AUV Control in the Presence of Fin Actuator Faults

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Abstract - **Autonomous underwater vehicles (AUV) are rapidly becoming useful and versatile tools in the ocean environment. They have only recently matured to the level of commercial viability, but there is currently recognition of the need for AUV, and an expectation of increased benefit from using these vehicles. In order for AUV to be firmly established as a viable, mature technology there are several issues that need to be addressed, not the least of which is reliability.**

A systematic study was made involving simulations of a vehicle under fault conditions to identify the vehicle behaviours typical of such fault conditions. The simulation tool used is a linear model of the dynamics of the Canadian Self-Contained Off-the-shelf Underwater Testbed (C-SCOUT), and the maneuvers used were those most likely to be desired during normal operation: holding course, a controlled dive, and a turn in the horizontal plane. C-SCOUT is typical of many current AUV, therefore the results of the study are applicable in a qualitative sense to a number of vehicles.

I. INTRODUCTION

In order for autonomous underwater vehicles (AUV) to be firmly established as a viable, mature technology there are several issues that need to be addressed, not the least of which is reliability. Reliable control requires clear understanding of the physics of the vehicle behaviour, even under fault conditions. Control plane faults are the most obvious cause of changes in vehicle behaviour. It may not always be economically useful or even physically possible to abort the mission and recover the vehicle when a fault occurs, and, in most cases, it would be better to be able to accomplish at least some subset of the mission objectives. Since it may be necessary to operate the vehicle when it has reduced control authority due to a control plane fault, such as a jammed or a missing control plane, knowledge of how the vehicle behaves under these conditions is important. It will allow the mission planner to make critical decisions about the viability of the mission or about certain specific subtasks. It may also help the mission planner determine the nature of the fault. Knowledge of vehicle behaviours under fault conditions can also facilitate the use of operational envelopes in restricted waters; i.e. a healthy AUV may be restricted in the magnitude of control plane deflections, so that it can maintain a safe trajectory even if a control plane fails.

This paper is intended to describe the effects of actuator fault conditions on vehicle behaviour. A systematic study was made involving simulations of the vehicle under fault conditions to identify the vehicle behaviours typical of such fault conditions. The simulation tool used is a linear model of the C-SCOUT, and the maneuvers used were those most likely to be desired during normal operation: holding course, a controlled dive, and a turn in the horizontal plane.

II. C-SCOUT: THE REAL AND THE VIRTUAL

The Institute for Marine Dynamics (IMD) of the National Research Council (NRC) Canada and the Ocean Engineering Research Centre (OERC) with the help of the Centre for Instrumentation and Control Automation (INCA) both of Memorial University of Newfoundland (MUN) began a collaborative effort in September of 1998 to design a streamlined AUV, the Canadian Self-Contained Off-the-shelf Underwater Testbed (C-SCOUT).

A *The Physical Vehicle*

The C-SCOUT vehicle was designed and built by graduate students at Memorial University of Newfoundland, by work term students employed by IMD and OERC, and by IMD and MUN technical personnel [1]. The AUV has become part of the Natural Sciences and Engineering Research Council (NSERC) Strategic Project: "Offshore Environmental Engineering using Autonomous Underwater Vehicles" which involves a number of research and industrial partners including MUN, IMD, C-CORE, the University of Victoria, Petro-Canada, International Submarine Engineering (ISE) Ltd., and Geo-Resources [2].

C-SCOUT (see Fig. 1**)** is typical of many vehicles active in the world today; it is a hydrodynamically streamlined, axi-symmetric, slender body using control planes for directional control. It is atypical in that the after control planes are mounted on the parallel mid-body rather than on the tail section. This allows greater variation of the configuration of the vehicle, i.e. different tail sections and main propulsors may be used without redesigning the control plane section. The elliptical nose and cubic spline tail section (designed to increase the inflow to the propulsor) are also somewhat distinctive.

