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Modification of a Nose Cone for a REMUS 100 Autonomous Underwater Vehicle to Improve Low-speed Stability

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Defence Science and Technology Organisation

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ABSTRACT

The REMUS 100 AUV is supplied with a flat plastic crash nose cone for use in lieu of the USBL when the potential for collisions is high. Experiments with the DSTO REMUS 100 showed that the stability of the vehicle is degraded at speeds under 2.5 knots when the flat nose is attached. This report describes the development and testing of a ballasted variant of the flat nose that successfully mitigates the stability problems seen at low speeds

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Executive Summary

MOD is undertaking a series of field assessments of commercial survey-class autonomous underwater vehicles (AUVs) in support of its research into hydrography, environmental assessment, mine countermeasures and maritime security. In support of these activities, DSTO has purchased a 'REMUS 100' hand-deployable AUV fitted with high-resolution sidescan sonar and a high-accuracy Global Positioning System (GPS)-aided Inertial Navigation System (INS). A series of field trials has been conducted to analyse various aspects of the vehicle's performance.

The REMUS 100 AUV is supplied with two modular nose cones: the general-use nose cone includes an acoustic ultra-short baseline (USBL) positioning system that enables acoustic navigation and homing behaviours, and a flat, impact-resistant plastic nose cone that is recommended for use in situations where the USBL function is not required or collisions are likely. In practice, the DSTO has rarely required acoustic navigation and has found that collisions are relatively frequent in the experimental program; hence the flat nose-cone is used by default.

A potential problem associated with the flat nose cone became apparent during a trial in tropical waters and was substantiated with short experimental missions in Sydney Harbour. It was found that the capability of the AUV to maintain a stable altitude when fitted with flat nose is significantly degraded when the vehicle is driven at 2.5 knots and degrades further as the speed is decreased below this point. This is a significant problem, given that some standard operating procedures call for operation of the vehicle at 2.5 knots.

Measurements of the flat nose and the USBL nose showed that the nose of the AUV is approximately 0.3 kg more buoyant when the 'flat' nose is fitted compared to when the 'USBL' nose is fitted; a significant figure, given that the total operating buoyancy of the AUV is nominally 0.5 kg. To ameliorate this, a metal insert was fabricated and inserted into the flat nose. Field trials were undertaken using the 'USBL' and 'ballasted flat' noses at a variety of speeds at constant altitude and also in a 'sawtooth' pattern where the vehicle is required to move up and down through the entire water column at a constant rate of climb and fall. With the ballasted flat nose fitted, the vehicle was able to navigate the sawtooth pattern with little apparent difference to its behaviour with the USBL nose fitted. It was also able to maintain altitude control at speeds down to 2.0 knots, although instability was seen at this speed when the USBL nose was fitted.

It is recommended that particular attention be paid to accurate ballasting whenever a new module or attachment is added to the REMUS 100 AUV, in order to avoid problems with guidance and control, particularly at low speeds.

Contents

1. Introduction

Survey-class autonomous underwater vehicles (AUVs) are becoming standard equipment for very shallow water naval mine detection and rapid environmental assessment (REA). The Maritime Operations Division of the Defence Science and Technology Organisation (DSTO) operates a REMUS 100 AUV, a widely-used hand-portable device that surveys at speeds between 2 and 4.5 knots. A summary description of the vehicle is given in Appendix A. The DSTO REMUS has no collision avoidance sensors and collisions with natural and man-made obstacles occur sporadically. In most cases, such collisions are head-on and involve only the nose of the AUV.

In its default configuration, the vehicle is fitted with a rounded nose containing an ultra-short baseline (USBL) sonar that is designed to sense the direction to an acoustic responder, typically to enable homing behaviours (Figure 1, Right). In this report it is referred to as the 'USBL nose'. The USBL nose has suffered several collisions in the course of 18 months of vehicle operation. While the USBL sonar is relatively robust and is shielded with resilient plastic, it is an expensive device and it is usually unnecessary for survey missions as alternative navigation sensors are available.

Figure 1L L: Flat, collision-resistant nose and R: Round, USBL nose

An auxiliary flat-ended, collision-resistant nose made from high-density plastic is also provided with the standard REMUS equipment pack (Figure 1, Left). This nose, which is referred to in this report as the 'flat nose' carries no sensors, so the risk of sonar damage in a head-on collision is eliminated. Therefore, it is desirable to use the flat nose whenever the USBL capability is not required. However, field trials have shown that the vehicle's ability to maintain control of its altitude and depth are significantly reduced at low speeds when the flat nose is fitted.

This report describes the process whereby the reason for the instability was identified, a simple solution was developed and a field trial was conducted within Sydney Harbour to confirm the correct operation of the vehicle when the solution was applied.

2. Stability Problems

Standard operating procedures for the REMUS 100 call for its use at a variety of ground speeds: transits and broad-area surveys are usually conducted at 4 knots, but may be conducted at 3 knots to extend endurance or 4.5 knots to save time; small-area 'reacquisition' patterns using the high-resolution sonar mode are conducted at 2.5 knots to maintain a proper along-track to across-track 'aspect' ratio in the sidescan sonar imagery. The REMUS operator's manual advises that the vehicle is operable at speeds between 2 and 5 knots, with the implication that it can maintain a uniform depth or altitude[1] at all speeds. Field trials of the vehicle in Far North Queensland[2] and later in Sydney Harbour[3], during which the ground speed was deliberately varied revealed that while the vehicle could maintain stable altitude at speeds of 3 knots and higher, its altitude control was degraded at 2.5 knots and severely degraded at 2 knots, to the point that it never managed to reach the target altitude (see Figure 2). On both occasions, the vehicle was fitted with the flat nose.

