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Dynamics and Control Simulator for the Theseus AUV

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ABSTRACT

A nonlinear, 6 degree-of-freedom maneuvering dynamics and control simulator for the Theseus autonomous underwater vehicle (AUV) has been validated against several sets of full scale trials and independent predictive methods. The vehicle hydrodynamic coefficients are estimated with standard theoretical and empirical methods augmented with towing tank test results. The control algorithm implemented in the simulator is the same as the one used in the actual vehicle. A propulsion model makes it possible to optimize vehicle range and transit speeds as the battery capacity changes during the mission. The simulated vehicle response compares well against full scale sea trials data. The paper discusses the simulator validation and its use for vehicle design and mission applications.

1.0 INTRODUCTION

In 1992, Defence Research Establishment Pacific (now amalgamated with Defence Research Establishment Atlantic (DREA)) contracted ISE Research Ltd. (ISER) to build an AUV capable of laying cable under Arctic ice. ISER designed and built the Theseus AUV shown in Figure 1 for a 450 km range, a cruising speed of 2 m/s, a working depth of 1000 m, and with variable ballast tanks fore and aft. With a 2.44 m long by 1.12 m diameter payload bay and additional ballast tanks to correct for deploying cable, Theseus can lay up to 220 km of fiber-optic cable in its current configuration. The vehicle has a modular design for ease of transport, fault-tolerant control software, navigational accuracy to better than 0.5% of distance traveled (cross track error is much better), acoustic and fiber-optic telemetry systems, and terminal acoustic homing (Ferguson et al, 1995).

In April 1995, Theseus went on its first Arctic mission in the ice covered waters off Ellesmere Island, Canada. The successful trial verified launch and recovery procedures, tested all vehicle systems in an under-ice environment (navigation, telemetry, cable deployment, etc.), and led to refined techniques for delivering fibre-optic cable under the ice. Four dives accumulated 13 km of under-ice distance traveled and laid 9 km of fiber-optic cable.

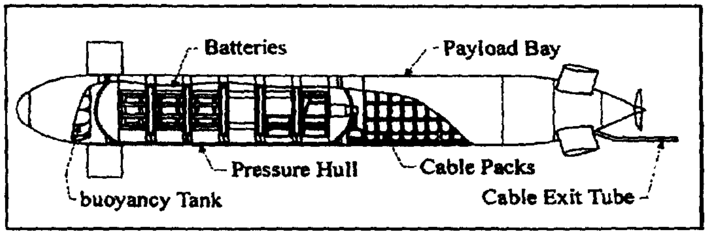

Figure 1: The Theseus AUV is 10.5 m long, 1.3 m diameter, displaces 119 kN, and has a 5 kW electric propulsion motor

In April 1996 at Alert, Canada, Theseus met its operational objectives and laid 175 km of cable. The AUV was deployed through a 2 m by 13 m hole in the 1.7 m thick ice, traversed at depths of up to 425 m, delivered the other end of the fiber optic cable by flying through a 200 m loop suspended from the ice surface and returned to the launch site (Ferguson et al, 1999). The vehicle was autonomous for all of the 54 hour, 350 km round trip except when delivering the far end of the cable, when manual control of the vehicle via this same cable was used. This experience, which spans design, construction, and operations, has shown that judicious use of vehicle dynamics and control models can contribute to many stages of the development process. The models are valuable tools for:

- vehicle hullform and control algorithm design;
- testing old and developing new maneuvers;
- evaluating vehicle responses;
- determining how top speed, endurance, battery power, and propulsion requirements can be met,
- experimenting with ballast compensation strategies to address payload changes during a mission;
- analyzing navigational schemes,
- investigating emergency scenarios, and
- minimizing costly sea trial time.

However, these models need to be validated to be of practical use. ISER has been collaborating with DREA to develop and validate vehicle dynamics models for several years (Seto et al, 1998, 1999). This paper documents our experience with the newly developed AUV simulator SIMAUV and the Theseus vehicle.

