Tethys-Class Long Range AUVs - Extending the Endurance of Propeller-Driven Cruising AUVs from Days to Weeks

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Abstract— **Most existing propeller-driven, cruising AUVs operate with a support ship and have an endurance of about one day. However, many oceanographic processes evolve over days or weeks, requiring propeller-driven vehicles be attended by a ship for complete observation programs. The Monterey Bay Aquarium Research Institute (MBARI) developed the 105 kg propeller-driven Tethys AUV to conduct science missions over periods of weeks or even months without a ship [1]. Here we describe a three week deployment covering 1800 km at a speed of 1 m/s, supporting sensor power levels averaging 5 watts. Unlike buoyancy driven gliders, Tethys uses a propeller that allows level flight and a variable speed range of 0.5 – 1.2 m/s. The extended endurance enables operations in remote locations like under the ice, across ocean basins in addition to enabling continuous presence in smaller areas. Early success led to the construction of a second Tethys-class AUV with a third in planning. An AUV docking station that can be mated to a cabled observatory or standalone mooring is in development to further extend Tethys endurance.**

Keywords-AUV, Cruising AUV, Propeller driven AUV, Long range, long endurance, persistence

I. INTRODUCTION

Autonomous Underwater Vehicles (AUVs) are revolutionizing the study of dynamic ocean processes. Vehicles in common use today carry limited payloads over periods of months, or more power hungry payloads for periods on the order of a day. The Tethys-class AUVs developed at the Monterey Bay Aquarium Research Institute (MBARI), fills the gap between these operational envelops, carrying chemical and biological sensors that generally consume more power than physical sensors and require greater payload volume.

A. Tools for persistent tracking and surveying

Commercially available buoyancy driven gliders offer persistent ocean presence of weeks to months [2][3][4]. These gliders travel very slowly (~0.3 m/s) and utilize ultra-low power computers to stay at sea continuously for weeks or months at a time. However, their sawtooth trajectory does not permit level flight and the slow speeds both present challenges in areas of moderate current, and preclude observation of dynamic processes. Recently the difference between propeller driven AUVs [1] and buoyancy driven gliders has been blurred with the prototyping of a hybrid glider [5] and the addition of a propulsor module to the Teledyne Webb 200 m electric glider [6]. This thruster module allows the glider to fly level and, if needed, at speeds up to 0.5 m/s. The Tethys AUV provides a solution when higher operational speeds and greater payload size and power consumption are needed.

B. Tethys Vehicle and Control System Overview

The Tethys vehicle has a unique ability to operate efficiently in three speed regimes. The vehicle runs at 1.0 m/s for most science data acquisition and event response; more slowly, at 0.5 to 0.7 m/s for extended periods to maximize range; and can drift at constant depth and zero speed. To support the different operational modes, the vehicle employs a range of actuators: traditional elevators for high speed, a moving internal mass (like a glider) for low speed, and variable buoyancy for drifting (like a float). The unique combination of actuators provides Tethys both some level of redundancy for vertical plane control, as well significant efficiency gains.

Figure 1: Two Tethys-class Long Range AUVs: Tethys in foreground and Daphne with a long-nose configuration in back.

The Tethys AUV has a hemispherical nose, parallel midsection, and a convex-conical tail, as shown in **Error!**

Reference source not found.. The total enclosed volume of the hull is 137 liters, with length 2.29 m and diameter 0.305 m (12”). The diameter was obtained by minimizing the combination of surface friction and form drag as a function of diameter, constrained by constant hull volume. The parallel mid-section is a dry 1-atmosphere pressure vessel with a volume of about 65 liters, and is the yellow section in the figure. The hull-tail shape was selected with particular attention to minimizing flow separation [1]. The vehicle also has a 0.28 m high antenna mast, located forward of the control surfaces, which contains the Iridium and GPS antennas. The nose and tail are flooded, although they each contain small instrument housings. The control surfaces are the standard arrangement of upper and lower vertical rudders, with port and starboard horizontal elevators. Each pair is ganged and moves in unison.

