MECHANICAL DESIGN AND DEVELOPMENT ASPECTS OF A SMALL AUV – MAYA

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Abstract: This paper contains a description of the mechanical design route that was adopted in building a small AUV (Autonomous Underwater Vehicle). At the outset, we decided to follow a set of guidelines that defined a broad set of specifications that featured safety, low weight, small length, large mission time, easy-to-use, application specific, and most importantly low cost. How closely did we arrive at this desired set of specifications? The paper will address the most important design issues, lessons learned, and problems that remain for further development.

Keywords: vehicles, mechanical, hull, design, seals, control, planes, pressure, hydrodynamic drag

1. INTRODUCTION

Small Autonomous Underwater Vehicles [AUVs] are increasingly appearing in different marine application areas particularly in oceanography, naval applications of mine reconnaissance, and as effective tools for monitoring the coastal environment (Desa, et al., 2005). This paper addresses the mechanical design aspects of a small AUV called Maya, developed at the National Institute of Oceanography in Goa, India; see Figure 1. Part of the development effort was done in the scope of an on-going India-Portugal collaboration program that aims to build and test the joint operation of two small AUVs for marine science applications.

2. INITIAL DESIGN CONSIDERATIONS

Our initial design process began by considering a floodable hull configured from several separate pressure modules mounted on a framework and covered by a suitable shaped low drag casing tightly fitted over the frame. This had the advantage that more than one motor could be attached to the frame giving the vehicle greater maneuverability, and perhaps without the need of control foils. However, there were concerns about buoyancy changes arising from entrapped air between the spaces of the multiple pressure units, more interconnecting cables, more power consumption, and multiple pressure seals.

After considering several hybrid variants, it was decided that a classical submarine design of a torpedo shaped nose attached to a cylindrical tube followed by a tapering rear cone having a single motor at the extreme end and four control foils in a cross arrangement was best for a small AUV for the following reasons :

- The Core Pressure Unit [CPU] in the form of a rugged cylindrical section could be used to contain electronics, batteries, and vehicle payloads (Gyros & Doppler Log), but terminated at either end by removable pressure end caps on which underwater connectors could be mounted for connecting to external science sensors, DC motor and communications antennae (GPS & RF). This simple approach offers built-in safety, provides a large buoyancy contribution from the hull volume, reduces cabling and connectors, simplifies access to internal modules from both ends of CPU, and lowers manufacturing cost.

- Removable nose and rear cones that are free flooding and can be secured to the respective pressure caps of the CPU. The nose cone volume can be used to house external science sensors, and the rear cone for other sensors and the thruster frame.

- Two horizontal stern planes near the main motor for vertical plane maneuvers, and two rudders in the vertical plane for heading or yaw changes. (in the final design, only one rudder was used). We opted for this, but in doing so realized that we would need to design our own special purpose shaft seals that would move the control planes by actuators mounted inside the hull volume.
- High degree of modularity as the small AUV reduces to an integration of modular components namely a nose cone, a straight cylinder section, and a rear cone with a single DC motor.

3. MAYA HULL DESCRIPTION

A simplified longitudinal section of the Maya AUV is shown in Fig. 1 below:

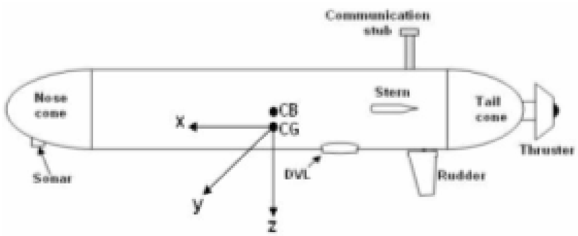


Figure 1: Longitudinal section of the Maya

The total hull length L is the sum of nose, mid-body, and tail cone lengths, and equals to 1.742m. The maximum hull diameter D = 0.234 m, results in a fineness ratio (L/D) equal to 7.44.

