Closer to Deep Underwater Science with ODYSSEY IV Class Hovering Autonomous Underwater Vehicle (HAUV)

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Abstract - The Autonomous Underwater Vehicle Laboratory (AUVLAB) at The Massachusetts Institute of Technology (MIT) is currently building and testing a new, general purpose and inexpensive 6000 meter capable Hovering Autonomous Underwater Vehicle (HAUV), the 'ODYSSEY IV class'. The vehicle is intended for rapid deployments, potentially with minimal navigation, thus supporting episodic dives for exploratory missions. For that, the vehicle is capable of fast dive times, short survey on bottom and simple navigation.

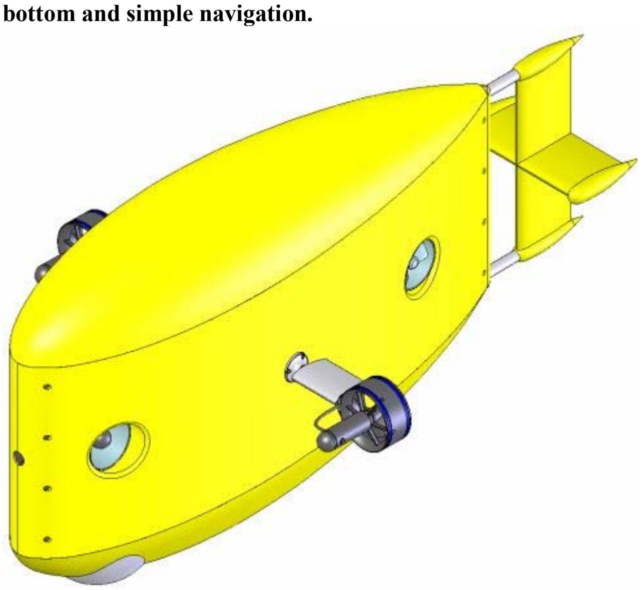

Fig. 1. Isometric view of ODYSSEY IV class AUV

I. INTRODUCTION

A. Motivation

There exists a gap between the assets available to the deep ocean science community, and the performance needs for those assets, as described by the US National Academies report on Future Needs in Deep Submergence Science [1]. Namely, while the pace of deepwater ocean science has accelerated in recent years, as a result of improved embedded sensing and analysis systems, the number of platforms capable of operating at several thousand meters depth remains small. Consequently, domestic and international competition for these few, albeit enormously successful, resources has been high, making it difficult to justify deepwater exploratory missions, i.e., those with little or no guarantee of a significant deliverable. This situation is exacerbated by the fact that existing deep ocean assets are complex engineered systems that have traditionally been expensive to build, maintain, and operate. The ODYSSEY IV (Fig. 1) class has been created to support the paradigm of short, exploratory missions, with a reduced data product.

This vehicle is intended to be an inexpensive asset that will be readily available for the deep ocean science community, and can be replicated easily. It is not meant to serve as a replacement for the human occupied vehicles such as *Alvin, Mir* and *Nautilus* submersibles, but rather can be used as an inexpensive means of performing preliminary surveys of areas that will potentially be explored by the larger, more capable assets; the data product from this platform will be substantially less and cost much less as well. Ultimately, it is our intent that this vehicle will provide scientists with a practical means of investigating new and unexplored areas in the deep ocean, e.g., cold coral reef habitats [2].

II. MISSION SCENARIO

Three target sites of interest, each separated by a distance of 20 nautical miles. Each survey will consist of the vehicle rapidly diving to a depth on the order of 3000 meters, performing a photo mosaic (4 meters swath) survey of a 100 meter x 100 meter square, and rapidly ascending. Each survey could be performed in one hour (15 min for diving, 30 min of survey, 15 minutes for ascending). We can allocate 1.5 hours between missions for downloading and previewing data, recharging batteries, and ship transit to the next location.

III. DESIRED DESIGN FEATURES

The initial design criteria for this vehicle were based on the knowledge gained from previous experiences in designing, building, and operating AUVs in the field. This vehicle should be manufactured and operated at a low cost. By relaxing the packing efficiency constraints, this design will save time and cost by eliminating the need for highly customized components.

