IX. EXPERIMENTAL RESULTS

A. INTRODUCTION

Experimental testing is essential to producing realistic response in a virtual world. Real world behavior can be predicted and analyzed in the laboratory by running tests which exercise all vehicle systems, and by reproducing mission scenarios which are used in the real world. Since no such thing as a completely benign AUV test environment exists in the real world, laboratory virtual world testing is essential and can overcome impediments associated with the use of tethers and acoustic telemetry. Repeatability of results and statistical control of sensor errors enable tests and machine learning algorithms which are not feasible in the real world. Duplication of at-sea test results in the laboratory can serve as validation of virtual world functionality, at least as is seen from a robot perspective.

An extended laboratory test mission is examined to illustrate how hydrodynamics response is highly complex and requires detailed analysis. Network response is also evaluated for several experiments that utilized the Internet-wide Multicast Backbone (MBone). Network parameters of greatest interest are temporal latency, bandwidth requirements, and suitability for large-scale distributed simulation.

B. PREDICTING AND ANALYZING REAL-WORLD BEHAVIOR IN THE LABORATORY

The key to producing reliable robot software is repeated testing. There are many reasons why risk-free end-to-end testing of all systems aboard an AUV is rarely possible. Leaks can occur in shallow or deep water. Vehicle hydrodynamics response is complex and is also crucial to understanding physical behavior. The many effects involved in underwater motion make accurate posture response an essential prerequisite for meaningful testing of vehicle control algorithms and intelligent control architectures. Underwater vehicles contain too many fragile components to "navigate by collision" as some indoor robots do. Underwater sonar range sensors do not operate in air. Underwater vehicles are usually very heavy, and test stand mountings with multiple degrees of freedom are impractical.

Repeated testing using a tether for remote monitoring and emergency intervention is an effective test technique when preparing for open-ocean autonomous missions (Brancart 94) (Pappas 91). Unfortunately tethers induce significant drag effects, and tether management either requires very expensive tether control systems or continuous human supervision. Acoustic telemetry can free the vehicle from these impediments, but acoustic communications are always prey to intermittent loss due to factors such as multipath arrival, masking, attenuation, and sound wave propagation away from source or receiver. Deployment and recovery of vehicles in the water is always costly and time-consuming, limiting the scope of test programs. In-water results are usually nonrepeatable due to changing conditions or lack of time. This inability to reliably repeat tests on demand greatly complicates software engineering tasks such as debugging, algorithm tuning, and logic verification.

Laboratory testing using a virtual world can produce repeatable results that are based on realistic hydrodynamics response and realistic sonar predictions. Laboratory tests can attempt to replicate in-water results as a means of tuning models to more accurately represent the real world. Since a virtual world includes everything normally detectable by the robot in the real world, a virtual world can be validated by identical robot operation in identical scenarios in either world. In a sense this serves as a kind of Turing test for the virtual world: if robot operation is identical in the real world and the virtual world, then the virtual world is functionally equivalent to the real world. In practice, small differences are usually expected which always need to be fed back into tuning virtual world component models more exactly. Note that the sophistication of this approach will likely lead to more rigorous consideration of interactions among multiple models which is impossible using standalone simulations.

As virtual world component models become more reliable and robust, vehicle deviations from predicted behavior in the real world will be less frequent. A robot can be programmed to recognize and measure such deviations, eventually automating many details regarding model error detection and correction. Embedding virtual world models as predictors in robot control logic will lead to robust failure diagnosis and correction schemes, perhaps coupled with machine learning techniques for greater generality.

A significant advantage of laboratory testing over real world testing is the ability to eliminate or statistically control error deviations in sensor measurements. Usually robot designers need first to test their programs under perfect conditions to demonstrate correctness, and then test again under error-prone conditions to demonstrate robustness. Setting error distributions of sonars or inertial measurement devices permits statistical analysis of arbitrary measures of effectiveness (MOEs) for large numbers of replications. Such testing is useful for determining overall system effectiveness over a range of operating conditions, and also enables machine learning techniques based on massive repetitive training.

Validation and verification of underwater virtual world models for dynamics and sonar needs to be an ongoing part of any AUV research and development program. The complexity and subtlety of these large models means that multiple effects may contribute to a given response, and any change to a hydrodynamic coefficient may ripple through the model with unexpected side effects. A set of standardized vehicle missions and documented responses needs to be duplicated and compared in the virtual world whenever such model changes occur. This process also is a likely candidate for automation as model reliability improves.

