USING MODELING AND SIMULATION TO DEVELOP THE AUTONOMOUS MOBILE PERISCOPE SYSTEM (AMPS)

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Abstract

The Navy's Pacific Missile Range Facility (PMRF) at Barking Sands Kauai Hawaii initiated a unique development program to enhance and expand the facility's capabilities for Navy training and research, development, testing, and evaluation (RDT&E). PMRF teamed with the Naval Surface Warfare Center Carderock Division (NSWCCD) to design and construct an autonomous submersible for periscope detection training. Extensive computer simulations and scale model testing were utilized to reduce both technical risk and overall development cost. The result of this successful effort is the Autonomous Mobile Periscope System (AMPS).

AMPS is an autonomous underwater vehicle (AUV) that presents the above water portion of a periscope to augment radar and visual detection RDT&E and training of anti-submarine warfare crews. During development, extensive 3-D dynamic simulations were performed to analyze the hydrodynamic design, the signal processing design, the motion control design, and the servo control design. Upon completion of the preliminary full-scale design effort, a 0.29 scale model basin evaluation was conducted to verify hydrodynamics, signal processing and motion control. The model incorporated the same inertial measurement unit (IMU) used in the full scale vehicle and was operated in simulated state 3 head and following seas. Good correlation between predicted performance and basin evaluation results led to the completion of the full scale design and fabrication, operational testing in the basin and the Chesapeake Bay, and finally, acceptance testing in November 1999 at the PMRF acoustic range off the coast of Kauai, Hawaii.

This paper will discuss the use of simulations and modeling as design and development tools to reduce technical risk and overall cost for this Navy project. The paper will conclude that computer simulations and scale modeling are effective tools to reduce risk and cost of new development efforts.

Introduction

The use of models is inherent in design. In fact, the use of models for experimentation, displaying of solutions and checking of spatial conditions is fundamental in industrial development. The development of craftsmanship was hampered by the fact that experimentation was carried out on actual constructions and not on models. Rapid industrial development occurred when the use of drawings and other inexpensive representations of the actual constructions which could be used for experimentation were introduced[1].

Modeling and simulation have long been used to analyze and reduce system risk. Risk in prototype system development includes technical risk, financial risk, operational risk and safety risk. The principle contribution of risk analysis is to focus the decision maker's attention on understanding the nature and extent of the uncertainty associated with some variables used in a decision-making process. Risk analysis incorporates uncertainty in the decision input data. With such inputs, the system response is then found by simulation. The decision maker not only has probabilistic information about the system response to uncertain input but also gains knowledge about the variability of such estimates as measured by the system response in the simulation. Both the expectation and its variability are important decision criteria in the evaluation of the project[2].

There are two main types of models, those that are physical representations of the system and those that are an abstract representation.

Physical models provide physical representation of a system and typically fall into two groups, drawings and scale models. Drawings can be used for displaying solutions, for example, a general arrangement. They can serve as the basis for estimating weights, areas, volumes, centers of gravity and the amount of material that will be needed. They can also serve for production planning and fabrication[3]. Scale Models can be used to test and display solutions and determine engineering values for which mathematical models are either too complex, unknown or whose accuracy is not validated.

Abstract models do not directly depict actual constructions. Mathematical models are one of the most common abstract models. Other abstract models include diagrams, straightforward calculation, flow charts and simulation models.

Simulation models are used to simulate randomness and uncertainty, either of nature, for example weather, or time required for man-controlled operations. Simulation models are used when design conditions become so complicated that it is no longer practical or possible to develop deterministic calculation models.[3] Computers are most commonly used when the response of a system is dependent on random or spectrum input.

The Autonomous Mobile Periscope System (AMPS) project was joint effort by the Pacific Missile Range Facility (PMRF) and the Naval Surface Warfare Center Carderock Division (NSWCCD). The project incorporated abstract, simulation and physical modeling during its development process as a means of risk and cost reduction. This paper emphasizes the importance of modeling and simulation on the successful implementation of AMPS design.

Background

AMPS was created to provide an inexpensive, mobile, and realistic diesel submarine periscope target for visual and radar detection training, research, development, testing, and evaluation. It is an autonomous vehicle which presents a simulated above water portion of an attack periscope with a realistic cross section, material, and size.

Once the decision was made to proceed with the design and fabrication of AMPS, a process was set in place for the effort. From an engineering design and fabrication prospective, the process of prototype development is fairly straightforward. The objective is defined, specific system requirements and goals are set, an initial concept is developed, and a preliminary design is established. While some prototype development teams proceed directly from the design phase to the build phase, the AMPS team included a modeling and simulation phase. Modeling, simulation, and analysis were used to optimize the preliminary designs and to validate the computer models before going into full-scale design and fabrication. Once the system was fabricated and checked out, testing was conducted to verify that the system objectives were met. With a validated computer model, the impact of upgrades and modifications can be accurately evaluated. Fig. 1 describes this process in flow chart form.

