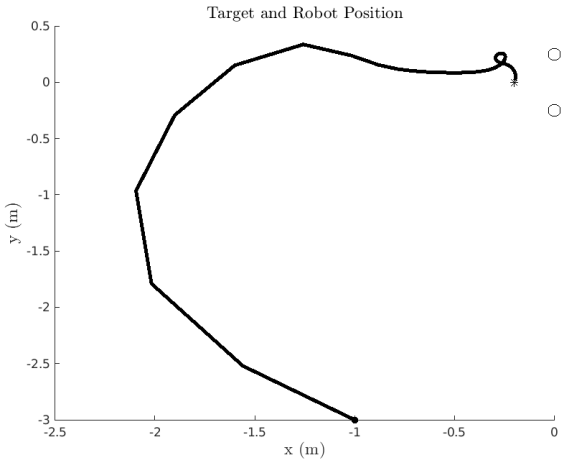


(a) 4-2 Full Solution Trajectory

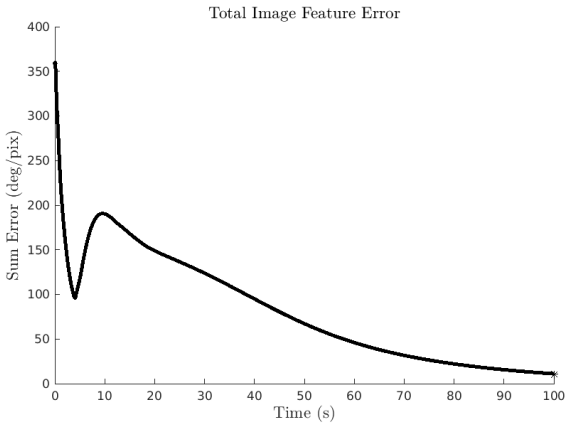


(b) 4-2 Full Solution Error

Figure 64: Test Case 4, Initial Condition 2: Full Solution

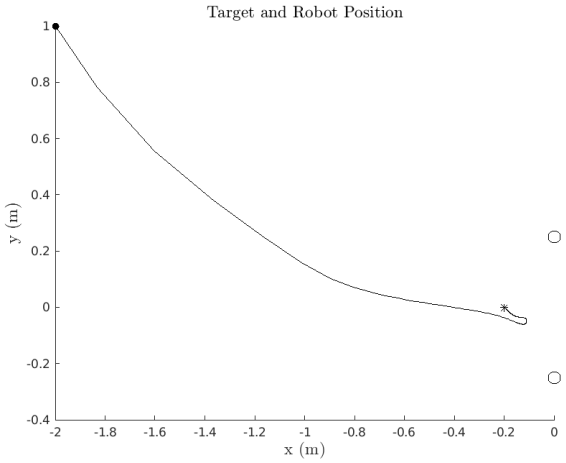


(a) 4-3 Full Solution Trajectory

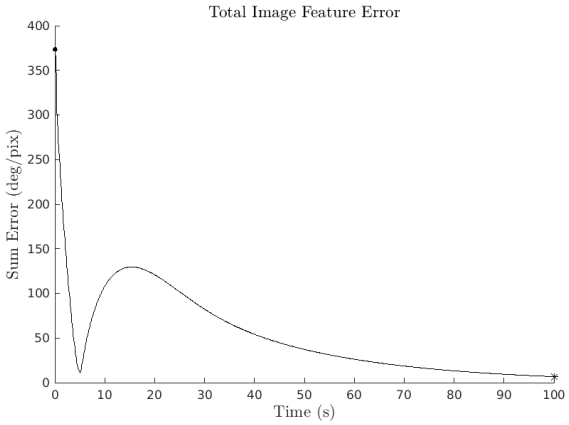


(b) 4-3 Full Solution Error

Figure 65: Test Case 4, Initial Condition 3: Full Solution



(a) 4-4 Full Solution Trajectory



(b) 4-4 Full Solution Error

Figure 66: Test Case 4, Initial Condition 4: Full Solution

	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	1360.1029	0.018809	15.5518
Start Case 2	1089.8311	0.013207	15.421
Start Case 3	193.757	0.0094096	11.0466
Start Case 4	61.1964	0.0042698	6.741

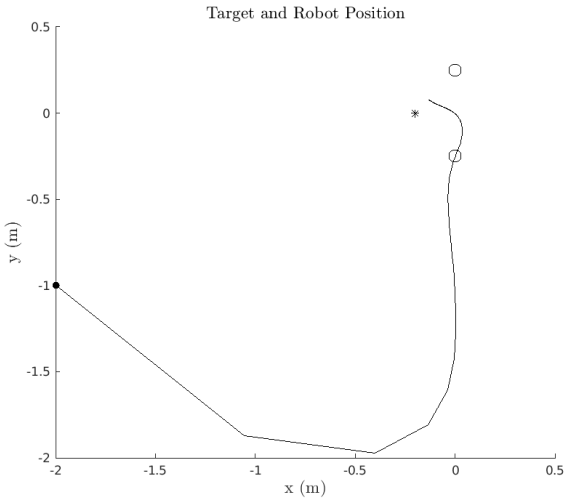
Table 16: Test Case 4 Full System Performance

3.4.5 Test Case 4 Summary and Observations

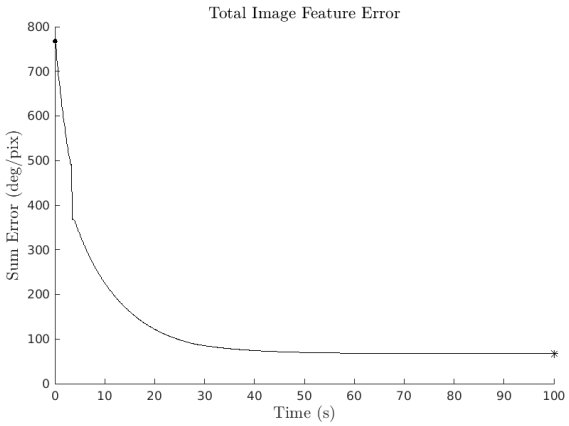
The Kalman filter performs quite well in this scenario, with performance consistent against the provided solution, while providing some marginal improvements to the PID control loop. The provided and PID controllers themselves perform very similarly to the no error case.

