Controller Reconfiguration for Stern Plane Jams in Underwater Vehicles

Guy O. Beale and Mian Zainularafeen Shahid
Electrical and Computer Engineering Department
George Mason University
Fairfax, Virginia

Abstract— **Stern plan jams are major failures during the maneuver of underwater vehicles. This paper describes an approach to reconfigure the controller to eliminate the dangerous effects of stern plan jams. Simulation results using LQR design with and without controller reconfiguration are shown. Results show that this approach provides good control of all the state variables when a stern plan jam occurs. Excursions in depth have been significantly reduced or eliminated by the reconfigured control.**

I. Introduction

This paper provides preliminary results for continuing research in the area of robust reconfigurable control. The specific application being considered in this paper is controller reconfiguration to provide recovery from major control surface faults in an underwater vehicle. This paper describes our approach to determining the control actions that would be initiated when a stern plane jam is detected. This work assumes that the fault detection and classification activities that have been described in [1], [2], [3], [4] have already been carried out. It is assumed that fault detection was performed using the PCA/T^2 method [5], [6], [7]. Either the Fisher Discriminant Analysis (FDA) [8] or Quantification of Contributing Variables (QCV) [3] method could be used for classification. Results of applying these techniques to surface ships are presented in [9].

Since a stern plane jam is a serious failure, with potentially catastrophic results, that fault has been selected as the first type for which reconfiguration of the control system has been developed. With this serious fault type, more than just parameter changes in the controller are necessary in order to maintain the vehicle's heading and depth at or near the desired values. It is assumed that the rudder, bow plane, and commanded forward speed are available for manipulation by the control system.

Section II presents a description of the approach that has been followed in this work. A description of the simulation and the simulation results are presented in Section III. Conclusions and recommendations for additional work are presented in Section IV.

II. Recovery From Stern Plane Jams

A. Overview

The primary goal of the controller reconfiguration is to prevent the fault from producing a catastrophic failure. Large depth excursions that would cause broaching or dangerously deep depths must be avoided. In addition, large roll or pitch angles and large errors in heading angle must be prevented.

The secondary goal for the reconfiguration is to control the submarine's trajectory as close as possible to the desired reference values, that is, maintain depth and heading under control in spite of the jammed stern plane. Since reference trajectories are provided for depth, pitch, and yaw, it is easy to assess how well this goal is met.

The variables that will be used for control are the rudder, bow plane, and forward speed. As mentioned later in Section III-A, the submarine is assumed to be neutrally buoyant at its initial depth, and a weight-buoyancy error, modeled by a cubic equation, is included in the dynamics. The weight is assumed constant throughout all simulations, with and without a fault, so the depth control tanks are not used in this reconfiguration.

B. Reconfiguration Procedure

The procedure that has thus far provided the best results for recovering from a stern plane jam consists of actions involving the rudder, the bow plane, and the commanded forward speed. Each of these actions is described below.

• LQR Control Gain: The control gains are computed using the Linear Quadratic Regulator (LQR) design method [10]. The Q and R weighting matrices used to compute the LQR gain K_c during normal operation are chosen to provide good tracking performance during maneuvers as well as good steady-state performance. Bryson's method was used to initialize the weighting values, and they were updated using an iterative procedure [11] until desired simulation results were obtained.
It was found that the gain matrix K_c used for normal operation would not provide adequate results in the event of a stern plane jam. Steady-state offsets in depth of approximately 100 feet were obtained. To reduce the offset, the element in the Q matrix corresponding to depth was increased from 0.01 to 10. All values in the R matrix and the other values in Q were kept at the same values. After the stern plane jam was detected, the new gain matrix was used as part of the controller reconfiguration.

• Rudder: The best results have been obtained by leaving the rudder under full automatic control. The trajectories in the horizontal and vertical planes appear to be uncoupled to a large extent, and leaving the rudder in automatic control allows the actual heading angle to follow its reference signal with little error. Manipulating the rudder in some other fashion produced large errors in heading angle without substantially improving control of depth.

