The Systematic Optimisation of the Propulsion Efficiency of In-Service Autonomous Underwater Vehicles

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Abstract. **Understanding the ocean environment is dependent upon adequate sampling of many parameters. For reasons of affordability and practicality many of the measurements within the ocean will need to be undertaken by AUVs. Current propeller driven AUVs have limited range and endurance. Whilst new designs of vehicle may readily incorporate new technologies to address this issue, considerable investment has gone into the current generation. These are often successful designs with many years of useful life remaining. This paper describes a means of assessing the propulsion performance of in-service vehicles with a view to their further optimisation.**

A systems-engineering approach to the problem is proposed. The characteristics of the system are examined and the in-service performance compared with that anticipated at the design stage. Shortfalls in performance are identified. This results in a need to take account of the effects of a greater level of sub-system detail than is usual at the design stage. The need to address complexity leads to difficulties in design of effective measurement systems. The design of a programme of scale model experiments and full-scale trials with the aim of improving understanding of the propulsion system, with particular attention to drag and its causes, are described. The baseline vehicle used is the AUTOSUB AUV, developed by the Southampton Oceanography Centre.

I. INTRODUCTION

A characteristic of AUVs (Autonomous Underwater Vehicles) is that they are energy limited. As with many other vehicles, demand for long range and endurance at an affordable price is insatiable. AUVs have only just become practical vehicles for use in the harsh environment of the deep ocean. Understandably, investment to date has been concentrated on the peculiar demands of autonomy for a vehicle that is essentially isolated. (The isolation is a consequence of the impossibility with current technology of maintaining long range, high data rate, communication.) This investment has resulted in a highly capable generation of AUVs, which are, however, limited in range by their propulsion systems. Future developments of all components of the propulsion system, but particularly in energy storage, should enable subsequent generations to achieve much greater range for a given size and mass. This paper, however, proposes that there is scope for building on the considerable investment in the current generation of AUVs by optimising their propulsion system through a system of continuous improvement.

For any complex system, performance in-service will vary from that anticipated during the design process. This applies to the propulsion system of AUVs as much as to that of any other system. There should, therefore, be scope for significant improvements to extant propulsion systems. The precursor to any improvement is a

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thorough understanding of the actual in-service performance of the vehicle. In particular, there is a need to take account of the full complexity of real systems as built, rather than remain with the simplifying assumptions necessarily made during initial development. This paper describes a process and set of tools for achieving this. In particular it addresses the problem of how to take account of the detail of the hull form and describes a set of tools for improving the performance of a particular, and very successful, in-service vehicle, AUTOSUB, designed and built by the Southampton Oceanography Centre.

II. SYSTEM ANALYSIS

The key to addressing the propulsion problem for in-service vehicles (defined here as how to obtain greater range from the existing system) is to take an holistic view. Those parts of the vehicle that affect propulsion need to be considered as an integrated system in its own right.

The approach taken here is to apply systems engineering principles to the through-life performance of the propulsion system as illustrated in Fig. 1.

System engineering is a process whereby the needs of the customer are satisfied throughout the life cycle of the system. The following tasks are undertaken [1, 2]:

- Identify the problem: capture the requirements and define the system.
- Investigate alternatives: evaluate different combinations of sub-system.
- Model the system.
- Integrate: characterise the sub-systems, interfaces and interactions.