Verification Validation and Accreditation (VV & A) is a set of methodologies concerned with showing that simulation models are correct representations of reality. Some key terms follow:

- *Verification*: Substantiation that the computer program implementation of a conceptual model is correct and performs as intended. (Kneppell 93)

- *Validation*: Substantiation that a computer model, within its domain of applicability, possesses a satisfactory range of accuracy consistent with the intended application of the model. (Kneppell 93)
- *Accreditation*: official determination that the model and program are valid enough.

Confidence assessments can be performed to assess the credibility of a simulation. Detailed methodologies have been developed for conducting such assessments (Kneppel 93) (Law, Kelton 91). All aspects of a simulation are evaluated including level of detail, scope of intended use, fidelity, granularity, data verification, constraining assumptions and model validity. Concerns specific to hardware-in-the-loop simulations include timing constraints, information exchange and system integration. While operational tests are considered to be of greatest importance in validation and verification, overall confidence assessments remain a value judgement determined by extensive evaluation of all aspects of a simulation. As with many software engineering practices, formal approaches to verification and validation are of greatest value in ensuring correct design and implementation. Accreditation is expected to be a future issue for models and virtual worlds used by the U.S. Department of Defense (DoD), but current accreditation policies are immature and not applicable to this project. Recommended future work for this and other virtual worlds is performance of a formal independent validation and verification confidence assessment in accordance with (Kneppel 93). Such an assessment might uncover inadvertently-missing virtual world components, and can also help establish a rigorous theoretical definition of the formal requirements needed for globally networked large-scale virtual worlds.

C. SIMULATION RUN ANALYSIS: ***mission.script.siggraph***

A great number of execution level mission scripts have been developed to test the many facets of the hydrodynamics model. There is a rich set of execution level script commands available, any of which can be provided via command file *mission.script* or by the user via keyboard. The execution level script command language is also designed to serve as application communications protocol between the real-time execution level and supervising tactical level. Syntax of the script command language appears in (Brutzman 94e). In general these simple commands are similar to those which might be given by a diving officer on a submarine, with the addition of waypoint following and hovering behaviors.

Comprehensive analysis of numerous detailed hydrodynamics variable plots is difficult to perform but remains essential when verifying quantitative robot and model performance. However, intuitive observation and qualitative evaluation of missions is not possible without a 3D real-time graphics viewer. The value of such a viewer cannot be overemphasized. Subtle (and occasionally gross) vehicle events are often not noticeable on the telemetry plots until the user recognition has been cued by the graphics viewer. In most work on hydrodynamics, plots are the only way to formally evaluate performance. Plots still serve an essential function in qualitative analysis, but integration of a live 3D real-time viewer means that users are no longer required to mentally integrate dozens of temporal response curves while attempting to visualize true vehicle behavior.

The most comprehensive robot hydrodynamics test provided in this work is the "SIGGRAPH" mission file (*mission.script.siggraph*), which was used repeatedly during the presentation of the underwater virtual world at the SIGGRAPH 94 conference (Brutzman 94b). The mission script appears in Figure 9.1. A time log of mission output orders appears in Figure 9.2. Twenty plots examining vehicle-environment hydrodynamic interaction follow (Figure 9.3 through Figure 9.22). These plots are automatically produced from robot mission telemetry and can be generated for any robot mission (Brutzman 94e). Essentially these plots show the temporal relationships among three dozen key hydrodynamic variables throughout a mission. A large number of additional test missions focused on specific robot-environment interactions are provided with the underwater virtual world distribution (Brutzman 94e). The SIGGRAPH mission vehicle behavior plots which follow have been manually verified using hydrodynamics coefficients and similar test results produced by earlier NPS AUV hydrodynamics theses (Warner 91) (Bahrke 92) (Torsiello 94).

```
# ,,,,
# Hello SIGGRAPH!
# ,,,,

# This is a mission
script
# for the
# N P S Autonomous
Underwater Vehicle
# ,,,,

# your mission is
# siggraph test

#
mission.script.siggraph

# ,,,,
# we are having some
fun!

# ,,,,
# Graphics rendering
uses Open Inventor
# from Silicon Graphics
,,, S G I
# ,,,,

# D I S multicast
version 2 0 3
# from the
# Naval Postgraduate
School
# ,,,,

# initialize vehiCle

position    0 0 0

orientation 0 0 0

# reset dynamics clock
time        0

thrusters-on

# propellers off
rpm       0

course  000
depth     0

wait      1

# going deep
# with thrusters
depth    45

# here we go!
wait     20
```

```
# still going deep
wait     20

# almost there, hang on
wait     25

# at depth
# change course

course  090
wait     10

# stabilizing depth
# during course change
wait     10

# lateral thruster
control

lateral   2
# feet per second
wait      3  seconds

lateral  -2
# feet per second
wait      3

lateral   0
# no more lateral
movement

RUDDER    0

heading  20
wait 5

# propellers on
rpm      400
wait       4

# aim for the window
course   005
rpm      700
wait       9

# building up speed
course   000
wait      11.3

depth     48.2
course   270
wait      26

course   180
wait      10

thrusters-off
# going shallow
# with propellers
```

```
depth      4
wait       5

# vehicle hydrodynamics
are
# coupled in six degrees
of freedom
wait       5

# please note that
# vehicle instability
# is very possible
# ,,,,

wait      10

# rudder spiral
rudder   -12
wait      10

# wow this is hard!
# ,,,,
wait      10

# we are spiraling up to
the surface
wait      23

# at the surface
thrusters-on
course   090
wait      10

# moving back above the
pool
wait       8

# we are now stabilizing
rpm     -700
wait      10

# propellers off
rpm        0
wait      10

course     0
hover  0 0 0
wait      81.5

wait       0.1

# A U V is stable at
origin

# time to restart the
mission
# don’t forget to add
your e-mail address

# mission complete
quit
```