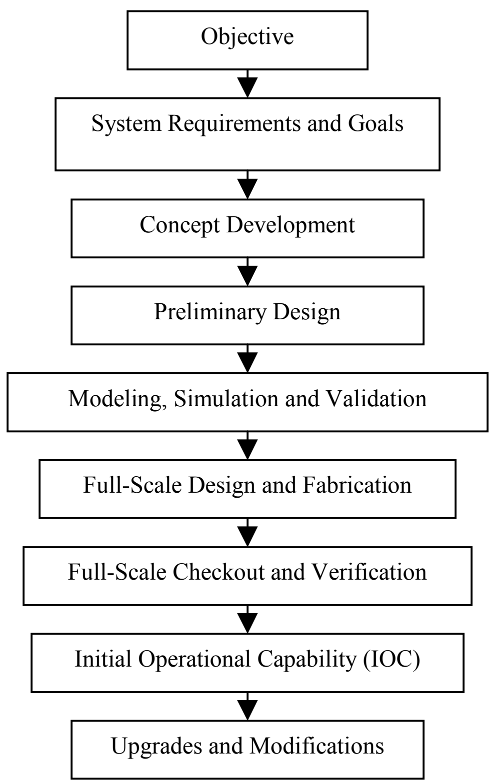

Fig. 1. Typical Prototype Development Process Flow Chart

AMPS Background

AMPS began with a PMRF objective to present the above water portion of an attack periscope as a radar and visual target for training anti-submarine warfare crews. The target was to have similar speeds and motions as a full-scale submarine's periscope. Performance, endurance, and handling were key issues to the overall design. Also considered were cost and schedule. Due to an extremely limited budget and development schedule, extensive development time and costs were not acceptable. Computer simulation and model scale testing were heavily relied upon to meet the program budget and schedule requirements.

The primary requirement of the AMPS is the realistic radar and visual presentation of a periscope target to train ASW crews. The periscope needed to be correct in size, shape, and material for an appropriate radar reflection and water surface scar. System requirements were developed with respect to this and are listed in Table 1 along with the resulting final full-scale results.

Parameter	Specification	Comment	Final Results
Environmental			
Operational Sea State	3	Wind speed of 15 kn	3+
Retrieval Sea State	4	Wind speed of 20 kn	3+
Performance			
Maximum speed	5 kn	In zero current	5 kn
Mast exposure	5 ft	In calm water	5 ft
Max. heave amplitude	1 ft	State 3 sea	1 ft (approx)
Heave amplitude (swells)	Swell amplitude	Long period swells	Swell amplitude
Pitch / Roll amplitude	±10 deg	Maximum 90% of time	± 3 deg
Endurance	2 hr	5 hr goal*	6 hr *
Survival depth	600 ft		600 ft (calculated)
Handling			
Support craft	Weapons Recovery Boat	Minimal modifications	WRB (no modifications)
Vehicle			
Max. in-air weight	3500 lb		3600 lb
Maximum length	30 ft		26.5 ft
Radio transmit range	2 miles	15 miles desired	11 miles
Battery recharge time	24 hrs	10 hrs desired	6 hrs
* 1/3 of operation time at periscope depth and 2/3 of operation time at submerged depth with mast retrieved.			

Table 1. Established AMPS operational requirements and final results.

Establishment of the system requirements led the way to writing the baseline functional, operational, and equipment specification which was used to establish design, interface, vehicle commands, handling, safety, and deliverables for the AMPS system. This document was constantly referred to throughout the project for decision guidance.

Once the general concept was chosen, conceptual design efforts were initiated. Concept development efforts established basic performance goals and sufficient analysis was performed to determine general physical parameters. Size, power sources, hydrodynamics, control system volume, and propulsor power requirements were analyzed. The final results indicated that a 24 in. diameter vehicle approximately 26 ft in length powered by sixteen 24-Volt Nickel-Cadmium (NiCd) batteries would be the design direction.

Preliminary development carried the concept to a level of detail sufficient to specify vehicle components and arrangements. During preliminary design, working-level drawings were produced; design analyses were conducted; baseline motion control software was developed; and signal level simulation and bench testing of control hardware and software were performed. Fig. 2 shows the overall dimensions of the vehicle.