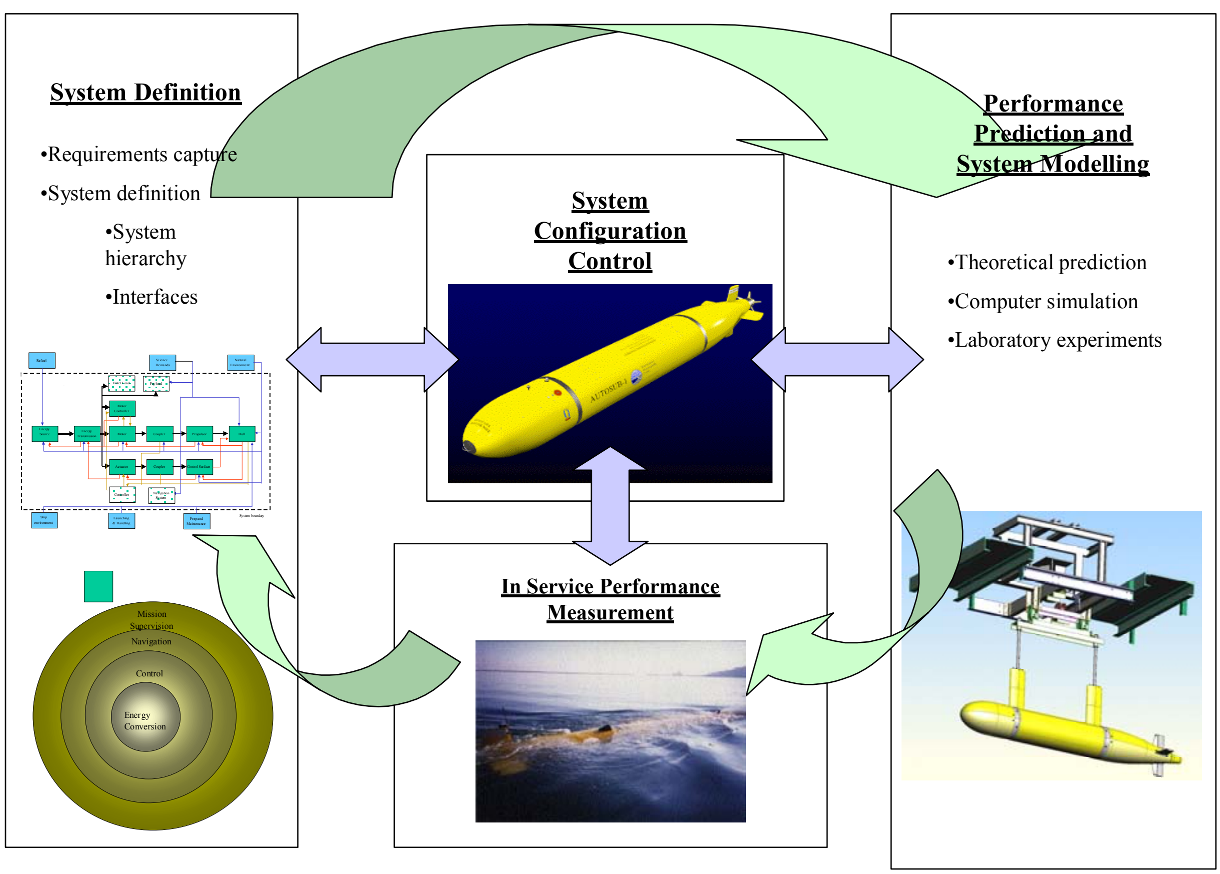

Fig.1. System engineering approach.

- Produce the system.
- Assess performance.
- Iterate whilst maintaining control of the system configuration.

Problems in system engineering are normally formulated at the beginning of the system design process. However, the issue addressed here is how to improve performance of a fully operational and successful vehicle. Whilst all of the elements of system analysis are pertinent, the undertaking of post-production systems analysis necessitates a modified approach [3]. In particular there is a need to:

- Capture both the original and the current requirement at a time when the customer's views will have changed in the light of experience.
- Understand the original design process when records may be incomplete.
- Characterise the system and sub-systems as built, rather than as conceived
- Acknowledge the fact that the systems engineer is likely to work to the project manager, not the customer.
- Recognise that the role of the systems engineer will be that of an investigator rather than instigator.
- Realise that resources will be necessarily more limited, whereas the task may be more complex.
- Accept that such investment will already have been made that many of the sub-systems and/or interfaces will be immutable.

Although there are a number of disadvantages to undertaking an analysis after the system has entered service, including ownership of the current design and the scope for innovation being constrained by investments already made, there are a number of advantages, including:

- The availability of archived data.
- The availability of a complete working system.
- The fact that many complex issues will already have been addressed.
- Ready acknowledgement by those who control resources that there remain difficult issues that require investigation.

The first step in the process is to define the system for analysis purposes, and the problem in quantative terms. Since the key to maximising overall range is to use the limited energy available effectively, a broad definition of the system has been taken to include the whole energy conversion process within the vehicle and the interfaces to the outside world that effect energy utilisation. The system is defined in Fig. 2.

Having defined the system, a simple steady state parametric model was devised to obtain an indication of how total system performance can be expected to change with key system parameters. The model is summarised in (1). This expresses range (R), in terms of total vehicle volume (v_t), cruise speed (u), payload and service volume (v_{pl} and v_s) and power requirement (P_{pl} and P_s), energy density of the energy source (ρ_e), power density (ρ_p) and efficiency (η) of the motor/propeller combination, and hull drag coefficient (C_d). That is

$$R = u\rho_e \frac{\left(v_t - \frac{v_t^{2/3} C_d u^3 \rho_{sw}}{2\eta\rho_p} - (v_{pl} + v_s)\right)}{\left(\frac{v_t^{2/3} C_d u^3 \rho_{sw}}{2\eta}\right) + (P_{pl} + P_s)} \quad . \qquad (1)$$

When the model is run with the parametric values for the vehicle assumed at the design stage, it is confirmed that the system should achieve the anticipated performance. However analysis of data obtained from the vehicle's log during in-service missions indicated that measured speed for a given rate of energy expenditure was significantly less than predicted. Furthermore, it was established that performance was degrading with changes to the vehicle.