Figure 9.1. Canonical execution level mission script: *mission.script.siggraph*

```
# NPS AUV file mission.output.orders: commanded propulsion orders versus time
#
#         timestep:  0.10 seconds
#
# time  heading North East Depth    rpm   rpm    stern  stern   vertical     lateral
#                 x    y     z      port  stbd   plane  rudder  thrusters   thrusters
#                                                               bow/stern   bow/stern

   0.0     0.0   0.0   0.0   0.0    0.0    0.0    0.0    0.0    0.0   0.0   0.0   0.0
   0.0     0.0   0.0   0.0   0.0    0.0    0.0    0.0    0.0    0.0   0.0   0.0   0.0
   1.0     0.0   0.0   0.0  45.0    0.0    0.0    0.0    0.0    0.0   0.0   0.0   0.0
  21.0     0.0   0.0   0.0  45.0    0.0    0.0    0.0    0.0    0.0   0.0   0.0   0.0
  41.0     0.0   0.0   0.0  45.0    0.0    0.0    0.0    0.0    0.0   0.0   0.0   0.0
  66.0    90.0   0.0   0.0  45.0    0.0    0.0    0.0    0.0    0.0   0.0   0.0   0.0
  76.0    90.0   0.0   0.0  45.0    0.0    0.0    0.0    0.0    0.0   0.0   0.0   0.0
  86.0    90.0   0.0   0.0  45.0    0.0    0.0    0.0    0.0    0.0   0.0   0.0   0.0
  89.0    90.0   0.0   0.0  45.0    0.0    0.0    0.0    0.0    0.0   0.0   0.0   0.0
  92.0    20.0   0.0   0.0  45.0    0.0    0.0    0.0    0.0    0.0   0.0   0.0   0.0
  97.0    20.0   0.0   0.0  45.0  400.0  400.0    0.0    0.0    0.0   0.0   0.0   0.0
 101.0     5.0   0.0   0.0  45.0  700.0  700.0    0.0    0.0    0.0   0.0   0.0   0.0
 110.0     0.0   0.0   0.0  45.0  700.0  700.0    0.0    0.0    0.0   0.0   0.0   0.0
 121.3   270.0   0.0   0.0  48.2  700.0  700.0    0.0    0.0    0.0   0.0   0.0   0.0
 147.4   180.0   0.0   0.0  48.2  700.0  700.0    0.0    0.0    0.0   0.0   0.0   0.0
 157.4   180.0   0.0   0.0   4.0  700.0  700.0    0.0    0.0    0.0   0.0   0.0   0.0
 162.4   180.0   0.0   0.0   4.0  700.0  700.0    0.0    0.0    0.0   0.0   0.0   0.0
 167.4   180.0   0.0   0.0   4.0  700.0  700.0    0.0    0.0    0.0   0.0   0.0   0.0
 177.4   180.0   0.0   0.0   4.0  700.0  700.0  -12.0    0.0    0.0   0.0   0.0   0.0
 187.4   180.0   0.0   0.0   4.0  700.0  700.0  -12.0    0.0    0.0   0.0   0.0   0.0
 197.4   180.0   0.0   0.0   4.0  700.0  700.0  -12.0    0.0    0.0   0.0   0.0   0.0
 220.4    90.0   0.0   0.0   4.0  700.0  700.0  -12.0    0.0    0.0   0.0   0.0   0.0
 230.4    90.0   0.0   0.0   4.0  700.0  700.0  -12.0    0.0    0.0   0.0   0.0   0.0
 238.4    90.0   0.0   0.0   4.0 -700.0 -700.0  -12.0    0.0    0.0   0.0   0.0   0.0
 248.4    90.0   0.0   0.0   4.0    0.0    0.0  -12.0    0.0    0.0   0.0   0.0   0.0
 258.4     0.0   0.0   0.0   0.0    0.0    0.0    0.0    0.0    0.0   0.0   0.0   0.0
 258.4     0.0   0.0   0.0   0.0    0.0    0.0    0.0    0.0    0.0   0.0   0.0   0.0
 339.9     0.0   0.0   0.0   0.0    0.0    0.0    0.0    0.0    0.0   0.0   0.0   0.0
 340.1     0.0   0.0   0.0   0.0    0.0    0.0    0.0    0.0    0.0   0.0   0.0   0.0
```