3.5 Test Case 5 - Wind Error

3.5.1 Provided Solution Performance

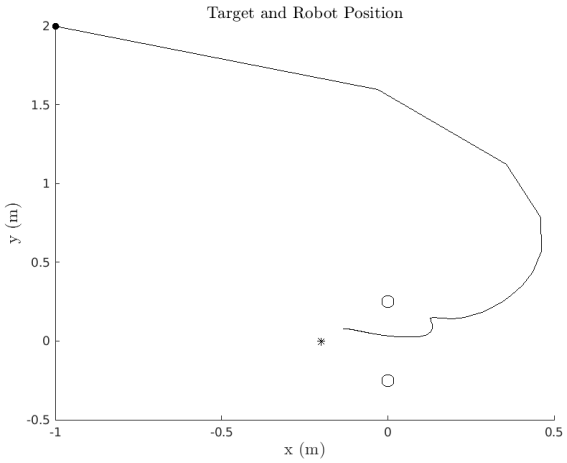


(a) 5-1 Provided Solution Trajectory

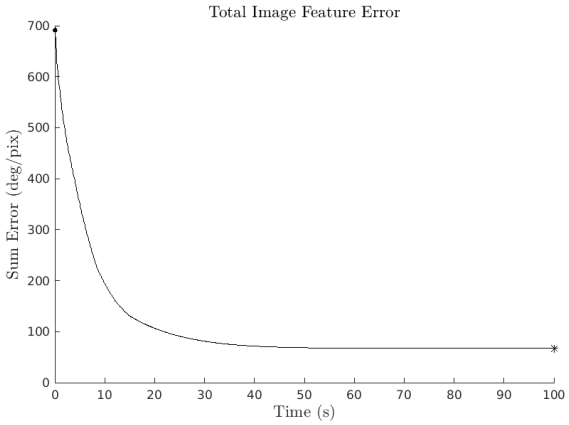


(b) 5-1 Provided Solution Error

Figure 67: Test Case 5, Initial Condition 1: Provided Solution

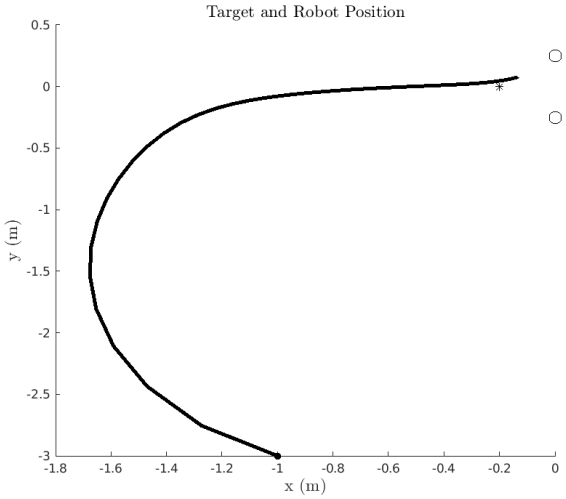


(a) 5-2 Provided Solution Trajectory

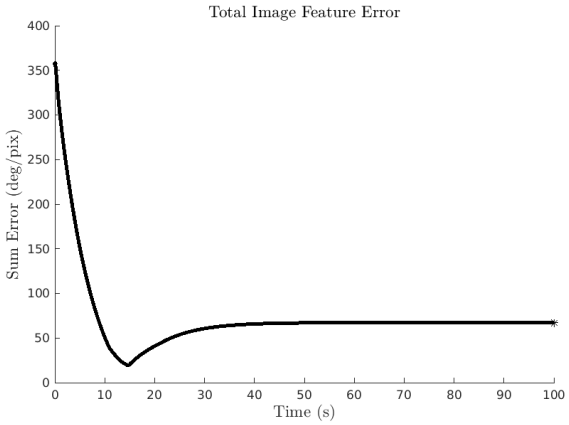


(b) 5-2 Provided Solution Error

Figure 68: Test Case 5, Initial Condition 2: Provided Solution

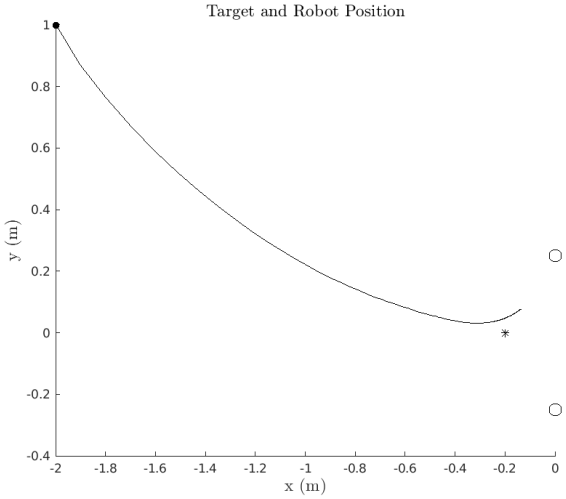


(a) 5-3 Provided Solution Trajectory

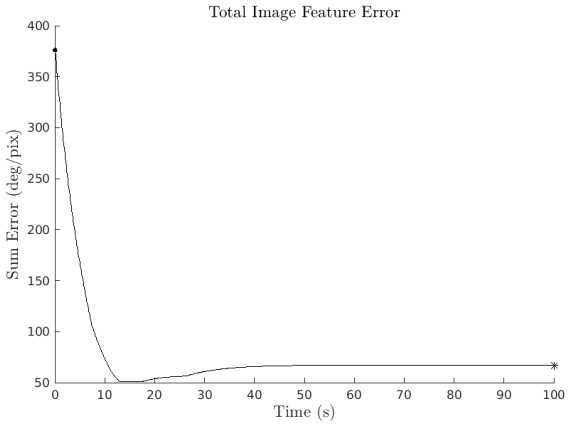


(b) 5-3 Provided Solution Error

Figure 69: Test Case 5, Initial Condition 3: Provided Solution



(a) 5-4 Provided Solution Trajectory



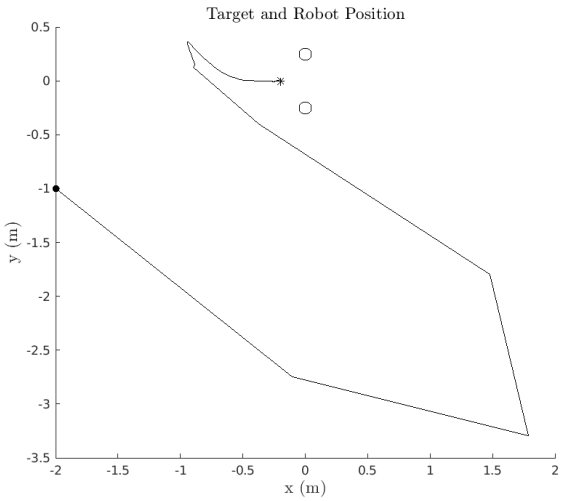
(b) 5-4 Provided Solution Error

Figure 70: Test Case 5, Initial Condition 4: Provided Solution

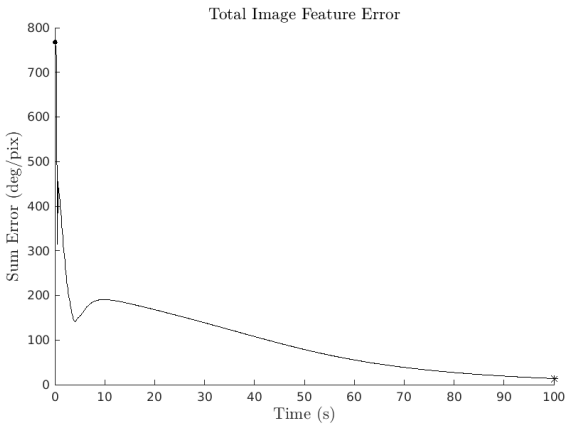
	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	170.2472	0.070049	67.2102
Start Case 2	96.3781	0.070044	67.1923
Start Case 3	54.1232	0.070043	67.1981
Start Case 4	19.6572	0.070043	67.1954