To date, the first vehicle has been built and is currently undergoing systems validation. A second hull has been fabricated for full-scale hydrodynamic experiments [3].

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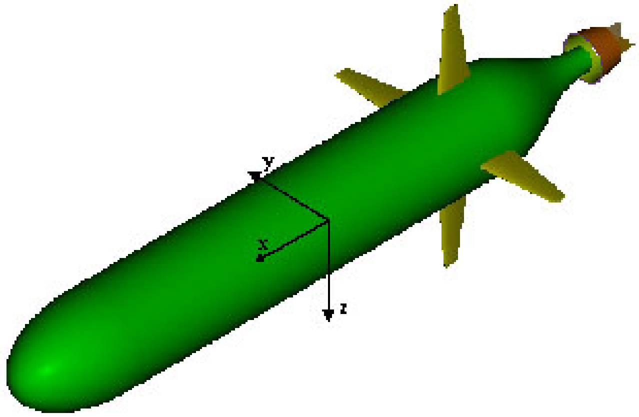

Fig. 1. Base Configuration C-SCOUT AUV.

B *The Virtual Vehicle*

In conjunction with the physical vehicle, a computer model was developed to test ideas and algorithms before committing them to hardware. The nonlinear computer model and the linearized model formulated from it were developed in Matlab™/Simulink™ [4].

1) The Nonlinear Model

The nonlinear model of the C-SCOUT is based on Newton-Euler equations of motion, which equates the changes in linear and angular momentum to the externally applied forces and moments on the body. The excitation forces due to viscous effects are formulated in terms of lift and drag equations applied to each of the components of the vehicle, i.e. to the hull and the control planes. The resulting sets of forces and moments are summed together to provide the forcing function applied to the vehicle. This method is called the body build-up technique [5] or the component build-up method [6]. The advantage here is that these forces can, for the most part, be determined analytically, and therefore provide a quick answer without excessive computational effort.

2) The Linear Model

A linear model can be developed from the nonlinear model by perturbing the nonlinear model by a small amount, ε, from some given equilibrium state, Ξ, such that the rate of change of force (or moment) with respect to the parameter perturbed may be determined. E.g.,

$$\mathbf{X}_u = (\partial \mathbf{X}/\partial u)\Delta u \cong ((X_\varepsilon - X_\Xi)/\varepsilon)\Delta u$$

This process was followed to obtain the velocity dependent derivatives for the linear model of C-SCOUT. The acceleration dependent derivatives ("added virtual mass") were determined off-line by a separate computer program [7], as they were for the nonlinear model.

The standard form for a state-space model is:

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu}$$
$$\mathbf{y} = \mathbf{Cx} + \mathbf{Du}$$

In order to achieve this format, the gravity-buoyancy effects ($\mathbf{F}_S$) must be included in the **A** matrix, since they are vital to the correct solution. In order to include them the state vector is augmented

$$\Delta\mathbf{x} = [\Delta u\ \Delta v\ \Delta w\ \Delta p\ \Delta q\ \Delta r\ \Delta\phi\ \Delta\theta]^T$$

and the dynamic equations are augmented by two kinematic equations to keep the **A** matrix square, facilitating linear analysis.

The equilibrium condition used is straight and level flight at 3 m/s with the vehicle deeply submerged at depth z_0 and traveling on heading ψ_0. All the simulations were performed for this condition.

III. VEHICLE RESPONSE WITH CONTROL PLANE FAULTS

A *Scope and Limits of Study*

Fault conditions that can occur in operation run from power loss to programming errors to mechanical difficulties. This study is focused on hardware rather than software problems, though there is much overlap in the effects of various fault conditions. Hardware faults include such things as degradation or loss of propulsion, which would have major impact on the motion of vehicles like the C-SCOUT, since these type of vehicles are entirely dependent on the propulsor not only for attaining motion, but for facilitating directional control as well. Other major faults involve the jamming of control planes, which may occur due to an electrical or mechanical defect, or due to operational hazards such as being fouled with seaweed, etc. It is even possible to loose a control plane if it gets snagged, or is involved with an impact with some other body. There are many other types of fault conditions possible during the course of operation of an AUV, but this study was limited to jammed and missing control planes. Further it was limited to single-point failures that represent a reduction in, but not a loss of, control authority. Two types of faults were investigated:

1. One control plane missing; and
2. One control plane jammed.

B *Control Authority*

Stability and maneuverability are conflicting requirements for any vehicle. For a vehicle to hold a stable course, it must be able to reject any kind of force that would cause it to deviate from that course. On the other hand, for a vehicle to be maneuverable, it must be able to change course quickly. One of the key elements of control plane design (size, shape, and location) is to find an applicable balance between these two requirements. The measure of the ability of the control plane to affect change in the vehicle direction is referred to as the control authority of the control plane. The fins taken together (with the propulsor) form the total control authority for the base configuration of C-SCOUT. If the ability of one or more of the control planes to take up the commanded deflection angle is impaired, the process of diving or turning may be adversely affected. The control authority of that fin, and indeed the vehicle, is reduced.

C *Simulation Procedure*

A series of simulations that included various fault conditions were performed. The series of simulations included three basic maneuvers common to AUV missions: holding course, diving (in this case a 100m descent), and turning (here a starboard turn through 180°. The vehicle was assumed to be in the fault condition at the start of the simulation, and the dive and turn maneuvers were initiated well after the start of the run. All the simulations used the linear model of the C-SCOUT with the dynamics corresponding to straight and level flight at 3m/s.

D *Physics of Fault-Free Vehicle Motion*

To understand the effects of control plane fault conditions, it is necessary to review the behaviour of the vehicle in its "healthy" state. To examine the nominal ("healthy") state and the fault conditions, three maneuvers common to normal operation will be simulated.

1) Hold (Course)

To hold course, the vehicle must maintain depth and heading; all rates except the surge velocity (i.e., forward speed) should be zero. The vehicle will move in the horizontal plane, however the heading angle, ψ, with respect to a specific inertial reference frame will be constant. Theoretically, the roll angle should be zero. There may be some small angle of pitch (θ) to balance the moment due to the asymmetry of the vehicle about the x-y plane (the center of mass being below the axis of symmetry of the vehicle), but this angle should not result in changes to the heading or depth.

2) Dive 100m

Diving is a maneuver in the x-z plane of the vehicle. Since the vehicle is symmetric about this plane, there is (theoretically) no cross-coupling into other DOF; i.e., no induced roll, yaw, or sway. The motions involved are surge, heave and pitch only. At the end of the dive maneuver, the depth, z, should have a new, constant value (z_0 + 100m). Otherwise the vehicle velocity and position variables should be as described under Hold (Course). In the simulations, z_0 is zero even though the vehicle is assumed to be deeply submerged even at the start; the 100m dive represents a Δz from the nominal depth.

3) Turn 180º

At the end of the turn, the heading, ψ, should have a new, constant value (ψ_0 + 180º). Otherwise the vehicle velocity and position variables should be as described under Hold (Course). In the simulations, ψ_0 is zero. It is desired that the turn be accomplished in the horizontal (x-y) plane. Because of the asymmetry about the x-y plane of the body reference axes, however, the forces that cause the turn also induce a roll angle and a pitch angle on the vehicle.

E *Role of Roll*

1) Coupling of Motions

Roll dynamics are (theoretically) only relevant for maneuvers in the horizontal plane; motion purely in the vertical plane should not induce any roll because of the symmetry of the vehicle about the x-z (vertical) plane. The horizontal fins (actuators for control in the vertical plane) can be used to cause roll or to compensate for roll caused by some other effect. Since roll is usually undesirable, the horizontal control planes are more apt to be used to compensate for roll than to cause it. The vertical fins (actuators for control in the horizontal plane) can also be used to cause roll or to compensate for roll induced by other forces acting on the AUV. Although roll is not desirable, when the vertical fins are used, they tend to cause a roll moment because of the asymmetry about the horizontal (x-y) plane, i.e. the distance from the center of mass to the center of pressure of the upper control plane is greater than the distance from the center of mass to the center of pressure of the lower control plane. When a turn is the desired maneuver, the hydrodynamic forces in the horizontal plane induce a roll moment on the vehicle, leading to a pitch and depth excursion.