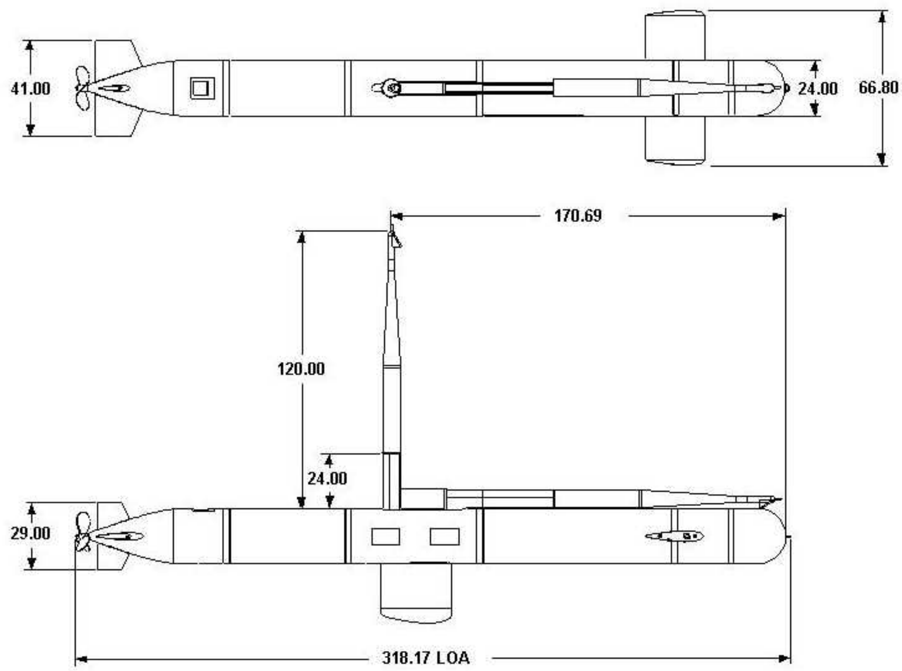

Fig. 2. Plan and side view of the AMPS vehicle (dimensions in inches).

Modeling, Simulation and Verification

Cost and risk reduction led to extensive dynamic simulation of the vehicle and its response to various sea conditions and commands. A simplified diagram of signal flow through the AMPS motion control processing loop is depicted in Fig. 3. The high-level external commands to the vehicle motion controller are defined by the mission requirements. The commands required are: (1) heading and (2) depth. Other commands are available. In fact, each control feedback loop has an implied command (currently set to zero except heading and depth).

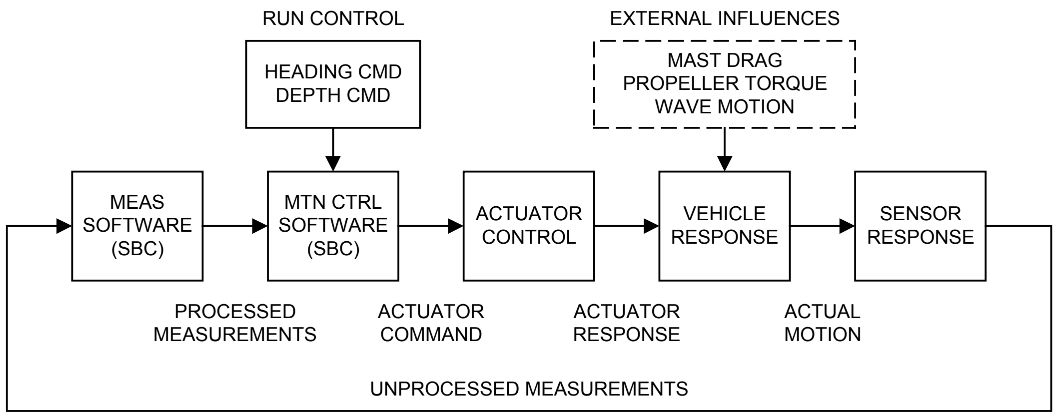

Fig. 3. Motion control signal process loop.

The task of the measurement software is to process vehicle motion measurements into signals required by the control software. This includes conversion of measured signals into derived quantities as well as filtering of signals as necessary.

The fundamental purpose of the control software in AMPS is to develop actuator commands that ultimately will maintain the commanded heading and depth and will minimize vehicle roll, pitch, and heave motions induced by external influences such as waves. The control software receives the processed motion signals from the measurement software and acts upon the values in a way specified by the control logic. Final output from the control block is actuator position command.

The actuator block receives the actuator command from the control software. The actuator has its own closed-loop position controller that requires measurement of actuator angle. The output of the actuator block is the achieved control-surface deflection. Each control surface on the AMPS vehicle has its own set of control software and its own actuator control.

Deflections of the control surfaces produce forces and moments that cause the vehicle to counteract unwanted external forces and also to respond to heading and depth change commands. Vehicle response depends on the dynamics of the control deflections, the hydrodynamic properties of the vehicle, and the characteristics of the external disturbances.

The motion sensors onboard the vehicle measure the vehicle response and send the measurement signals to the measurement software for processing. The sensors required depend upon the control feedback loops. Signals coming from the sensors differ from the actual motion depending on sensor bandwidth, noise, biases, and quantization.