2 0 MODELING AUV DYNAMICS AND CONTROL

Dynamics

The SIMAUV simulator is built around the equations of motion for a deeply submerged underwater vehicle (Feldman, 1979) These are six, second order, nonlinear, ordinary differential equations, one for each degree-of-freedom. Control surface deflections, propulsion, variable ballast, and steady and unsteady hydrodynamic effects are modeled in the applied force terms on the right hand sides of these equations. The hydrodynamic forces are described using derivatives based on in-house DREA empirical and theoretical methods (Watt, 1988, Watt et al, 1997), augmented with plane control derivatives obtained from 1/4 scale model towing tank tests at the Institute for Marine Dynamics, St John's, Newfoundland (1993). Over 55 hydrodynamic derivatives are used in the equations of motion. SIMAUV integrates these equations to generate the 6 degrees-of-freedom time domain response to vehicle commands

Control and Navigation

Theseus has two forward hydroplanes and four tail hydroplanes in the 'X' configuration. All planes are individually controlled and actuated. There are three operational modes that represent three distributions of control authority among the hydroplanes. The mode used for the trials we are concerned with uses bow planes for depth and roll control and the aft planes for pitch and yaw control. In the other available modes, depth, pitch, and roll control are handled by a mixture of bow and aft planes, providing greater effectiveness and/or redundancy at the expense of complexity.

Theseus has closed-loop proportional, integral, and differential (PID) control for depth, pitch, roll, and yaw Speed over ground, additionally, has feed forward control. The control algorithm determines the control surface / propeller rpm set points based on feedback vehicle attitudes and set points. The control surface / propeller rpm time responses to set points are modelled by linear, second order, ordinary differential equations Control surface response damping, frequency, and maximum rate inputs, together with initial conditions, determine a unique response (Watt, 1990)

The AUV control surface set points determined by the PID and feed forward controller in the vehicle control computer, are modeled as:

$$\{\delta\} = [G]\{\delta Y\} + [I]\{\delta Y_{ss}\} + [F]\{\delta Y_{sp}\}$$

where:

$\{\delta\}$	vector of control surface set points;
$[G]$	feedback matrix (P, D gains);
$[I]$	integral matrix (I gains),
$[F]$	feed forward matrix (F gains),
$\{\delta Y\}$	AUV state vector (yaw, pitch, roll, yaw rate, pitch rate, roll rate, depth, depth rate);
$\{\delta Y_{ss}\}$	steady state error vector, and
$\{\delta Y_{sp}\}$	commanded state set point vector.

Theseus has three navigation modes. It can be flown by the pilot, given a heading setpoint, or flown in waypoint mode. A pilot or heading setpoint is convenient during docking or prior to launch and recovery so the vehicle is under some form of operator control. When autonomous, Theseus navigates in waypoint mode In this mode, a file of geographical positions is specified and Theseus attempts to fly straight line paths joining them. This is easily implemented in SIMAUV as part of the closed-loop control for the vehicle 'rudder'.

Propulsion

A propulsion model was required to properly model vehicle steady state speed under various loads, and speed changes during maneuvers in which both vehicle drag and propeller inflow change. This model will eventually be used in optimizing mission power usage profiles given an initial battery charge.

To meet these requirements, it was necessary to model propeller thrust and torque as a function of rpm, vehicle speed and load, and onset crossflow angle Propeller crossflow effects are estimated from wind tunnel experiments with a powered submarine model (Watt, 1993). The time response of the electric motor to commanded rpm changes is modelled with a second order ordinary differential equation, and rpm is limited to that achievable (based on the motor's maximum torque output of 30 N m between 0 and 1500 rpm). A similar model was successfully used for the DOLPHIN semi-submersible (Seto et. al., 1999). For Theseus, however, no wake survey or definitive open water propeller thrust and torque characteristics were available. These were estimated using empirical relations and trials results.