Table 17: Test Case 5 Provided System Performance

3.5.2 PID Control Performance

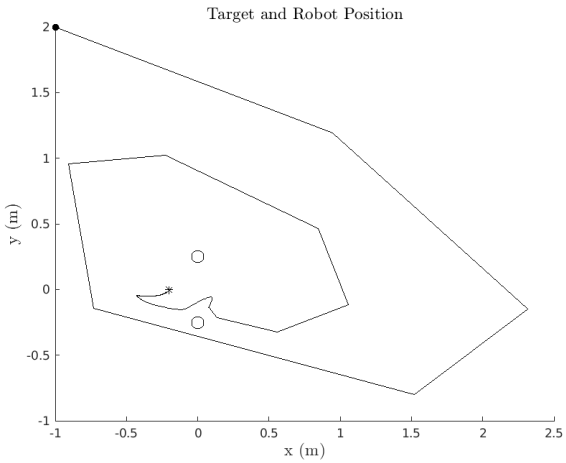


(a) 5-1 PID Controller Trajectory

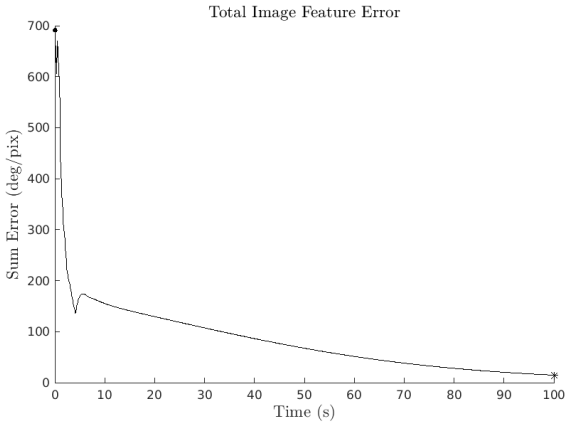


(b) 5-1 PID Controller Error

Figure 71: Test Case 5, Initial Condition 1: PID Controller

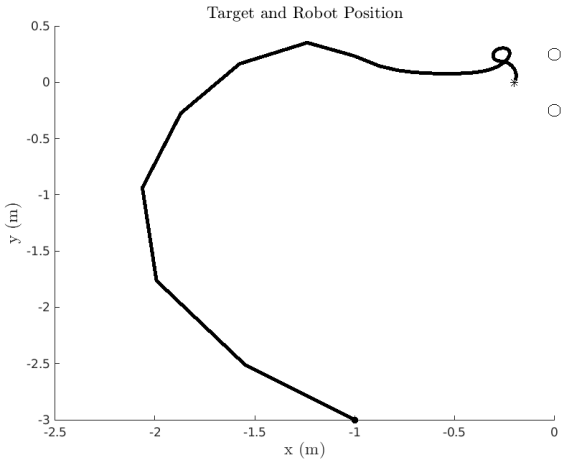


(a) 5-2 PID Controller Trajectory

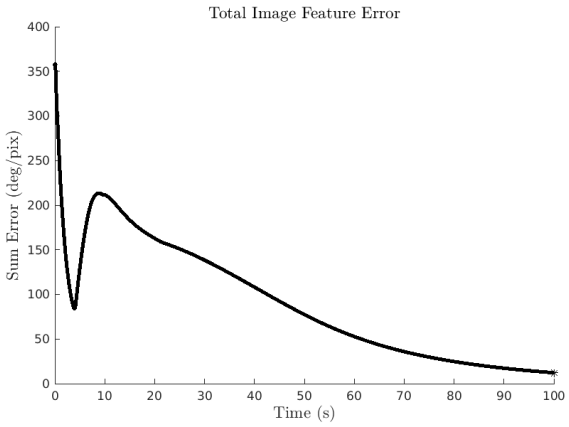


(b) 5-2 PID Controller Error

Figure 72: Test Case 5, Initial Condition 2: PID Controller

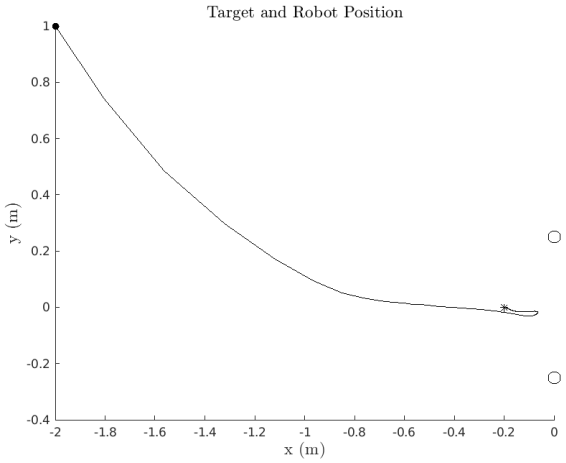


(a) 5-3 PID Controller Trajectory

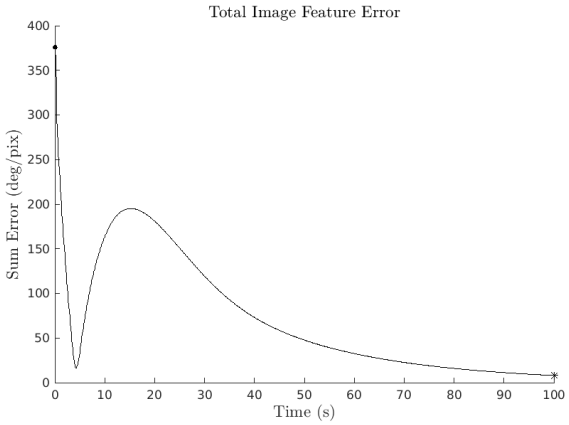


(b) 5-3 PID Controller Error

Figure 73: Test Case 5, Initial Condition 3: PID Controller



(a) 5-4 PID Controller Trajectory



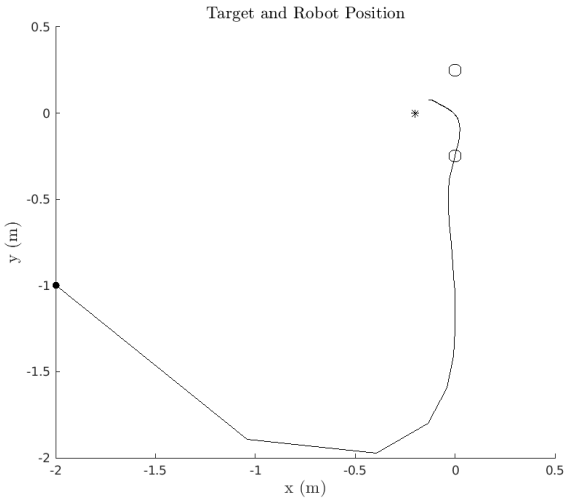
(b) 5-4 PID Controller Error

Figure 74: Test Case 5, Initial Condition 4: PID Controller

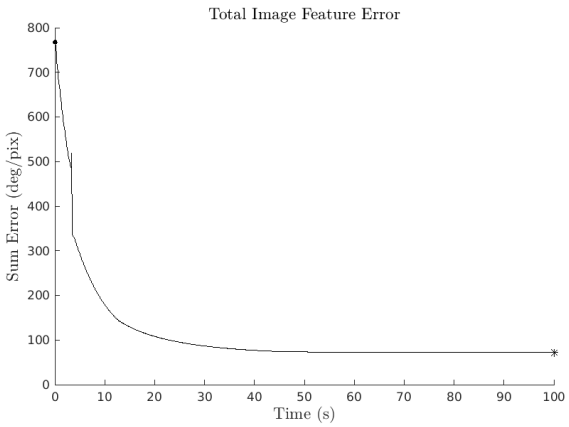
	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	1268.6685	0.014222	13.6444
Start Case 2	1137.1628	0.013625	14.711
Start Case 3	192.3807	0.010878	12.1752
Start Case 4	63.8309	0.0065976	8.0004