If roll can be eliminated, or at least, minimized, there should be a forced decoupling between horizontal and vertical maneuvers, such that there is no change in depth when the desired motion is a turn. Further, since a fault condition on any single control plane is likely to induce a roll motion, controlling the roll motion may be key to ensuring reliable motion characteristics even when such faults occur.

2) Roll Compensation and Depth Control Gain

The simulations were performed using closed-loop (proportional) control for the heading, depth, and roll. The individual control plane deflections (after starboard, after port, after upper, and after lower, respectively) were commanded as follows:

$$\delta_{as} = k_z\,(z_{setpoint} - z_{actual}) + k_{\phi a}\,k_{\phi e}\,(\phi_{setpoint} - \phi_{actual})$$
$$\delta_{ap} = k_z\,(z_{setpoint} - z_{actual}) - k_{\phi a}\,k_{\phi e}\,(\phi_{setpoint} - \phi_{actual})$$
$$\delta_{au} = k_\psi\,(\psi_{setpoint} - \psi_{actual}) - k_{\phi a}k_{\phi r}\,(\phi_{setpoint} - \phi_{actual})$$
$$\delta_{al} = k_\psi\,(\psi_{setpoint} - \psi_{actual}) + k_{\phi a}k_{\phi r}\,(\phi_{setpoint} - \phi_{actual})$$

For the horizontal control planes a positive deflection means trailing edge down, while for the vertical control planes, a positive deflection means trailing edge to port. In either case, a positive deflection of the control plane pair will result in a negative moment on the vehicle - negative pitch (nose down) for the horizontal pair, and negative yaw (nose to port) for the vertical pair.

For each of the three maneuvers a simulation was performed for four modes of roll compensation:

No active roll compensation: only the passive roll stability effects provided by the vertical distance between the center of buoyancy (the buoyant force acting through the center of the volume from which water is displaced – (seeFig. 2) and the center of mass (or gravity, where the weight of the vehicle acts). When the vehicle is upright, the forces of buoyancy and weight have a common line of action, but opposite directions, and for a neutrally buoyant vehicle, they cancel each other. When the vehicle rolls, the lines of action of these two forces are no longer colinear, and a righting moment is produced which will tend to return the vehicle back to the upright position (Fig. 2). The lack of active roll compensation was implemented by setting $k_{\phi a}$ to zero.

- Active roll compensation via elevators (starboard and port "horizontal" control planes). Here a differential deflection of the horizontal control planes will actively force the vehicle back to the upright position; e.g., a positive deflection of the port plane and a negative deflection of the starboard plane will generate a positive roll moment on the vehicle. This form of active roll compensation was accomplished by setting the all-plane-roll gain, $k_{\phi a}$, to unity and the rudder-roll gain, $k_{\phi r}$, to zero, while the elevator-roll gain is set to the desired value.

- Active roll compensation via rudders (upper and lower "vertical" control planes). This method of active roll compensation was implemented by setting $k_{\phi a}$ to unity, $k_{\phi e}$ to zero, and $k_{\phi r}$ to the desired value.

- Active roll compensation via all control planes. Here the roll compensation was performed by setting both $k_{\phi r}$ and $k_{\phi e}$ to unity, and setting $k_{\phi a}$ to the desired value.