Minimum weight and size should be driven by the payload capacity and the use of COTS (commercial off the shelf) components. Maximum AUV weight and size should be driven by the deck space and crane load limits of a vessel of opportunity [3]. The maximum depth limit should be based on the science need but limited by the cost and the complexity. In expeditions, AUVs are used for science at the bottom, not in the water column. In these cases, diving and ascending are expensive down time. For this reason the AUV should be able to dive and surface as fast as possible. Increasing the speed of the robot will also decrease the time spent in the boat, as well as the operating cost. Torpedo shaped AUVs are generally efficient for surveys, but lack the capability to follow closely a bumpy bottom. Operating ODYSSEY II at 3 meters from the bottom, during a cruise in Greece in 2004 [4], showed us the need to have 4 DOF (Surge, Sway, Heave and Yaw) hovering capable platform.

IV. DESIGN ACHIEVEMENTS BASED ON NEEDS

A. *ODYSSEY IV Specifications*

Weight:	~350 kg
Overall Length:	2.6 m
Overall height:	1.3 m
Overall width:	1.3 m
Thruster:	4 x Deep Sea Systems 1hp
Max Thrust per axis:	400N
Surge velocity:	3.5m/s
Heave velocity:	1.0m/s
Sway velocity:	0.5m/s
Yaw velocity (hovering mode):	20 degrees per second
Dive speed (with 10 kg weight)	>200m/min
Payload (wet weight):	30kg
Depth rating:	6000 meters
Budgeted Part Price:	$170,000
Battery technology:	lithium ion
Onboard Energy stored:	4500 Wh
Power density:	6000 W
Controlled DOF:	4 (Surge, Heave, Sway and Yaw)
Righting moment	120Nm at 45 degree pitch
Dropt weight	1 external for descent, 1 internal for ascent

B. *Weight and size*

This class of AUV is "roomy". The internal volume of the flooded hull is 1m^3, whereas the total displacement is around 0.350 m^3, allowing easy access to the interior, use of COTS components, and a variety of payloads. The shape is based on the low drag body design for the ODYSSEY II Class AUV. Fig. 2 shows the extrusion in the vertical direction to improve stability in pitch and roll by increasing the righting moment. Also, this allows us to place cross-body thrusters and a pair of rotating thrusters along axes of symmetry, and still have a significant payload bay. The resulting shape is similar to that of a reef fish.

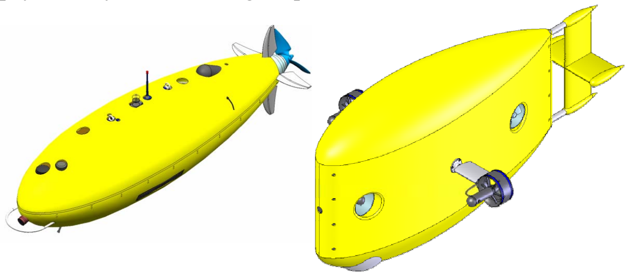

Fig. 2. From ODYSSEY II to ODYSSEY IV

C. *Cheaper*

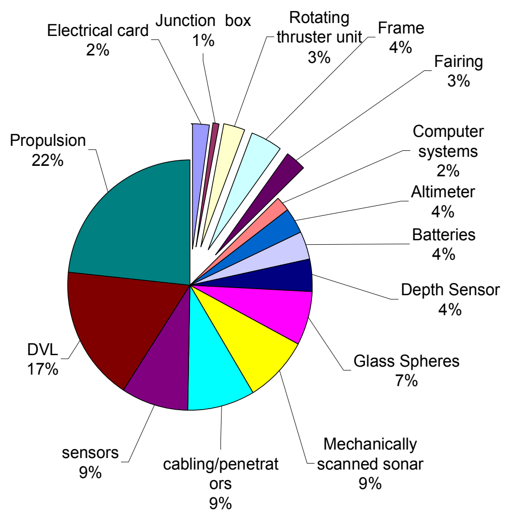

Fig. 3. Budgeted price (separated pie slices are non COTS components)

Total parts cost is around $170,000 for the base vehicle. Fig. 3 shows the breakdown of COTS components.