Table 18: Test Case 5 PID-only Performance

3.5.3 Kalman Filter Performance

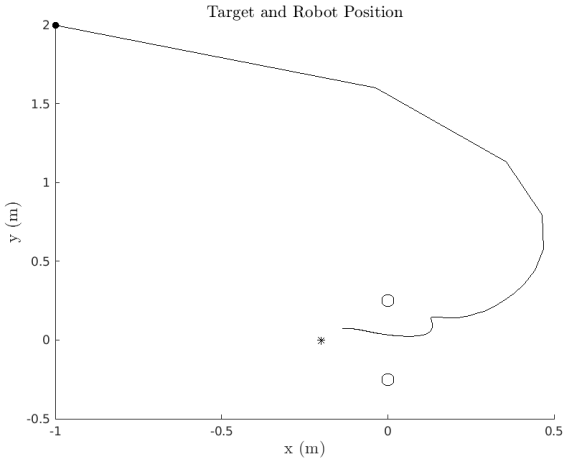


(a) 5-1 Kalman Filter Trajectory

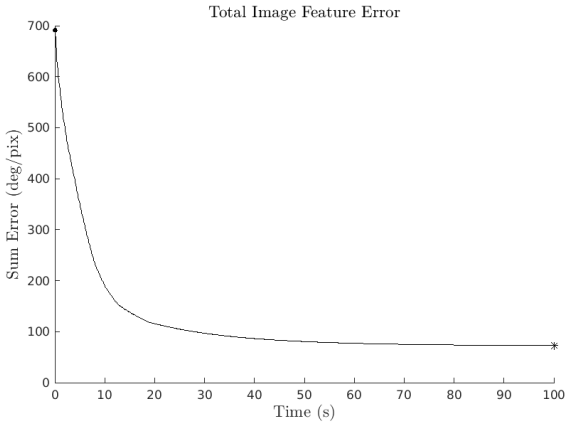


(b) 5-1 Kalman Filter Error

Figure 75: Test Case 5, Initial Condition 1: Kalman Filter

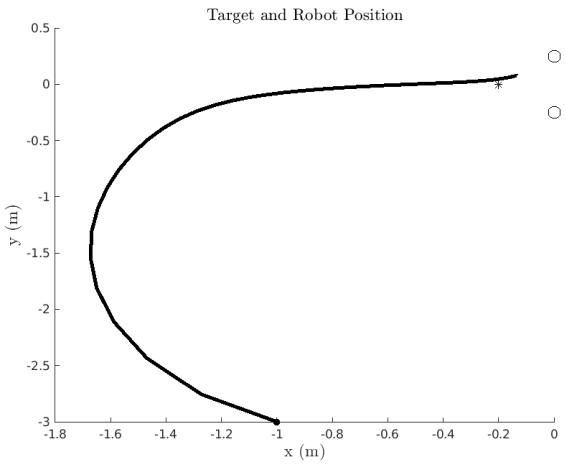


(a) 5-2 Kalman Filter Trajectory

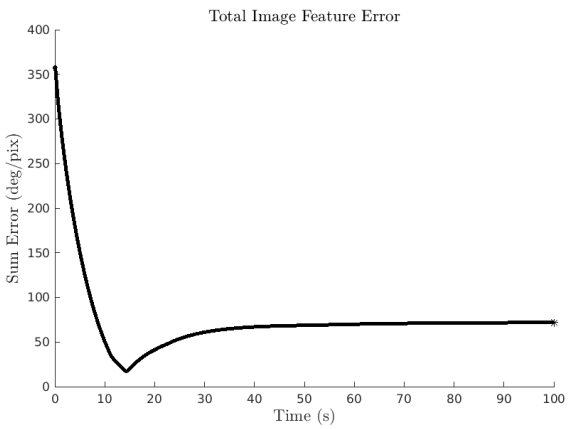


(b) 5-2 Kalman Filter Error

Figure 76: Test Case 5, Initial Condition 2: Kalman Filter

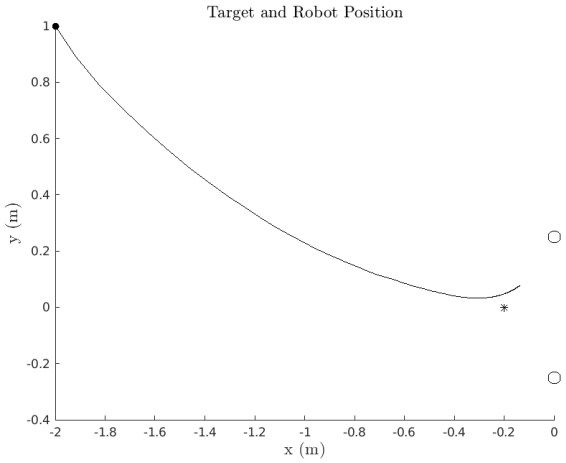


(a) 5-3 Kalman Filter Trajectory

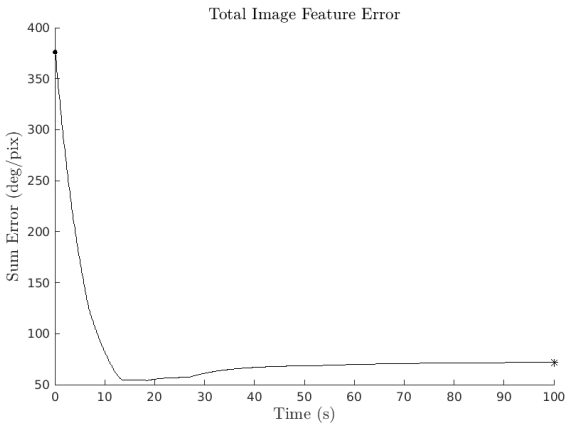


(b) 5-3 Kalman Filter Error

Figure 77: Test Case 5, Initial Condition 3: Kalman Filter



(a) 5-4 Kalman Filter Trajectory



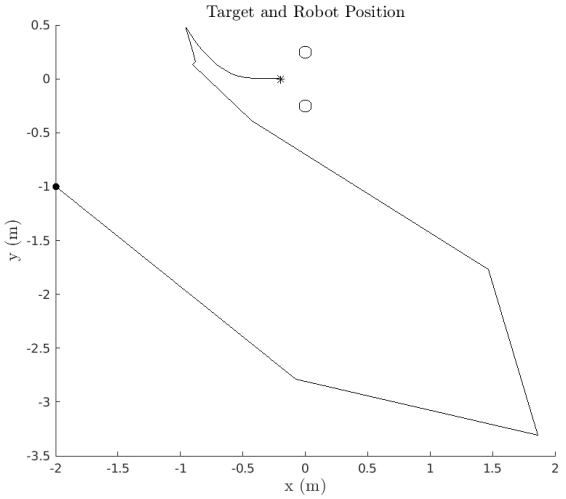
(b) 5-4 Kalman Filter Error

Figure 78: Test Case 5, Initial Condition 4: Kalman Filter

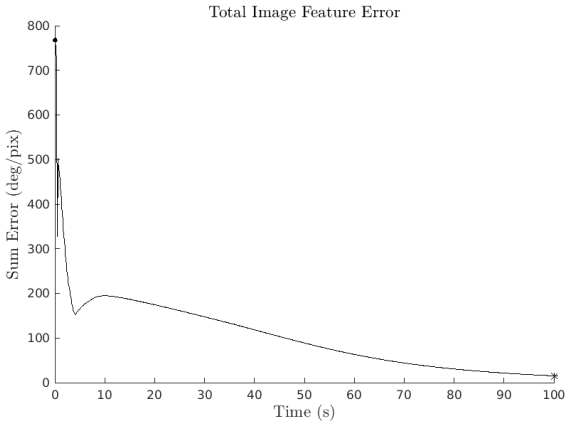
	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	174.0383	0.075635	72.1487
Start Case 2	95.7517	0.075894	72.7324
Start Case 3	53.7944	0.075483	71.8306
Start Case 4	19.3428	0.075473	71.8089

Table 19: Test Case 5 Kalman Filter-only Performance

3.5.4 Full System Performance

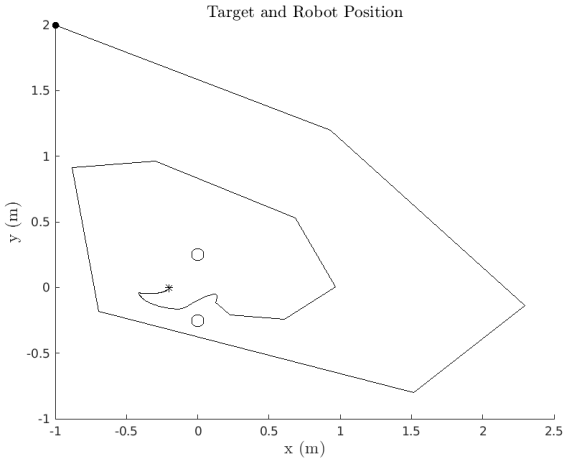


(a) 5-1 Full Solution Trajectory

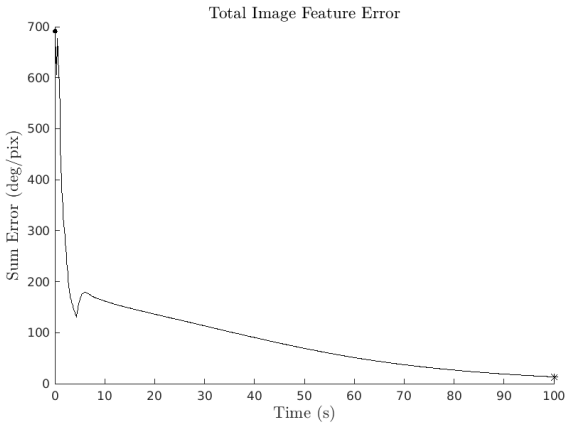


(b) 5-1 Full Solution Error

Figure 79: Test Case 5, Initial Condition 1: Full Solution

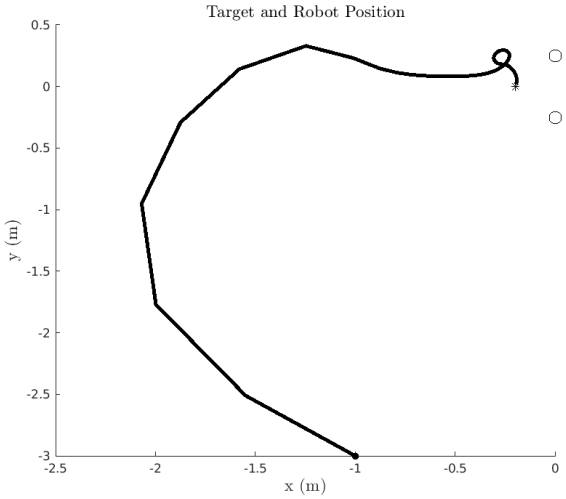


(a) 5-2 Full Solution Trajectory

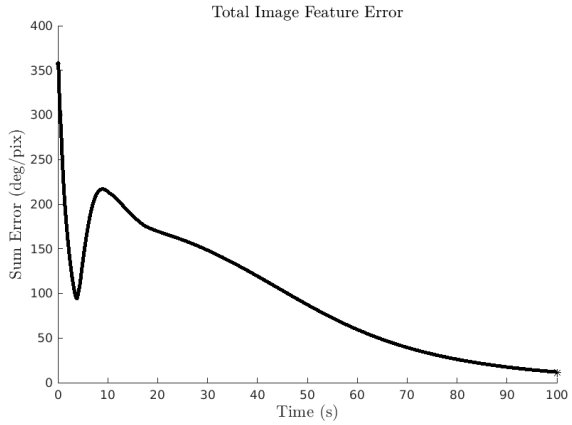


(b) 5-2 Full Solution Error

Figure 80: Test Case 5, Initial Condition 2: Full Solution

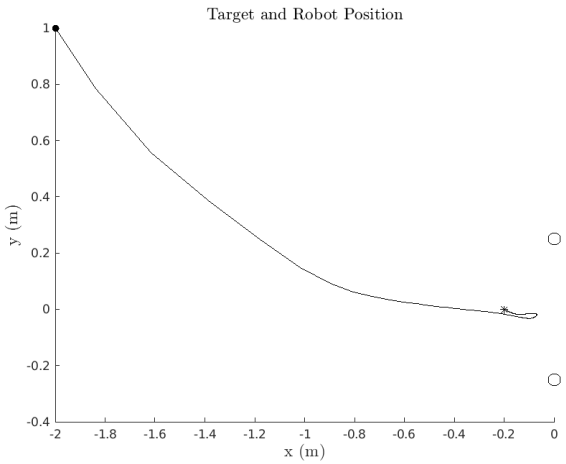


(a) 5-3 Full Solution Trajectory

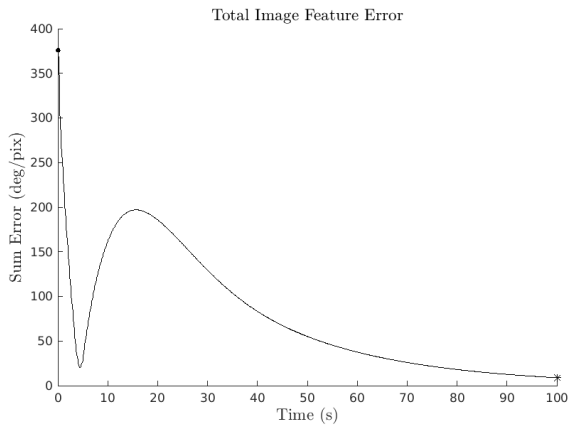


(b) 5-3 Full Solution Error

Figure 81: Test Case 5, Initial Condition 3: Full Solution



(a) 5-4 Full Solution Trajectory



(b) 5-4 Full Solution Error

Figure 82: Test Case 5, Initial Condition 4: Full Solution

	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	1327.7032	0.015962	15.2094
Start Case 2	1069.1526	0.012519	13.3232
Start Case 3	190.7968	0.011312	11.8357
Start Case 4	61.7597	0.0074948	8.8675