A conventional propeller/hull interaction hydrodynamics model is used (Lewis, 1988) Thrust deduction and wake fraction are estimated using empirical fits (Brockett, 1998) to data presented by Barr (1974).

The propeller manufacturer suggested a Wageningen B-screw series propeller open water thrust and torque model (Carlton, 1994) as being representative of propeller performance. This was checked using the above hull interaction coefficients and steady, level flight propulsion data obtained from Theseus trials in Indian Arm, B.C. in 1994. These data, the suggested B-screw model, and the actual B-screw model used for thrust and torque are shown in Figure 2. The best-fit B-screw model was obtained by increasing the specified pitch to diameter ratio of the blades by 6%, an amount consistent with the level of manufacturing error to be expected in either blade pitch or camber.

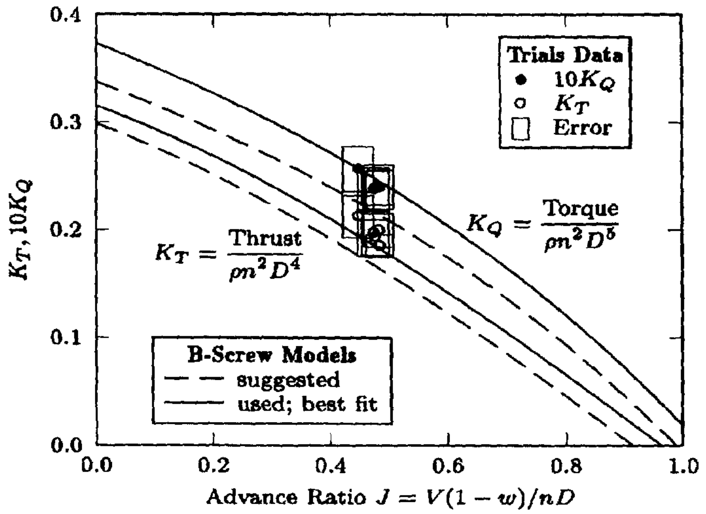

Figure 2: Propeller open water thrust and torque coefficients. The trials data show one standard deviation of measurement error. V is vehicle speed; w is the Taylor wake fraction, n is propeller revolutions per second; D is propeller diameter.

Vehicle drag was estimated using 1996 Theseus trials data for steady, level flight conditions with no additional load on the vehicle. This provided self-propulsion data which, using the above propulsion model, allowed drag to be extracted.

Model Interface

The SIMAUV interface is structured so a general AUV is easily modelled using separate input files specifying the hydrodynamic characteristics, vehicle control algorithm, propulsion, and static weight and variable ballast characteristics. A separate input file describes the AUV mission profile: the vehicle attitude and speed setpoints, flight path, navigational modes, ballast commands, and more.

3.0 MODEL BUILDING AND VALIDATION

The simulation model is built from and validated against AUV attitude, depth, and speed for given vehicle flight path, depth, roll, pitch, and speed over ground/propeller speed setpoints. These responses are compared against those measured during the following Theseus full scale sea trials:

- 1994 Indian Arm, B.C. Propulsion trials,
- 1995 Indian Arm, B.C. Maneuvering trials , and
- 1996 Nanoose, B C. Endurance trials

In propulsion trials, propeller speed setpoints are issued instead of speed over ground, and speed through water is logged. In maneuvering trials, vehicle attitude and planes' setpoints and feedbacks are logged; closed-loop speed over ground control is used and logged. In both types of trials, the AUV communicates to the support ship through either radio telemetry or a fiber-optic umbilical via a float. The wire used in both cases can affect the vehicle while underway. For example, during propulsion trials, the antenna float generates enough of its own drag that it is difficult to determine what the true vehicle drag and speed through water would have been without the wire. The 1996 Nanoose Endurance trials provide a set of conditions for overall validation of the model with closed-loop control on speed over ground and navigation through waypoint mode as in operations. There was no vehicle trailing wire during the Nanoose Endurance trials, so the straight and level flight runs from these trials were used to establish the self-propulsion characteristics required in the last section.