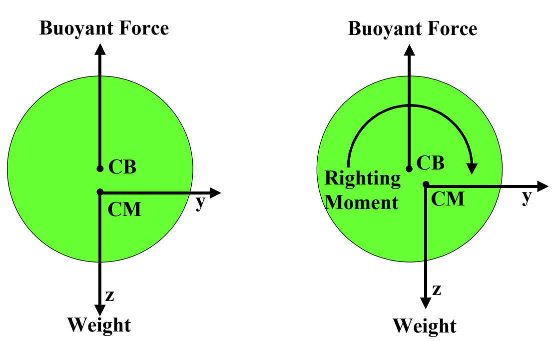

Fig. 2. Passive Stability.

In each case where $k_{\phi a}$, $k_{\phi r}$ and $k_{\phi e}$ were not being used as a filter mechanism (i.e. set to unity or zero), the desired value was the same, 0.0148.

In addition, each of these cases was further simulated at two values of depth controller gain, k_z. In the vertical plane, the gravity-buoyancy couple acts as a restoring moment, making the vehicle response very similar to a first-order system, where the magnitude of the controller gain can cause the system to exhibit an overdamped (no overshoots) response or an underdamped (overshoots present) response in depth. The former response was achieved by setting the depth controller gain, $k_z = 0.01$, while the latter response was accomplished with a depth controller gain of 0.07.

F *Vehicle Behaviours (Simulation Results)*

1) Nominal (No-Fault) Behaviour

All maneuvers were achieved. In the cases of holding course and diving 100m, no roll was induced, therefore there were no parasitic motions even without active roll compensation. The vehicle response under all modes of roll compensation is identical during course holding. The vehicle response under all modes of roll compensation is identical during the diving maneuver as well. In the turn through 180º, however, a roll angle was induced on the vehicle and a change in depth occurred. Using the rudders to affect roll compensation did reduce the roll angle, but increased the depth excursion. Roll compensation via the elevators or via all control planes working together reduced both the roll angle and the depth change. However, with no active roll compensation, the depth excursion is less than 1% of the distance travelled. Therefore, compensation is not really required for the healthy vehicle even in turns.

The vehicle response with the underdamped ($k_z = 0.07$) depth controller was very similar to the vehicle response with the overdamped ($k_z = 0.01$) depth controller, except that the depth was better controlled (less steady state error), as expected. Note that the higher gain does mean overshoots are present in the transient response.

2) Symmetry of Maneuvers and Symmetry of Fault Conditions (Jammed Control Planes)

Both dives and holding course are maneuvers in the x-z plane of the inertial reference frame. Assuming the vehicle starts (and ends) the maneuver in straight and level flight (i.e., the body-fixed z-axis is parallel to the inertial z-axis), this plane is also the plane of symmetry of a vehicle like C-SCOUT. Vehicle response is expected to reflect this symmetry. Since the vehicle is not symmetric about the x-y plane of the body-fixed reference axes, the vehicle response is not expected be symmetric in the horizontal plane. The fault condition simulations show that, for holding course and diving maneuvers, the following are true:

- Symmetry condition 1: vehicle response with a jammed starboard control plane is similar to vehicle response with a jammed port control plane for any given angle of jam, the major difference being the direction of heading error induced;

- Symmetry condition 2: vehicle response with the upper (or lower) control plane jammed at a positive deflection angle is similar to vehicle response with the upper (or lower) control plane jammed at the same magnitude of negative deflection angle, with the direction of induced heading error again the major difference;
- Asymmetry condition 1: vehicle response with a jammed upper control plane is not necessarily similar to vehicle response with a jammed lower control plane for comparable angles of jam; and
- Asymmetry condition 2: vehicle response with the starboard (or port) control plane jammed at a positive deflection angle is not necessarily similar to vehicle response with the starboard (or port) control plane jammed at the same magnitude of negative deflection angle.