- Bow Plane: For dive jams and stuck-in-position jams, the bow plane is left under fully automatic control. For rise jams, the bow plane is manipulated in an open-loop fashion based on time from the detection and classification of the fault. The bow plane is driven into saturation in a two-step process. When the fault is detected, the plane is driven to a value equal to 10% of its maximum allowed value at a rate limit of 7 deg/sec. At a specified later time, the bow plane is driven into full saturation at the same rate limit. The direction of the bow plane movement (rise or dive) is the opposite of the stern plane jam. Leaving the bow plane under automatic control will also cause it to go into saturation. However at the time the fault occurs, the bow plane may go through a transient period that produces larger depth excursions than desired. The delay time is given by

$$T_{bow\_plane\_delay} = 10 \text{ s} \tag{1}$$

for stern plane rise jams.

- Commanded Forward Speed: The ability to control forward speed is the dominant factor in preventing large depth excursions when a stern plane jam occurs. It appears to be crucial to have this ability. Forward speed is controlled in a two-step process. During the first phase, the forward speed is reduced in an open-loop fashion to a specified value $u_{\min}$ at a rate of 0.1266 ft/s^2 (0.075 kt/s). This deceleration should be achievable since it is approximately 43% of the value provided by the sponsor. The specified value of speed depends on whether a dive jam or rise jam has occurred. For a dive jam, the values used are $u_{\min} = 4.59$ knots for a jam during steady-state and $u_{\min} = 6.45$ knots for a jam during the transient part of a maneuver. For a rise jam the value is $u_{\min} = 6.46$ knots. After a specified delay time, the forward speed is controlled in a closed-loop fashion. For rise jams, the time delay is given by (1); for dive and stuck jams, the time delay is 100 seconds. The variables used to control speed are the difference between the current depth and the desired final depth, the depth rate, and pitch rate. The closed-loop expression for forward speed is

$$u_{com}(t) = u_{\min} - 0.025\,[z_{ord} - z(t)] - 0.1q(t) + 0.85w(t) \tag{2}$$

where $q(t)$ is the pitch rate and $w(t)$ is the body-referenced vertical velocity.

Results of applying this reconfiguration procedure are discussed in the following section. Although the numerical values for the gains in (1) and (2) have been developed for the specific set of reference trajectories described in Section III-A, it is felt that they will also be valid for other trajectories, or at least a design algorithm can be developed to produce the appropriate gains for a specified trajectory.

III. Simulation Results

A. Simulation Description

The simulations were performed in SIMULINK using the nonlinear equations of motion for a generic submarine model. The only exception to full six degree-of-freedom motion was that the surge velocity u was held constant throughout a simulation, except when the commanded forward speed was being controlled after reconfiguration. In this case, actual and commanded speeds are assumed to be equal since the surge dynamics are missing from our model. The sway and heave velocities were obtained during the solution to the differential equations at each simulation timestep. All simulations were performed at 12 knots. The simulation timestep was 0.125 seconds in every case.

The trajectory taken in each of the simulations was a combined course and depth change. Depth was changed from 400 feet to 800 feet, and the course was changed by a turn to starboard of 120°. Reference trajectories were generated for depth, pitch angle, and yaw angle. Raised cosine curves were used for the reference trajectories, with the transient part of the trajectory lasting 600 seconds. The submarine was assumed to be neutrally buoyant at the initial depth, and a cubic equation was used to compute the weight-buoyancy error as a function of change in depth from the initial condition. No change in ballast to reduce the weight-buoyancy error was performed as depth changed.

The controller used in the simulations was an LQR design. The variables that were measured were {depth, pitch, depth rate, pitch rate} for the vertical plane motion and {roll, yaw, roll rate, yaw rate} for the horizontal plane motion. Control variables during normal operation were {rudder, stern plane, bow plane}. The control signals were generated based on the difference between the measured variables and the reference trajectory variables. The reference values for the variables other than depth, pitch, and yaw were zero. During controller reconfiguration, commanded forward speed u_{com} was also used as a control variable. The control surfaces were saturated at $\pm 35°$, $\pm 20°$, $\pm 25°$ for the rudder, stern plane, and bow plane, respectively. The rate of change of each of the control surfaces was limited to ± 7 deg / sec.