D. *Depth*

For cost and weight reasons, we have chosen to use glass spheres as housings, and pressure compensated motors and controllers. The extra buoyancy given by the glass spheres eliminates the need for syntactic foam, making the robot even lighter, cheaper and allowing an operating depth to 6000 meters. This will give us access to 98% of the ocean.

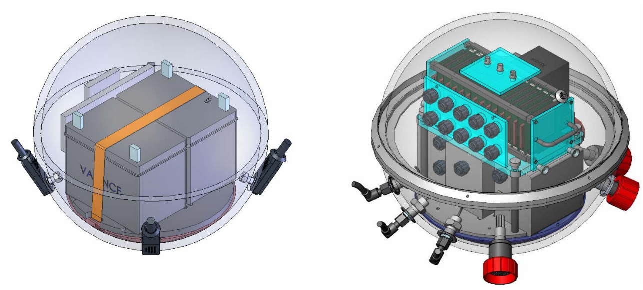

Fig. 4. Left - Battery housings using 17" glass spheres.
Right – Main Electronic Housing (MEH) using 17" glass spheres.

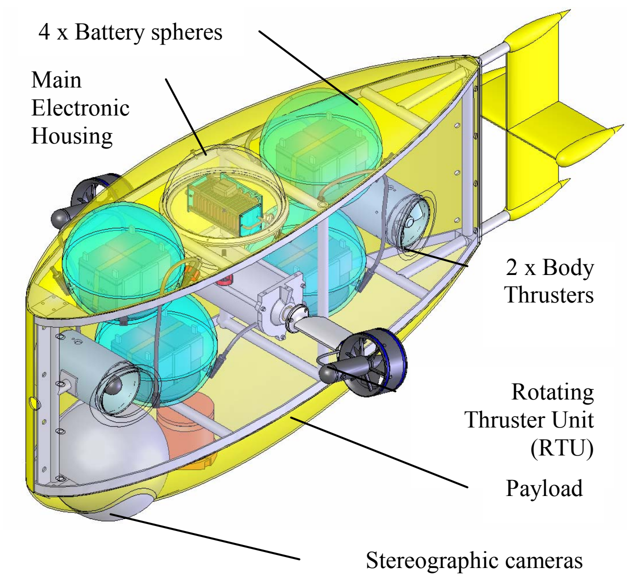

Fig. 5. Simplified internal view of the ODYSSEY IV

E. *Speed*

Fig. 6 represents an estimate of the surge speed that the AUV could reach if it uses from 1 to 4 thrusters (1000 watts maximum per thruster). The axis on the left shows the necessary electrical input power (in Watts) to the thruster(s). This graph explains the benefit of using two thrusters instead of one: ~10% faster for the same consumed power, due to an increase in propulsive efficiency attributed to the increased swept area.

In our chosen configuration (Fig. 5) of 2 surge thrusters, the AUV will be able to reach a top cruising speed of 3.5m/s (6.8kts), due to:

- Higher power density batteries (~6000W peak).
- 2 x 1HP ROV thrusters (200N at 750W).
- Highly streamlined body in the surge direction.
- Passively stable design due to a fixed rudder and elevator.

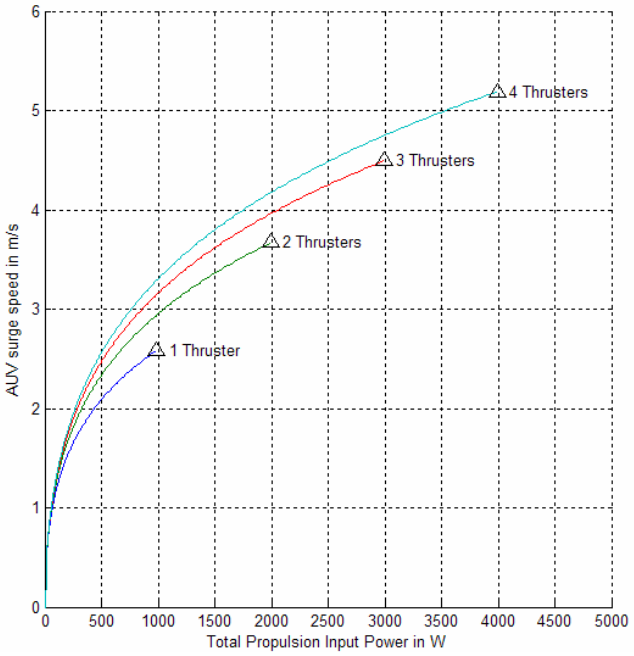

Fig. 6. AUV surge speed function of total propulsion input power for 1 to 4 thrusters.