For the turning maneuver, while the asymmetry conditions hold, the two symmetry conditions do not necessarily apply; there may be significant differences in response between the port and starboard jam conditions. In the case investigated here (a 180º turn to starboard), the starboard fin is inboard, while the port fin is outboard. The reverse occurs for a turn to port, and the responses outlined below for each of these fins would be reversed; i.e. the responses for a jammed starboard fin during a turn to starboard should be similar to the vehicle response when the port control plane is jammed (at the same angle) during a turn to port, since each is the inboard control plane in their respective maneuvers. The same asymmetry is applicable to the sign of upper or lower control plane deflection angles. For example, the vehicle response in a turn to a particular side at a given rudder deflection angle, for a positive angle of jam on the upper control plane will not be similar to the response in a turn to the same side when the upper control plane is jammed at an equivalent (in magnitude) negative deflection angle. However, the response to the upper fin positive-deflection-angle jam during a turn to starboard should be similar to the equivalent upper fin negative-deflection-angle jam during a turn to port.

3) Jammed Control Planes

When the jammed control plane is one of the elevators (horizontal control planes), and the angle of jam is large (~±25º), the remaining control plane has insufficient control authority to compensate for roll and regulate the depth. The same was true of the rudders (with respect to roll compensation and heading regulation) when the jammed plane is one of the vertical planes. The vehicle response (in terms of depth and heading error) when active roll compensation via all planes is not always acceptable either, but in specific cases, roll compensation in one of the forms used in this study will improve vehicle behaviour over the response of the vehicle without active roll compensation.

Jams to the lower control plane seem to degrade the vehicle response more severely than do jams to the other planes. A jam of the lower plane at 25º will result in the inability of the vehicle to turn to starboard at 3 m/s (see Fig. 3).

The vehicle response with the underdamped depth controller (k_z = 0.07) was similar to the vehicle response with the overdamped depth controller (k_z = 0.01), except that the depth was better controlled (less steady state error), as expected. In turns, this improved depth control also induced a reduction in heading error.

4) Symmetry of Maneuvers and Symmetry of Fault Conditions (Missing Control Planes)

Symmetry condition 1 and asymmetry condition 1 above hold (in dives and holding course) for missing fins as well as jammed fins, while symmetry condition 2 and asymmetry condition 2 are not applicable.

For the turning maneuver, again while the asymmetry condition holds, the symmetry condition does not necessarily apply; there may be significant differences in response between the port and starboard plane missing, because of the inboard outboard relationship to the maneuver.

5) Missing Control Planes

When the missing control plane is one of the elevators, the remaining horizontal control plane has insufficient control authority to maintain depth or effect the commanded magnitude of depth change while limiting the roll of the vehicle. When the missing control plane is one of the rudders, there is no significant problem apparent in dives or holding course; the loss of fin does not affect the symmetry of the vehicle, and (theoretically) only means a loss of the drag of the vertical plane in question. Data for vehicle response with loss of vertical fins is unavailable, because the model could not be resolved for these cases.

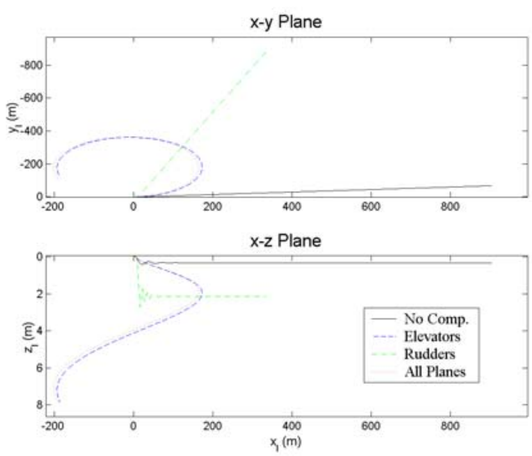

Fig. 3. Comparison of Vehicle Response in a 180º Turn to Starboard while the Lower Control Plane is Jammed at 25º (k_z = 0.07).

The vehicle response with the underdamped depth controller ($k_z = 0.07$) was unstable when a control plane was missing. Only the overdamped depth controller ($k_z = 0.01$) provided stable, though sometimes unacceptable, responses. This is in conflict with the controller requirements for jammed control planes, where the depth controller with the higher gain resulted in better vehicle response.