Figure 9.2. Resulting time log of robot mission output orders: *mission.output.orders*

An event-by-event analysis of the SIGGRAPH mission follows in Table 9.1 to identify key relationships and results. This analytical timeline was produced by examining the original mission script Figure 9.1, the condensed mission orders Figure 9.2 and individual hydrodynamics plots (Figure 9.3 through Figure 9.22). Finally graphics images showing vehicle thrusters, propellers and plane surfaces operating simultaneously appear in Figure 9.23 and Figure 9.24. In these figures, green wireframe cones are proportional to the thrust of sea water from the cross-body thrusters and the propellers.

Table 9.1. Timeline Analysis of SIGGRAPH Mission.

time mm:ss	time sec	Analytic results, ordered robot changes and pertinent plots.
0:00	0.0	Initial posture at origin (0, 0, 0) with orientation (0, 0, 0).
0:01	1.0	Behavior stable and unchanging prior to first order. Change depth to 45 ft using vertical thrusters only. Plots 4, 20, 10, 13, 20.
1:16	66.0	At ordered depth, heave rate stabilizing. Change ordered course to right from 000° to 090° using lateral thrusters. Plots 8, 9, 16, 20. Note slight downward pitch angle θ due to coupling with vertical heave velocity rate $\dot{w}$ via coefficient $M_{\dot{w}}$. Plots 6, 7, 15.
1:26	86.0	Reached ordered course 090°. Begin lateral motion to right using lateral thrusters. Plots 2, 12, 16, 20.
1:29	89.0	Reverse lateral thrust to cancel sway velocity $\boldsymbol{v}$. Plots 2, 12, 16, 20.
1:32	92.0	Lateral sway velocity $\boldsymbol{v}$ reduced. Change course to left to 020° using thrusters. Plots 8, 9, 16, 20.
1:37	97.0	Still changing course. Turn on propellers to 400 rpm, enabling rudders and planes. Plots 1, 8, 9, 11, 16, 17, 18, 19, 20.
1:41	101.0	Continue changing course left to 005° for test tank window exit. Forward surge velocity $\boldsymbol{u}$ starting to increase. Plots 1, 8, 9, 11, 16, 17, 18, 19, 20.
1:50	110.0	Continue changing course left to 000° for test tank window exit.
2.01	121.3	Building up speed, ready to maneuver to enter torpedo tube. Come left to course 270°, go down to depth 48.2 ft using propellers, planes and thrusters simultaneously combined. Corresponding graphics images appear in Figure 9.23 and Figure 9.24. Plots 1 through 20.