Only one type of failure mode was considered, namely a stern plane jam. Stuck-in-position jams, rise jams, and dive jams were simulated, with the stern plane going into saturation at a rate limit of 7 deg / sec. The starting times for the faults ranged from 150 seconds to 950 seconds in 100 second increments. Thus, there was a total of 9 simulations for each of the 3 jam conditions.

B. Simulations Without Reconfiguration

Before results are presented that illustrate the effects of controller reconfiguration, graphs will be shown of the normal operation basis data and two cases of data with stern plane jams but no reconfiguration of the controller. These graphs will illustrate the ideal behavior—basis data—and the worst-case data—failure without any reconfiguration.

With no faults occurring during the simulation, the trajectories are smooth and follow the reference signals very closely, particularly for depth and heading angle. Because of the uncompensated weight-buoyancy error, there is approximately a four foot offset in final depth and approxi-

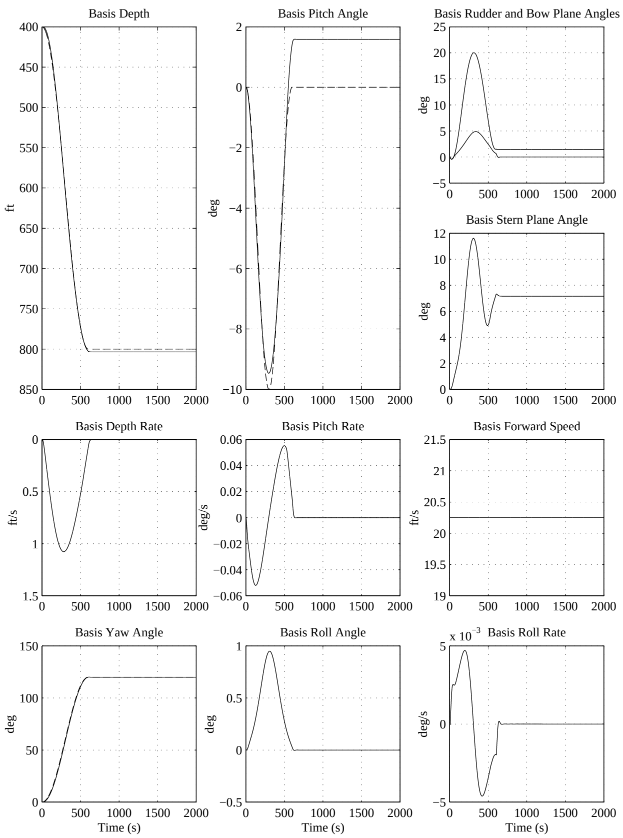

Fig. 1. Trajectories under normal operation.