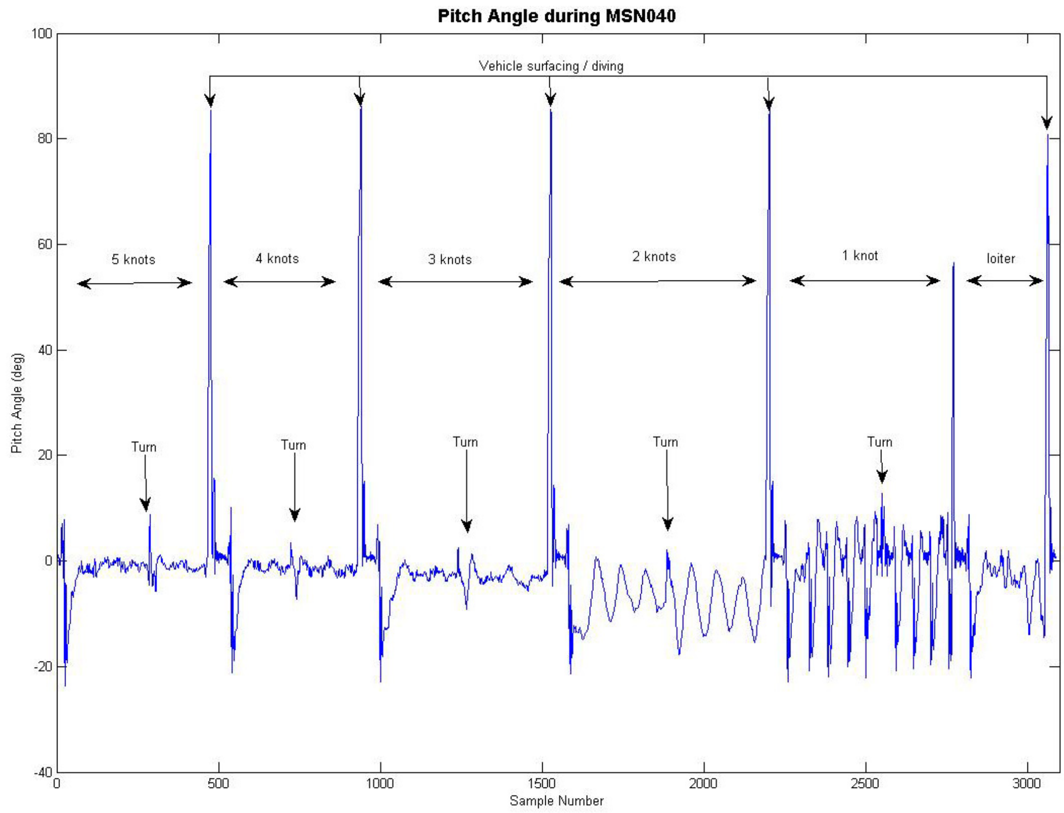

Figure 2: Pitch angle during MSN040, showing increasing instability as speed decreases. The flat nose was fitted for this mission.

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[1] Altitude in this context is height above seabed

[2] Kratzer, T. (2008) *Operation of a REMUS 100 Autonomous Underwater Vehicle from a Survey Motor Launch in Far North Queensland*, DSTO Client Report DSTO-CR-2008-0092.

[3] Experimental REMUS mission MSN040, conducted in Sydney Harbour, 08 March 2008

Further experiments (missions MSN042 and MSN043) were conducted in White Bay, Sydney Harbour, on the 14th March 2008 to compare the diving characteristics of the vehicle when the USBL and flat noses were fitted. They revealed that the vehicle suffered reduced stability at 2.5 knots with the flat nose fitted and was unstable with either nose at 2 knots. As noted above, instability at 2.5 knots is incompatible with standard operating procedures.

Figure 3 shows the variance and mean of the altitude during MSN042 and MSN043. The two missions were identical, except that the vehicle was fitted with the USBL nose during MSN042 and the flat nose during MSN043. In both cases, the target altitude was 3 m. Note that the target speeds in Figure 3 are expressed as propeller rotation rates: 850, 1050, 1250 and 1450 RPM are roughly equal to 2.29, 2.85, 3.52 and 4.04 knots, respectively. Figure 3 indicates that the vehicle maintains an average altitude closer to 3 m when it is fitted with the USBL nose rather than the flat nose, and that its altitude varies less when fitted with the USBL nose.