IV. AUV FAULT SELF-DIAGNOSIS MANEUVERS

The idea of the "self-diagnostic" vehicle maneuver is to use the behaviour of the vehicle during a commanded maneuver to determine whether there is a jammed or missing control plane. The condition would be detected by measuring an asymmetry in the hydrodynamic loads on the vehicle or fin, that would indicate the type of fin fault e.g. free-swivelling, gone, jammed at non-zero angle. The ideal situation would be to have the actuator housing mounted on a three-component balance so that the fin lift, drag and pitching moment can be measured, for each fin. This is not usually practical for an operational AUV.

However, when a fault condition occurs, and the vehicle trajectory is affected, the control system should detect the deviation in track. It can then institute a maneuver or series of maneuvers to ascertain the nature of the fault. Knowing the nature of the fault, the control system is able to classify the expected effects of the fault, and make decisions concerning the viability of the task at hand (or even the mission), and concerning which fault recovery procedures to implement. This assumes the behaviour in the fault condition is significantly different than nominal behaviour, but if it isn't there is no need for fault recovery procedures.

For example, if the fault condition is a jammed control plane, once the control system detects a fault, and determines which fin is stuck, it may find a deflection angle for the opposing fin that brings the vehicle behaviour (response) back to being "symmetrical" (although degraded), e.g. dives without turning. Then the angle of jam of the defective fin can then be deduced from the angle at which you need to set the opposing fin in order to regain "symmetrical behaviour".

V. OPERATIONAL ENVELOPES (PERFORMANCE CONTEXT)

The idea of operational envelopes can be utilized for performance criteria as well as safety considerations. Fig. 4 is an example graphical display of an envelope of acceptable operation. The roll compensation method used is indicated by the letter (A – active roll compensation via all control planes) in the upper left corner of the figure, and the depth controller gain is noted along with the maneuver type above the coloured block. The depth controller gain is 0.07 for the example case shown, and the maneuver involved is a turn (180º to starboard). The heading across the top indicates the angle of jam for the particular control plane. The control planes are listed down the left side.

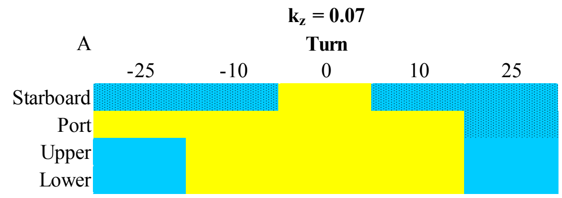

Fig. 4. Operational Envelope Based on Control Plane Jams for the AUV Turning Through 180º ($k_z = 0.07$; Active Roll Compensation via All Control Planes).

The coloured block is a matrix of jammed plane conditions, and the colour of a particular element of the matrix indicates the acceptability of the vehicle response in the specified maneuver with the particular control plane jammed at the given angle. The yellow (lightest gray) and shaded yellow (next lightest gray) areas show the response of the vehicle is acceptable in depth (z_{err}<1m), and heading (ψ_{err}<0.01rad). The shaded blue (dark gray) and blue (next darkest gray) areas indicate the vehicle response is not acceptable in depth and heading. The shading indicates where the roll requirement (ϕ<0.01743rad) is not met. The best situation would see the entire block as yellow (lightest gray).

For example, in Fig. 4, the upper and lower control planes at ±25º, the port control plane at 25º, and the starboard plane at ±10º and ±25º, are all blue, indicating a compromise of the above criteria if any of these faults occurs. Therefore, during a turn to starboard, the starboard control plane should be restricted to operation near 0º, while the port plane may be operated in the range [-25º,10º] and the upper and lower planes may be operated within a range of ±25º. In addition, the port control plane at 25º, and the starboard plane at ±10º and ±25º, are shaded, indicating that if a small angle of roll is important, these control planes cannot be operated in these regions.