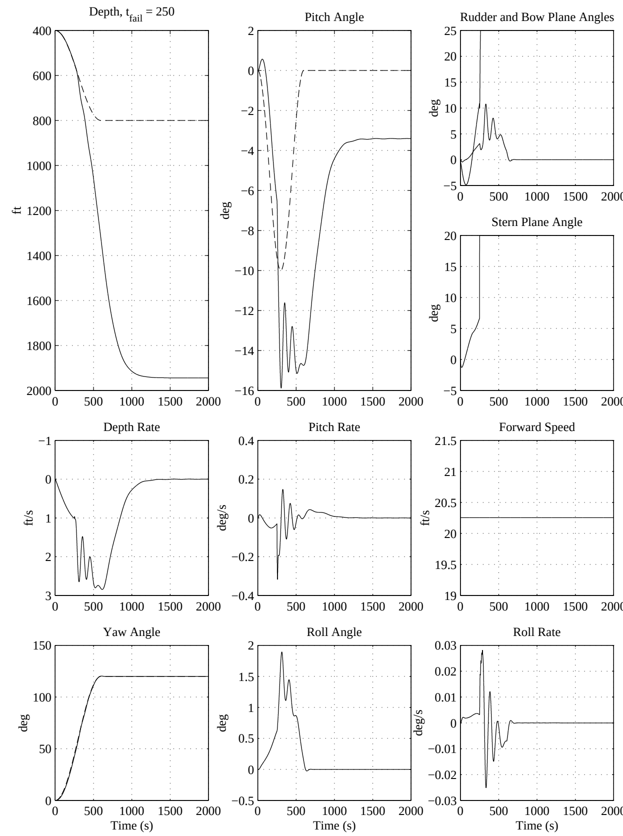

Fig. 2. Trajectories for a stern plane dive jam at 250 seconds without controller reconfiguration.

mately two degrees of pitch in steady state. The bow and stern plane angles also have nonzero values in steady state to produce this equilibrium situation. Figure 1 shows the trajectories of the major variables when no fault occurs. The forward speed is held constant at $u_{com} = 12$ kts (20.3 ft/s)

If a stern plane jam occurs during the simulation and control reconfiguration is not performed, equilibrium conditions are achieved by the submarine, but not at acceptable values in terms of depth. If the control surfaces are left under fully automatic control and the speed is maintained constant, the equilibrium depth is substantially different than the desired value for both dive and rise jams. Figures 2 and 3 show the simulation results for the stern plane failing at 250 seconds for a dive jam and rise jam, respectively. For the dive jam, the final depth is more than 1100 feet below the desired value. For the rise jam, the "equilibrium" condition has depth oscillating with an average value approximately 200 feet above sea level, with the period of oscillation being about 210 seconds. Although this is an obviously unrealistic result, it does indicate the need for controller reconfiguration. From a realistic perspective, the submarine broaches approximately 200 seconds after the failure occurs when there is no reconfiguration. The maximum pitch angles are also much larger when there is no reconfiguration than for the basis condition. On a positive note, it can be seen that the horizontal plane dynamics are relatively uncoupled from the vertical plane dynamics, even in the nonlinear model.

C. Dive Jams With Reconfiguration

With the bow plane and rudder under completely automatic control and the reconfiguration control law given by (2), the depth and pitch were controlled well for each of the fault starting times. The final value of depth is nearly identical to the desired value of 800 feet. The final value of pitch is larger than the 2 degree value for basis data, but still a satisfactory value in each case.

It has been determined experimentally that the final values of depth and pitch depend only on the value of $u_{\min}$, not on the delay time. Thus, all the dive jams starting during the transient part of the maneuver end with the same values for depth and pitch since they had the same value of $u_{\min}$. The same can be said about the dive jams beginning after the maneuver is completed at $t = 600$ seconds. The simulations clearly show that a steady-state condition for each of the jam times is reached; all the rates are essentially zero.

Figure 4 shows the trajectories for a stern plane dive jam occurring at 250 seconds. This plot is typical of those obtained for other failure times. The depth has a smaller final error than the basis data; this is due to the different gain matrix used when the fault is detected. The forward speed is seen to be constant until the fault is detected. After that time, the speed is ramped down from u_{com} to