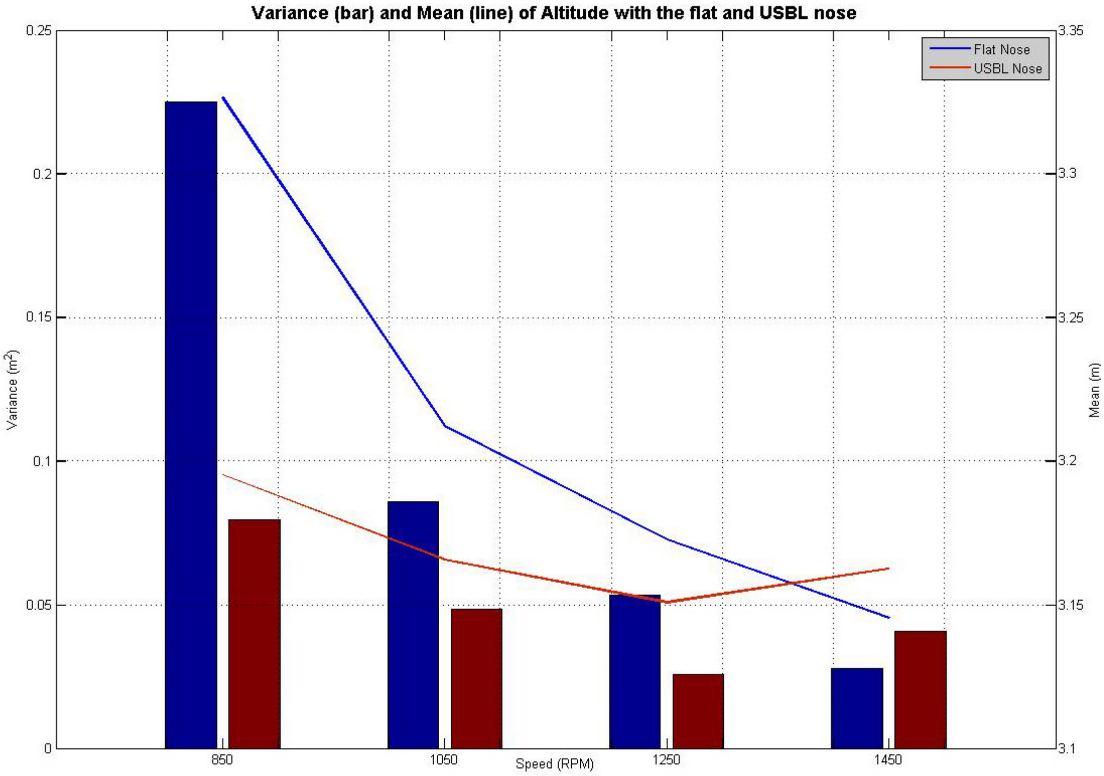

Figure 3: Variance (bar) and mean (line) of Altitude with flat and USBL nose at various speeds with a target altitude of 3 m during MSN042 & MSN043

3. Buoyancy Measurement and Correction

As the flat nose is noticeably lighter than the USBL nose in air, a difference in the buoyancy of the two noses was immediately suspected to be the cause of the altitude control problems. When the two noses were immersed in water, it was noted that the flat nose floated, whereas the USBL nose sank.

Buoyancy calculations require a measurement of the amount of water displaced by a body when it is fully immersed. In this case, the measurements were made by completely filling a large beaker with water and placing it in a tray. The amount of water displaced when each nose was lowered into the water (or pushed underwater, in the case of the flat nose) was then measured by pouring the displaced water from the tray into a measuring cylinder. This procedure was repeated a number of times, as considerable variations were noted between successive measurements. A beam balance was also used to weigh the noses in air. The results are given in Table 1.

Table 1: Table summarising properties of the flat and USBL noses

	Mass	Volume displaced	Buoyancy
Flat Nose	479 g	580 mL*	~ +100 g**
USBL Nose	1600 g	1400 mL	~ -200 g**

*approximate value, ** measured in fresh water

The measurements show that replacing the USBL nose with the flat nose has the effect of increasing the buoyancy of the nose section of the vehicle by approximately 0.3 kg. Given that the vehicle is typically operated with total positive buoyancy no larger than 0.5 kg, this change can be expected to have a significant effect on the total buoyancy and also on the location of the centre of buoyancy. When the buoyancy at the nose is increased, the autopilot may be required to compensate by changing the angle of attack of the elevator fins so that the vehicle is driven downwards. The effectiveness of this behaviour can be expected to reduce as the speed through water decreases, which explains the loss of altitude control at low speeds.

Two solutions to the buoyancy mismatch problem were investigated. Ideally, a new flat nose could be fabricated with buoyancy matching that of the USBL nose. This would allow a more streamlined shape to be employed, incorporating a collision-absorptive soft rubber section similar to what is affixed to the USBL nose (see Figure 4). This solution has not yet been implemented.

A simpler and cheaper alternative to fabricating a new nose was pursued as an interim measure. A metal insert was machined to fit the void space at the back of the existing flat nose as ballast and thereby correct the buoyancy. The insert is a 0.33 kg piece of stainless steel, which has been affixed to the inside of the new nose cap with a marine sealant. The displacement of the steel was measured to be approximately 30 millilitres; thus the total buoyancy change was expected to be approximately 0.3 kg, in line with the requirement. The resulting ballasted configuration is pictured in Figure 5.