It is important to differentiate between model building and validation. Theseus straight and level flight runs from the 1994 and, to a lesser extent, the 1996 trials have been used for model building. There is no validation value in making further comparisons with the 1994 data, and only partial value in looking at the 1996 straight and level flight runs. The main SIMAUV validation is established through comparisons with the 1995 Maneuvering trials.

4.0 RESULTS

The Level Flight Case

It is worth comparing the propulsion model under level flight, steady state conditions to the 1996 Nanoose Endurance trials. During most of these trials Theseus was running at depth with closed-loop control on speed over ground. The speed and propeller rpm were recorded along with other pertinent vehicle states, such as attitude. The speed over ground controller uses feed forward on the speed setpoint to determine the propeller rpm. Minor fluctuations from the speed set point are addressed through a PID controller.

SIMAUV simulates these runs by using the operational set points for speed over ground, depth, and ballast from the trials. Table 1 summarizes the comparison for the 1.5 and 2 m/s speed set points used during these trials. The trials data are subject to measurement error which are noted, whereas SIMAUV is not. Currents of as much as 0. m/s may be present so that speed over ground is not necessarily spee through water; however, current effects are averaged out in the dat shown which are from 80 runs of over 20 minutes each going in many directions. The vehicle speed and propeller rpm (two independent quantities in the propulsion model) achieved by SIMAUV are within one standard deviation of the data. As discussed earlier, the 1996 data were used to establish vehicle drag (a single independent quantity in the propulsion model) and so the good agreement with both speed and rpm provides some validation value.

Table 1: Comparison between trials data and SIMAUV predictions in level flight

	speed achieved (m/s)		propeller speed (rpm)		AUV pitch (degrees)	
speed (m/s)	trials	SIMAUV	trials	SIMAUV	trials	SIMAUV
1.5	1.534 ± 0.04	1.506	173.9 ± 2.1	175.47	-2.08 ± 0.12	-0.224
2.0	2.064 ± 0.04	2.024	230.2 ± 2.1	232.99	-0.90 ± 0.18	-0.118

Pitch discrepancies between the trials and SIMAUV of 1 to 2 degrees are seen in Table 1 and in the remainder of the comparisons in this paper. This is attributed to a static weight trim offset in the trials not modelled in SIMAUV. This can be seen by the fact that the pitch offset gets closer to zero in Table 1 as the speed increases. The pitch control model is set to correct one degree of pitch with a preset virtual 'sternplane' deflection, regardless of speed, so this corrective action is more effective as speed increases. If the pitch offset was hydrodynamic in origin, the offset would not decrease with speed as all hydrodynamic forces scale the same with speed. In practice, the PID plane gains are not set high enough to fully zero the vehicle pitch as high gains can be destabilizing in some situations.

Maneuvering

An important maneuvering requirement is that Theseus dive and climb at reasonable rates with acceptable pitch stability. The contents of the fore and aft ballast tanks were recorded during the 1995 Maneuvering trials, as well as plane deflections and vehicle attitudes. This information allows the vertical plane dynamics of the vehicle to be validated.

The maneuver consists of level flight at 5 m depth, a dive to 15 m, maintain depth, then a climb to 5 m. The dive rate is determined by the time it takes to go from 6 to 12 m depth. Similarly, the climb rate was determined by the time to go from 12 to 6 m depth. The dive and climb trajectories were also calculated between the 6 and 12 m levels. Table 2 shows generally good agreement between the dive and climb rates and trajectories. The last two rows in Table 2 compare transient quantities which are always more difficult to model. The discrepancies here, especially for the maximum climb pitch angle, are again speed dependent and it is likely the trim offset influenced the trials results.