The mid-body section (or CPU) was machined from a single high quality solid round aluminium bar free of surface and deep defects as verified by ultrasonic tests of the raw material. The bar was first accurately bored along a horizontal X axis from either end, and then bored in a vertical Z direction to create a hollowed out receptacle that matched the external contours of the Doppler Velocity Log (or DVL). This is best seen in the Solid Works drawing of Fig.7 which provides an isometric 3D view of the complete AUV with the internal components. This approach to the construction of the main hull provides the freedom to adjust its wall thickness to the desired yield stress of the hull volume, besides accommodating the odd shape of the DVL sensor. Both ends of the CPU are O-ring sealed by identical pressure end caps on which underwater connectors are mounted. Locking collars are threaded over the outer surface of the hull. Threaded holes on the collars are used to bolt the nose and rear cones to the main hull body.

3.1 Pressure tests on the bare main hull

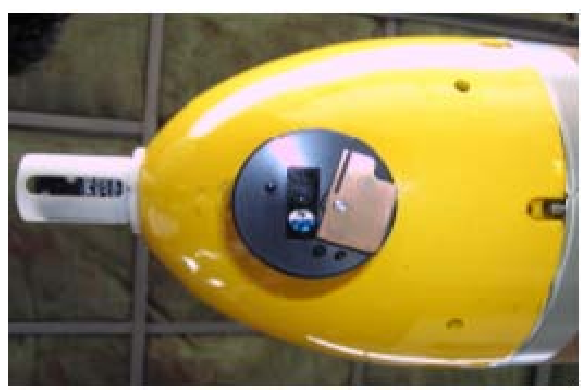
The main hull of length 1.24m and wall thickness of 6 mm was designed to withstand a maximum pressure of 40 bar (aprox. 400m). As it was too long to fit in available pressure test chambers, it was decided to pressure test it at sea on a cruise of opportunity to the Arabian Sea. The unit was sealed at both ends by the end caps, and DVL port plugged with a dummy cap. The hull collars were secured to C-clamps and the entire unit lowered using the ships winch to a depth of 178 meters. It was submerged at this depth for a period of 1 hour. This straightforward method checks integrity against leakage of water through O-ring seals, the hull, and the pressure sensor mounted on the end cap all in one go. A drop of ~ 55 mbar (from atmospheric) in internal pressure caused by colder waters at 178m in contact with the bare hull was monitored with a miniature data logger.

3.2 Internal components within the CPU

The arrangement of internal parts is shown visually in Fig.7. Starting from the nose end of the hull, there is a module consisting of the batteries, electronics, and the attitude sensor mounted on a removable tray. The DVL and associated electronic cards fit neatly into the hollow made for it. Moving past the DVL, the hull volume provides space for three integrated shaft seals and actuator motors. The upper rudder port was fitted out with a short white acetal stub which encloses the GPS and RF antenna. At the time of fabrication, it was decided to use the rudder port to house the antenna stub, as no provision had been made for it in the prototype design. There was an added curiosity to check how AUV performance would be affected with the use of a single rudder. Subsequent field tests have shown that 3 control foils (two stern and one rudder) can produce acceptable performance, but with increased roll during a heading change. (The 'roll' effect is examined in a companion paper by P. Maurya et. al. at this conference)

3.3 Nose and tail cones of Maya

The front nose cone and the tail fairing of the AUV were made from GFRP (glass fibre reinforced plastic) which is not designed to withstand high pressures, but as initial costs are low it allows speedy experimentation of the total body form in water. The front nose section can be detached from the main hull so as to access the end cap and the internal parts within the main hull. The volume within the cone can be used to accommodate wet sensors wired to power and signal connectors on the front end cap. A variety of nose cones can be fabricated and populated to accommodate mission-specific sensors. The shape of the nose cone is a low drag slender ellipsoid different from the torpedo shaped noses of other small AUVS namely REMUS (USA) or GAVIA (Iceland).



The photograph shows Dissolved Oxygen (DO) sensor mounted on tip of nose cone and the sensing part of chlorophyll-turbidity protruding from the base of the nose cone. A miniature CTD nose cone has also been used with the Maya hull.

The tail cone section of Maya is split into two symmetrical halves that encase the stainless steel framework on which the DC thruster is mounted. It is attached to the collar over the rear end-cap of main hull. The shape of the combined tail cone section follows a Myring profile with an enclosed angle of 25 degrees and exponent 2 (Myring 1976). We adopted this shape as it has a gentle tapered profile that serves to direct the flow of water along the hull into the propeller blades of the motor. There is ample volume within the tail cone to also accommodate sensors, and a communications stub that now occupies the top rudder port.