The in-service performance of each component of the propulsion system was then assessed and compared with that expected at the design stage. This analysis of component performance

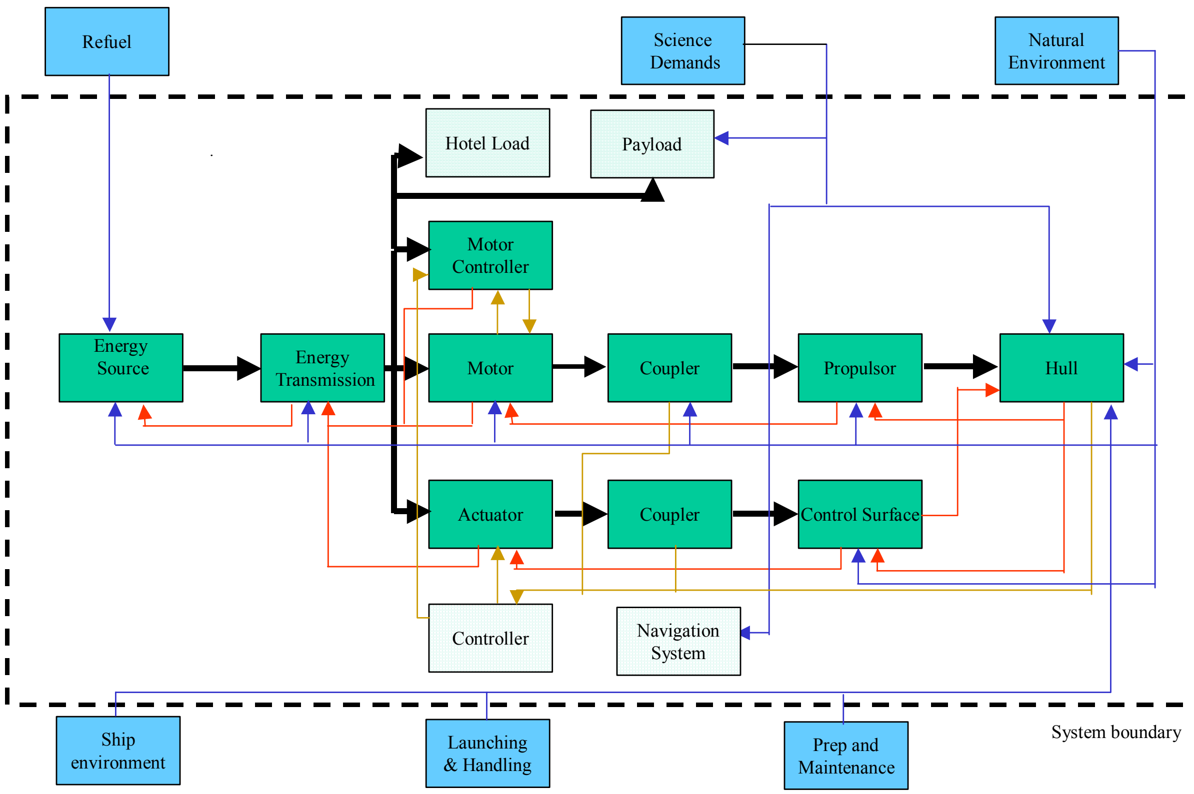

Fig. 2. Energy conversion system.

concluded that the principal cause of under-performance was a result of the characteristics of the hull and/or propeller, and/or propeller/hull interaction not being as expected.

Now the hull of the in-service vehicle differs in detail from the idealised form modelled during development. Furthermore, as this is a general-purpose vehicle, the detailed shape changes from mission to mission with changes in payload. It was therefore decided to characterise so far as possible, the actual hull-form in use, so that the effects of the deviations from the original clean hull could be quantified and forecast.

III. ACCEPTING COMPLEXITY

The detailed form of the vehicle is more complex than that modelled at the design stage due to the addition of appendages required to provide services such as communications, sensing and vehicle handling. Additionally the detailed shape changes with time. It is modified for each mission as a result of changes to payload and services required and it suffers from the results of normal handling within the harsh environment on a ship in a seaway.