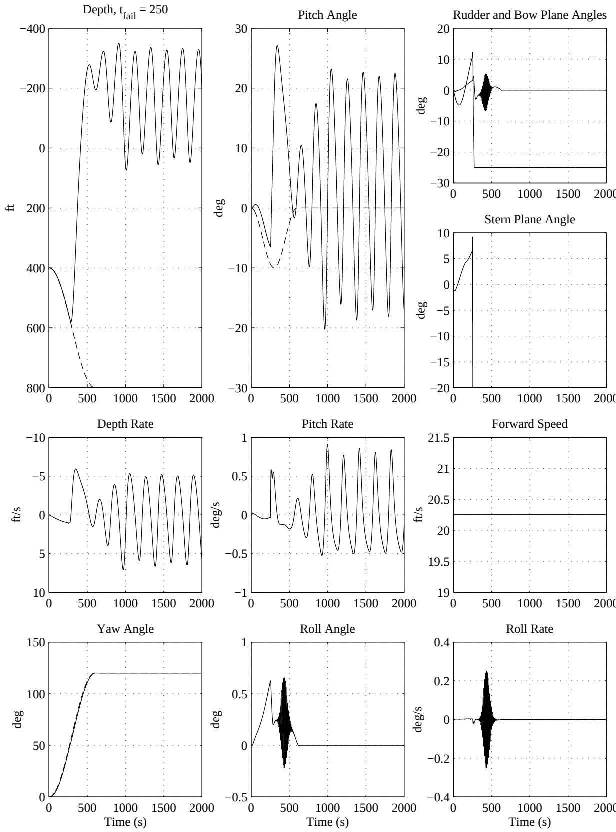

Fig. 3. Trajectories for a stern plane rise jam at 250 seconds without controller reconfiguration.

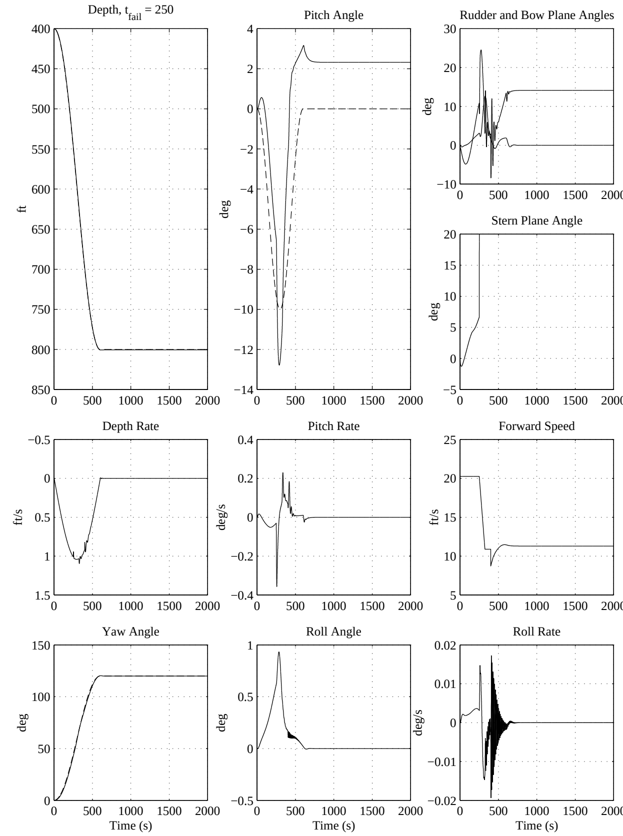

Fig. 4. Trajectories for a stern plane dive jam at 250 seconds with controller reconfiguration.

$u_{\min} = 6.45$ kts (10.9 ft/s). After the delay time, the speed is controlled in accordance with (2).

The heading angle (yaw), roll angle and depth rate are nearly the same as for the basis data. The pitch rate and roll rate are larger in the failure case than in normal operation, but there are still well within reasonable ranges. Assuming that Fig. 4 is typical of other failure times, it is clear that the controller reconfiguration with the change in K_c and the control of forward speed have drastically reduced the effects of the stern plane jam.

Figure 5 shows the maximum absolute errors for depth, roll, pitch, and yaw between the basis data and the data obtained with the stern plane faults and controller reconfiguration. Since the depth and course changing maneuver is completed at 600 seconds, the results in Fig. 5 are fairly constant when the stern plane jam occurs after that time. The roll error is very small in each case, and the roll rate is typically less than 0.05 deg/s, clearly an acceptable value. The pitch error is largest at the time the pitch angle reverses direction, but it is never so large as to be unreasonable.