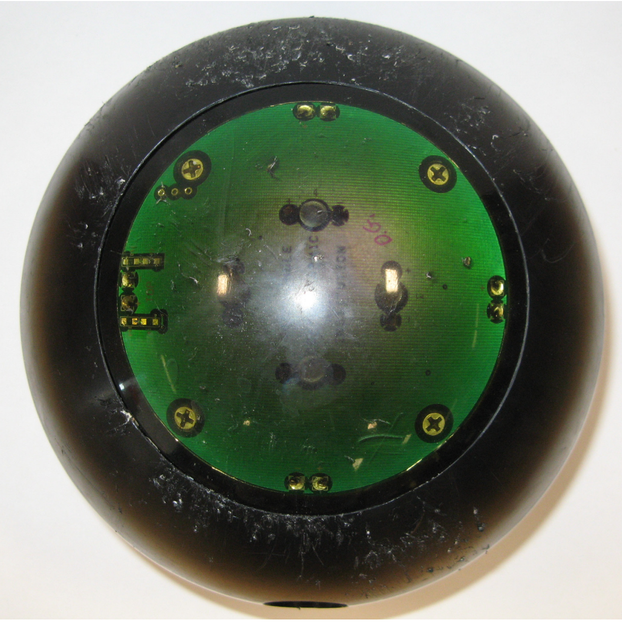

Figure 4: Top view of the USBL Nose. The outer black area is plastic whilst the inner green area is the sonar processor board visible through a covering of stiff transparent rubber. The damage that the nose has sustained to date is also visible.

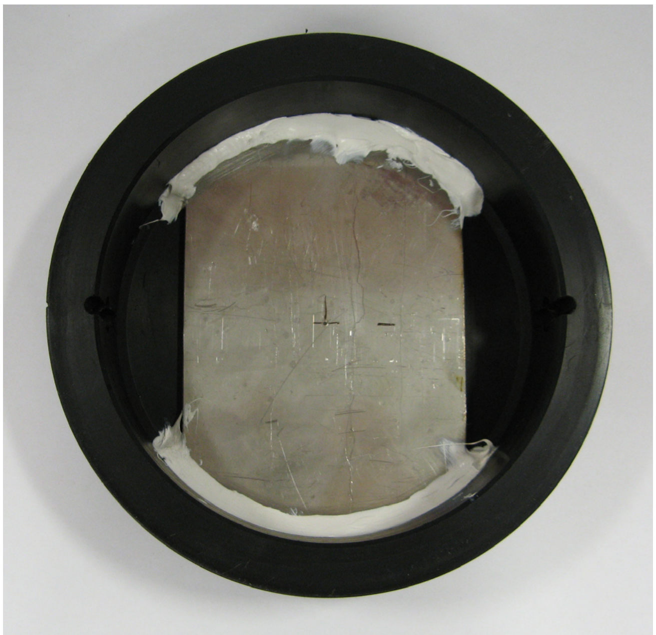

Figure 5: Inside of the flat nose showing the steel plate attached to the inner face

4. Field Trials

A short experiment was undertaken to confirm that ballasting the flat nose is an effective means of stabilising the DSTO REMUS 100 vehicle at low speeds. Two survey missions, MSN065 and MSN066, were conducted in Hunters Bay out of HMAS Penguin during the daylight hours of the 25th September 2008. The missions were identical except for the exchange of noses – the USBL nose was used for MSN065 and the ballasted flat nose was used for MSN066. Environmental conditions, which were calm and clear, changed little over the course of the day. Figure 6 shows the plan used for both missions. Each mission started and finished near the point marked 'loiter' in the southwest corner. The first part of each mission consisted of a series of parallel legs at a constant altitude of 3 metres along a survey line running approximately east-west over relatively flat terrain. Each leg was conducted at a different speed. This was followed by a long traverse to the north-east where the vehicle undertook a rectangular lawnmower pattern survey using a triangular ('sawtooth') depth profile.