Consequently it is necessary to understand not only the gross effect of the hull, but also the effects of comparatively fine detail. This detail includes both that resulting from appendages and orifices needed for sensors and services, and that which results from in-service handling, such as ill-fitting panels, and dents and abrasions on the hull surface.

The detailed form of the vehicle may be considered under three headings.

a) Baseline: appendages necessary to provide common services. These are present on every mission and allow the vehicle to perform its basic task. These include for example, control surfaces, lifting lugs and communications antennae.

b) Payload: appendages required for mission-specific services and mission payload. The latter usually requires hull-penetrating sensors.
c) Damage: changes to surface finish and detailed hull form resulting from operating in the harsh environment of a seaway.

Item (a) is constant: (b) changes from mission to mission: and (c) changes with time according to the maintenance regime. The characteristic features are listed in Table 1.

Table 1
Typical AUV Features

Baseline	Payload		Damage	
Description	Variety	Representative of:	Variety	Represntative of:
Argos Aerial	Cylinders & rods		Surface roughness	
Beacon lamp A		Large sonar dome (AUI)		Scratches
Beacon lamp B		Small sonar dome (Navigator size)		loss of gellcoat
CTD Sensor (port)		Small sonar dome (AUI)	Ill fitting panels	
CTD Sensor (stbd)		Comms antenna (Argos)		Channels
Lifting line stow hole		Strut (GPS support)		longtitudinal
Flooding hole A (fwd)	Domes			circumferential
Flooding hole B (fwd)		Small housing (Beacon)	Spot features	
		Large housing (Navigator)		screw/rivet heads
Lifting lug (fwd)	0015 NACCA Section beams			longtitudinal
Lifting line (fwd)		Long strut (GPS support)		Circumferential
Lifting line (aft)		Short strut (1/2 size support)	Annuli	
		Large streamlined Housing		
Lifting lug (aft)		(Navigator)		Ill fitted sensors
		Small streamlined Housing		
Flooding hole A (aft)			Holes	
Flooding hole B (aft)	Tubes:			
	Horizontal			
Top fin mast, GPS				
antenna & Argos aerial		ctd sensor		
ADCP 1	Vertical			
		sensor		
	Cage			
	Dome - 0.5cm rod - large	LF Sonar protective cage		
	Dome - 0.3cm rod - small	1/2 size protective cage		

It is necessary not only to understand the effects of each of these individually, but also to understand the effects of their interactions. From this knowledge a model and set of rules may be developed to guide the design and positioning of orifices and appendages and enable analysis of the cost effectiveness of improved vehicle handling strategies.

The need to cope with such complexity requires a novel approach. This is explored further in section V.

IV. A TWO PRONGED APPROACH

There are a number of principal means by which the investigation may be made:

- Theoretical modelling.
- Computer simulation.
- Analogue simulation. (Laboratory experiments using physical models.)
- Real world trials. (On the full-scale vehicle at sea.)

Theoretical calculations underpinned the original design. Methods are available to provide a broad indication of the level of drag and the analysis described in Section II has confirmed that, taking a broad parametric approach, the vehicle as built should be capable of meeting the original performance aspirations. A more detailed assessment is possible by taking into account the effects of angle of attack and hydroplane angle [4], although data is not readily available to allow these to be calculated for non-standard geometries such as that of the hull.

These methods are suitable for producing an indication of the performance of the bare hull. Extending the analysis to include the effect of appendages may be possible but necessarily increases its complexity. There is a considerable literature [5], providing empirical guidance on specific appendages, although these are often for highly idealised geometries. Formulae that take into account combinations of appendages and allow for their relative positions in sufficient detail are not readily available. A theoretical approach will therefore become increasingly unreliable with increase in the level of detail sought and is unlikely on its own to provide a sound basis for a detailed determination of the issue.

Computer simulations of the vehicle using hydrodynamic code have been undertaken elsewhere. An investigation into the drag of AUTOSUB has been undertaken [6] using a panel code, 'PALISUPAN', devised by Turnock [7]. This explored the transition point and boundary layer thickness, and from this derived the drag force. However, adding increasingly fine detail to the model to produce the answers required of this investigation is both time consuming and conceptually difficult. To include fine detail, a much larger number of panels than has been used to date is required. There will be a tendency for the number of panels to increase geometrically as the level of detail increases and for the time required for the consequent computation to increase exponentially. Care is required to maintain the stability of the code under these conditions.

Part of this investigation is to assess how drag varies with angle of attack and hydroplane angle. This necessitates modelling the vehicle as a lifting body. Whilst the panel code will allow this, there will be uncertainty on the nature of the Kutta condition for the detailed model. Thus the success of such detailed modelling could only be ascertained once it had been validated by comparison with measurements made in the real world. Physical modelling is, therefore, considered to be indispensable.