FORTRAN dynamic models were developed to simulate each of the signal process blocks shown in Fig. 3. A non-linear, six-degree-of-freedom, time domain simulation was utilized to model vehicle hydrodynamics.[4] The model is based on the DTMB Standard Equations of Motion for submarine simulation.[5] In these equations, vehicle inertial and hydrodynamic force and moments are represented by non-dimensional coefficients of the various motion variables. The AMPS dynamic model also includes the effects of a surface-piercing mast and a seaway. The seaway is modeled by a Pierson-Moskowitz[6] energy spectrum superimposed on a single-frequency wave swell. Thirty wave components typically were used to represent the seaway.

Non-linear hydrodynamic coefficients for the AMPS vehicle were estimated using an extension of methods described by Knutson.[7] These methods calculate potential-flow forces primarily. However, the viscous effects of fuselage afterbody separation, fuselage cross-flow separation, and lifting-surface tip flow also are approximated.

Actual software, later converted to ANCI-C and used directly in the vehicle, was developed to represent the measurement and control blocks in the simulation model. A second-order actuator model was implemented to quantify dynamic actuator response including closed-loop bandwidth (time delays), effective damping, peak rate, and mechanical backlash. Models also were developed to simulate sensor response. The sensor models included the effects of measurement range, dynamic response, noise, and quantization. Ultimately, the integration of these simulation models allowed a time-efficient examination of all of the physical and control characteristics that affect vehicle dynamic performance.

Multiple simulation runs were performed to examine vehicle response to systematic variations of each of the parameters listed in Table 2. As a result, well-defined specifications and criteria were developed early in the design phase for vehicle and control-surface geometry; sensor performance; signal processing design; control architecture and feed-back gains; and servo control requirements. A dynamic heave rate compensator also was developed and checked with the simulation. The heave compensator is a bandpass filter that allows the vehicle to consistently expose the mast when operating in the large swells often present in Hawaii but minimizes the heave motions induced by the shorter-period sea spectrum. An example of a time history response predicted by the simulation is shown in Fig. 4.

A 0.29 scale model was evaluated in calm water and waves in the Deep Water Towing Basin of the David Taylor Model Basin, Fig. 5 and Fig. 6. To further reduce risk, the model incorporated the full-scale AMPS inertial measurement unit (IMU) and control architecture with closed-loop depth, roll, and pitch control. Heading and speed were operated manually. Test results verified the hydrodynamic design and had good correlation with the dynamic simulation results. Control system performance was successful in all tested conditions.

Hydrodynamic	Signal Processing	Motion Control	Servo Control
1. Geometric design 2. Mast water surface penetration 3. Drag 4. Stability 5. Control authority 6. Trim 7. Maneuverability 8. Open-loop seaway response (frequency/time domain)	1. Sensor range 2. Sensor accuracy 3. Signal analog filter design 4. A-D conversion (digitizing, resolution) 5. Derivation of state variables (roll, pitch, heave rate, heave) 6. Digital bias filter gains 7. Signal phase shift 8. Signal noise	1. Architecture 2. Feedback parameters 3. Feedback gains 4. Motion error integration 5. Limiters 6. Dynamic heave compensation 7. Closed-loop seaway response (frequency/time domain) 8. Heading control 9. Dive transients	1. Drive friction 2. Drive inertia 3. Angular rate requirement 4. Torque requirement (static/dynamic) 5. Frequency bandwidth requirement 6. Mechanical backlash

Table 2. AMPS dynamic simulation parameters.