F. Diving speed

In simulation, active thrust control, a fixed-elevator tail and a streamlined drop weight (10kg) give the ODYSSEY IV a vertical speed greater than 3.5m/s, allowing the AUV to reach a descent rate of 210 meters per minute (Fig. 8). In order to maximize the accuracy of these simulations, the hydrodynamic coefficients are being experimentally measured using a 30% scale model (Fig. 7) at the MIT Towing Tank facility.


Fig. 7: Scale model

The fixed elevator tail fin will increase pitch to heave coupling at high vertical speed, whereas the Rotating Thrusters Unit (RTU) (Fig. 10) will assure a vertical thrust independent of the pitch angle. For a survey at 3000 meters, we will spend 18% of stored energy and 30 minutes total in the water column (diving and ascending).

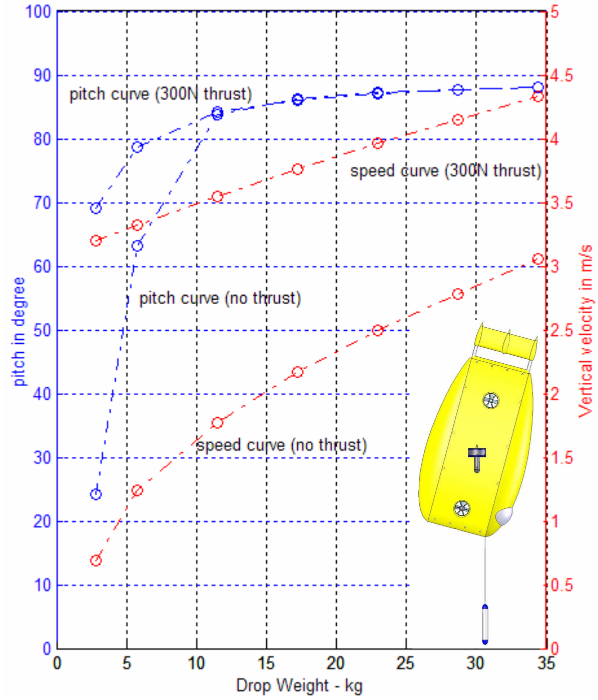

Fig. 8. Pitch angle and descent rate versus weight.

G. Range

The ODYSSEY IV has a range of 100 km at 1.1m/s for a hotel load of 100 Watts. Fig. 9, is an estimation considering the efficiency of the thruster at different thrust values and also the coefficient of drag of the robot, which decreases to ~0.1 after 0.5m/s (Reynolds number>10^6) .

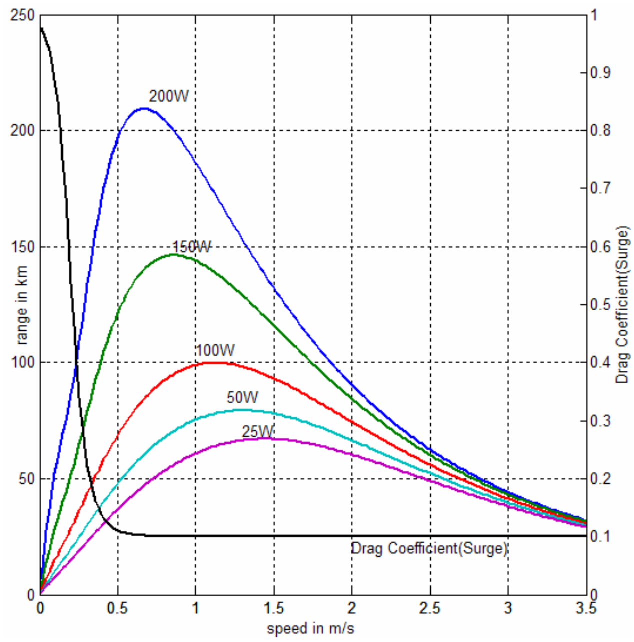

Fig. 9. Range vs. speed (for 5 hotel loads).