Since the vehicle under consideration is already in service, two alternatives are available for facilitating physical measurements: manufacture a model for use in a laboratory; or take measurements on the actual vehicle at sea. With the availability of a working system and the intention to replicate reality so far as possible, use of the in-service vehicle at sea appears attractive. However the utility of this approach is limited by the difficulty of controlling the environment. Equally, reproducing the full complexity of the real vehicle in the laboratory is taxing. It was, therefore, decided to undertake complementary measurements on the in-service vehicle at sea and on a model in the laboratory. The trials at sea are designed to establish the range of operating conditions to be replicated in the laboratory and to verify the conclusions of the laboratory experiments.

Additionally a simple trial has been designed for use during normal operations to enable the actual performance of the vehicle to be established as configured for its impending mission. These trials are complemented by detailed measurements of different configurations made in the laboratory.

V. LABORATORY EXPERIMENTS

A. Experiment Design

The aim of the laboratory experiments is to establish the drag of the hull as a function of speed, attitude, and vehicle shape, where the shape of the vehicle is itself a function of the position of the control surfaces and the size, shape, number, position and relative position of the appendages. Each of these is a continuous variable; so typical values must be selected for use in experiments. A list of the principal factors affecting drag is given in Table 2, together with the number of levels necessary to be explored for each.

Table 2

Primary controlled factors and levels

	Factors					Unit	Range	Number of levels
1	Motion							
1.1		Direction				deg		1
1.2		Speed				m/s	1 - 2.4	8
2	Attitude							
2.1		Pitch angle				deg	0 - 15	5
2.2		Hydroplane angle				deg	0 - 15	
3	Model							
3.1		Size	Scaling				fixed	1
3.2		Shape						
3.2.1			Bare hull				fixed	1
3.2.2			Fins				0 - 4	3
3.2.3			Detail					
3.2.3.1				Baseline				
3.2.3.1.1					Number			16
3.2.3.1.2					Shape			9
3.2.3.1.3					Size			1
3.2.3.1.4					Position			4
3.2.3.2				Mission				
3.2.3.2.1					Number			5
3.2.3.2.2					Shape			5
3.2.3.2.3					Size			3
3.2.3.2.4					Position			17
3.2.3.3				Wear and Tear				
3.2.3.3.1					Number			3
3.2.3.3.2					Shape			6
3.2.3.3.3					Size			3
3.2.3.3.4					Position			4

Even with this restricted number of levels a complete exploration of all of the factors at all levels would take in excess of 10^{10} runs. Clearly this is impractical, even for the simplest experiment. The nature of the measurement of drag (to be done here in a towing tank) is such that the data accumulation rate is low and it utilises scarce and expensive resources. This severely restricts the scope and number of measurements that can be made. The total experimental programme therefore needs careful designed to limit it to a few hundred runs.

The overt intention is to capture the effects of complexity. It is necessary to be able to describe the performance of the range of configurations. Although knowledge of the physics involved is necessary to design the experiment, a full understanding of all of the interactions is not required at this stage. A primarily statistical and descriptive approach is therefore taken. Because of the complexity of the real vehicle, and the limited number of runs feasible for any realistic experiment, careful selection of the combinations of levels for each factor for each experiment is required. As a result of the large number of factors involved, the experiment may well expose unexpected interactions between factors. The experiments are, therefore, designed based on the experience of those fields of science that habitually deal with complexity and uncertainty in their experiments: those of the life sciences [8, 9], and those associated with quality assurance (QA) [10-12]. A body of knowledge has been developed for these fields that enables the relationships between significant numbers of factors to be established in the presence of unknown, and possibly many, uncontrolled or uncontrollable factors, and unknown interactions between the controlled factors.

The experiment under consideration here has similar characteristics to those designed for QA and life sciences in that it involves many factors at many potential levels. However it differs in some key aspects. The characteristics of the experiments for which designs are proposed in the literature were developed for two main classes of work:

- Biological or agricultural experiments, where the aim is to quantify repeatability. The number of controlled factors is chosen to be low, but the number of uncontrolled factors may be high. Interaction between factors is unknown and may be significant. The time required to produce data can be long, but large numbers of data samples may be generated relatively cheaply.
- Experiments to improve the quality of mass-produced components, where the aim is to identify the causes of critical differences in performance between nominally identical items. Again the number of uncontrolled factors can be high, but the number of samples taken can be large.