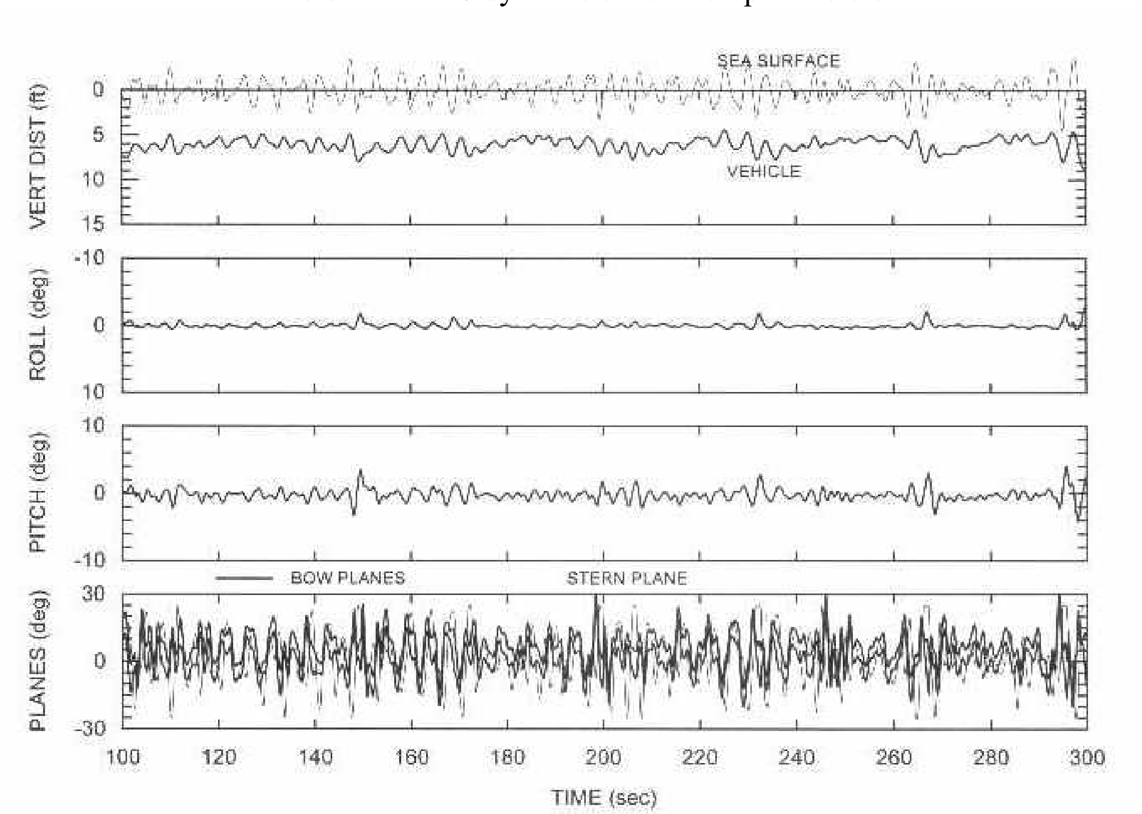

Fig. 4. Sample time history output of selected data from AMPS dynamic simulation for a speed of 5 kn and state 3 head sea run.

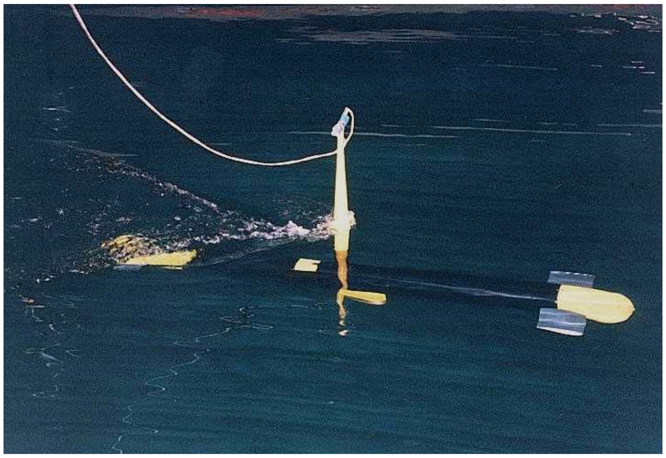

Fig. 5. AMPS 0.29 scale model operating in simulated following seas in the David Taylor Model Basin (DTMB).

Fig. 6. AMPS model test run preparation in DTMB.

Control System

The Control and Data Acquisition System (CDAS) monitors and controls vehicle operation using an array of engineering sensors. Control software processes the sensor information and provides command input to the servo actuators and the propulsor. The AMPS control system is comprised of the Run, Motion and Speed Control sub-systems.

A block diagram illustrating run control is shown in Fig. 7. The vehicle is controlled primarily by the pre-programmed run text file downloaded into the CDAS IDE drive by the Test Set PC prior to the run. The file contains all of the information necessary to command the vehicle. Each line in the file is considered a waypoint. Parameters specified for each waypoint include:

⇒ Command waypoint coordinates (lat / long)
⇒ Pre-calculated command heading (deg) and duration (sec) between successive waypoint coordinates
⇒ Command speed (kn)
⇒ Command depth (periscope / submerged)
⇒ Command mast status (folded / raised)