4. HYDROSTATICS OF MAYA AUV

All AUVs are designed with safety feature of incorporating a small positive buoyancy so that it can re-surface in the event of a system failure. The total weight of the Maya AUV with all attachments averages to W = 54.7 Kgf. The intrinsic buoyancy from the hull and nose cone is about 43.4 Kgf; insufficient to make the AUV float. Therefore, the bare hull was clad in a foam jacket such that a net buoyancy between 0.5 to 1 Kgf was achieved.

4.1 Foam jacket around main hull

A systematic study of different low cost PVC foams with densities of 90, 100, and 190 kg/m^3 was carried out in order to check for suitability. The final choice was a lightweight PVC foam of density 200 kg/m^3 suitable for use up to 200m water depth. After trimming the AUV with small lead discs in the nose cone, a net buoyancy of 500 grams was sufficient to achieve a good trim attitude at the surface.

4.2 Center of buoyancy (CB) and Center of Gravity (CG)

A well trimmed AUV in stable equilibrium assumes a horizontal attitude along the X axis (see Fig.1), with zero pitch (θ = 0) and zero roll angle. The vertical separation between the CG and CB in the YZ plane i.e $[Z_{CG} - Z_{CB}]$ = ~7.0 mm, is proportional to the hydrostatic pitch moment M_{HS} which for small pitch, is given by:

$$M_{HS} = - W. \theta [Z_{CG} - Z_{CB}] \qquad [1]$$

The separation of 7 mm is smaller than expected, as it implies that a small self-righting moment is available to reduce higher pitch angles during the start of a dive. The vehicle roll is also affected by the small separation. Even though, good control system design absorbs these drawbacks, it makes good sense when building an AUV to ensure that all placements of parts within the hull contribute to lowering the center of gravity. An optimal value of the distance $[Z_{CG} - Z_{CB}]$ should be sought through simulation, and by proper part placement, to obtain a large enough M_{HS} that will suppress the moment generated by the propeller rotation [2]. Simple center of gravity calculations can be used to easily derive the moments of inertia of the vehicle. These are useful in deriving some of the vertical and horizontal plane hydrodynamic derivatives, (Barros et al 2004). For Maya, the principal moments about the X, Y, Z axes are Ixx = 0.03241 $Kg.m^2$, Iyy = 9.9207 $Kg.m^2$, and Izz = 12.2784 $Kg.m^2$.

5. CONTROL PLANES OF MAYA

There are three control foils on Maya i.e a pair of stern planes and a single rudder. The shape profiles of these foils follow a standard NACA 0015 section with an aspect ratio of 4.27 and a leading edge angle of 10.6 degrees. The NACA section is symmetric, is easy to machine, has a zero lift force at zero angle of attack, and possesses a good torsional rigidity with a high thickness to chord ratio. The shaft of the actuator motor otherwise known as the 'rudder stock' is embedded at a distance equal to a quarter of the root chord (Cr) from the leading edge of the foil (see Fig.2 below)