Vertical plane control is provided by elevators, shifting mass, and a buoyancy engine. In combination these allow the vehicle to trim to fly at zero angle of attack with no elevator angle at a range of pitch angles, and thus minimize drag. At low speed the elevators do not have sufficient lift to pitch the vehicle against the mass/buoyancy righting moment, particularly when flying an undulating (or yo-yo) vertical profile. Thus the ability to shift the battery pack forward and aft to create additional pitch torque is particularly critical at low speed.

The propulsion system consists of a 16-pole direct-drive brushless DC motor, connected through the pressure housing by a magnetic coupling. The shaft is supported by glass/delrin bearings, and connects without gears to a two-blade propeller. The bearings are open-frame and lubricated by seawater.

1) Navigation

The flight code runs on a LPC3250 processor with a Linux operating system. The control loop sampling frequency is 2.5 Hz, but can be reduced during slow flight.

The vehicle navigates by DVL-aided dead reckoning with periodic GPS fixes, though USBL or LBL navigation is also possible. The DVL is a 600 kHz LinkQuest, and provides velocity with respect to the bottom up to about 100 meters altitude. At higher altitudes it provides water-referenced velocity. The period between surfacing for GPS fixes can be programmed and is usually on the order of an hour. The overall navigation accuracy is 3-4% of Distance Travelled (DT), assuming the DVL has bottom lock. Navigation error is primarily due to error in the magnetic compass, which in turn, is dependent on the proximity of ferrous parts or electrically induced magnetic fields. The compass is located in a separate pressure housing in the nose to maximize the distance from the electronics as well as to any other metal parts that can either distort the Earth’s magnetic field, or be magnetized by the Earth.

2) Control

The horizontal and vertical planes have independent control loops. Horizontal-plane control consists of an outer PID loop that nulls cross-track error by commanding heading. Cross-track error is the perpendicular offset of the vehicle from the line defined by the previous and the next waypoints. The inner loop tracks heading by actuating the rudder. This outer/inner loop is functionally similar to the waypoint/docking/heading control shown in Fig. 8 of [7].

The depth control has a similar overall structure, but with parallel loops. Parallel outer PID loops read depth error and depth rate, and command pitch and buoyancy. The pitch command goes to the inner elevator PID loop, whereas the buoyancy command goes to the pump motor controller. The operators have the option to disable any combination of the three depth control actuators, buoyancy, elevators, or moving mass. The flight code automatically uses the remaining actuators.

3) Range and Endurance

When outfitted with a primary battery Tethys has a demonstrated range at 1 m/s of 1800 km. By adopting energy saving strategies, we estimate ranges in excess of 3000 km are possible. Over such a long distance the salinity variation may cause more than 5 N change in buoyancy, which would cause the control system to have a significant angle of attack on the hull and elevators to maintain depth. This, in turn, induces drag and decreases range. Additionally, a design goal was for this vehicle to be able to park at depth either to wait in a low power configuration, or to take data while drifting with the water mass. Both of these reasons led to an active buoyancy control system.

To conserve power, the motor controllers, and any component onboard, are powered off when not commanded to move. The rudder, elevator, buoyancy, and mass shifting control loops all pass their error signals through programmable dead bands to prevent the motor controllers from responding to small commands. This causes low-amplitude limit cycling in depth and heading. Operators can trade dead-band amplitude (causing longer periods of motor controller inactivity) against vehicle depth and heading limit cycles to minimize the overall power consumption.

Power management of sensors is an integral element of the vehicle control strategy, with implications for vehicle control. The hotel power draw is controlled by the load control electronics, which allows nearly every sensor and subsystem to be individually powered off or on. During periods where the higher-power science instruments are off, the steady-state hotel load is in the range of 5-8 Watts, which yields an optimal speed for maximum range of 0.5-0.75 m/s. During periods of high hotel draw the best speed is around 1.0 m/s. Thus the design speed range was chosen to be 0.5-1.0 m/s.