Figure 3 shows a combined vertical and horizontal plane maneuver, all of which took place at a speed set point of 2 m/s. The first 200 seconds of the maneuver is an example of the dive and climb maneuver just discussed (see Figure 3(e))

Table 2 Comparison of SIMAUV predictions against 1995 Theseus Maneuvering Trials data

quantity	1.5 m/s		2.0 m/s		2.3 m/s	
	trials	SIMAUV	trials	SIMAUV	trials	SIMAUV
max dive rate (m/s)	-0.07	-0.08	-0.17	-0.18	-0.23	-0.21
max climb rate (m/s)	0.23	0.23	0.26	0.25	0.32	0.29
dive trajectory (deg)	-2.7	-3.05	-4.7	-5.04	-5.8	-5.12
climb trajectory (deg)	8.4	7.99	7.1	6.50	7.7	6.73
max transient dive pitch (deg)	-4.0	-3.38	-2.5	-3.21	-3.0	-3.19
max transient climb pitch (deg)	0.0	3.90	1.5	3.42	2.0	3.36

In the 1995 Maneuvering trials, speed control was achieved using speed over ground and so minor discrepancies between the SIMAUV predictions and trials data are inevitable if the vehicle is in a current Ambient currents are unknown and cannot be modelled by SIMAUV Consequently, small misalignments exist between events in the trials data and SIMAUV predictions. This is especially evident in the horizontal plane maneuvering validation, as seen in the last 200 seconds of Figure 3(a).

Horizontal plane turn comparisons between the data and SIMAUV predictions take place in Figure 3 following the 200 second time stamp

In Figure 3(b), Theseus starts at (0,0), executes the dive and climb maneuver at a constant heading, and then makes a starboard followed by a port turn. For the maneuvering trials, the absolute position of the vehicle was not logged, only the vehicle heading, so the trials flight shown has been reconstructed from the logged heading and speed over ground. This reconstructed flight path was used to create input 'waypoints' for SIMAUV Therefore, the good comparison between the trials and SIMAUV flight path simply shows that SIMAUV can follow way point instructions well.

Figures 3(a) and 3(c) show the vehicle speed over ground and propeller speed achieved given the 2.0 m/s speed over ground setpoint. The predicted speeds are within 5% of the trials results. The agreement during the turns is also good. The agreement for the mean propeller rpm (Figure 1(c)) is quite good, but SIMAUV underpredicts the unsteady rpm level. Overall, the agreement for the vehicle propulsion model is acceptable

SIMAUV does a good job of modelling the dive and climb rates, as shown in Figure 3(e) The pitch comparison (Figure 3(d)) is acceptable and again shows the 1 degree pitch offset

As with pitch, the trials roll angle (Figure 3(f)) is offset from the SIMAUV predictions. SIMAUV itself predicts a roll angle offset; this is the result of propeller torque (which by itself would roll Theseus about 1.5 degrees) being only partially neutralized by the roll control planes. The larger offset in the trials results is mainly attributed to a laterally displaced center of gravity not modelled by SIMAUV, but may also reflect a difference in roll control effectiveness.

Both the pitch and roll trials measurements have larger high frequency component amplitudes than SIMAUV. Improving the damping and natural frequency parameter values in the planes control system model may improve this comparison.

5.0 CONCLUDING REMARKS

This paper documents the validation of the six degree-of-freedom AUV maneuvering simulator SIMAUV with the ISER/DREA Theseus vehicle. Several sets of full scale sea trials were used to validate the SIMAUV predictions against measured vehicle performance for hydrodynamics, controls, navigation, maneuvering, and propulsion. The trials and SIMAUV predictions generally compared well.

A comprehensive vehicle propulsion model accounts for the closed-loop speed over ground control, power plant response, powering, and vehicle/propeller wake interactions This makes it possible to examine AUV navigational accuracy and power consumption through additional modelling of the on-board sensors and energy sources This work is scheduled for future SIMAUV development.

SIMAUV is a tool for vehicle design and development intended to complement full scale sea trials and wind tunnel/tow tank model tests.

