Fault Tolerant Actuation for Dorado Class AUVs

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Abstract: This paper describes a new control surface actuating design for the Monterey Bay Aquarium Research Institute (MBARI) Dorado class AUVs. The intent was to increase reliability as part of obtaining the goal to greatly increase access to the Arctic Ocean. The new actuating mechanism is part of creating a robust and economical solution towards increased reliability and fault tolerance. Specifically, as part of developing the ALTEX Autonomous Underwater Vehicle (AUV) for Arctic research with basin scale endurance, the concept for under ice missions was redundancy in critical areas. As the development of the DORADO systems progressed from the original ALTEX concepts, added drivers came from the operations group looking for more useable volume in the aft section.

The DORADO vehicle is guided using an articulated tail steering section. The tail is comprised of a ducted propeller acting as control surfaces and propulsion, in contrast with the more traditional fin control surfaces used by most vehicles. This approach was taken to be more robust to impacts as experience using Odyssey IB vehicles showed the control surfaces damaged during launch and recovery were the number one failure by far. As predicted by analysis the design also improved propulsion efficiency. Also worth noting is that this entire tail system stays inside the 21" diameter of the main vehicle body. The new system being developed is unique in that it keeps all of the key propulsion and actuators but eliminates the current gimbaled tail through the use of what we refer to as a false center. While several new components are being developed, the objective is to leverage the existing technology to the degree possible and allow for an inexpensive as well as direct swap into existing systems.

The new steering mechanism uses a Three Actuator False Center Control solution. The design was first modeled and tested for feasibility. After passing the preliminaries, the decision was made to build a full-scale sea going unit. We now have that system built and in bench testing, ready to swap in for at sea testing in the very near future. We've already demonstrated that the new design offers a superior use of space yielding more useable volume for other equipment. The model demonstrated the added redundancy that we will duplicate at sea. We believe the design is very robust and has a broad range of uses in long duration unattended operations where fault situations must be dealt with by the autonomous system. In this paper we will discuss our progress to date, our current test efforts, and the near term future uses of this new control section for DORADO science vehicles.

Key words: Control surfaces, Tailcone, Dorado, AUV, autonomous platforms, fault tolerant actuation

INTRODUCTION

MBARI's Dorado Class Autonomous Underwater Vehicles (AUV's), Figure 1, are both propelled and steered by a single thruster mounted at the rear of the vehicle [1]. The usual fins for rudder or elevator control have been replaced by a tailcone using a ring wing with foil section support struts. Turning the vehicle is accomplished by moving the articulated tailcone, which consists of the propeller, shroud, and motor mounted in a gimbaled mechanism driven by two linear actuators. The gimbal consists of an outer ring that rotates about the vertical axis (providing rudder control or yaw), and an inner ring that rotates about the horizontal axis (providing elevator control or pitch) [2]. The main computer, naviagation and controls of the core AUV are contained in the tail of the vehicle, The needs of the Dorado program were therefore primarily concerned with developing a robust, versatile AUV tail section.

Additionally, the DORADO vehicles are required to support a broad range of missions. The use of modular sections made this possible, but it also puts requirements on the core vehicle systems, in particular the tailcone. For example, roll stability is critical to multibeam mapping and is a high priority, so any tailcone advancements are required at a minimum to maintain the current capabilities. A second key requirement is the tailcone must be capable of accepting the frequent adjustments to the vehicle control gains. The control gains are altered as the reconfigured length varies due to adding or removing modules installed for various missions.