The experimental programme considered here, by contrast, is to provide a means of exploring how the performance of a nominally consistent design changes as the detail of the design varies, both with time, and between missions. To capture the full extent of possible changes to detail, the number of factors is necessarily large and the number of potential levels is high.

The number of samples compared with the extent of the interaction surface being explored is therefore likely to be significantly smaller than would be expected in the other disciplines.

On the other hand, it should be possible by careful design of the apparatus, to ensure that the statistical variability between measurements is comparatively small. Additionally it should be possible to characterise the residual noise so that it can be identified as such.

The instinctive reaction to the need for any scientific exploration is to maintain maximum control by changing, so far as possible, only one parameter at a time. This is done on the assumption that the accuracy of the measurement may otherwise be degraded by unforeseen interference. However, this approach is very expensive in terms of the number of measurements required and enables only a limited amount of information to be extracted from the data.

Equation (2) gives the minimum number of experiments (n_{min}) that measures the effect of all combinations of levels (l) and factors (f) by varying one at a time.

$$n_{min} = (l)^{f} \qquad (2)$$

Taguchi [11] and others have demonstrated that, provided two conditions for the experiments are met, more than one factor may safely be varied between measurements. With this approach, the investigation of systems of considerable complexity, involving many parameters changing simultaneously, becomes feasible. The method also makes it possible to estimate, not only the effect of each factor in isolation, but, under defined conditions, the effect of the interactions between factors.

The two necessary conditions for varying factors between measurements are:

- That each level for each factor is measured an equal number of times.
- For each measurement at one level the other factors are represented an equal number of times.

Arranging the factors and levels in the form of an orthogonal array produces such a balance. Arrays that satisfy these conditions have been published by a number of authors [8-12]. These arrays have been formulated to enable balanced factorial experiments to be designed for different numbers of factors and levels. Provided that the there are no systematic errors in the measurement system and that residual errors are normally distributed, the standard statistical descriptors of mean, variance, etc, provide a sound representation of the signal level. Standard regression techniques may then be applied to the results to fit a response surface to the levels and factors.

It is a characteristic of such experiment designs that significant interactions between factors must be foreseen, and additional runs included within the design, to allow the effect of the interactions to be estimated. Any unforeseen interactions will express themselves as additional noise in the measurement. With the number of factors involved it is likely that unforeseen interactions will occur. It is therefore important to design and characterise the measurement system such that this additional noise may be identified.

An example of an experiment designed to examine the effect of in-service damage, using the techniques described and based on an $L_{16}3^4$ array is given in Table 3.

B) Laboratory Equipment

For reasons of availability the drag measurements were undertaken in a towing tank rather than, for example, in a wind tunnel. To accurately reproduce flow effects it was necessary to run the model at representative Reynolds numbers (R_e). A model was therefore designed to a scale that provides R_es representative of operational speeds within the limits of the capability of the towing tank.

A highly linear dynamometer, designed for another series of high accuracy experiments [13] was adapted for use with this model. The dynamometer was designed such that the angle of attack could be adjusted to represent the attitude

Table 3
Experiment to examine the effect of in-service damage

Campaign 2c - Determination of the Effect of In Service Damage on Hull Performance

Factor	Type				Size/shape				Position			
Level	Roughness 1	Channel 2	Spot 3	Annulus/ Hole 4	1	2	3	4	a	b	c	d
Run												
1	*				*				*			
2	*					*				*		
3	*						*				*	
4	*							*				*
5		*			*					*		
6		*				*			*			
7		*					*					*
8		*						*			*	
9			*		*						*	
10			*			*						*
11			*				*		*			
12			*					*		*		
13				*	*							*
14				*		*					*	
15				*			*			*		
16				*				*	*			

adopted by the vehicle in-service. The control surfaces on the model hydroplanes could also be varied. The model and dynamometer are illustrated in Fig. 3. The mounting struts are faired to minimise wave effects and wave cuts are taken so that wave drag may be calculated.

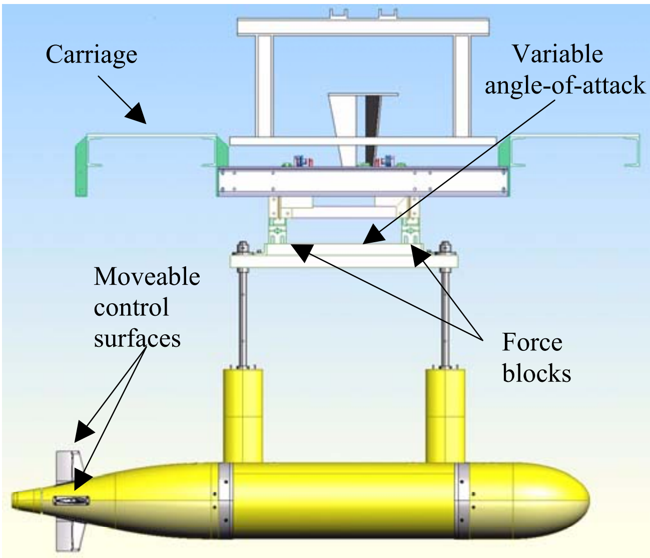

Fig.3. Model and dynamometer attached to towing tank carriage.