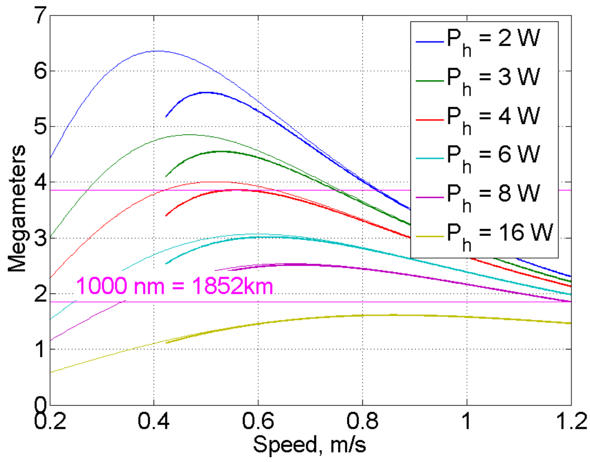

Figure 2: Estimated range with various hotel loads, given a primary battery of 13 kWhr. Thin lines are the ideal case with zero buoyancy and c.g. error; the thick lines show the decrease in range with 1 N buoyancy error.

The vehicle drag model is a combination of computation fluid dynamics (CFD) and empirical methods. A CFD analysis provided the base hull drag [1]. Drag from the antenna, control fins, and instrument ports were estimated empirically and superimposed [8]. Additional skin drag due to scrapes and biofouling is estimated from (assumed) turbulent flow over a surface with uniform roughness [9]. A grain size of 250 microns was chosen to represent average roughness which is similar to the natural surface of cast iron [9]. This model results in a coefficient of drag of .0075, referred to hull surface area. Figure 2 shows a family of range estimates for various hotel loads.

4) Optimal Speed Sea Trial Range Results

The above estimates were tested in sea trials. Figure 3 shows propulsion and hotel loads for straight-and-level flight at 1.0, 0.75 and 0.6 m/s. The cyan plot shows the efficiency in Watt-seconds/meter, which is the integral of the total measured power drawn at the battery terminals, divided by the integral of the horizontal-plane water-referenced velocity components measured by the DVL. Thus the denominator is horizontal distance through the water. The hotel load is constant for each leg, although appears about 1 watt higher during the 1.0 m/s leg than the other two. For an average hotel load of 7 Watts, Figure 2 shows an optimal speed of about .65 m/s.

5) Hover:

A unique capability of the Tethys AUV is its ability to perform a low power hover. This is achieved through an oil filled buoyancy engine that allows the vehicle to trim +/- 5 Newtons from neutral buoyancy in sea water. When combined with missions and vehicle behaviors, some novel functions, such as the following, are possible:

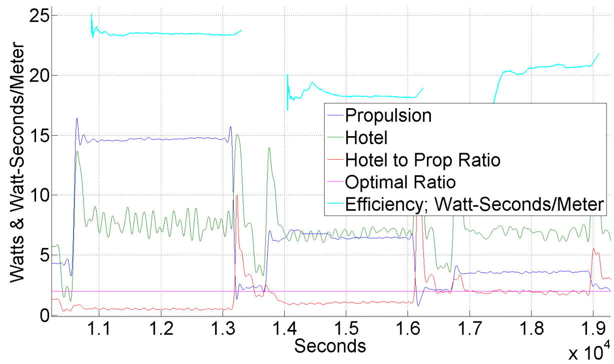

Figure 3: Power breakdown and efficiency for 1.0, 0.75 and 0.60 m/s in straight and level flight. Note that the propulsion power term includes some electronic power consumption associated with the motor control electronics.

a) Automatic ballast and trim: To minimize drag and maximize propeller efficiency a propeller driven AUV should fly with zero angle of attack. This is achieved through proper ballast and trim of the vehicle. Changing conditions including salinity, biofouling, and the escape or compression of trapped air within a vehicle can introduce change net buoyancy during the deployment. Consequently, allowing the AUV to determine its neutral buoyancy at a given depth offers greater efficiency throughout the length of the deployment.

b) Low power station keeping: The ability of an AUV to hold station offers its users a more persistent presence for observation of temporally unpredicatable events of interest or low frequency sampling. Additionally, the ability to conserve power while remaining on station allows for flexibility in dealing with unforeseen delays, for instance, poor weather. In typical usage, a watch circle radius is specified around a single point. The vehicle periodically sufaces to obtain a GPS update, and upon drifing outside the watch circle, the AUV drives to the opposite side of the circle. Once the transit is complete, the vehicle returns to depth, using its buoyancy engine to return to the commanded depth.

c) Lagrangian data collection: Drifting at a given depth allows the AUV to remain within a section of water providing the ability to sense or sample in a lagrangian frame of reference. Propeller driven AUVs can provide targeted lagrangian observation options since they can be driven to locations of interest without the assistance of a surface vessel.

d) Thin layer characterization: The ability to mantain hover depth within a meter allows for thin layer sampling both within and around the thin layer for reference. Onboard sensors combined with buoyancy control allow for automous detection and vertical following of a thin layer.