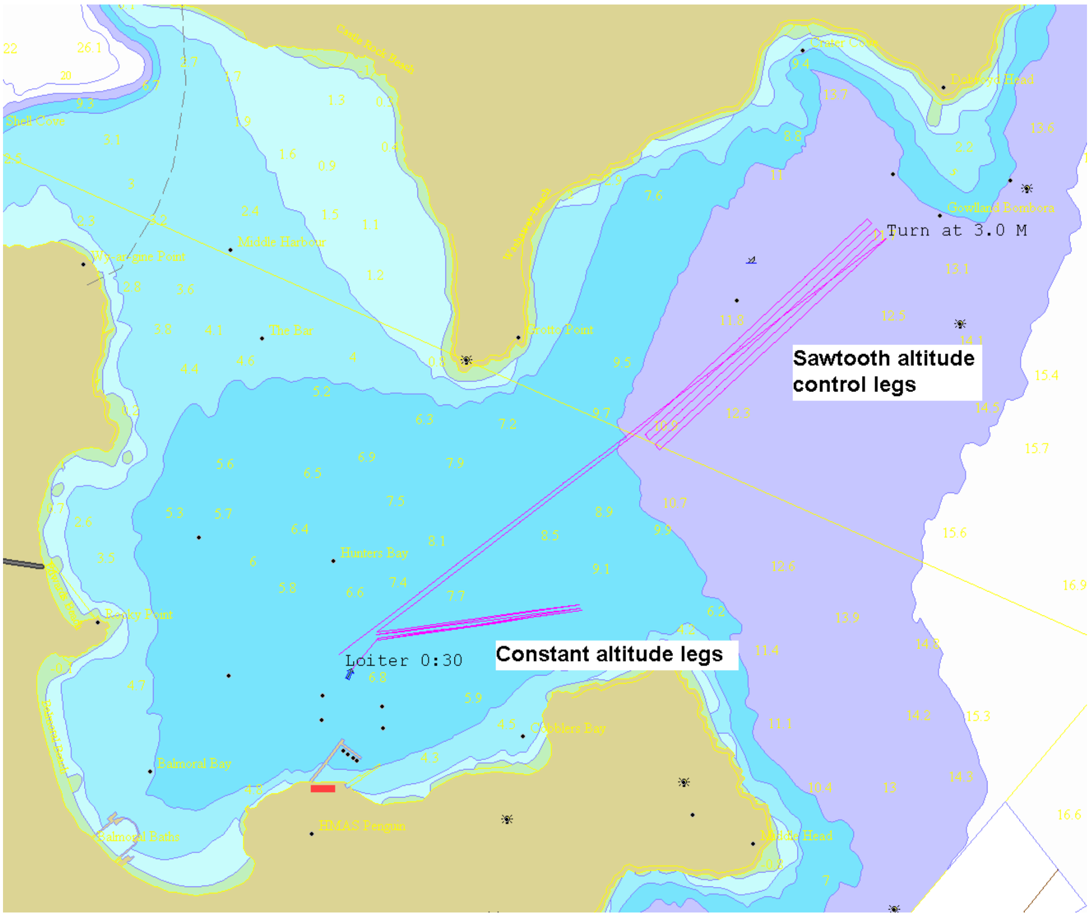

Figure 6: Mission Plan for MSN065 and MSN066

The second part of each mission is not directly relevant to the present case, except to note that the sawtooth depth-control mode requires accurate depth and altitude control and that the AUV completed this part of both missions at 4 knots without incident and with barely noticeable differences between the two altitude records. This suggests that the altitude/depth control function of the autopilot was able to control the vehicle effectively, regardless of which nose was attached to the vehicle.

The variable-speed section of each mission consisted of successive single legs at speeds increasing from 2 knots to 4 knots in 0.5 knot increments. This section of the data was used for the analysis following. The data was split so that each block of data contained information about a single speed. Data selection was done manually, with segments for analysis commencing when the vehicle had settled on a constant heading after making a turn and finishing prior to the turn at the end of the leg. No other filtering was done.

The vehicle controls its altitude by altering its pitch angle. Large changes in pitch angle indicate that the vehicle is struggling to control its altitude. The range and distribution of the pitch angle show how much the pitch angle has varied and how often the control system has employed a larger than usual pitch angle to reach an acceptable altitude.

Figure 7 and Figure 8 show the cumulative distribution plots of the pitch angle at various speeds during MSN065 and MSN066 respectively.

Cumulative distribution plots of variables such as pitch angle and altitude are a useful means of comparing control system performance, as they allow direct comparison of the amounts of variation in different data sets.

The lines in Figure 8 are, on average, steeper than the lines in Figure 7, indicating that the variable is more closely clustered around its median value in the later mission; in other words, the pitch angle of the vehicle varied less with the ballasted flat nose than with the USBL nose. The vehicle is therefore more stable with the ballasted flat nose than with either of the original choices.

This stability extends to the lowest speed, 2 knots, when the vehicle is unstable with the USBL nose when programmed to fly at constant altitude. Figure 2 shows the evolution of the vehicle's pitch angle with the original flat nose attached. These data show that the pitch oscillates through a large range at two knots, a behaviour that is associated with a vertical undulation or 'porpoising' through the water column even though the vehicle was programmed to fly at a constant altitude. Porpoising is responsible for the 'flat' 2 knot cumulative distribution curve in Figure 7.

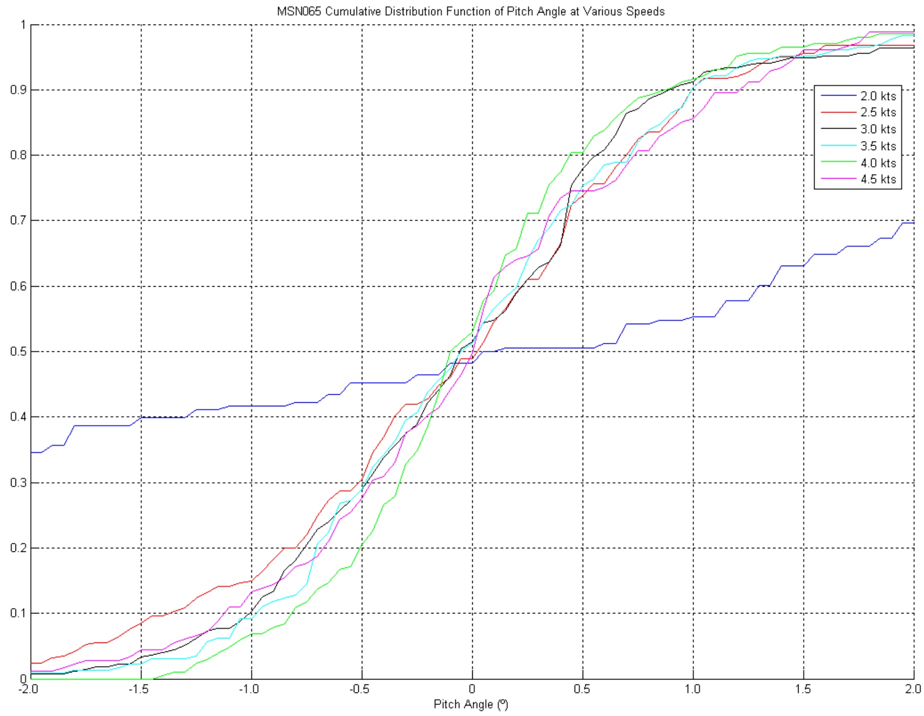

Figure 7: Cumulative distribution plot of pitch angle at various speeds during MSN065