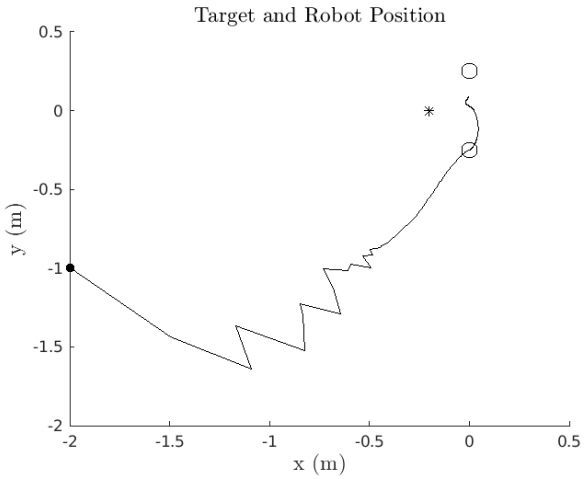
Table 20: Test Case 5 Full System Performance

3.5.5 Test Case 5 Summary and Observations

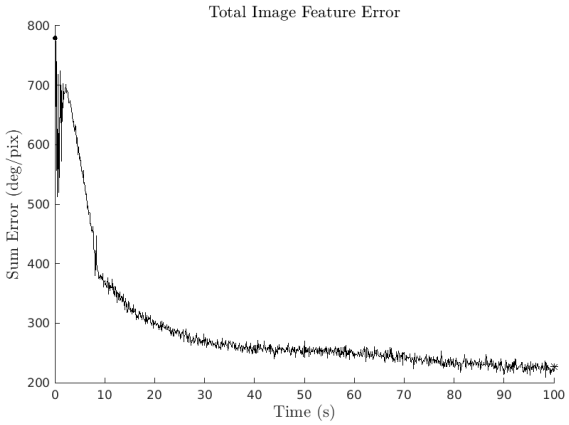
The introduction of wind error shows the limitations of the original controller - with no disturbance rejection, the controller drifts from the target. The PID controller shines in this regard, having quite similar trajectories to the no error case, but with some minor alterations. The Kalman filter continues a trend of limited benefit, however.

3.6 Test Case 6 - All Error

3.6.1 Provided Solution Performance

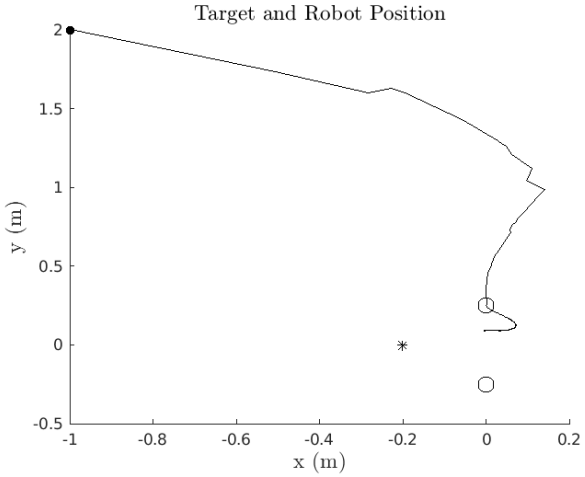


(a) 6-1 Provided Solution Trajectory

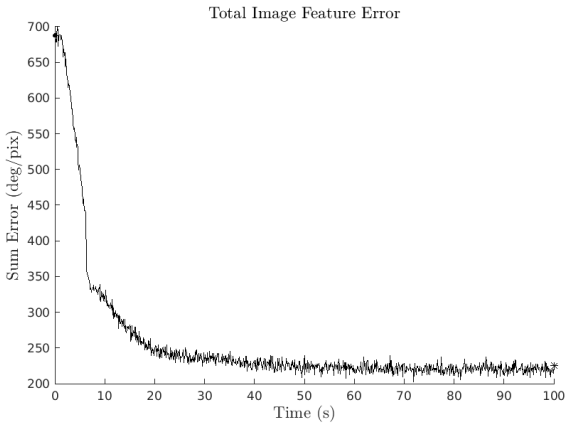


(b) 6-1 Provided Solution Error

Figure 83: Test Case 6, Initial Condition 1: Provided Solution

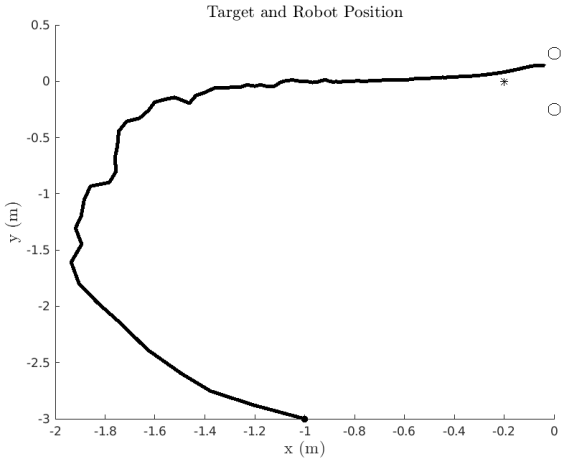


(a) 6-2 Provided Solution Trajectory

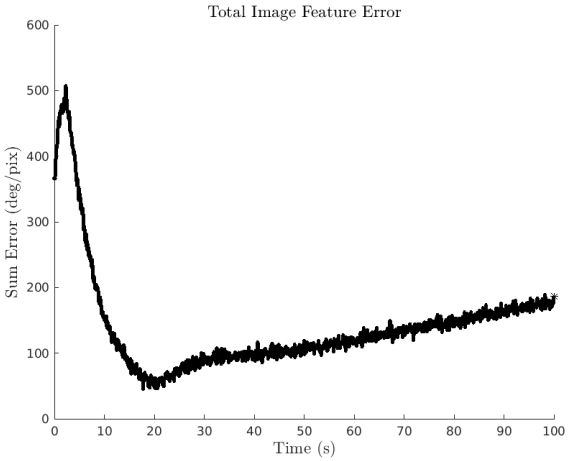


(b) 6-2 Provided Solution Error

Figure 84: Test Case 6, Initial Condition 2: Provided Solution

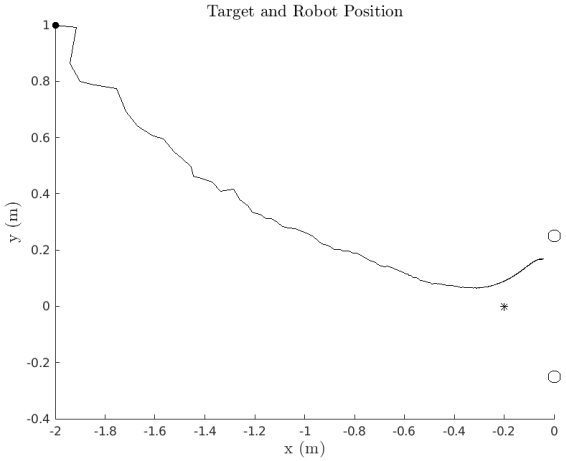


(a) 6-3 Provided Solution Trajectory

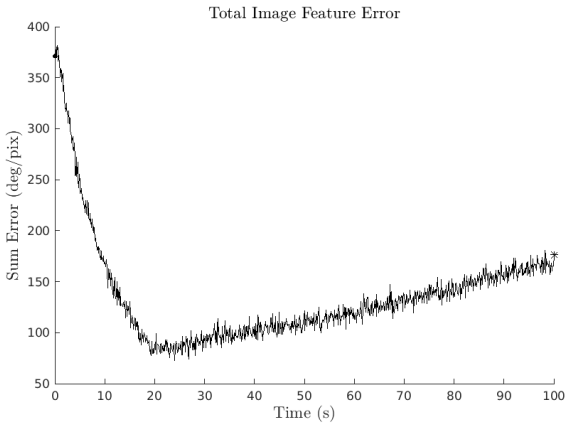


(b) 6-3 Provided Solution Error

Figure 85: Test Case 6, Initial Condition 3: Provided Solution



(a) 6-4 Provided Solution Trajectory



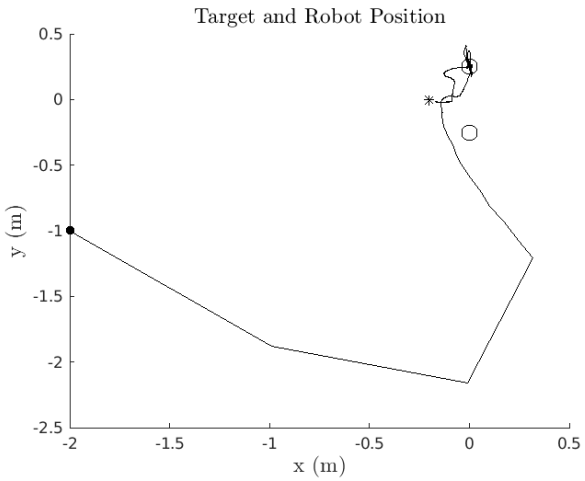
(b) 6-4 Provided Solution Error

Figure 86: Test Case 6, Initial Condition 4: Provided Solution

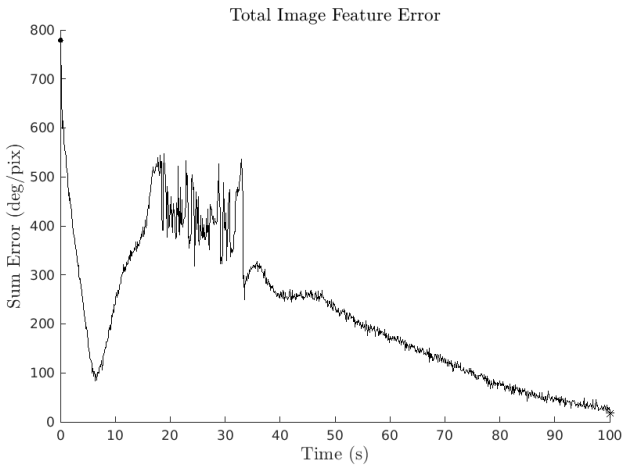
	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	71.1373	0.14189	227.2674
Start Case 2	36.8561	0.14209	225.0492
Start Case 3	38.9934	0.13729	186.6874
Start Case 4	10.7941	0.14691	176.4606