time mm:ss	**time sec**	**Analytic results, ordered robot changes and pertinent plots.**
2:27	147.4	Torpedo tube transit completed via dead reckoning. Change course to left to 180°. Plots 1, 2, 3, 5, 8, 9, 11, 12, 14, 15, 16, 17, 20.
2:37	157.4	Steady on course, forward surge velocity ***u*** starting to increase. Secure thrusters. Begin going shallow to ordered depth 4 ft using forward momentum, plane surfaces and propellers. Plots 1, 4, 6, 7, 10, 13, 15, 18.
2:57	177.4	While continuing to shallow, begin a spiral to right. Ordered rudder held at -12°. AUV geographic position stays within ordered turning radius during extended depth transient. Changes and interactions are again visible among all hydrodynamics variables. Plots 1 through 20.
3:40	220.4	Near ordered depth just below the surface. Turn on thrusters, resume closed-loop rudder control by ordering course 090°. Head back to origin above the pool. Vehicle roll ***p*** from spiral turn restabilizes with forward motion. Plots 1, 2, 3, 5, 6, 8, 9, 10, 11, 12, 14, 16, 17, 20.
3:58	238.4	Nearing origin, slow and stabilize. Reverse propellers to -400 rpm, reducing forward velocity ***u***. Plots 1, 2, 3, 11, 19.
4:08	248.4	Forward velocity ***u*** almost zero, near origin. Zero propellers, coast, slow due to drag and stabilize. Plots 1, 2, 3, 11, 19.
4:18	258.4	Approximately at origin with small velocities remaining. Change ordered course to 000° and shift to hover mode. New ordered position for hovering is origin, depth 0 ft. Propellers now follow forward/aft position error, all plane surfaces zeroed, vertical thrusters control depth, and lateral thrusters track port/starboard position error. Plots 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 15, 16, 19, 20.
5:50	350.0	Hovering has fully stabilized AUV at origin with zero posture. Mission complete. Plots 1 through 20 stable.

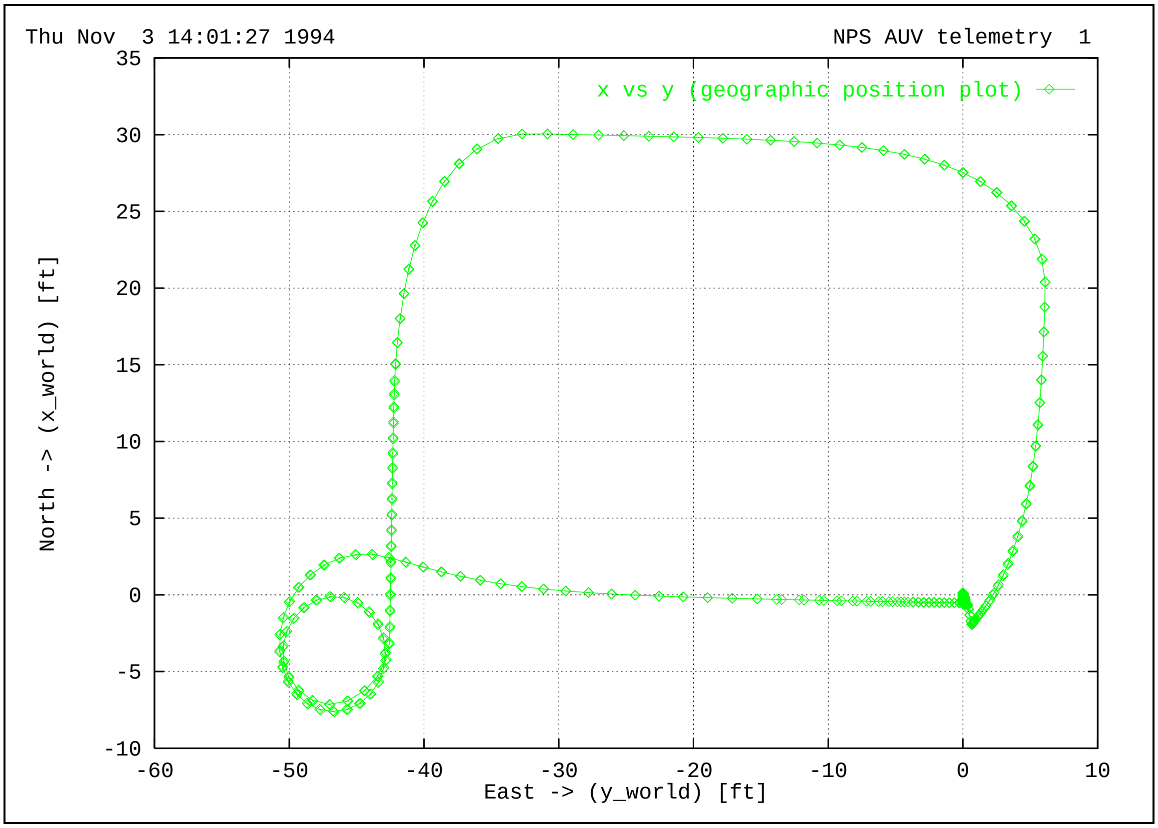

Figure 9.3. Geographic plot (world ***x*** and ***y*** coordinates) of AUV position track.