Idealised forms may be attached in various combinations, positions and relative positions on the surface of the model to represent services, payload and in-service damage.

The force measurement system has been extensively characterised and residual sources of noise identified, as illustrated in Fig. 4.

VI. TRIALS AT SEA

To complement the laboratory measurements a trial has been designed to allow rapid and inexpensive verification of the propulsion performance of the vehicle in-service. The aim is to enable drag, attitude and hydroplane angle to be ascertained under normal cruising conditions, with no additional on-board or range instrumentation. Attitude and hydroplane angle are readily obtainable from extant on-board sensors, the signals from which are already

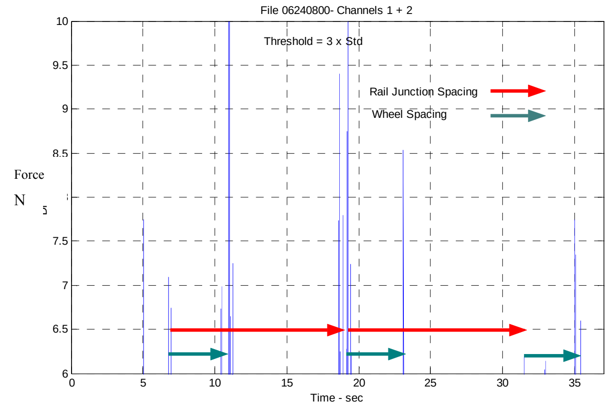

Fig. 4. Force signal noise transients compared with wheel rail events.

recorded in the on-board log. A number of options for determination of drag have been considered including direct measurement by towing the vehicle from an escort vessel and fitting the vehicle with thrust measurement sensors. However, the most attractive is to attempt to derive the force from measurements of the vehicle's dynamics.

Under steady state conditions (no linear or angular accelerations) the thrust force from the propeller exactly balances the total drag forces. On removal of the thrust the vehicle will decelerate under the influence of the drag force (F_d). The equation of motion describing forward velocity (u) as a function of time (t) under these conditions is:

$$F_d(t) = \frac{d}{dt}(m_t u) \tag{2}$$

Now the effective inertial mass, m_t, is a function of the mass of the vehicle, m_v, the mass of the entrained water, m_e, and the added mass resulting from the vehicles deceleration, m_a, (3).

$$m_t = m_v + m_e + m_a\,. \tag{3}$$

The vehicle is powered by primary cells and so no exchange of mass across the vehicle boundary occurs as a result of energy consumption. It is assumed that very little exchange of water occurs between that entrained in the vehicle and the outside world. m_v is therefore constant over the deceleration period. m_t may therefore be considered to be its displacement mass, m_d, which, assuming the vehicle to be neutrally buoyant, is given by:

$$m_d = m_v + m_e \,, \tag{4}$$

that is,

$$m_d = v\rho_{sw}(T) \,. \tag{5}$$

Where v is the volume of the vehicle and $\rho_{sw}(T)$ is the density of seawater at the prevailing temperature.

Added mass is solely a function of the size and shape of the vehicle and may be measured on the scale model in the towing tank. It may also be estimated since the hull of a typical AUV may be considered to approximate to a prolate spheroid. For surge acceleration, i.e. in the direction of the principal axis the added mass of a prolate spheroid is given by:

$$m_a = \frac{4}{3}\pi\rho a b^2 m_x \,, \tag{6}$$

where a and b are the radii along the major and minor axes, and the factor m_x for the AUTOSUB dimensions can be estimated using Bishop and Price [14] as 0.04.

Thus, since all of the mass terms may be considered constant for the period of the experiment, at the measured velocity, u,

$$F_d(t) = (v\rho_{sw}(T) + m_a)\frac{d}{dt}u \,. \tag{7}$$

The drag coefficient for the vehicle can then be determined from:

$$C_d(t) = \frac{F_d(t)}{\frac{1}{2}\rho_{sw}u^2(t)s} \tag{8}$$

where s is a term representing the surface area of the vehicle.