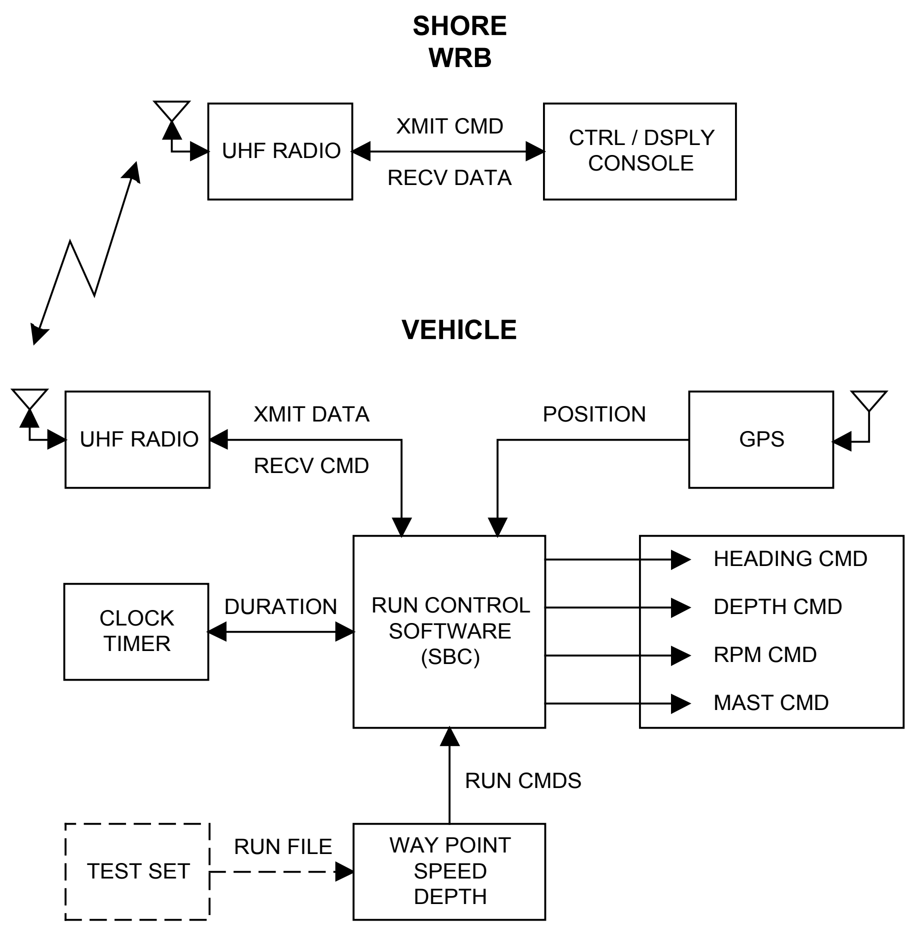

Fig. 7. Run Control Signal Process.

The run-control software reads the run command information from the file. The primary parameters needed for run navigation are command heading, duration, speed, and depth. At periscope depth, the control program uses the GPS measured position at the beginning of a segment and the segment command speed to calculate the command heading and duration to reach the waypoint at the end of the segment. When the calculated duration has expired, the program performs new calculations for the next waypoint. If GPS data are not available (for example, when the mast is submerged), the program uses the pre-calculated command heading and duration from the file.

The vehicle run must be started by the shore-side Control/Display Console (or by the WRB Test Set) through the UHF communications link and can be altered in several ways. Commands that can be transmitted to the vehicle by the Console include:

⇒ START - Needed to start the run.
⇒ EOR - Ends the run.
⇒ SECURE - Folds the mast and retracts the keel for recovery onto the WRB. SECURE cannot be activated before EOR.
⇒ IDLE - Causes the vehicle to stop and wait for further command.

⇒ RESUME - Continues the run from the point at which it was stopped.

⇒ TRANSIT - Allows the vehicle to transit (at 4 kn periscope depth) to a new location. The run will start over at the new location by commanding RESUME.

A block diagram illustrating vehicle speed control is shown in Fig. 7. Vehicle speed is controlled by open-loop commanded propeller RPM. The speed control software converts command speed (knots) from the run file to command propeller RPM via a calibrated proportionality factor. The servo controller uses measured RPM as the feedback parameter to control motor speed.

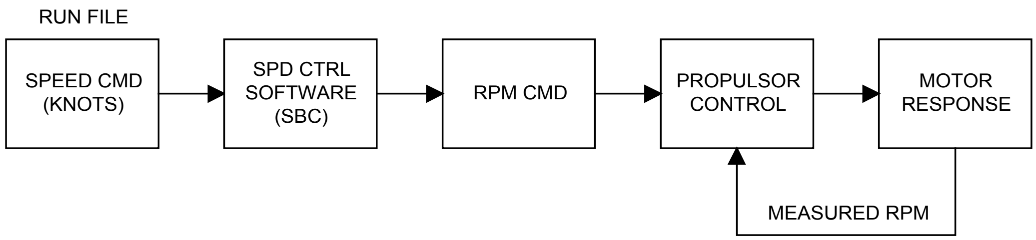

Fig. 8. Speed Control Signal Process.

The control planes provide vehicle stability and motion control. The bow-plane surfaces move independently to control both vertical-plane motions and roll. The stern-plane surfaces (port/starboard) and the rudder surfaces (upper/lower) move in unison. Large-size bow plane and stern plane surfaces are required to overcome a substantial pitching moment indices by mast drag, to negate a large induced propeller torque and to overcome vehicle buoyancy at low speeds. Seaway response is influenced both by total control authority and by vehicle dynamic stability. All-movable control surfaces and large deflection angles are utilized to maximize control authority.