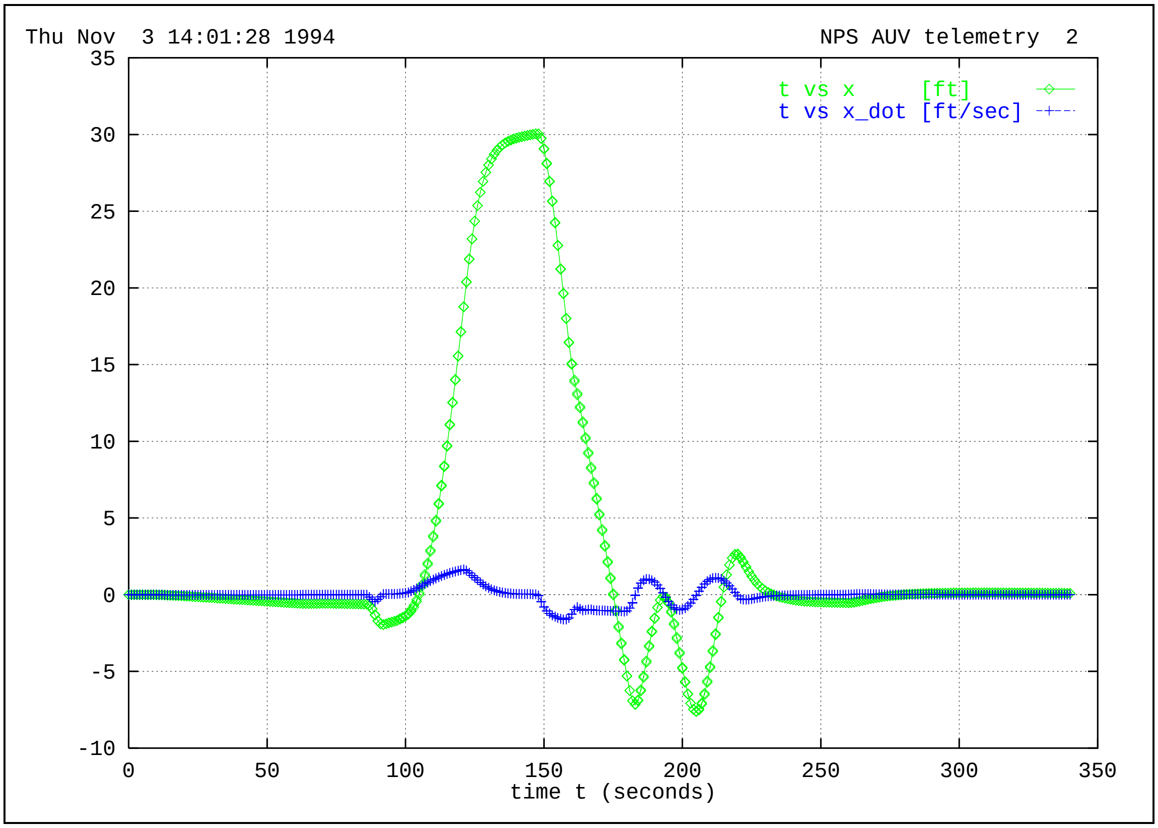

Figure 9.4. World position coordinate ***x*** and derivative versus time ***t***.