Table 21: Test Case 6 Provided System Performance

3.6.2 PID Control Performance

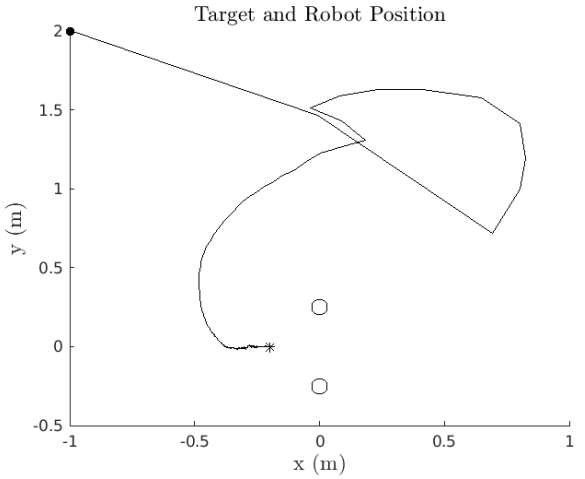


(a) 6-1 PID Controller Trajectory

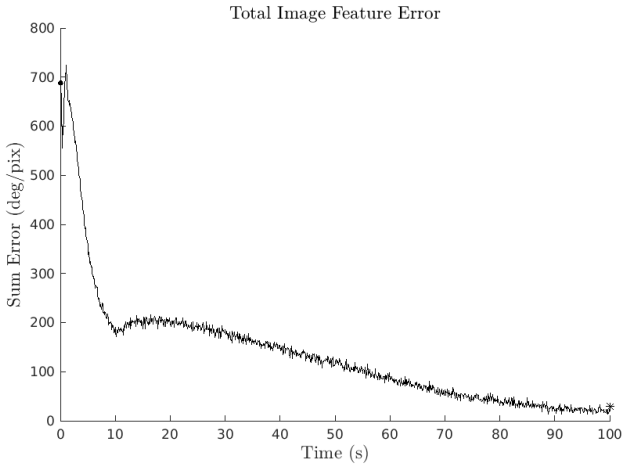


(b) 6-1 PID Controller Error

Figure 87: Test Case 6, Initial Condition 1: PID Controller

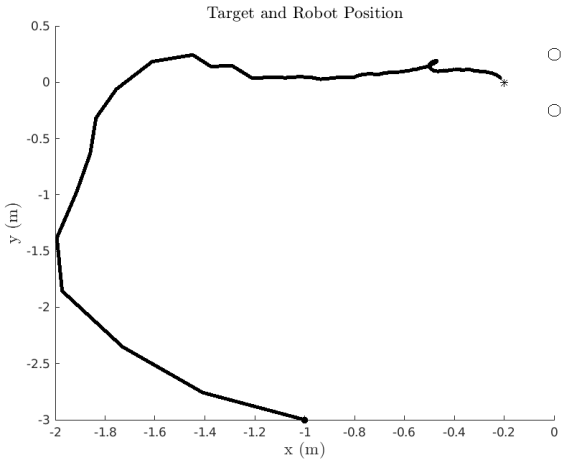


(a) 6-2 PID Controller Trajectory

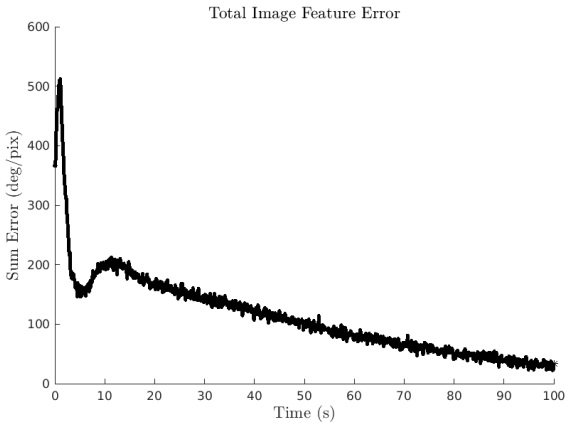


(b) 6-2 PID Controller Error

Figure 88: Test Case 6, Initial Condition 2: PID Controller

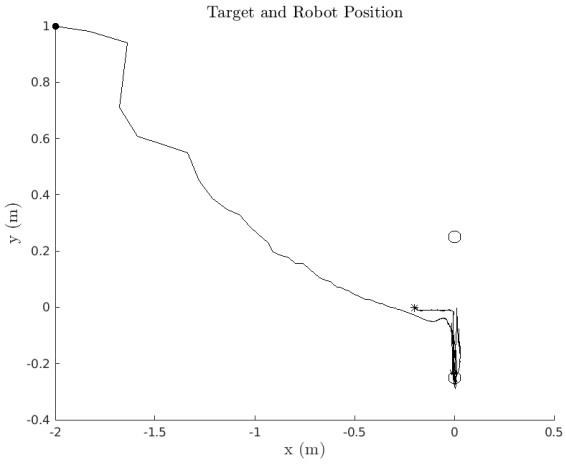


(a) 6-3 PID Controller Trajectory

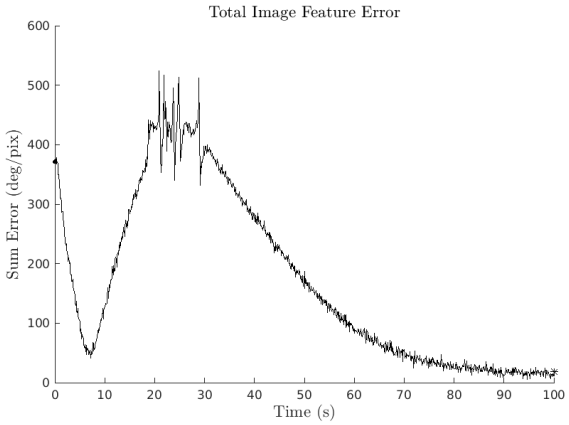


(b) 6-3 PID Controller Error

Figure 89: Test Case 6, Initial Condition 3: PID Controller



(a) 6-4 PID Controller Trajectory



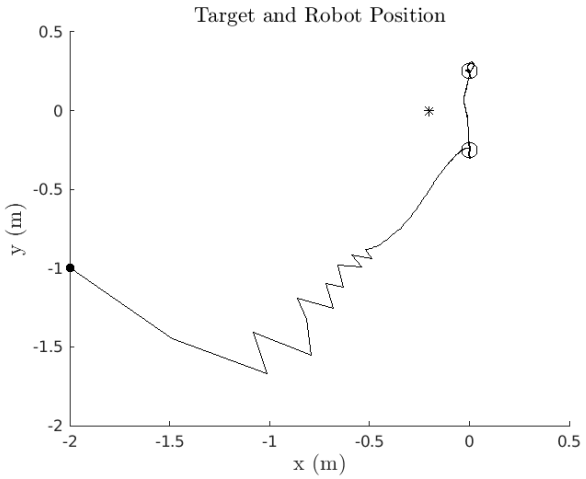
(b) 6-4 PID Controller Error

Figure 90: Test Case 6, Initial Condition 4: PID Controller

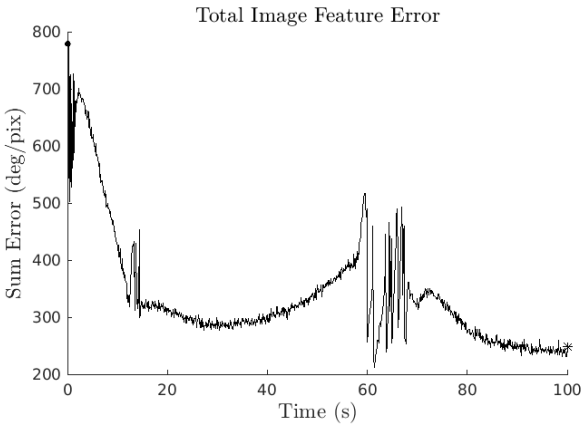
	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	266.8256	0.028352	18.4885
Start Case 2	159.2532	0.0081214	28.7907
Start Case 3	99.5501	0.024715	34.3064
Start Case 4	35.508	0.0040481	18.2089