Note that the errors shown in Figure 5 are not the steady-state values; rather, they are the maximum values that might occur at any time during the maneuver. The steady-state differences between the basis and fault data are much smaller than the maximum values; they are given in Table 1. As previously mentioned, the steady-state values of depth and pitch depend only on $u_{\min}$ (for a given K_c). Two different values of $u_{\min}$ were used for the dive jams (< 600 seconds and > 600 seconds), and Table 1 shows that the steady-state values of depth and pitch are constant for each of the two values of $u_{\min}$ used. The steady-state depth errors are approximately the same for the two cases; it has not yet been determined why the pitch angles differ by the amount that they do.

Table 1. Steady-state errors for dive jams, relative to basis data.

t_{fail}	Depth	Roll	Pitch	Yaw
150 s	2.94 ft	≈ 0	0.74 deg	≈ 0
250 s	2.94 ft	≈ 0	0.74 deg	≈ 0
350 s	2.94 ft	≈ 0	0.74 deg	≈ 0
450 s	2.94 ft	≈ 0	0.74 deg	≈ 0
550 s	2.94 ft	≈ 0	0.74 deg	≈ 0
650 s	2.19 ft	≈ 0	5.01 deg	≈ 0
760 s	2.19 ft	≈ 0	5.01 deg	≈ 0
850 s	2.19 ft	≈ 0	5.01 deg	≈ 0
950 s	2.19 ft	≈ 0	5.01 deg	≈ 0

D. Rise Jams With Reconfiguration

For rise jams, the reconfiguration control law is given by (1) and (2), but the minimum speed is changed to $u_{\min} = 6.46$ knots. The depth and pitch trajectories were still controlled well in steady-state for each of the fault

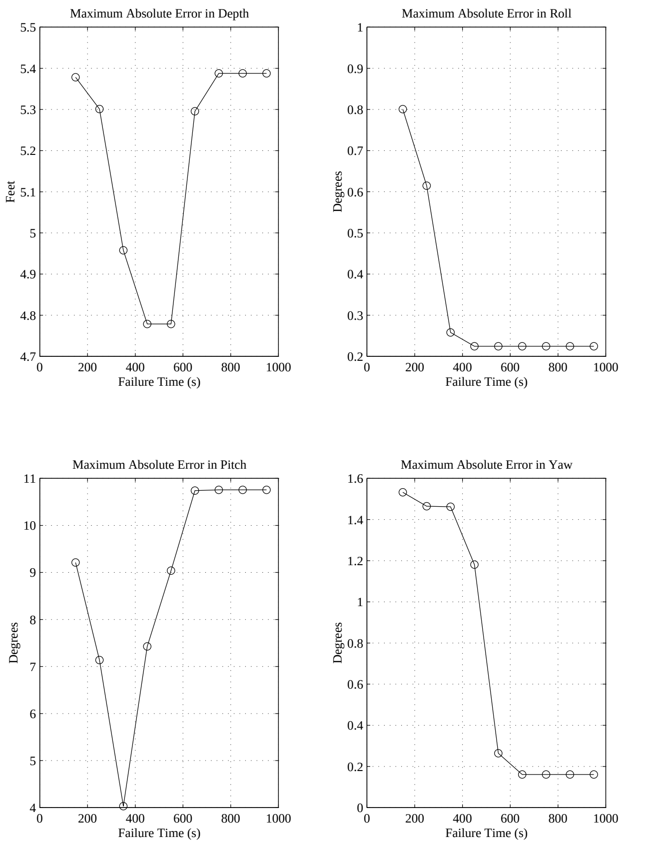

Fig. 5. Maximum absolute errors in depth, roll, pitch, and yaw for dive jams.