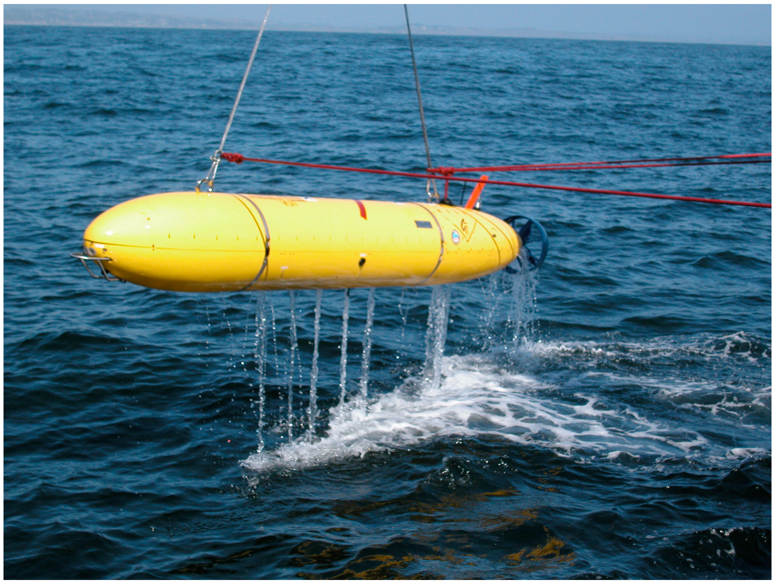


Figure 1: An early version of DORADO during development

SUPPORTING A VERY LONG ENDURANCE AUV

Extended operations are constantly a discussion with AUV users and builders. This makes sense since the cost of data can go down significantly if the platforms being used can work longer. MBARI's initial motivation came from the need for extended operations in the Arctic basin, the Atlantic Layer Tracking EXperiment (ALTEX) program. This program was first funded through a NOPP grant that started in 1998, and starting in the summer of 2000 the primary funding to complete the AUV and perform the arctic mission came through the National Science Foundation (NSF).

The objective of the NSF funded effort was to greatly increase access to the Arctic Ocean by creating and demonstrating a safe and economical platform capable of basin-scale surveys. However, working under the ice with no ability to find and repair problems was seen as a serious situation that should be addressed if possible. The desire to find a suitable solution is what prompted the original False Center Tailcone concept.

ORIGINAL TAILCONE BUILD

The original tailcone concept was created at MBARI in 1999 for the three-actuator false center mechanism. Schedules and responsibility to build an entire AUV called for simplification wherever possible. The False Center actuation concept was shelved in favor of a simpler gimbaled system that offered easier software, one less motor controller and a mechanism more readily understood by the external collaborators and funding agencies. Other pressure to keep the two-actuator design came from the industrial vendor who eventually bought the patent rights from MBARI. So, the gimbaled version for the tailcone was built by the MBARI /Dorado AUV team, Figure 2. There have been years of successful missions, with well over 15,000 kilometers logged including several successful missions underneath the Arctic ice. However the original questions persisted: What can be done if an actuator fails? Can we add fault tolerance while not deteriorating actuator positioning? Is smaller packaging possible? In the current design if one of the two actuators fails and the AUV is in open water, the vehicle will abort its mission and should eventually float back to the surface [3]. However if that AUV is deep under the arctic ice the story is very different. Both of these scenarios pose a problem, because aborting a mission and not having ready access to recover the vehicle means loss of data, possible loss of the vehicle, and the obvious loss of the invested funds for the mission [4].