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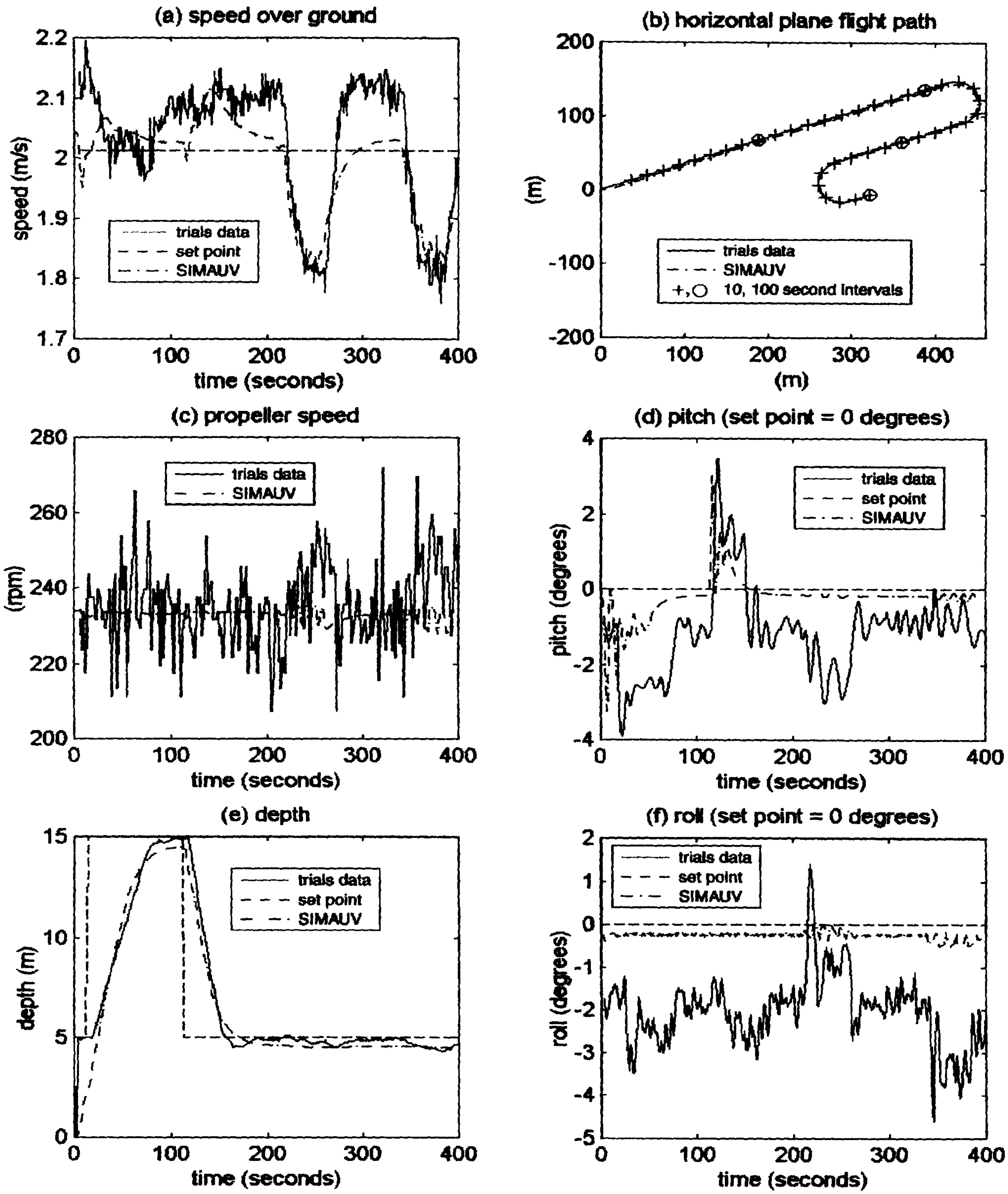

Figure 3: Comparison of SIMAUV predictions and trials data against common set points

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