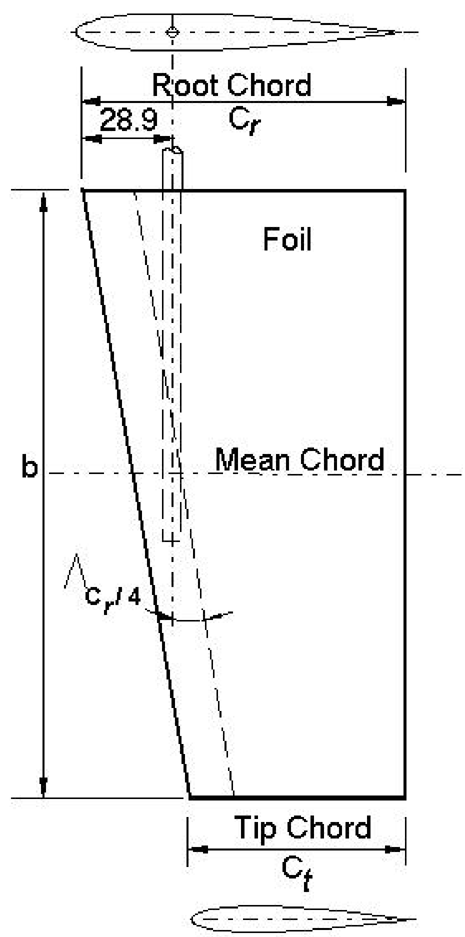


Figure 2: Schematic of control foil on Maya

Foil parameter	Symbol	Value
Single foil span	b	0.160 m
Root chord	C_r	0.09 m
Tip Chord	C_t	0.06 m
Mean Chord	C	0.076 m
Thickness Chord	(t/C)	0.15
Taper ratio	$\Lambda = (Ct / Cr)$	0.67
Exposed foil area	Se	0.024 m^2
Aspect ratio (foil)	ARe	4.26
Leading edge angle	Λle	10.6 º
Sweep angle at c/4	$\Lambda_{c/4}$	8.03 º

Table 1: Major parameters of control planes

This location of the rudder stock ensures that it is outside the locus of the 'centre of pressure' (CP) for all angles of attack of the foil. At a practical level, the stock is driven through the thickest part of the root chord section, and in line with the coordinates of Mean Hydrodynamic Centre (MHC) as shown in the foil section above.

The static hydrodynamic torque T_{LD} on the control planes acts at the centre of pressure (CP) along a normal to the fin and is composed of lift (L) and drag (D) forces which change with the angle of attack of the foil. Using simple relations of the lift and drag coefficients in terms of the geometrical parameters of the foils, it turns out that the torque T_{LD} varies monotonically from 0 to 10 Ncm for the corresponding changes in angle of attack from 0 to 30 degrees. These figures provide the torque specifications for the digital micro-actuator that can be used to rotate the external fins and rudders surfaces through a special pressure resistant shaft seals.

6. DESIGN OF PRESSURE SHAFT SEALS

A shaft seal is required to connect the shaft of the internal actuator motor to the external control planes. The seal is built around the shaft and its function is to stop seawater entry, and to enable the rotation of the shaft by the actuator at pressures up to a maximum of 20 bars. Three similar shaft seals have been designed, fabricated, tested and mounted on the hull at the location of the two stern planes and one rudder. Figure 3 below shows a cross-section of the shaft seal.

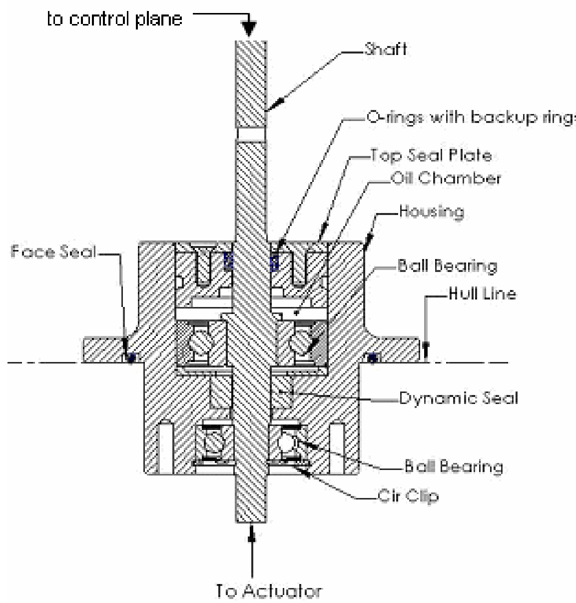


Figure 3: Cross section of shaft seal body

The seal is made up from internal parts consisting of a single steel shaft, two static O-rings, one dynamic seal, a backup O-ring, two stainless steel bearings, and two circ clips, all contained within an integral aluminium body. The seal can be described as being made from two sections namely :

1. A top external interface section that sits above the hull line (see Fig.3) that comprises a dynamic O-ring mounted on the shaft, and a wall mounted O-ring. This movable section floats over an oil well and its function is to isolate the lower section from direct seawater contact, and also to compensate for pressure & temperature changes from surrounding seawater. A ball bearing aligns and supports the top section of the shaft.