Command heading and depth from the vehicle run-control software specify the motion control set points. The motion-control software compares vehicle motions to command motions to derive command control-surface angles. Processed digital signals roll, pitch, roll rate, pitch rate, yaw rate, heave rate, heading and depth are all used as feedback parameters by the motion control software. The heave-rate control block is designed to minimize heave response in local wind-generated waves but to allow the vehicle to follow large, low-frequency swells. To perform this function, processed heave rate is shaped by a dynamic compensator before entering into the motion-control software.

The motion-control software is organized in a parallel structure without inner loops. Limiters are utilized at strategic locations to prevent saturation of the control during stressing situations such as a command depth change. Final control-surface command angle is limited to a safe value below the mechanical limit. Integrators are used in the depth-control block and the roll-control block to negate offset errors that would otherwise result due to mast drag, propeller torque and vehicle net buoyancy.

Full-Scale Verification

The full-scale design finalized the vehicle mechanical, electronic, and software designs as well as handling, shore side interface and ship and shore support systems. An exploded view of the vehicle and its major components is shown in Fig. 9.

Full-scale performance was demonstrated throughout the design and fabrication process through laboratory checks and proof tests. Prior to at-sea testing and initial operational capability, 37.5 hours of static in-water endurance testing was completed in the Deep Water Towing Basin dry-dock. During this test propeller speed was set to simulate loading corresponding to 5 knots, and the control surfaces were commanded to move continually in a sinusoidal motion. The mast was deployed and retrieved every 5 minutes throughout the test with mast drag approximated. Preliminary operational tests were then conducted in the Chesapeake Bay, Annapolis, Maryland.

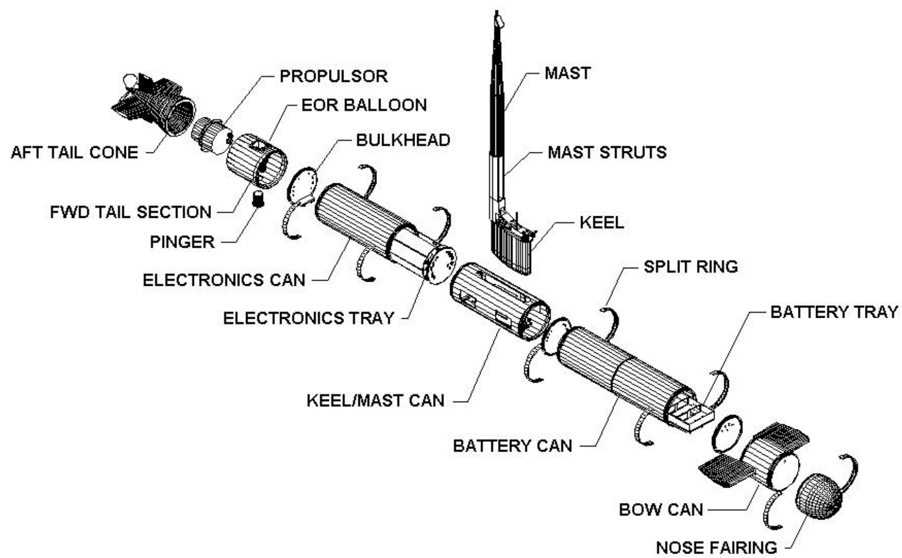

Fig. 9. Exploded view of the AMPS vehicle.

All aspects of full-scale vehicle performance with the exception of radio range, underwater acoustic tracking, submerged operations, and in situ handling with the support boat were tested.

AMPS acceptance testing was started during the full-scale development with a series of proof tests designed to validate performance per specified requirements. However, final acceptance required full operations at PMRF. Checkout runs and tests were initially conducted outside the acoustic ranges to check vehicle performance and train local personnel in handling, operating, and maintaining the vehicle. Final acceptance testing was successfully conducted on the acoustic ranges at PMRF, Fig. 11. A representative sample of vehicle performance in a state 3 sea observed during testing at PMRF is illustrated in Fig. 10. Vehicle motion is easily within the performance requirement specified by Table 1.