H. Hovering using a pair of rotating thrusters

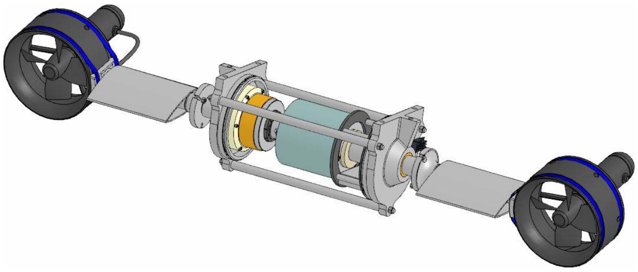

Fig. 10. Rotating Thruster Unit (RTU).
(Main housing tube is removed for viewing purpose)

Four degree of freedom hovering capability is enabled by passive stability and symmetric thruster placement. Passive roll and pitch stability are enabled by a large hydrostatic righting moment (121Nm at 45 degree) and fixed lifting surfaces. Symmetric thruster placement reduces required control bandwidth, and decreases energy required for station keeping. The RTU (Fig. 10) reduces the total number of thrusters, and therefore enables more payload space and a more streamlined shape. The location of the rotating thruster pair was chosen to minimize the heave-pitch coupling in the hydrodynamics. The center of gravity has been brought as close as possible of the line of symmetry (in the vertical direction), in order to eliminate roll oscillation during sway motion (Fig. 11). ODYSSEY IV's hovering capability will assure close inspection of areas that are dangerous for survey vehicles and towed bodies.

To allow energy efficient hovering at great depth, the next version of ODYSSEY IV will be equipped with a Buoyancy Control Unit (BCU). The BCU will enable active compensation for displacement lost due to compression of less rigid materials, such as plastic and rubber.

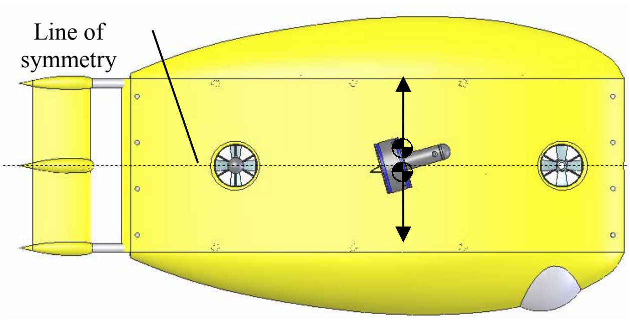

Fig. 11.location of Center of Gravity (bottom) and
Center of Buoyancy (Top)

V. NAVIGATION

ODYSSEY IV has a Doppler Velocity Log (DVL) and an Attitude and Heading Reference System (AHRS) to allow precise dead-reckoned navigation [5]. During normal cruising, vehicle position will be estimated using an Extended Kalman Filter, with accuracy slowly degrading at a rate of 1-2 percent of distance traveled. However, during deep dives, the DVL will be unable to acquire bottom lock. The high pitch angle of the body will point the transducer head away from the sea floor, and the great depth of the water column will often be beyond the instrument's maximum sensing range. No DVL velocimetry means no position estimates, so the vehicle must suspend estimator operation and dive "lost".

Once ODYSSEY IV reaches its target altitude above the sea floor, a subsequent pause to hover in place will enable the science team at the surface to precisely locate the survey start point. The vehicle may be tracked using ship-borne USBL, or GPS-enabled LBL buoys [6]. ODYSSEY IV is compatible with a fixed LBL net, but we do not foresee frequent use of this mode of navigation, due to the time and expense of deployment. In quick inspection dives, the vehicle need not perform continuous Earth-referenced navigation, but may simply follow a pre-planned dead-reckoned survey path relative to its start point. In post-processing, the estimated vehicle path may be overlaid on a map relative to the georeferenced start point, or the path may be plotted directly from surface tracking data if it is sufficiently accurate. Experiments are planned to test the feasibility of updating the AUV's self-position estimate with surface tracking data, via acoustic modem, such that the on-board estimator can work with Earth-referenced coordinates at all times.