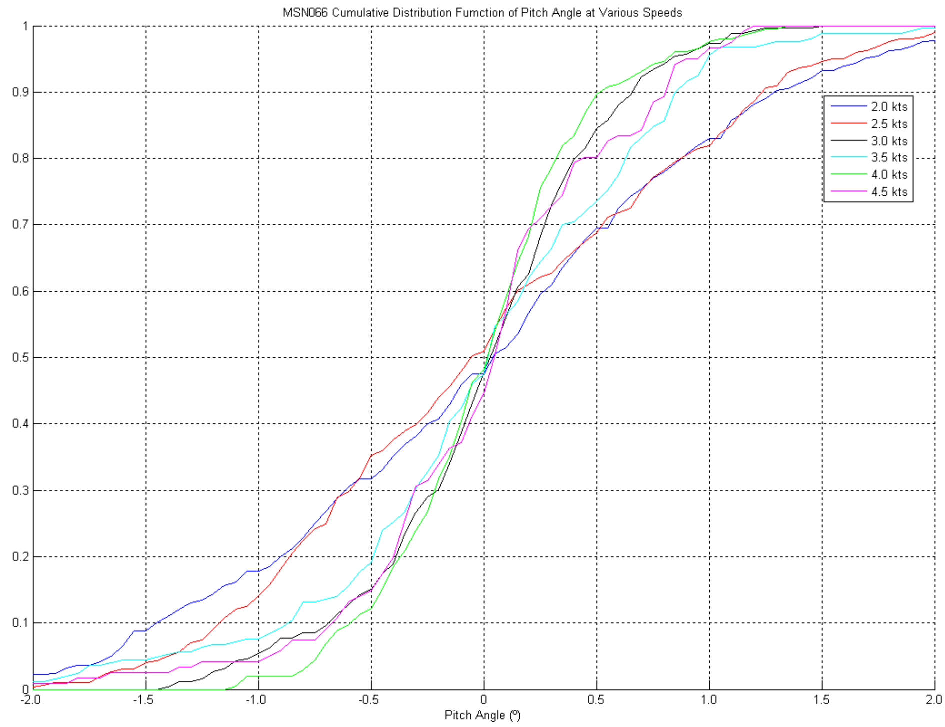

Figure 8: Cumulative distribution plot of pitch angle at various speeds during MSN066

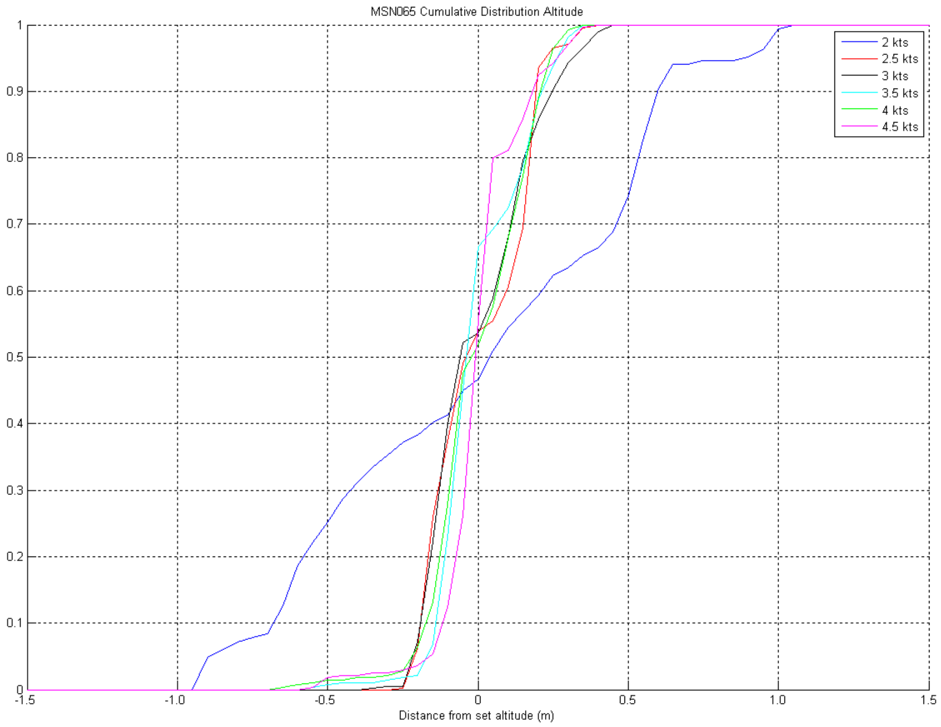

Figure 9: Cumulative distribution plot of altitude at various speeds during MSN065