6) Reliability:

Reliability for an AUV can be defined as the probability of the system to perform functionally without failure. Thus, reliability is quantified by the number of failures per unit of life. A common method of expressing reliability is the mean time between failures (MTBF) in units of time. Minimizing operator intervention is also an important step in increasing AUV endurance. Even a single AUV operation in which deployments last for weeks is hard to sustain if operators are required to interact with the vehicle frequently.

To track unplanned user interactions on Tethys, a variation on a common reliability measurement is used: Mean Time Between Critical Failure – Interventions (MTBCFI) [10]. This metric reflects the amount of time between unplanned operator interventions, which in the case of Tethys occurs via the satellite link from shore. The two Tethys-class vehicles currently have a MTBCFI of about 24 hours. We expect the MTBCFI to rise to over 100 hours as improved exception handling is implemented on the vehicles. It should be noted that most of the interactions are software related that can be addressed with the vehicle at sea. There has only been one incident when a Tethys-class vehicle required ship recovery, and that was due to operator error.

7) Onboard reliability and failure response

The Main Vehicle Application (MVA) breaks down subsystems into code components that can be run depending on the configuration of the vehicle. These components can be the interface to a scientific instrument or motor, a calculator that derives values (e.g. dead reckoning), or more behavioral such as the component that handles driving the vehicle to a given waypoint. Behaviors are used when invoked by a mission that is written in XML and stored on the vehicle [11]. The MVA runs these components on a regular schedule up to 2.5 Hz, though the scheduling is flexible and can also be asynchronous if necessary. Figure 4 shows the sequence of component execution.

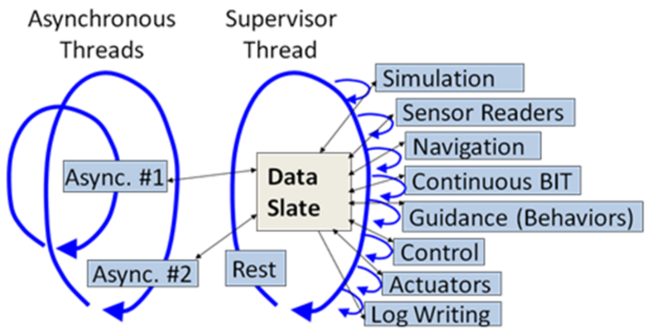

Figure 4: MVA software architecture. Components run in sequential nested threads. The architecture also supports asynchronous concurrent threads for higher data rate sensors.

8) Architecture for onboard monitoring:

Subsystem faults are often easy to detect. For example, an instrument might not initialize as expected or an incorrect checksum may be returned. In this case it is important to have an architecture that is tolerant of faults and can take measures to recover from them. Of the 16 or so subsystems that are independently powered on the Tethys AUV, we find that many subsystems simply require a power cycle when they stop operating correctly. Having an architecture that can detect common faults before they turn into failures saves valuable time and also provides confidence in the vehicle before it leaves shore. The basic fault detection architecture that exists in the Tethys AUV consists primarily of the following components:

a) Independent load control system – Each subsystem/payload has its power supplied by an individual load control board with the ability to galvanically isolate both power and communications. This allows for ground fault detection and isolation while at sea and also prevents potential corrosion damage. The load control system also monitors current and voltage and provides circuit breaker functionality to protect the vehicle.

b) Fault reporting and corrective action – The software that interfaces directly to a payload has the best knowledge of whether or not that payload is operating correctly. However, in the event of a fault, there needs to be a method for logging and decision making at a higher level than the individual payload interface. In the Tethys AUV, this is achieved through a software component called Continuous Built In Test (CBIT). CBIT checks all other components once a cycle for faults and decides, based on criticality and number of allowable faults, what the course of action will be. That action may be as benign as temporarily deactivating the offending component and reporting the failure, or as drastic as terminating the current mission and dropping the drop weight.

c) Flexible configurations – When faults are detected that cannot be remedied, often the best approach for non essential components is to stop using them. This can be done with a human in the loop, or the vehicle can make the decision and inform the user at the next communication interval. Either way, having a vehicle that can be reconfigured at sea provides another option for the fault detection architecture.