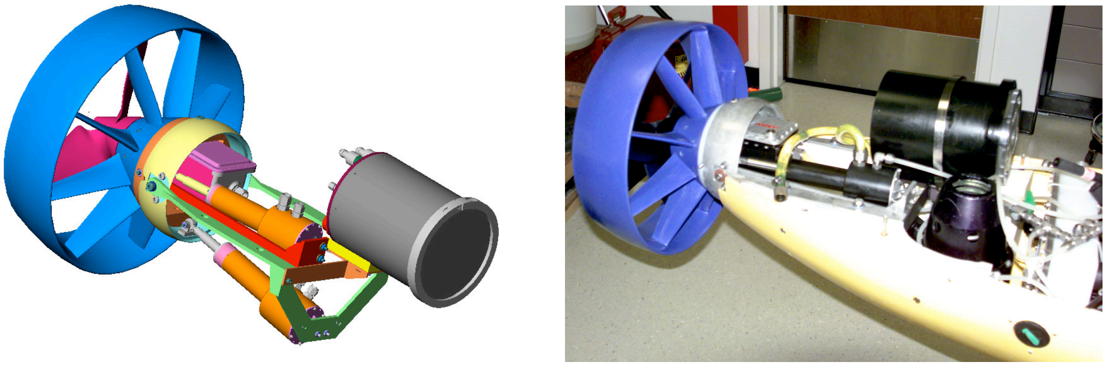


Figure 2: The original DORADO/ALTEX Gimbaled Tailcone Assembly

The current design is also constrained by the physics of the gimbaled mechanism requiring that at least one of the actuators be mounted on the inner gimbaled hub for rudder control. These attachment points are fixed locations and cannot be changed if the actuator is to work. This inflexibility of mounting angles greatly reduces the ability to place additional sensors in the tail section of the AUV. Furthermore the current gimbaled mechanism means one actuator "rides" on the other actuator and therefore has to swing through an open volume. Accomplishing this uses a large amount of volume in the rear section of the AUV.

NEW TAILCONE ACTUATION DESIGN

There are three primary issues to address by removing the gimbaled components that are required to handle the changes in kinematics. The first issue to address is the torque induced on the actuators. The second issue is the requirement to shift the pivot point for actuation when any given actuator might fail. The last issue is recognizing the fault and reacting appropriately.

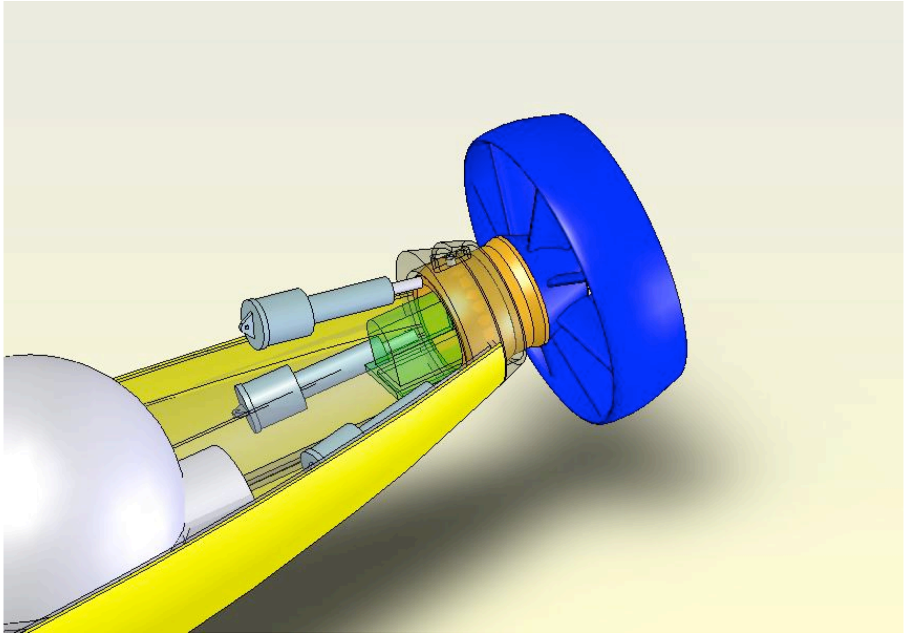


Figure 3: The 3D conceptual model of false center control

The concept design addresses all of these concerns using a sliding surface bearing with the additional actuator to give redundancy. This architecture is somewhat like a Stewart Platform but has removed 3 of the actuators normally associated with such a platform. To address induced torque roll a retention collar bearing is used to constrain one actuator from rotational motion. This in turn retains the entire system. However, the key to this collar bearing is that it cannot constrain the actuator in all directions, only in rotation. This also allows the system to extend or contract the actuators as needed should a failure occur when the system is maneuvering and the tailcone could be in any given position. The problem then becomes how to identify which actuator failed and how to remap the actions of the remaining actuators for proper control of the vehicle.