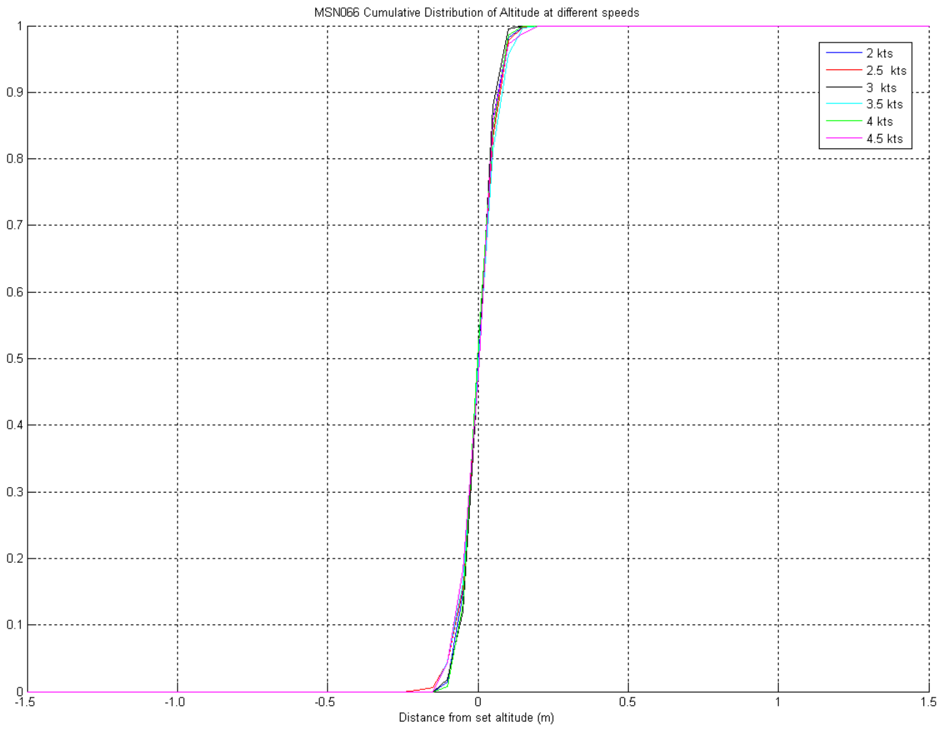

Figure 10: Cumulative distribution plot of altitude at various speeds during MSN066

Figure 9 and Figure 10 show the cumulative distribution plots of altitude at various speeds for MSN065 and MSN066 respectively. In these figures the abscissa shows the difference between the programmed altitude and that achieved by the vehicle.

Both of these missions were run in altitude mode, meaning that the vehicle was given a target altitude and did its best to maintain that value. The ability to maintain a constant altitude is important to sonar image quality and vehicle survivability; hence an improvement in altitude keeping is beneficial.

The narrower spread and steeper gradient of the curves in Figure 10 compared to those in Figure 9 confirm that the ballasted flat nose allows the vehicle to maintain a constant altitude more easily than the USBL nose. Inspection of the data showed that it significantly decreases the response time to a change in the seafloor profile. Furthermore, the greater degree of correlation between the multiple speeds indicates that the vehicle with the ballasted nose runs more consistently over a larger range of speeds.

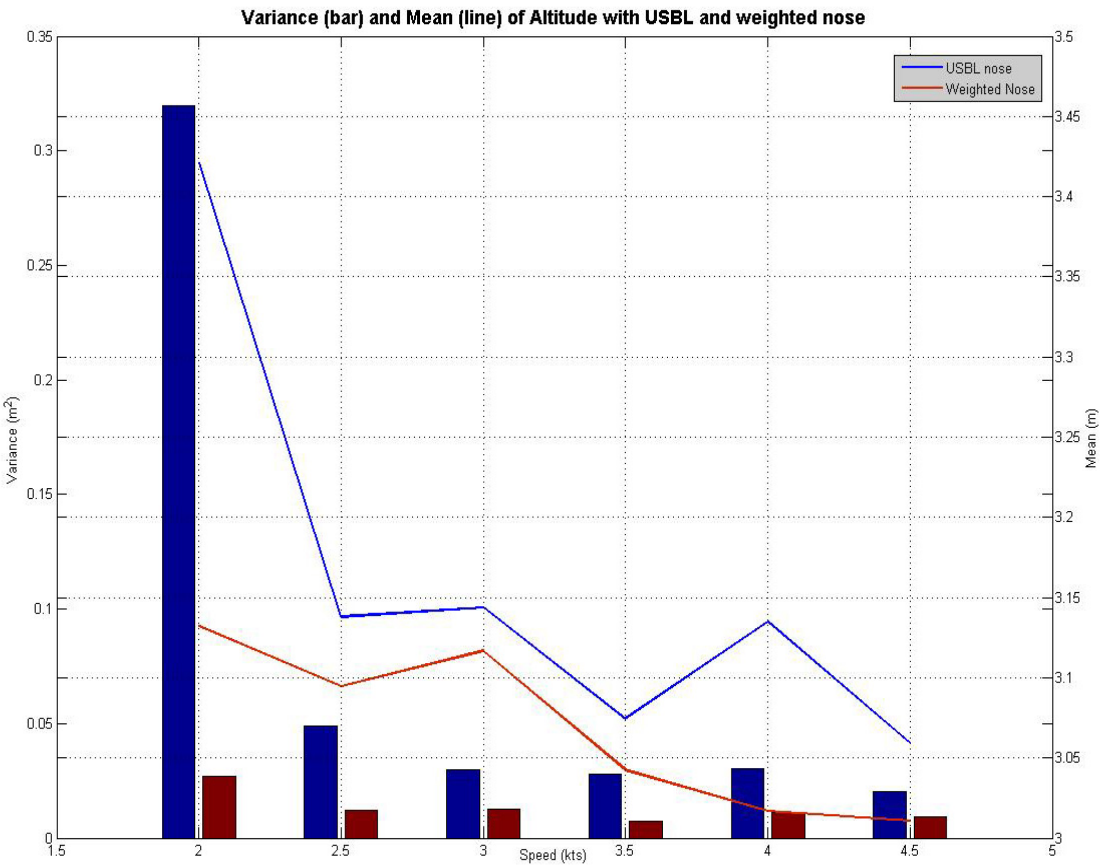

Figure 11: Variance (bar) and Mean (line) of altitude with the USBL and weighted nose with a target altitude of 3m MSN065 & 066