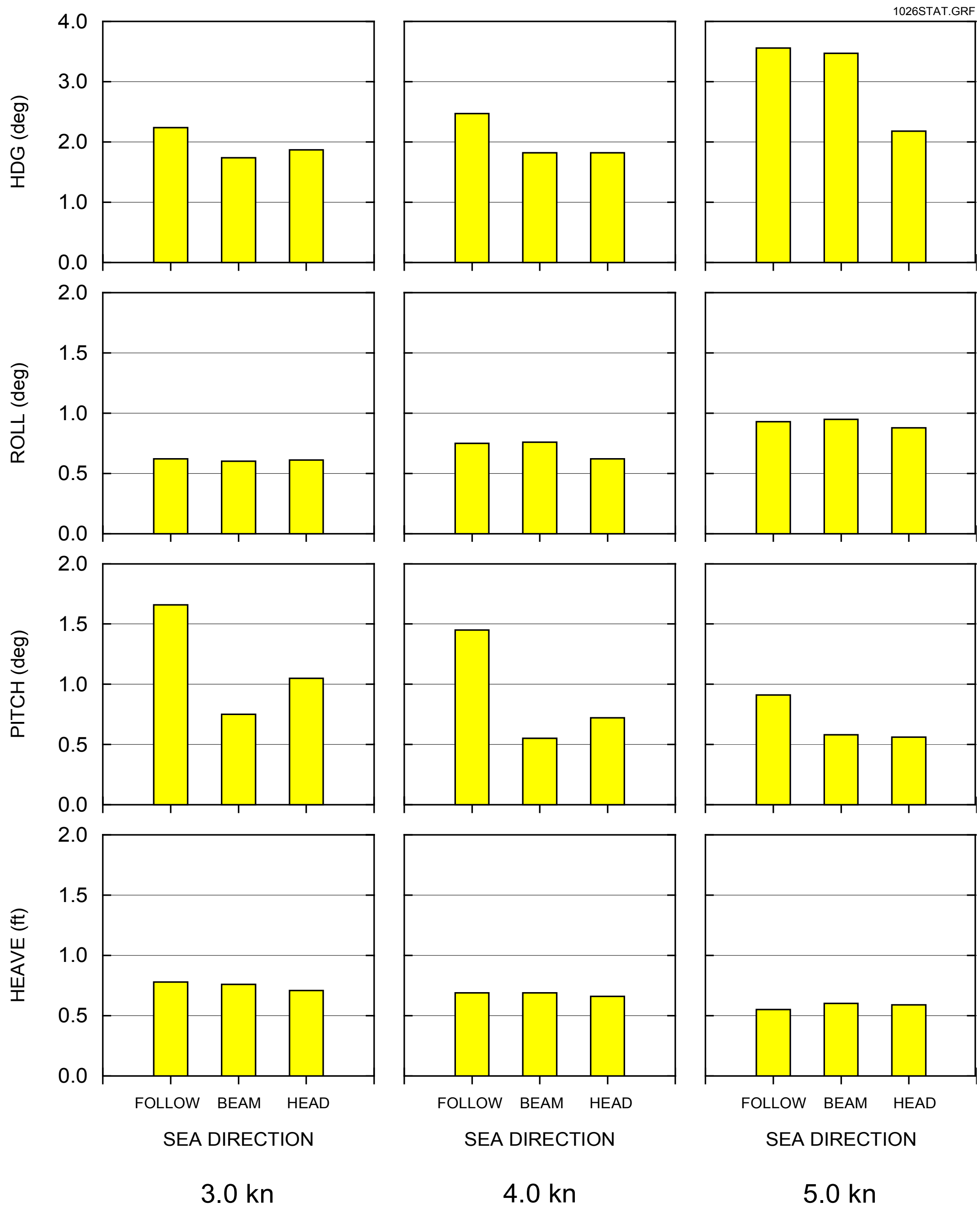

Fig. 10. Motion standard deviation at periscope depth (measured significant wave height = 4.4 ft).

Since acceptance testing, several AMPS operations have been conducted in which AMPS has been tracked by helicopter, aircraft and surface ship ASW crews. NSWCCD continues to provide support for AMPS operations until PMRF personnel are fully familiar with operational and maintenance procedures.

Fig. 11. AMPS acceptance testing on the acoustic ranges at PMRF, Kauai, Hawaii.

Conclusion

This paper has presented a process for developing full-scale prototype systems in a cost-effective manner with reduced technical and financial risk by using modeling and simulations.

The use of modeling and simulation in the AMPS project was critical to the design process. The hydrodynamic design was evaluated with simulation and scale model testing prior to full-scale fabrication thus reducing design risk and potential redisign/modification costs. Additionally, simulation efforts provided information for control architecture and component specifications (i.e. sensor range, accuracy and allowable signal noise; servo control frequiencty bandwidth requirements; control surface angluar rate requirements, drive friction, and backlash effects). It was also used as a tool to check control gain settings and their effects prior to and during testing, thus reducing iterations of control tests and testing risks. Overall, project costs were reduced due to extensive 3-D dynamic simulation for design analysis which reduced design iterations and reduced model and full-scale development iterations. Successful acceptance tests and continued operations of AMPS after a 3 year development effort and minimal budget attests to the risk reuduction, cost and time savings that can be achieved with extensive simulation, proper design processes, and comprehensive testing.

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