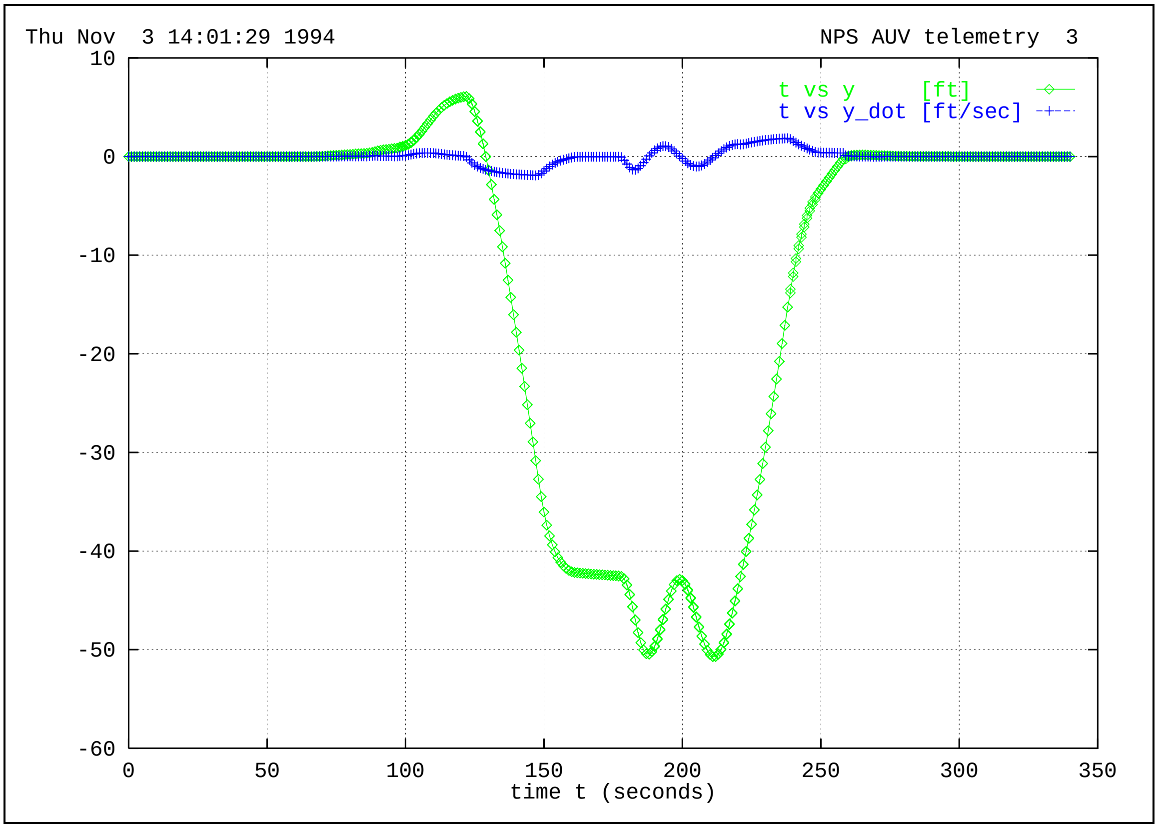

Figure 9.5. World position coordinate ***y*** and derivative versus time ***t***.