II. TETHYS OPERATIONAL RESULTS:

As of August 2012 the two Tethys-class vehicles built by MBARI have accumulated over 3000 hours at sea. One Tethys mission lasted 23 days and the vehicle traveled over 1800 km at a speed of 1 m/s while supporting sensor power levels averaging 5 watts, as shown in Figure 5 The Tethys-class vehicles have been fitted with the following sensor packages:

Core Payload Instruments

- CTD —Neil Brown GCTD
- O2 — Aanderaa Optode 4330F
- Nitrate — MBARI ISUS
- Bottom velocity, current velocity, and acoustic backscatter — LinkQuest MicroDVL
- Chlorophyll and optical backscatter — Wetlabs ECO Puck Triplet
- Photosynthetically available radiation – LI-COR Underwater Quantum Sensor

Additional Payload Instruments

- Benthos acoustic modem
- Micro Turbulence - NPS/Tim Stanton
- AUV Docking: Homing, Power and Data transfer

In Development

- MBARI Gen 3 ESP [12]
- Water sampler

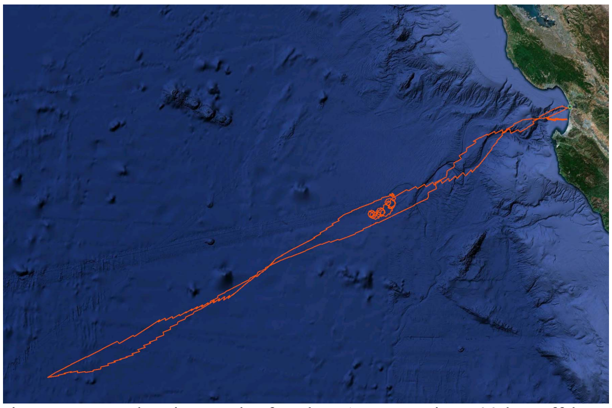

Figure 5: Map showing track of Tethys AUV running 500 km offshore for a total mission distance of 1850 km over 23 days.

A. Typical Tethys-class AUV Science Missions

1) Tracking the Center of a Phytoplankton Bloom Patch

Far-reaching effects of harmful algal blooms (HABs) on the ecosystem and human health motivate greater understanding of natural and anthropogenic factors that modulate blooms. We have developed an algorithm for an AUV to autonomously localize and track the center of a phytoplankton bloom patch, aiming at separating temporal variability from spatial variability in the observation of phytoplankton dynamics [13]. The vehicle is instructed to drive along a horizontal transect, performing rapid descents and ascents along the way, following a sawtooth or "yo-yo" trajectory. On each descent or ascent, the AUV records vertical maximum chlorophyll. It also monitors these vertical maxima over the horizontal transect, looking for a horizontal peak chlorophyll level. When a horizontal peak is detected, the AUV drives a short distance away and drives back over that peak location at a perpendicular angle, once again looking for a horizontal peak, and continually refines the peak chlorophyll location (i.e., the patch center). In a test in Monterey Bay, California, on 24 April 2011, the Tethys AUV ran the algorithm to successfully localize and track the center of an advecting phytoplankton bloom patch.