The possibility exists for rapid deployment of multiple vehicles from a single vessel. Each vehicle would be tracked during its dive, and its survey start point carefully noted, then each recovered after its mission was completed.

VI. THE PAYLOAD

The ODYSSEY IV is designed to be a flexible instrument platform, with dedicated space to support a variety of science payloads throughout the lifetime of the vehicle. The high maneuverability, substantial depth rating, low cost and easy deployment of this AUV will make it a good choice for many different scientific inquiries. ODYSSEY IV has a generous 100 liters of dedicated interior payload space, and has sufficient reserve buoyancy to carry 30 kg (wet) of additional instrumentation. The main electronics housing has three identical payload ports, each able to deliver up to 2kW peak power from the main battery bus (accounting first for thrust demands). Each payload port can be wired internally for 10/100 Ethernet, RS-232/422/485 serial, and/or general purpose analog and digital I/O, with galvanically isolated connections to the PC/104-based main vehicle computer.

The flexibility of the payload port enables the use of simpler serial- or analog-interface COTS sensors, alongside custom-built semi-autonomous 'smart sensors' that feature independent control computers, on-board data storage, and full Ethernet connectivity. Thus the AUV can easily be configured to support the scientific user. A variety of simple COTS science 'peripherals' might be used in ODYSSEY IV missions: conductivity/temperature/depth (CTD), dissolved gases, chlorophyll and other biological substances, optical backscatter, etc.

As for more complex instruments, past experience has shown that the 'smart sensor' is a very effective approach to AUV payload development. Despite the additional engineering required, a 'smart sensor' design allows independent construction and testing of the complete subsystem on the bench (and even in limited field deployments) prior to installation in the AUV. The on-board computer is typically responsible for data collection (triggering sensor sampling) and data storage; some devices even perform real-time interpretation (e.g., online CAD/CAC in MCM sidescan sonar applications). Examples of smart sensor subsystems integrated in MIT Sea Grant AUVs include a synthetic aperture sonar [7], mass spectrometer [8], high resolution digital still camera and high-frequency sidescan sonar [9].

ODYSSEY IV is designed especially to support sensors that are shortchanged by currently available platforms. The two main categories of interest are sensors with a long sampling time constant (e.g., certain chemical and biological probes), and sensors with very high imaging resolution (optical and acoustic) that must be brought very close to the seafloor to gather good data. Surveys with high spatial resolution will be possible even with sensors that require 10-20 seconds or more per sample [8], using the ODYSSEY IV's precision low-speed hovering behaviors. Imaging sonars [11] and optical cameras will also be well-suited to ODYSSEY IV's ability to get up close to complex environments.

The first payload planned for ODYSSEY IV integration is a stereographic digital camera system. A pair of six-megapixel color cameras will share a polished optical viewport in a spherical glass pressure housing. The remaining space inside the camera sphere will be occupied by lighting electronics. These will support one or more strobes (roughly 200 J each), for high-quality still photography and conservative battery usage, while a future revision may feature HID lamps for continuous illumination and videography.

Stereo imagery from this camera, displayed through an appropriate stereoscopic device, will enable scientific users to feel as though they are flying over the seafloor along the track of the AUV, with sharp full-color images to examine. After careful calibration of the camera, the raw data may be post-processed into a three-dimensional photomosaic, allowing precise measurements to be made of high-relief targets (typically distorted in 2-D images) [12].

Future payloads for ODYSSEY IV may include sampling devices. The logical goal of a hovering vehicle is the ability to hold perfectly still - scientists might take advantage of this ability by requesting a returned sample from the seafloor that is not easily collected at cruise speed. Simple corers, sediment traps, and biological "slurp guns" have been tested successfully on other vehicles, most notably ROVs [13][14]. The high power density available to ODYSSEY IV payloads may enable more powerful samplers: jackhammers are not out of the question.

Acknowledgments

We acknowledge support from the U.S. Department of Commerce and the National Oceanic and Atmospheric Administration (NOAA), under Grant NA-16RG2255. The authors thank their colleagues at the MIT Sea Grant Program, the MIT Ocean Engineering, the MIT Towing Tank and the MIT Propeller Tunnel.

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