Prior to investing a great deal of effort a project to develop a tabletop model of a three-actuator mechanism, including the linkages, propeller mount and the control box was undertaken, Figure 4. With this effort we tested several key requirements for the new tailcone and then solved the issues in a manner that could accomplish the results in a real application. The requirements included the ability to carry the thruster and transfer the load into the hull, be able to meet or exceed the response of the current mechanism, use the same or less power, reduce the size, weight and electrical noise, and be able to achieve 20-25° of elevator and rudder control. Although the currently deployed Dorado systems rarely used any inputs over 10° in pitch or yaw.

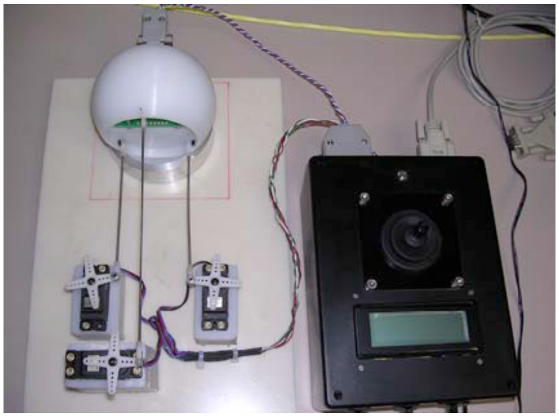


Figure 4: The desktop model of the False Center Mechanism to identify requirements

Based on the successful model tests, a full-scale unit was developed. Part of the development included new actuators that simulate the motions of the current units used to control the gimbaled tailcone. The full-scale unit also incorporates the ducted propeller and propulsion drive motor with a gear reduction unit. Because of the lack of vehicle hull mount points for bench top testing a framework was also constructed to imitate the mounting points of the DORADO style vehicles. The temporary frame is the white plastic as seen in Figure 5. The fully developed prototype was constructed to be a direct replacement for the current tailcone and after bench testing will be integrated into a vehicle when a system becomes available.

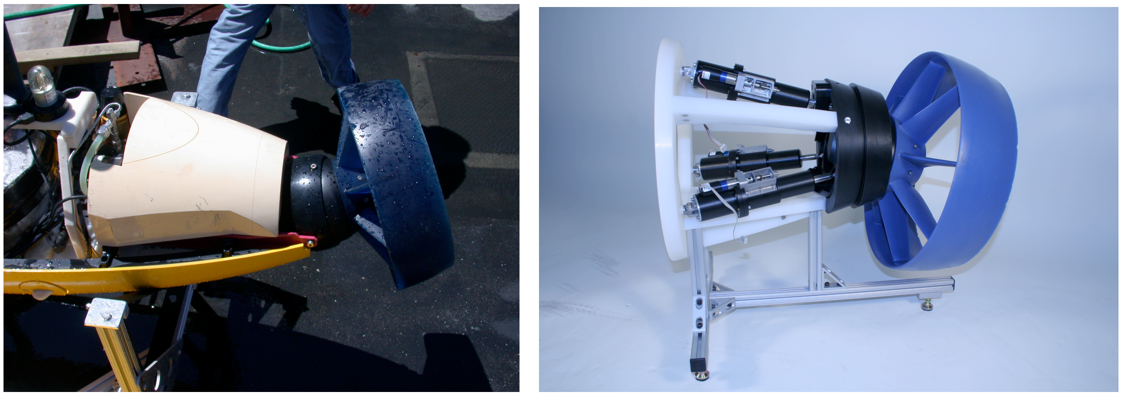


Figure 5: External comparison of the Gimbaled Tailcone and the False Center Tailcone