Table 22: Test Case 6 PID-only Performance

3.6.3 Kalman Filter Performance

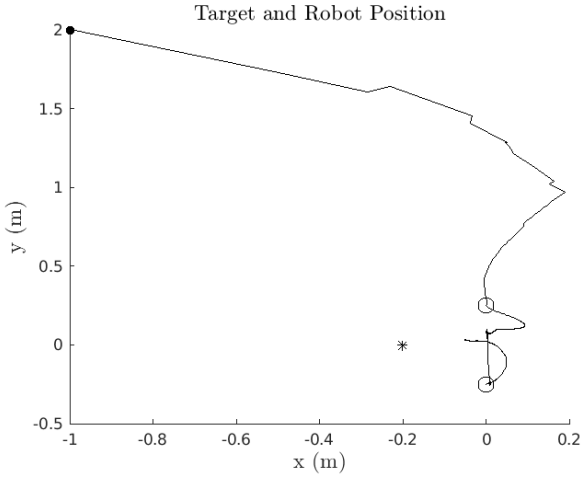


(a) 6-1 Kalman Filter Trajectory

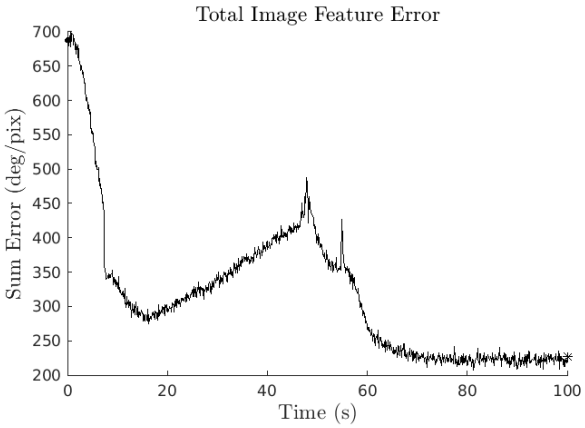


(b) 6-1 Kalman Filter Error

Figure 91: Test Case 6, Initial Condition 1: Kalman Filter

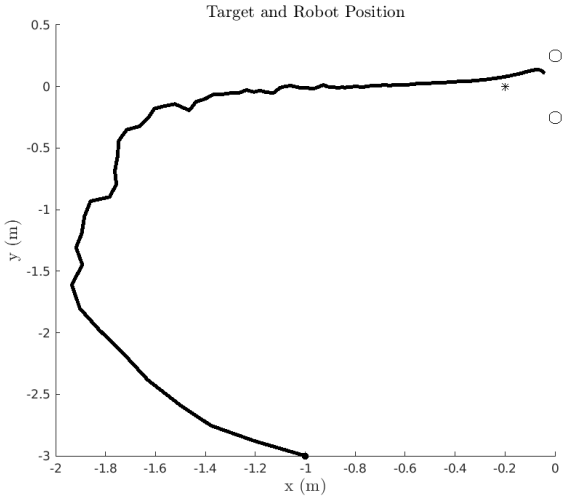


(a) 6-2 Kalman Filter Trajectory

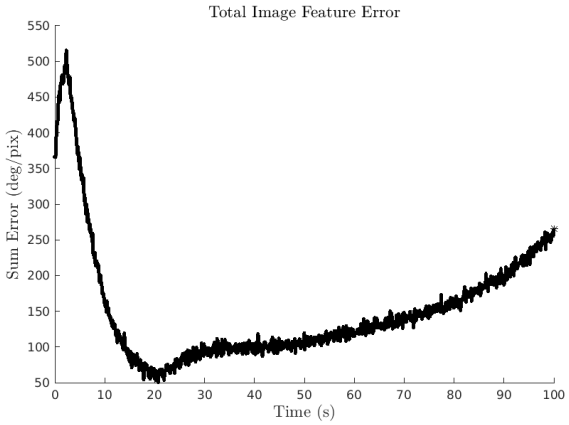


(b) 6-2 Kalman Filter Error

Figure 92: Test Case 6, Initial Condition 2: Kalman Filter

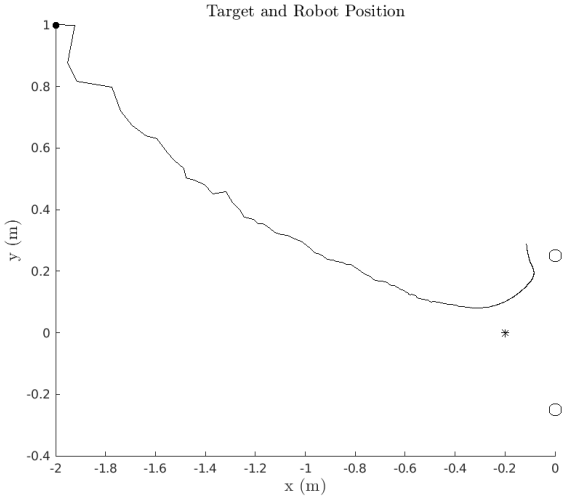


(a) 6-3 Kalman Filter Trajectory

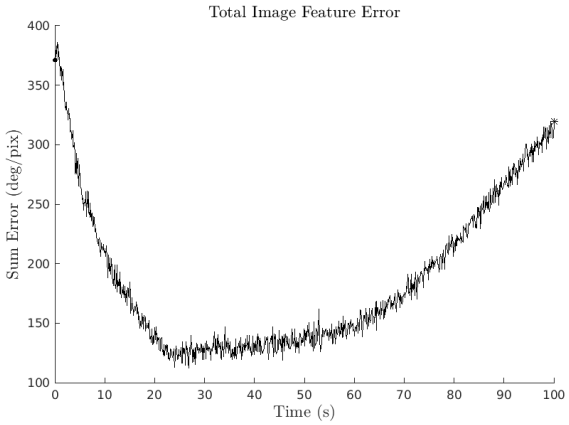


(b) 6-3 Kalman Filter Error

Figure 93: Test Case 6, Initial Condition 3: Kalman Filter



(a) 6-4 Kalman Filter Trajectory



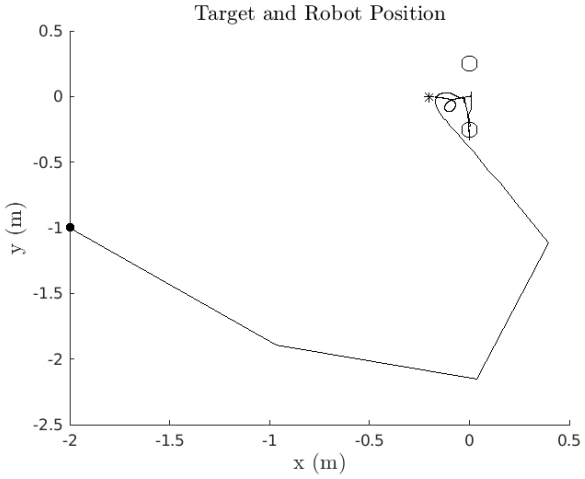
(b) 6-4 Kalman Filter Error

Figure 94: Test Case 6, Initial Condition 4: Kalman Filter

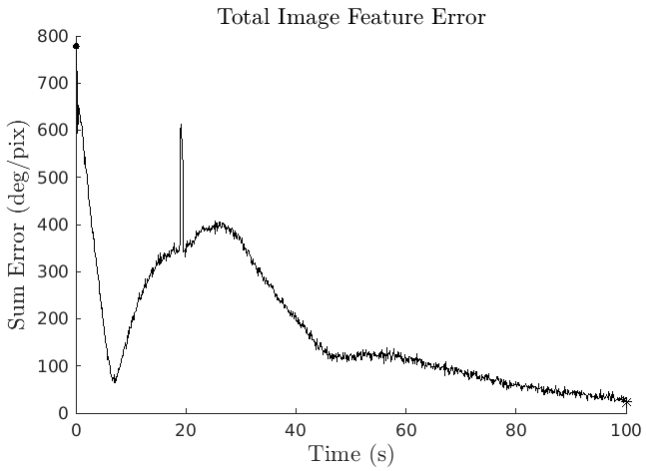
	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	74.2006	0.18072	247.6544
Start Case 2	39.3499	0.19244	227.6213
Start Case 3	39.0157	0.17382	265.2551
Start Case 4	10.5327	0.17772	319.7603