Figure 11 shows the variance and mean of altitude in data from MSN065 and MSN066 in the same format as is seen in Figure 3, although the target speeds are specified in knots, not as a propeller rotation rate. As mentioned previously, the missions were identical except for the different nose configurations. These results indicate that the ballasted flat nose provides a noticeable advantage over the USBL nose, and hence also over the original flat nose.

The USBL nose data shown in Figure 3 and Figure 11 are consistent. Although the variance and mean of the altitude at 2 knots are well above what was seen at 2.29 knots (850 RPM) in Figure 3, it should be noted that the altitude-keeping ability of the vehicle deteriorates severely at speeds below 2.5 knots; hence this result is not unexpected.

5. Conclusion

When used as originally manufactured, the flat-ended plastic ‘flat’ nose supplied with the DSTO REMUS 100 AUV causes the vehicle to become unstable and degrades its ability to accurately maintain a target altitude when the vehicle is used at the lower end of its operational speed range; say 2 to 2.5 knots. The addition of 330 g of steel ballast to the nose significantly improves stability; in fact, the data indicates that the vehicle actually performs better with the ballasted flat nose than with the standard USBL nose. No adverse effects due to the use of the ballast have been observed. If there is no need to use the USBL nose, it is recommended that the ballasted nose be used.

In future, it is recommended that the manufacture and use of a round-ended version of the flat nose be investigated. Although there is no indication that a round nose would have better hydrodynamic parameters than a flat nose, it could accommodate extra absorptive material, providing extra protection for the components of the vehicle in the event of an impact.

This investigation has also demonstrated that the REMUS 100 autopilot has limited capability to offset the effects of buoyancy changes for which it was not designed. Care will be necessary in future to avoid similar effects from other attachments as careful ballasting appears to be necessary to achieve stable altitude control.

Appendix A: The REMUS 100 AUV

A.1. Hand-deployable AUVs

Large-scale development of autonomous underwater vehicles (AUVs) commenced in the 1980s, when a number of very large experimental vehicles were designed. As advances in computing, navigation and sensing technologies occurred, subsequent generations of AUV were made successively smaller, culminating in hand-deployable vehicles such as the REMUS 100, which weighs approximately 40 kg. The Remote Environmental Measurement UnitS (REMUS) were first designed in the early 1990s at the Woods Hole Oceanographic Institute (WHOI), and evolved through the 1990s with funding from the US Office of Naval Research (ONR). The current design, which incorporates streamlining, an optimised propeller and lithium ion batteries to support long missions, was introduced from around 2000, and commercial manufacture of the design by a commercial company, Hydroid Incorporated of Massachusetts, USA, began in 2001. REMUS was used for mine clearance of river channels with great success during the Coalition invasion of Iraq in 2003. The vehicle has continued to evolve up to the present, with the introduction of inertial navigation and satellite communications facilities.

Since 2000, a small number of vehicles with specifications similar to the REMUS 100 have emerged: the Bluefin-9 from Bluefin Robotics, the Gavia from Hafmynd ehf, and the Iver 2 from Ocean Server Technology. Although each of these vehicles has interesting attributes, none has yet enjoyed the commercial success of the REMUS 100.

A.2. General Specifications

- Maximum operating depth – 100 metres
- Maximum speed – 5 knots
- Survey speed – 3 or 4 knots
- Maximum endurance (DSTO configuration) – approximately 8 hours at 4 knots
- Weight in air – 37 to 40 kg
- Length – 1.60 to 1.72 metres
- Body Diameter – 19 cm

A.3. Configuration of the DSTO REMUS 100

The unique 'DSTO' configuration of the REMUS 100 vehicle, which was delivered in June 2007, is similar to that of the 'Swordfish' vehicles recently delivered to the US Navy. The vehicle is fitted with:

- A YSI pressure (depth) sensor,
- A YSI temperature-salinity sensor,
- A Marine Sonic Technology dual-frequency (900/1800 kHz) sidescan sonar,

- A Kearfott T-16 Inertial Navigation System,
- A Woods Hole Oceanographic Institute (WHOI) acoustic long-baseline (LBL) positioning system,
- A WHOI 'Micromodem'[4] acoustic communications system that shares the same transponder as the LBL system,
- A nose-mounted acoustic ultra-short baseline (USBL) positioning system,
- A Garmin GPS system, and
- An Iridium satellite communications system.

Unlike the Swordfish vehicle, the DSTO vehicle is not fitted with an optical backscatter sensor or a low-light video camera. The vehicle is shown in Figure A1.

Figure A1: The DSTO REMUS 100 vehicle in its travelling case

[4] 'Micromodem' is a trademark of the Woods Hole Oceanographic Institute

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