KINEMATICS OF THE FALSE CENTER

The new false center design and fault tolerant design requires a completely new algorithm for operation. The controls are constructed in one piece of code but operate based on three functional elements. The first is normal operation that uses the rod length and position to operate about the mathematical center, calculated using the known parameters. The second element is the fault diagnostics that recognize the vehicle motions are not corresponding to the commanded inputs. This element then uses a series of health and status checked to determine which actuator has failed. Once the failure has been determined the third element is invoked which remaps the actuation path algorithm by moving the pivot center to the endpoint of the actuation rod that failed. The result of which is slightly slower response times to inputs as the overall moment arm of actuator to pivot point approximately doubles, but the vehicle is still in complete control. It should be pointed out that the tailcone actuation speed is far faster than the response of the DORADO AUV system, so the penalty of longer operation time for any given input in the failure case is mostly imperceptible.

The tailcone will operate successfully in any one of four states: 1) the normal operating mode where all the actuators are functioning properly and 2-4) where actuator 1, 2 or 3 has failed. Rather than using a different set of math formulas for each of these states, the approached used was to develop the math such that one set of formulas worked in every state. The key to make this work is to calculate the required location of the virtual pivot in each state, input this location into the common formulas, and output the correct actuator lengths.

Using kinematic analysis the math was first developed for the normal operation mode. The result was equations 1, 2 and 3, for actuators 1, 2 and 3 respectively. The input variables are pitch (α), yaw (β) and the location of the virtual pivot of the gimbal (L_{vp}). The outputs are the length of the actuators (L_n). The remaining variables are static and represent the ends of the actuators, the points where the actuators are attached to either the forward bulkhead or the gimbal. See Figures 6 and 7 for a visual description of the variables. Points 1, 2, and 3 are the points where actuators 1, 2 and 3 respectively, are fastened to the forward bulkhead. Points 4, 5, and 6 are the locations where actuators 1, 2, and 3 respectively, are attached to the gimbal. The variables R_n and Θ_n are the radius and angle that locate each of the points, the subscript "n" representing the attachment point number. R_n is measured from the centerline of the gimbal, at a pitch and yaw equal to zero, and Θ_n is measured about the centerline from the Y-axis. In this state the virtual pivot of the gimbal does not change and L_{vp} is a constant.

$$L_1 = \left[\left(-L_{vp} - R_4 \cos\theta_4 \cos\alpha\, sin\beta + R_4 sin\theta_4 \sin\alpha\right)^2 + (R_1 \cos\theta_1 - R_4 \cos\theta_4 \cos\beta)^2 + (R_1 \sin\theta_1 - R_4 \cos\theta_4 \sin\alpha \sin\beta - R_4 \sin\theta_4 \cos\alpha)^2\right]^{1/2} \qquad 1)$$

$$L_2 = \left[\left(-L_{vp} - R_5 \cos\theta_5 \cos\alpha\, sin\beta + R_5 sin\theta_5 \sin\alpha\right)^2 + (R_2 \cos\theta_2 - R_5 \cos\theta_5 \cos\beta)^2 + (R_2 \sin\theta_2 - R_5 \cos\theta_5 \sin\alpha \sin\beta - R_5 \sin\theta_5 \cos\alpha)^2\right]^{1/2} \qquad 2)$$

$$L_3 = \left[\left(-L_{vp} - R_6 \cos\theta_6 \cos\alpha\, sin\beta + R_6 sin\theta_6 \sin\alpha\right)^2 + (R_3 \cos\theta_3 - R_6 \cos\theta_6 \cos\beta)^2 + (R_3 \sin\theta_3 - R_6 \cos\theta_6 \sin\alpha \sin\beta - R_6 \sin\theta_6 \cos\alpha)^2\right]^{1/2} \qquad 3)$$