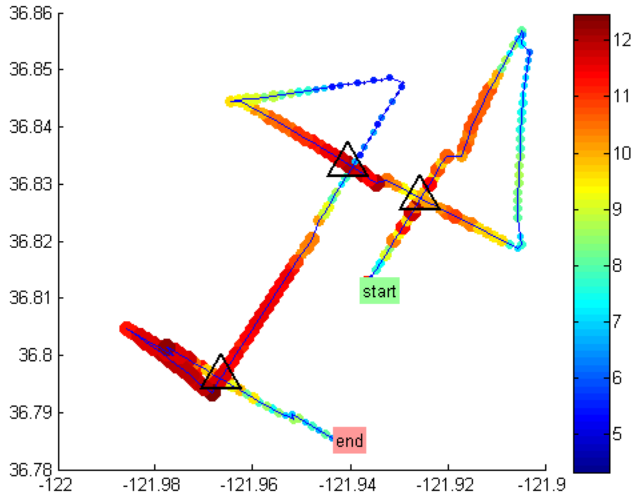

Figure 6: The Tethys AUV's track in the 24 April 2011 mission. The center of the phytoplankton bloom patch seemed to be moving to the southwest. On each descent or ascent profile, the AUV recorded the maximum chlorophyll (indicated by color and size of each dot) [13].

2) Tracking a Coastal Upwelling Event

Coastal upwelling is a wind-driven ocean process that has an important impact on ocean ecology. In an upwelling water column, temperature and other water properties are much more homogeneous over depth as compared with in stratified water. We formulated a simple yet effective classifier --- the vertical homogeneity of temperature (i.e., the vertical temperature difference in the water column) for differentiating upwelling and stratified water columns. With this classifier, we developed an algorithm for an AUV to recognize that it has departed a stratified water column and entered an upwelling water column (or conversely), and accordingly track the front [14]. On 27 April 2011, the Tethys AUV ran the algorithm to autonomously track an upwelling front in a dynamic coastal upwelling region in Monterey Bay, CA. The AUV transected the upwelling front 14 times over two days, providing a very high-resolution depiction of the front.

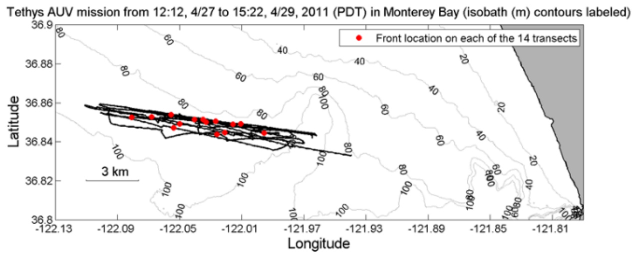

Figure 7: The horizontal track of the Tethys AUV in the mission on 27 April 2011 for tracking an upwelling front in Monterey Bay, CA. The AUV transected the front (back and forth) 14 times. The front's location detected on each transect is marked by a red dot (delay corrected) [14].

3) Thermocline Tracking

Thermoclines play an important role in ocean circulation, marine ecology, and underwater acoustics. We have developed an autonomous algorithm for an AUV to detect and track the thermocline [15]. On each descent or ascent leg on a yo-yo trajectory, the vehicle detects the maximum vertical gradient of temperature (the corresponding depth is the depth of the thermocline). The AUV uses the thermocline depth to set the target depth for the upcoming ascent or descent leg, thus closely tracking the thermocline over distance. In missions on 31 August and 1 September 2010, the Tethys AUV ran the algorithm to closely track the thermocline across a sharp temperature front in Monterey Bay.

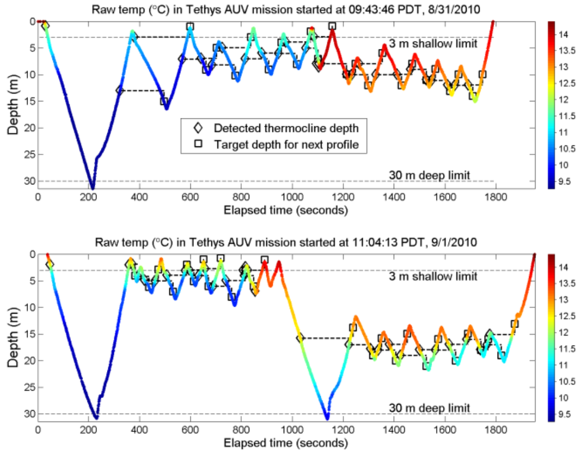

Figure 8: Vertical trajectories of the Tethys AUV in the thermocline-tracking missions in Monterey Bay, on 31 August 2010 (upper panel) and 1 September 2010 (lower panel). On each descent or ascent leg, the vehicle detected the thermocline (marked by the diamond), and accordingly set the target depth for the upcoming leg (marked by the square) [15].