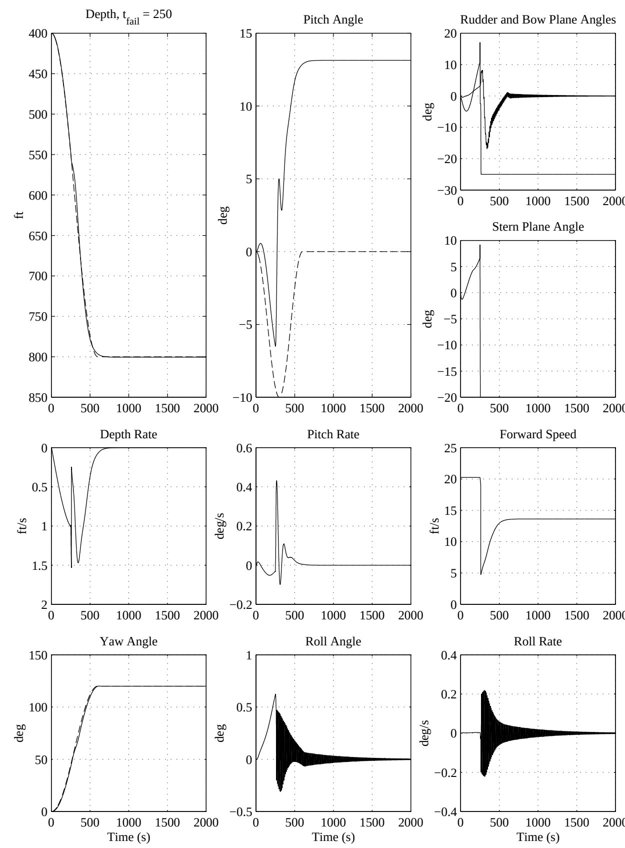

Fig. 6. Trajectories for a stern plane rise jam at 250 seconds with controller reconfiguration.

starting times. However, in some cases, the transient response exhibits more overshoot or other depth excursions than for the corresponding dive jam case. The final value of depth is within 4 feet of the desired value of 800 feet. The final value of pitch is 13.7 degrees, larger than the 2 degree value for basis data and larger than the 8 degrees for dive jams, but still not an unreasonable value. As in the case of dive jams, the final values of depth and pitch depend only on the value of $u_{\min}$, not on the delay time. Thus, all the rise jam results end with the same values for depth and pitch.

Figure 6 shows the trajectories for the state variables for a stern plane rise jam occurring at 250 seconds. Plots of the trajectories for other failure times would be similar. The depth trajectory is nearly identical to that obtained when a dive jam occurs. The pitch angle has a more noticeable change. The roll angle and roll rate have more oscillations in the rise jam case, but the amplitudes of the oscillations are small, and the period of oscillation is approximately 10.6 seconds for both variables. Controller reconfiguration has again provided drastically improved performance when a major failure occurred.

Figure 7 shows the maximum absolute errors for depth, roll, pitch, and yaw between the basis data and the data obtained with the stern plane rise jam and controller reconfiguration. The steady-state differences between the basis and fault data are given in Table 2. Similar to Table 1, the steady-state values of depth and pitch are constant for the single value of $u_{\min}$ used.

Table 2. Steady-state errors for rise jams, relative to basis data.

t_{fail}	Depth	Roll	Pitch	Yaw
150 s	2.93 ft	≈ 0	11.6 deg	≈ 0
250 s	2.93 ft	≈ 0	11.6 deg	≈ 0
350 s	2.93 ft	≈ 0	11.6 deg	≈ 0
450 s	2.93 ft	≈ 0	11.6 deg	≈ 0
550 s	2.93 ft	≈ 0	11.6 deg	≈ 0
650 s	2.93 ft	≈ 0	11.6 deg	≈ 0
760 s	2.93 ft	≈ 0	11.6 deg	≈ 0
850 s	2.93 ft	≈ 0	11.6 deg	≈ 0
950 s	2.93 ft	≈ 0	11.6 deg	≈ 0

E. Stuck Jams with Reconfiguration

In addition to the stern planes going into positive or negative saturation, they can become stuck in position at their current deflection. Like dive jams, stuck plane jams are also controlled by leaving the rudder and bow plane under full automatic control and manipulating commanded speed using the reconfiguration control law given by (2). Excellent results were obtained for depth and pitch, with the entire trajectory being very similar to the basis trajectory. The final value of depth is nearly identical to the desired value