If an actuator failure does occur the actuators length becomes fixed and the concept of a virtual pivot is no longer valid. In this state the point where the failed actuator is attached to the gimbal becomes the new pivot point and L_{vp} changes as pitch and yaw changes. To calculate L_{vp} equations 1-3 were rearranged such that pitch, yaw and actuator lengths are the inputs and L_{vp} the output. These are equations 4, 5 and 6 for actuators 1, 2 and 3 respectively. This new L_{vp} can be used to calculate the lengths of the remaining two working actuators.

$$L_{vp1} = \frac{-b \pm \sqrt{b^2 - 4c}}{2}\ , \qquad \text{where} \tag{4)}$$

$$b = 2R_4(\cos\theta_4 \cos\alpha \sin\beta - \sin\theta_4 \sin\alpha)$$

$$c = R_1^2 + R_4^2 - L_1^2 - 2R_1R_4(\cos\theta_1 \cos\theta_4 \cos\beta + \sin\theta_1 \cos\theta_4 \sin\alpha \sin\beta + \sin\theta_1 \sin\theta_4 \cos\alpha)$$

$$L_{vp2} = \frac{-b \pm \sqrt{b^2 - 4c}}{2}\ , \qquad \text{where} \tag{5)}$$

$$b = 2R_5(\cos\theta_5 \cos\alpha \sin\beta - \sin\theta_5 \sin\alpha)$$

$$c = R_2^2 + R_5^2 - L_2^2 - 2R_2R_5(\cos\theta_2 \cos\theta_5 \cos\beta + \sin\theta_2 \cos\theta_5 \sin\alpha \sin\beta + \sin\theta_2 \sin\theta_5 \cos\alpha)$$

$$L_{vp3} = \sqrt{L_3^2 - (R_{3\_}R_6 \cos\alpha)^2} - R_6 \sin\alpha \tag{6)}$$

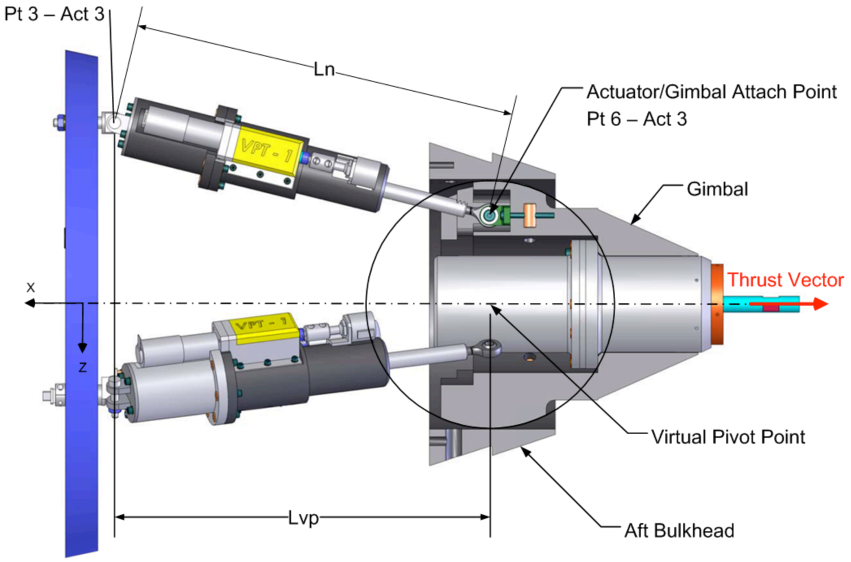
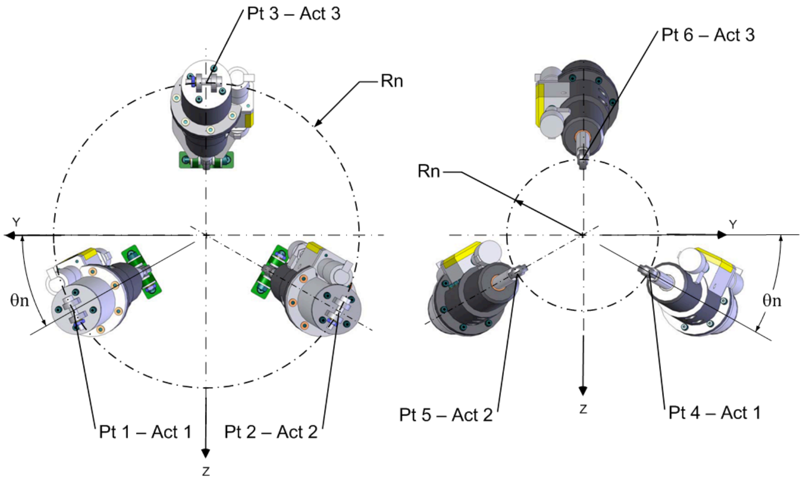