III. HOW DO WE GET TO MONTHS?

There are at least four ways to support multi-month field programs propeller driven AUVs:

A. Minimize average power draw – lots of sleep

The 3500+ ARGO floats deployed in the world's ocean achieve their 5-year duration by spending most of their life asleep in the midwater. MBARI's Benthic Rover AUV has been deployed in 4000 m of water for over 15 months and can run for 9 months on one battery pack [16]. This endurance is possible because the AUV spends most of its time with 98% of its systems shut down while measuring sediment community oxygen consumption. Long-term Lagrangian drift missions have been proposed for the hover-capable Tethys AUV but to date, none over 24 hours has been performed.

B. Carry lots of energy – Large vehicles

The drag of an AUV scales as its area, while its energy capacity scales roughly as volume. Consequently, the classic method for achieving greater range is to simply make a larger vehicle. However, a larger vehicle is not only more expensive, it is also more difficult to launch, and recover. The combination of increased cost and decreased ease of use reduces adoption, thus we view increasing vehicle size as a last resort.

C. Use multiple vehicles – hot-swap

If the work site is within a range less than about 10% of the vehicle range, and a normal service interval is less than about 50% of vehicle endurance, then hot-swapping vehicles presents a viable solution. In this scenario, a vehicle presense is maintained onsite continuously by recovering a vehicle only after its relief is already on station. If the vehicles are easily handled and comparatively low cost, then this can be an attractive option.

D. AUV Docking – recharge on-site

Most of the designs proposed so far require an AUV to fly horizontally into a docking station, which would be challenging for buoyancy driven glider. AUV docking has been demonstrated many times [7][17][18][19] and is a component of NSF Ocean Observatory Initiative plans [20]. MBARI is developing a docking capability for the Tethys AUVs, shown in Figure 9 below. The dock has been built and is waiting follow-on funding to support deployment and testing.

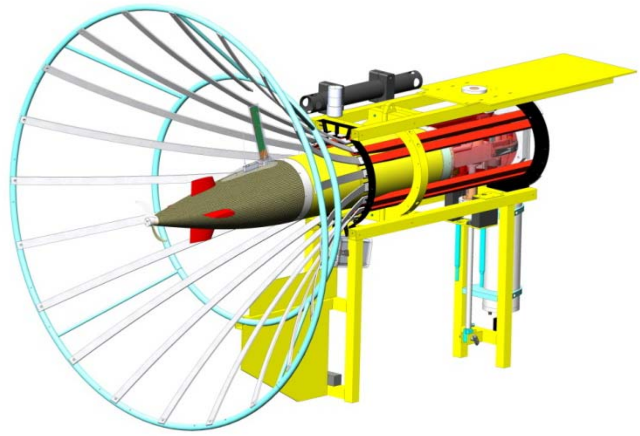

Figure 9: Computer model of a docking station developed for the Tethys AUVs.

On the Tethys dock, power and data are supplied to the vehicle through a direct electrical connection in the flooded nose section. Tethys locates and homes into the dock using a nose mounted Ultra Short Baseline Array (USBL) acoustic system. The dock is designed to mount on a vertical riser from a seafloor mooring. Power and communications could be routed from either a seafloor cabled array such as MBARI's MARS observatory [21], a solar/wind powered surface buoy such as MBARI's MOOS mooring [22], or a wave energy extraction system like the one MBARI is developing, or the one marketed by Ocean Power Technologies [23].

Whichever technique future long endurance AUVs employ to extend their operations, reliability remains one of the greatest challenge. Spacecraft and commercial aerospace systems have demonstrated great reliability, but these ventures don't contend with a corrosive, heavy, biology filled medium that never ceases to move. Between shark attacks, jellyfish filled sensor inlets, and fisherman dragging AUVs out of the water, many challenges conspire to limit the persistence of AUVs in the ocean realm. However, recent years have seen substantial advances, and we are confident that continued effort will result in reliable platforms capable of continuous operations in even the most remote portions of the world ocean.

ACKNOWLEDGMENT

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