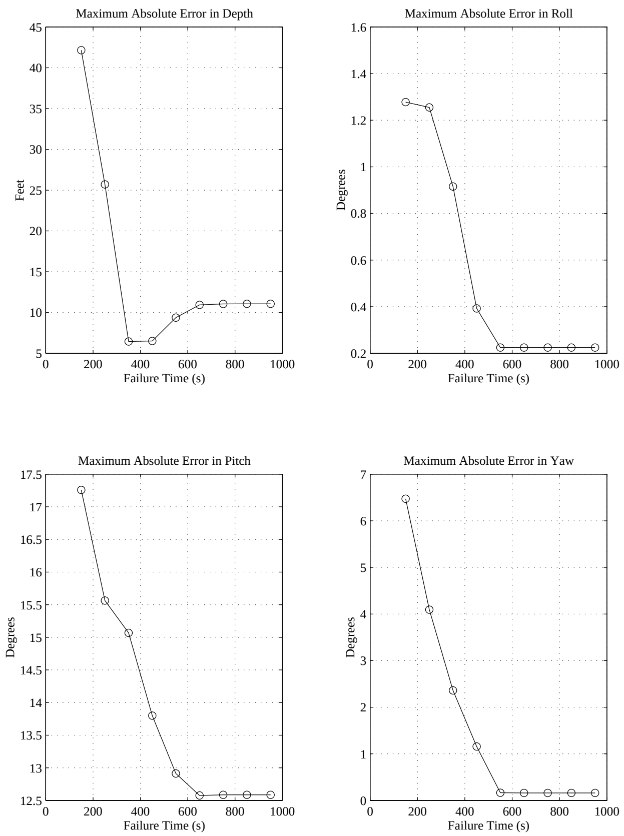

Fig. 7. Maximum absolute errors in depth, roll, pitch, and yaw for rise jams.

of 800 feet. The specified value of speed for a stuck jam is $u_{min} = 6.45$ knots. Thus, all the stuck jam results end with the same values for depth and pitch. Since the plots for stuck jams are similar to that of rise and dive jams, they are not included here.

IV. Conclusions

This research has shown that controller reconfiguration is required when a major fault like a stern plane jam occurs. Although an equilibrium condition is reached if the normal automatic control system is used without modification, significant excursions in depth and/or pitch will be exhibited. Reconfiguration in general needs to be more than just gain changes on the control surfaces. The speed of the submarine also needs to be manipulated, in addition to changes in the control gains, and the other control surfaces may need to be manipulated in specific ways.

The critical parts of the reconfiguration are closed-loop control of the commanded forward speed and changes in the gain values. This has been shown to provide excellent control of all the state variables. Excursions in depth have been significantly reduced or eliminated by the reconfigured control. The results thus far are very promising.

In addition to expanding this work to include other types of failures, the reconfiguration procedures described in Section II-B need to be generalized. The minimum value and the rate of change in the forward speed have been chosen in an ad hoc fashion for the fault type considered in this present work. An effort is being undertaken to incorporate control of the commanded speed into the overall maneuvering control system.

It is planned that a first-order model will be used to describe the dynamics between commanded and actual speeds. The time constant in the model is chosen based on the time that is currently being used to ramp the speed from the initially commanded value to one-half of that value during controller reconfiguration. This is typical of the minimum value for the commanded forward speed. The linearized model of the underwater vehicle in the horizontal and vertical planes will be augmented with this model for the speed dynamics.

The commanded forward speed will be included as a control input; therefore, the R weighting matrix in the LQR design procedure will have an element for the speed. The control surface that is jammed, stern plane in this case, will be deleted from the R matrix and the control vector. The discrete-time, finite final time LQR problem formulation will be used to compute the new gain matrix, with the final time being one timestep ahead of the current time. With the linearized dynamics being updated at each timestep, a new gain matrix will be computed at each sample time. Since the final time horizon is one timestep, the Riccati difference equation must only be solved once per sample time to calculate the updated gain matrix. This gain matrix will provide the optimal control, including the commanded forward speed, over the time interval until the next sample. It is expected that this procedure will provide easily generalizable results.

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