This figure represents a performance envelope at a speed of 3 m/s. For a more complete picture of the operational performance limits, a similar analysis at other vehicle speeds must be added.

6) General Simulation Results

Based on similar envelopes developed from the simulation results, the higher depth control gain (0.07) tended to result in broader operating ranges for horizontal control planes. The higher gain in effect increases the control authority of the horizontal control planes, leading to faster response and tighter depth control.

If the vehicle roll angle is unrestricted, obviously roll compensation is not required. The envelopes developed from the simulation results indicate there is no restriction on the horizontal control planes for a course hold, while the vertical planes are limited to approximately ±10º. For the dive maneuver the horizontal planes may have to be restricted to angles of attack near zero degrees. However, this restriction would not allow the dive maneuver to be achieved in reasonable time, therefore the envelope should be expanded to at least ±10º and some degradation of performance expected if one of the horizontal planes does jam at an angle not near zero. In turns, the restrictions on the horizontal planes differ according to whether jammed plane is the inboard or outboard with respect to the direction of the turn (e.g., see Fig. 4).

If the roll angle must be kept within one degree of zero, active roll compensation using all the remaining unjammed control surfaces appears best, since it expands the operational envelope of the vertical control planes from near 0º to about ±10º. The operational envelope would again indicate that horizontal control planes should be restricted to angles near zero, but this should be expanded to at least ±10º and some degradation of performance expected if one of the horizontal planes does jam at an angle not near zero.

VI. CONCLUSIONS: VEHICLE CONTROLLABILITY IN THE FACE OF CONTROL PLANE FAULT CONDITIONS

Rather than aborting a mission because of a control plane failure, knowledge of the expected vehicle behaviour can enable the controller to replan the mission so as to complete some or all of the mission objectives. This study has presented some typical results from simulations of vehicle behaviour (based on the C-SCOUT). The findings can be applied in a qualitative sense to a large number of AUV active in the world today.

In general, the depth controller gain should be kept as high as possible without inducing instability in the vehicle response. The higher value of gain for the depth controller ensures smaller unwanted depth excursions, and can lead to smaller heading errors when the heave or pitch motions are coupled into the yaw by a non-zero roll angle. There may, however, be conflicting requirements under differing fault conditions. For example, the gain requirements for a jammed control plane condition are very different from those of a missing control plane condition.

The choice of active roll compensation depends on how important the roll angle is to the maneuver; use all the remaining planes to compensate for the effects of the jammed plane if roll must be limited, otherwise no roll compensation is necessary or of benefit. This general rule is not optimal in all cases though, and the results from a variety of simulated fault conditions should be used to provide data for effective control strategies.

The fault condition simulations provide useful information, especially concerning safe operating envelopes for the C-SCOUT for particular mission requirements; providing limits of operation for the control plane deflections that will ensure achievement of particular maneuvers even in the event of a control plane jam or loss.

It is speculated that the information from these simulations can also be used to enable the vehicle to perform self-diagnosis procedures during operation.

In order to increase reliability of AUV, it is useful to look at vehicle behaviour under conditions beyond the scope of nominal, fault-free control; under conditions such as control plane jams and loss of a control plane. In order to accomplish the mission objectives or even a given subset of the mission objectives (e.g., a particular task), there must be some knowledge of the dynamics and hydrodynamics involved; i.e. the vehicle behaviour. Knowledge about the behaviour of the vehicle under fault conditions may be very useful in extending the vehicle's capabilities so as to "save" the mission or task. Simulations of typical fault conditions provide information about vehicle behaviour that will aid in mission re-evaluation and re-planning. The information may even lead to streamlined fault detection algorithms. Since control plane faults are the most obvious cause of changes in vehicle behaviour, reliable control requires clear understanding of the physics of the vehicle behaviour, even under fault conditions. This knowledge facilitates achieving the goal of continuing the mission when the vehicle experiences degraded operational status.

ACKNOWLEDGMENTS

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