Table 23: Test Case 6 Kalman Filter-only Performance

3.6.4 Full System Performance

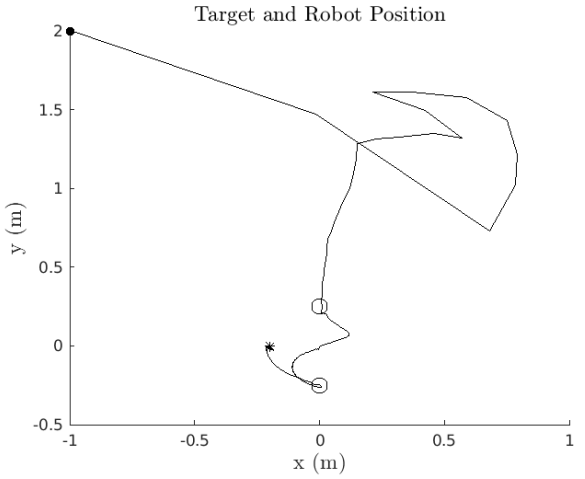


(a) 6-1 Full Solution Trajectory

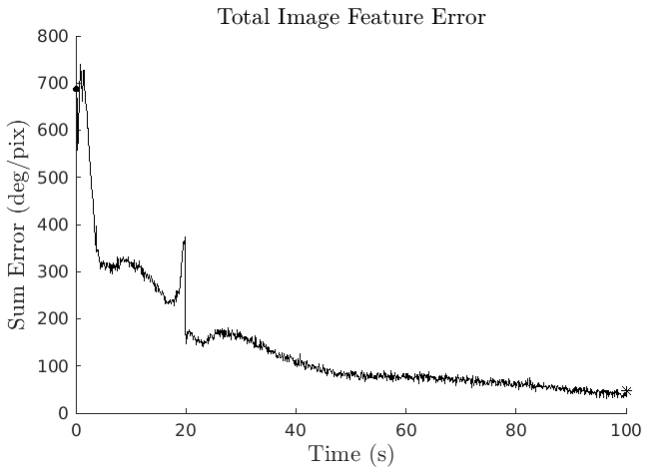


(b) 6-1 Full Solution Error

Figure 95: Test Case 6, Initial Condition 1: Full Solution

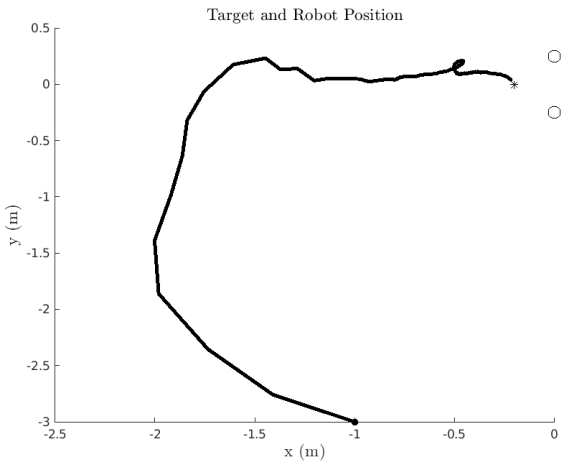


(a) 6-2 Full Solution Trajectory

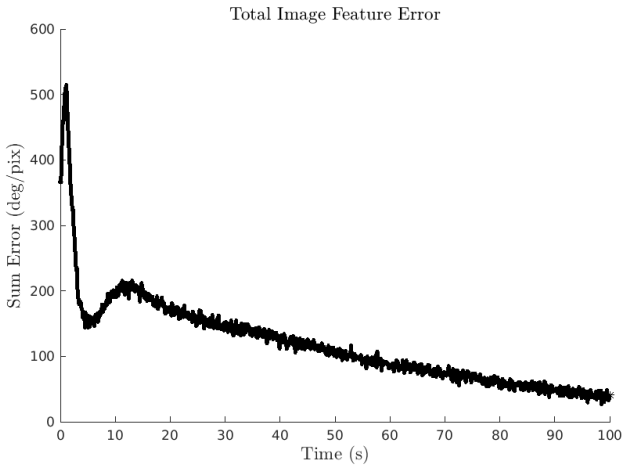


(b) 6-2 Full Solution Error

Figure 96: Test Case 6, Initial Condition 2: Full Solution

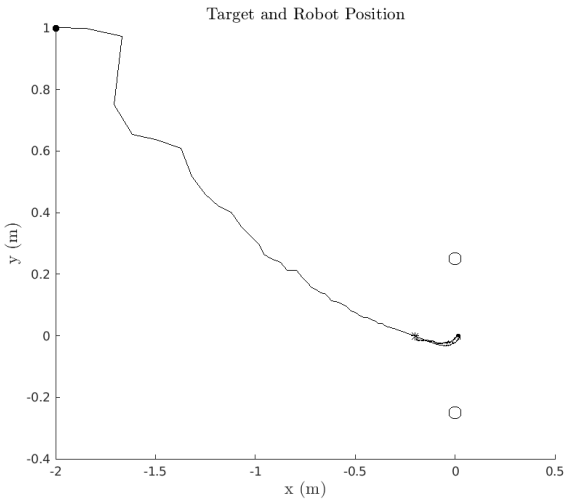


(a) 6-3 Full Solution Trajectory

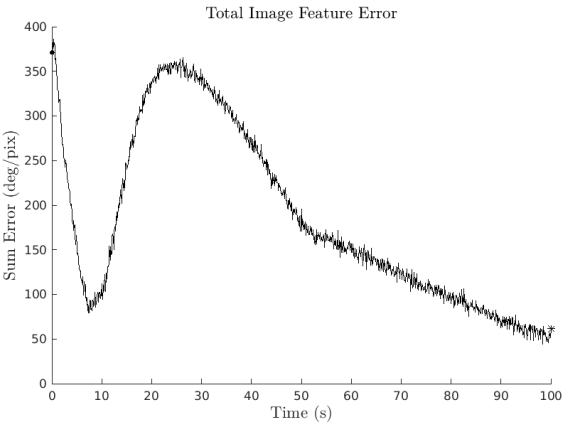


(b) 6-3 Full Solution Error

Figure 97: Test Case 6, Initial Condition 3: Full Solution



(a) 6-4 Full Solution Trajectory



(b) 6-4 Full Solution Error

Figure 98: Test Case 6, Initial Condition 4: Full Solution

	Total Control Energy/Effort (actual) (J)	Final Robot Position Error (m)	Total Image Feature Error (deg/pix)
Start Case 1	279.2224	0.026489	23.4233
Start Case 2	160.8381	0.025044	48.0988
Start Case 3	99.48	0.028682	41.4062
Start Case 4	26.8637	0.029537	61.9171

Table 24: Test Case 6 Full System Performance

3.6.5 Test Case 6 Summary and Observations

The presence of all error sources causes the base control setup to struggle significantly, and likewise the PID controller enters some regions of instability, but is able to recover and reach its target position. The Kalman filter does little to assist the provided solution, but mitigates some of the issues present in the PID control response.

4 Part C - Your MATLAB Code

4.1 ENN586YourControl.m

```
kf = YourVariables.kf;

[kf.e_est, kf.P_prev] = kf.measure(kf.e_pred, kf.P_pred, e.actual, kf.H, kf.
    R);
B = Ja(:,control.dof)*YourVariables.dt;

err = kf.e_est
YourVariables.var1=YourVariables.var1+pinv(Ja(:,control.dof))*err;

if YourVariables.first==1
     Derror2=pinv(Ja(:,control.dof))*zeros(size(err));
     YourVariables.first=0;
else
      Derror2=pinv(Ja(:,control.dof))*err-YourVariables.error_old;
end

YourVariables.error_old=pinv(Ja(:,control.dof))*err;
uactual =-YourVariables.gainP*pinv(Ja(:,control.dof))*err-YourVariables.
    gainD*Derror2+YourVariables.gainI*YourVariables.var1;
YourVariables.disturbance_est=YourVariables.gainI*YourVariables.var1;

kf.B_prev = B;
kf.u_prev = uactual;

[kf.e_pred kf.P_pred] = kf.predict(kf.A, kf.e_est, kf.B_prev, kf.u_prev, kf.
    P_prev, kf.Q);

YourVariables.kf = kf;
```

4.2 Lines 43 to 73 of MainVisualServoingENN586.m

```
simulation_length=100;  %length in s.
YourVariables.T = simulation_length;
YourVariables.dt = 0.1;

% pid controller
simulation_length=100;  %length in s.
YourVariables.var1=zeros(6,1);   % a structure (or variables) you can pass
    between functions.  You can relabel the var1 field and add fields as you
    like.
YourVariables.error_old=zeros(1,1);
YourVariables.first=1;
YourVariables.gainI=-0.0009;
YourVariables.gainD=-0.3;
YourVariables.gainP=0.3;
YourVariables.varv=YourVariables.var1;

% Kalman Filter
YourVariables.kf.A = eye(8);
YourVariables.kf.R = 25;
YourVariables.kf.Q = diag(0.01*ones([8 1]));
YourVariables.kf.H = eye(8);
YourVariables.kf.P_prev = 1000 * eye(8);
YourVariables.kf.B_prev = 0.01*rand([8 6]);
YourVariables.kf.u_prev = zeros([6 1]);
YourVariables.kf.predict = @kalman_predict;
```

```
YourVariables.kf.measure = @kalman_measure;

x_0 = 5*(rand([8 1]) - rand([8 1]));
YourVariables.kf.e_est = x_0;

kf = YourVariables.kf;
[kf.e_pred kf.P_pred] = kf.predict(kf.A, kf.e_est, kf.B_prev, kf.u_prev, kf.
   P_prev, kf.Q);
YourVariables.kf = kf;
```

5 General Recommendations

The ability shown by the PID control to reach the target position in scenarios that the base controller could not shows a promising alternative approach. Some kinks need to be ironed out, such as the high control energy resulting in inefficient control results, and the linear responses that indicate an improper tuning of gains, in which case the high K_P and lack of damping results in responses beyond the capabilities of a real system.

The Kalman filter had disappointing performance, consistently showing degraded performance over the system without it. Due to the nature of the noise, it is feasible to use unfiltered data, and in the event limit is reached, a simpler filter, such as a low pass filter, is recommended over the Kalman filter.

This investigation focussed primarily on the total feature error, and while recorded, the range error was mostly pushed aside. Further work that applies this information could resolve some of the issues experienced in PID control.

6 References

References

[1] P. C. Aaron McFadyen, Jason Ford, "Stable image-based visual servoing with unknown point feature correspondence," 2017.