III. CONCLUSIONS

An observation platform has been developed which is able to navigate on the surface of the sea making vertical immersions to obtain water column profiles. The vehicle has a double hull, a fiberglass exterior with a profile that provides a good hydrodynamic characteristic, and a watertight inner module built in aluminum. Also, an autonomous control system for the vehicle has been designed and implemented. Its proper operation has been tested in the laboratory. Now, all elements of the structure of the vehicles are being assembled and then a test of navigation at sea will be performed.

ACKNOWLEDGMENT

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FAULT TOLERANT ACTUATION FOR DORADO CLASS AUVS

William Kirkwood[1,2], Will Anderson[2], and Dr. Christopher Kitts[2,1]
(1) Monterey Bay Aquarium Research Institute
7700 Sandholdt Rd, Moss Landing, Ca. 95039 USA
(2) Santa Clara University, School of Engineering
500 El Camino Real, Santa Clara, CA 95053

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.

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

I. 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.

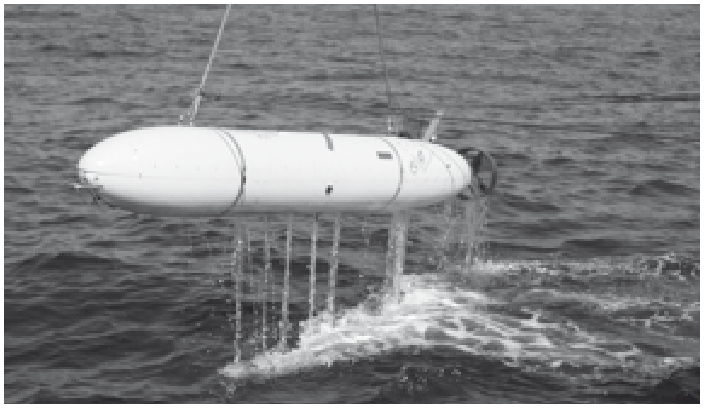

Fig.1: An early version of DORADO during development

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 the in 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].

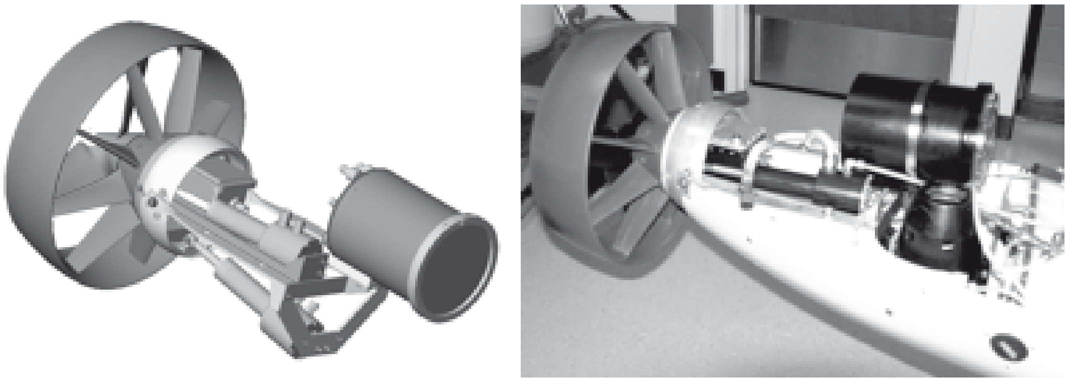

Figure 2: The original DORADO/ALTEX Gimbaled Tailcone Assembly

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.

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 3. We identified the 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.

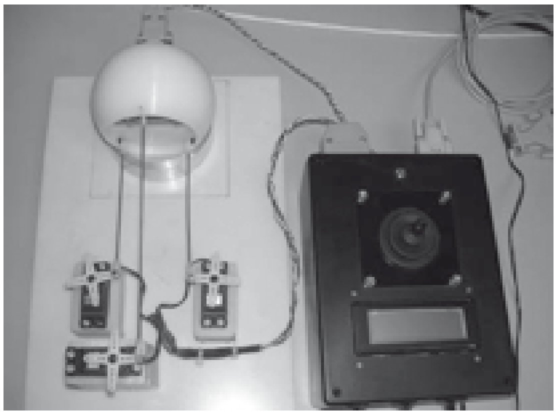

Figure 3: The desktop model of the False Center Mechanism to identify requirements

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 as seen in Figure 4.

II. RESULTS

The rotational matrix and failure software is now written and desktop testing is beginning. Using a simple system of driving the motors by joystick, the mechanism operates as designed and properly addresses the issues 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.

III. CONCLUSIONS

The desk top prototype successfully modeled the concept to: effect servo mo-

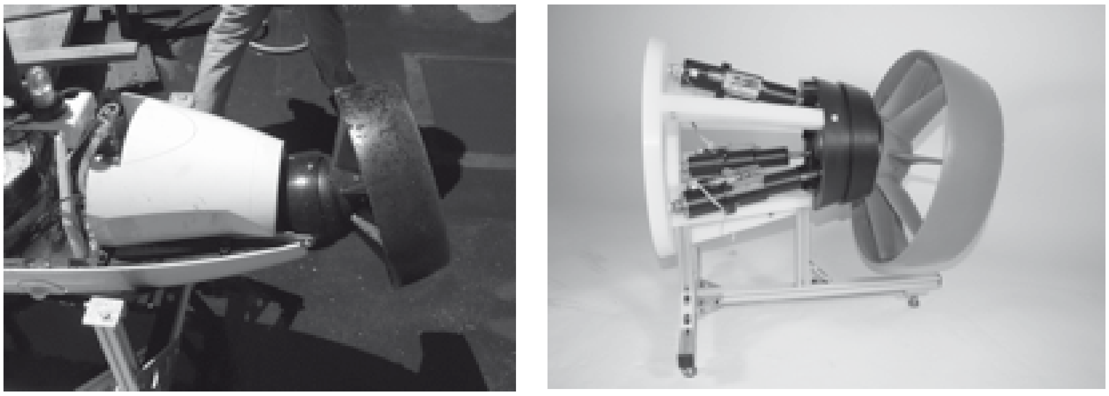

Figure 4: External comparison of the Gimbaled Tailcone and the False Center Tailcone

tor positioning, read in sensor position on a serial ComPort, display actual vs. desired angles, and look at the motions when shifting pivot centers in a simulated failure. The three-actuator mechanism model showed some modifications were required to fully enable its implementation as a fault tolerant system. The expected spherical cradle mechanism demonstrated by unconstrained simple construction that a false center can create out-of-plane movement. This movement has to be managed but without increased actuator strength, power, or any potential for binding in the event of failure of one of the actuators.

The system requires further testing but the strictest requirements for stable control should be easily achievable. As per design, the method of handling this is to limit the full range of motion if any of the motors fail, but maintain a suitable degree of control to complete a mission. Using this approach also takes advantage of the changing lever arm length thereby reducing motor strength demands. It is possible this approach will also reduce the size of the actuators required to operate a DORADO. With propulsion and control being a large part of a DORADO power budget we are exploring this further as the next phase of upgrades that could result in increased endurance and science payload as well as being more tolerant of failures in the field.

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