2. The lower section of the seal below the hull line has a dynamic seal (made from fabric rubber) which is directly mounted on the shaft diameter, and sits just below the top steel bearing (see Fig.3). This part of the shaft emerges from the body of the seal through a second smaller sized ball bearing and connects to the actuator through a miniature backlash free shaft coupler. A circ-clip mounted on the shaft diameter at the bottom prevents the shaft from being pulled out forcefully from the seal body.

The integrated module with shaft seal, coupler, and digital micro actuator is shown in the 3-D form of Fig.4. This module is inserted through a port hole on the hull, and sits flat on hull line over an O-ring face seal.

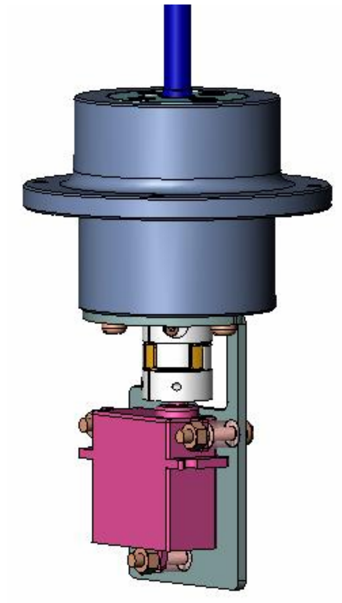


Figure 4: Integrated module of shaft seal with bracket holding coupler and micro-actuator

Extensive pressure tests were conducted on the seals up to a maximum pressure of 20 bars. The complete module was placed in a pressurised water chamber, and the shaft rotated continuously for several hours at various pressures.

7. DRAG TESTS ON THE MAYA HULL

The fully assembled Maya AUV was attached to a calibrated speed trolley at the Central Water and Power Resources Tow Tank facility in Pune, India, and the drag force measured at different trolley velocities. The results are shown below:

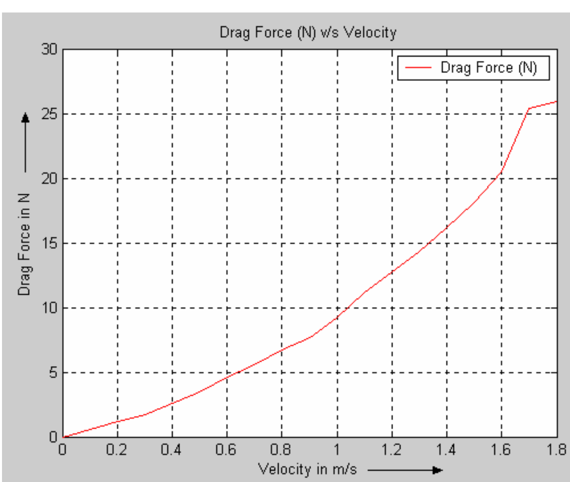


Figure 5: Drag Force (N) against velocity of trolley/AUV

The drag force D in Newton (N) is given by:

$$D = 0.5.A_f .C_{d0}. \rho. U^2 \qquad [2]$$

Where A_f .is the projected frontal area in m ^{2}, C_{d0} is the drag coefficient with fins and rudder at zero angle of attack, ρ is the density of water, and U is the speed of the trolley in m/s. Using this formula , one can calculate C_{d0}. from experimental data. The results show that C_{d0} is almost constant for U in the range 0.9 to 1.8 m/s with an average value of 0.31.

8. PROPULSION & POWER REQUIREMENTS

Safety, high power density, and low weight of batteries were primary concerns in selecting solid Lithium Polymer cells to meet the power demands from propulsion and payloads on Maya.

8.1 Choice of power source –Lithium Polymer

The most important characteristics in Lithium polymer batteries are:

- High power density (182Wh/kg)
- High cell voltage
- Continuous current up to 2C discharge rate
- Enhanced safety (no out-gassing when charging)
- Long cycle life > 400
- Easy scalability

8.2 Towing power & propulsion efficiency

The drag measurements of Fig.5 show that the towing resistance D at a nominal average velocity of 1.5m/s is ~ 17.5N which is equivalent to a towing power of ~ 26 W. The main thruster is powered by a dedicated bank of Lithium–Polymer batteries which provides input power of 100W. The total propulsion efficiency is therefore (26/100) ~ 0.26. The efficiency figure will increase at higher velocities and larger towing power (see eqn. [2]).