Figure 6: Side View of Tailcone with Gimbal Sectioned



View from Forward End

View from Aft End

Figure 7: End View of Tailcone with Only Actuators Shown

The process for calculating the length of the three actuators, for both the normal mode as well as when an actuator has failed, is shown in Fig 8. Each rectangular box represents one of the six equations above and the specific equation is identified by its number in the box. The process in the diagram starts with the input of the desired pitch and yaw which are read through a serial port. If all the actuators are working properly the length of each actuator is calculated using the normal L_{vp} . If, however, an actuator has failed, its length is read via a sensor and a new L_{vp} is calculated using the length of the failed actuator and the new pitch and yaw values. This new L_{vp} is used in turn to calculate the required length of the two remaining functional actuators.

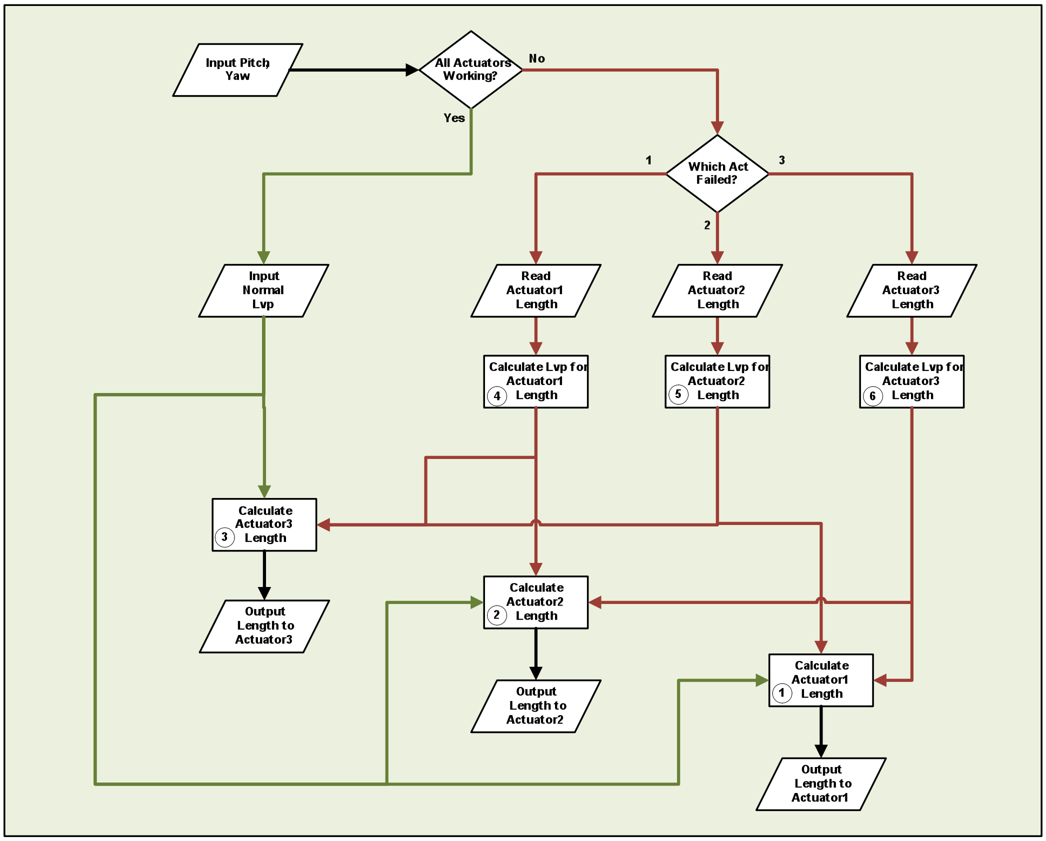


Figure 8: Process to calculate actuator length

The current implementation of the control software simply drives the actuators from their old to new length without regard to the motion the gimbal may take as it pivots to its new orientation. The gimbal may move, therefore, in such a way that is not optimal from an AUV controllability perspective. Testing has shown that large pitch and yaw commands may cause the gimbal to move in a nonlinear fashion which could induce a wobble into the vehicle. This is an important consideration as this type of tailcone does not provide active roll control. In the next phase of the development this tailcone concept will be integrated into a digital simulation of an AUV to explore the effect of the gimbal motion on the flight of theAUV. If necessary, methods of suppressing this effect will be modeled which may include path planning, actuator sequencing and/or scaling of acceleration. A feedback loop(s) will then be implemented into the simulation to explore and demonstrate the controllability of the system.

RESULTS

The rotational matrix and failure software is now written and bench top testing has begun. Using a simple user interface to command the motors, the mechanism operates as designed and has successfully addressed the challenges of binding, shifting center of motion, rotational load handling, and creates the additional volume desired. Further testing is underway and the results are expected to allow for sea trails in the near future.