Thus

$$\frac{du}{dt} = C_d\frac{u^2(t)}{k} \tag{9}$$

where

$$k = \frac{2(v\rho_{sw}(T) + m_a)}{\rho_{sw}s} \,. \tag{10}$$

If we assume C_d is a constant over a small range of u, then a plot of $\frac{du}{dt}$ against u^2 should have a linear slope of $\frac{C_d}{k}$.

The depth and temperature at which the experiment takes place is available from standard on-board sensors and hence the density of seawater, ρ_{sw}, may be established. The vehicle's surface area, s, may be calculated. Hence from measurements of velocity at small time intervals, F_d and C_d may be calculated.

Because of the apparent simplicity and low cost of this approach it was chosen for initial trials. The resultant specification for the trial is given in Fig. 5 and the results in Fig 6, where the term 'Bin' refers to the range bin of the on-board acoustic Doppler log.

The results of the single trial undertaken to date have been limited by a paucity of useable data. This has been due to the low (2s) data rate of the acoustic Doppler log, the high incidence of data loss within the data logger, and the detailed design of the trial, which allowed insufficient time for transients to decay. All of these are easily remedied. Nevertheless the method has been demonstrated and a description of the propulsion performance of the vehicle in-service obtained.

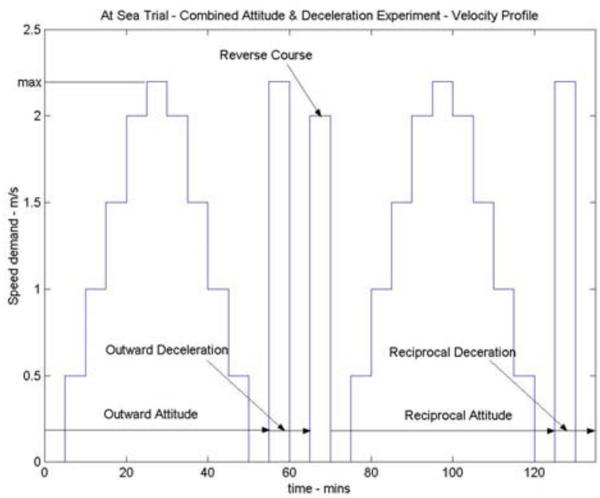

Fig. 5. Trial Specification.

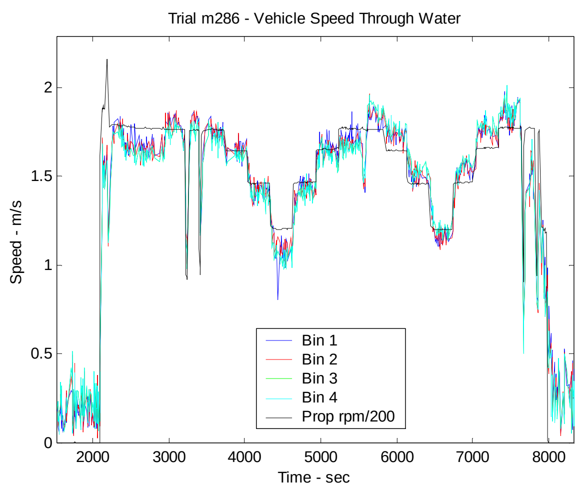

Fig. 6. Speed by bin

VII. CONCLUSIONS

The nature of AUVs is that they are range limited. New designs incorporating new technologies should enable future generations of vehicle to perform better than current AUVs. However there remains scope to build on existing investment by careful optimisation of extant propulsion systems through the application of systems engineering methods. This paper has outlined a means of achieving this.

Complex systems seldom perform in service as forecast during development. Formal analysis of the system may be used to identify the sources of performance shortfall and establish where resources should be devoted. Often discrepancies between forecast and actual performance occur because of simplifying assumptions necessarily made at the design stage. Much of the scope for in-service improvement, therefore, results from taking account of the true complexity of the system under consideration. In taking account of this complexity, physical modelling is indispensable. Accepting complexity implies accepting that a large number of factors are likely to affect the key performance parameters. Methods for designing experiments that can determine the effect of a large number of factors and their interactions, within an affordable number of measurements, have been described.

An advantage of undertaking system engineering on an in-service vehicle is that the vehicle itself can be used to verify performance predictions. A simple and economic method of assessing in-service propulsion performance based on the analysis of readily obtainable data has been described. In particular a method of determining the drag coefficient from velocity data has been derived and demonstrated.

Once the tools described here have been developed for a particular design of vehicle, they can be used to promote continuous improvement in propulsion system performance. By supporting in-service vehicles in this way normal through life performance degradation can be ameliorated.

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