8.3 Endurances – payloads & propulsion

Power on the AUV was distributed separately to payloads and to the underwater thruster for propulsion. The Electronics and sensors include all the computer systems, electronics hardware, the RF communications, GPS, attitude sensors, DVL, and other vehicle sensors. A dedicated battery bank (24V/18Ah) for the payloads provided 432Wh for a load of ~30W. A separate battery bank (100V/9Ah) offered 900Wh for a continuous load of 100W. Assuming 20% energy degradation on both battery banks, the endurances of the payloads and the propulsion systems are 11.5 hrs and 7.2 hrs respectively.

9. SPECIFICATIONS OF THE MAYA AUV

Having described the major components of the Maya AUV, we are now able to summarise the specifications in a table:

Vehicle particulars	
Total Length	1.742 m
Diameter	0.234 m
Nose Shape	Slender Ellipsoid
Hull	Aluminum- 6082
Nose and Rear Cones	FRPG/ Acetal
Total weight in air	~54.7 Kgf
Drag coefficient C_{d0}.	0.31
Depth range	200 m
Propulsion	DC brushless motor
Propulsion efficiency	0.26
Nominal speed	1.5 m/s
Endurance	~ 7.2 hrs (propulsion)
Power source	Lithium Polymer cells
Total average power	130W
RF Communications	2.4 GHz, 115kbaud
Scientific Payloads	CTD, DO, Fluorometer

Table 2: Specification of MAYA

The figure 6 and 7 show the fully assembled and exploded views of the MAYA AUV.

Fig.6 : A photograph of complete Maya AUV

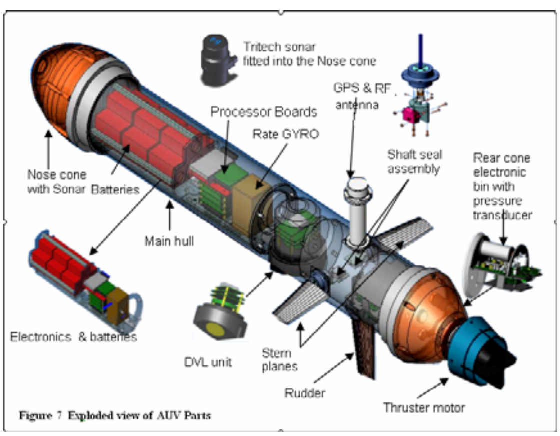


Figure 7 Exploded view of AUV Parts

Fig. 7: Solid Works isometric view of Maya.

10. SAFETY ASPECTS

Building in safety features on the AUV is of prime importance and we have considered and implemented the following:

1) Power safety which monitors the bus voltage on a network node, and redirects the AUV towards home coordinates if the power level falls below a minimum threshold level.

2) Software safety ensures that the AUV thruster is shutdown if the vehicle crosses programmed depth or exceeds a set pitch angle.

3) Mechanical safety that drops a weight should electronic methods fail.

The last method has not been implemented as yet, but will be incorporated in the near future.

11. CONCLUSIONS

A detailed design description of the small AUV MAYA has been given in this paper. Our original specifications of low weight, small size, large mission endurance have been broadly met, and the Maya AUV belongs to the small size class of contemporary vehicles e.g. GAVIA, REMUS. However, improvements could be done with hindsight on reducing the length and weight of the vehicle, and locating the control planes on the rear cone.

Some lessons have been learned in this development namely (1) the need for a design basis report (DBR) in the early stages of the development. The DBR specifies the parts to be used in the available volume, by restricting the choice on weight, required accuracy and cost; (2) modular design with online testing and integration of different modules e.g the hull, shaft seals, control foils, sensor nose cones, internal modules of electronics; (3) continuous prediction of the vehicle's hydrostatic behaviour as parts are added, namely a watch on optimal CG/CB separation; (4) continuous testing of the vehicle even before final development has reached. The Maya AUV has been tested rigorously in dam reservoirs that provide the best setting for implementing and testing autopilots for diving and heading control in the horizontal and vertical planes.

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