Although the primary goals have been achieved to some extent, two others goals are ready for testing but at the time of this writing yet untested. One is the approach of taking a failure in this tolerant system and implementing the algorithm that moves each motor in turn to properly identify the error and remap the commands to new actuations outputs. The second is the demonstration of small incremental motions that minimize the error in pitch and yaw due to a distance error from the true-center of rotation that is mechanically fixed in the gimbaled solution.

CONCLUSIONS

The desk top prototype successfully modeled the concept to: effect servo motor positioning, read in sensor position on a serial communications port and looked at the resulting motions due to shifting pivot centers in a simulated failure. The three-actuator mechanism model directed us to required modifications we would need before a fully enabled system could be implemented and be fault tolerant. The spherical cradle mechanism, although not true to the concept, demonstrated by use of unconstrained bearing construction that a false center can be created out-of-plane and movement can be remapped successfully.

Early bench testing of the prototype has shown the system does in fact respond as predicted. This is a critical point since the project hinges on the ability to move the pivot center and maintaining complete control while never creating a potential bind situation.

The system requires further testing. Prior to implementing the system on a real vehicle our next phase will be to integrate the tailcone to a vehicle simulator and to take the system through a rigorous course of controls testing followed by failure scenarios. We are also planning to look at the variety of sensor suites that would be best suited to identifying a failure. The idea of this is to look at the minimum or least expensive options although in practice the control system will use the full data set from the instrument compliment that is available.

The false center tail, as previously stated, was designed to use the existing DORADO propulsion and actuators. Once the system has been fully integrated and tested in the model a decision will be made based on vehicle availability whether we will pursue power reductions by exploring smaller actuators per the design principals outlined in the paper or if we will go directly to sea to demonstrate the functionality in a full system test. Either path has great value and when a DORADO style system becomes available all other work can be set aside without any loss of progress to take advantage of the assets. With propulsion and control being a large part of a DORADO power budget we will be pursuing this phase of the project since the results are a path to increased endurance and/or science payload which is a highly sought value added situation for the Fault Tolerant Tailcone.

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