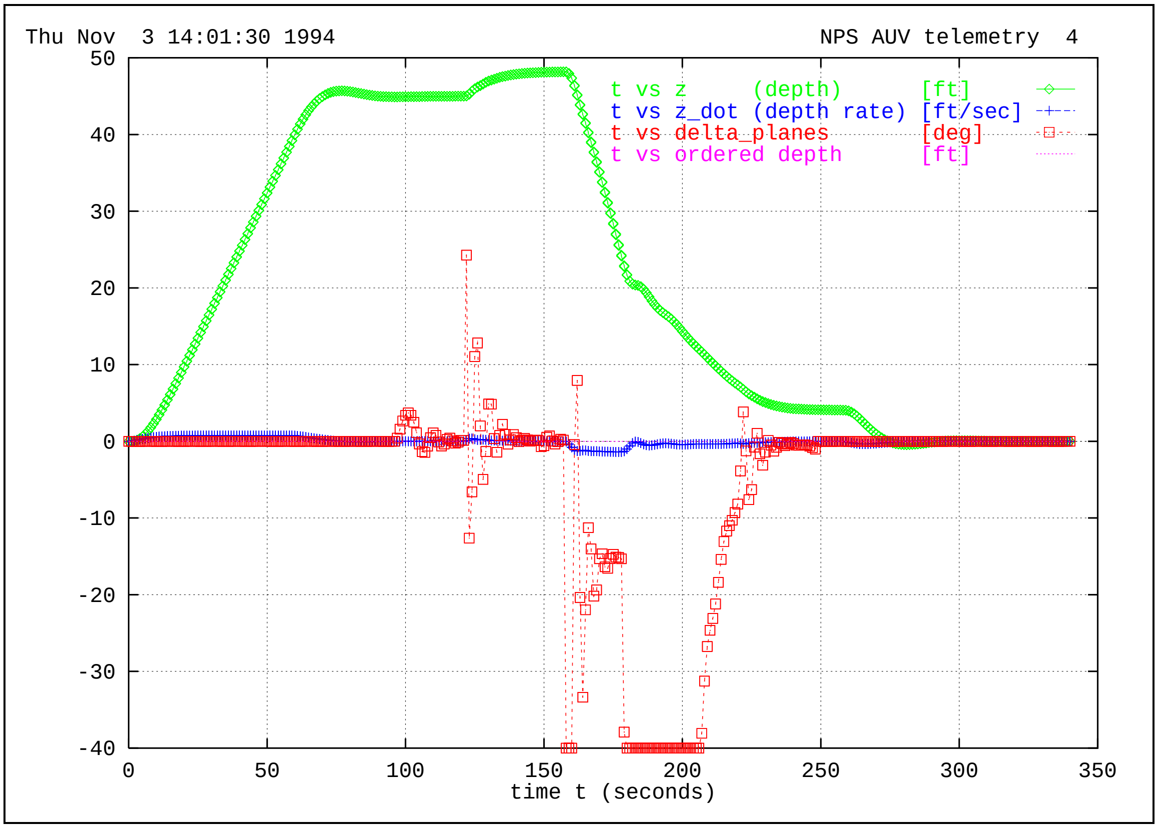

Figure 9.6. World depth coordinate ***z*** and derivative versus time ***t***.

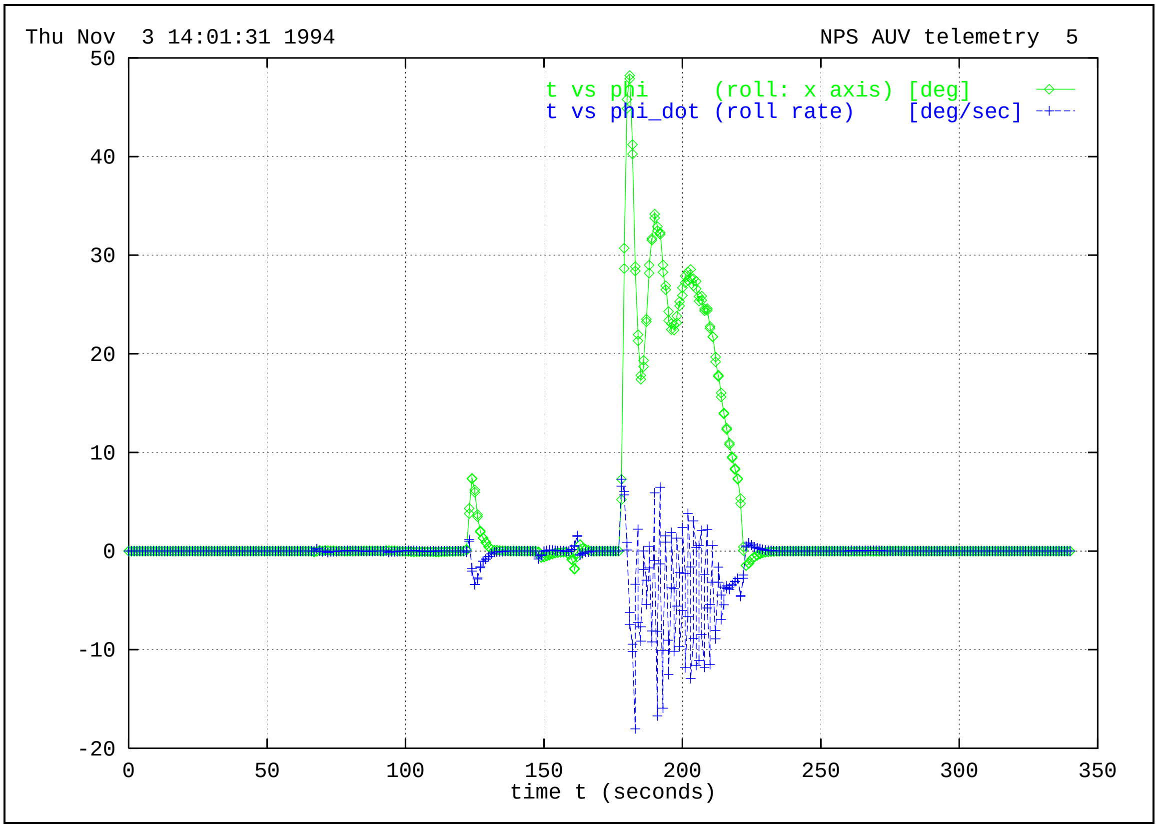

Figure 9.7. World roll Euler angle ϕ and derivative versus time ***t***.

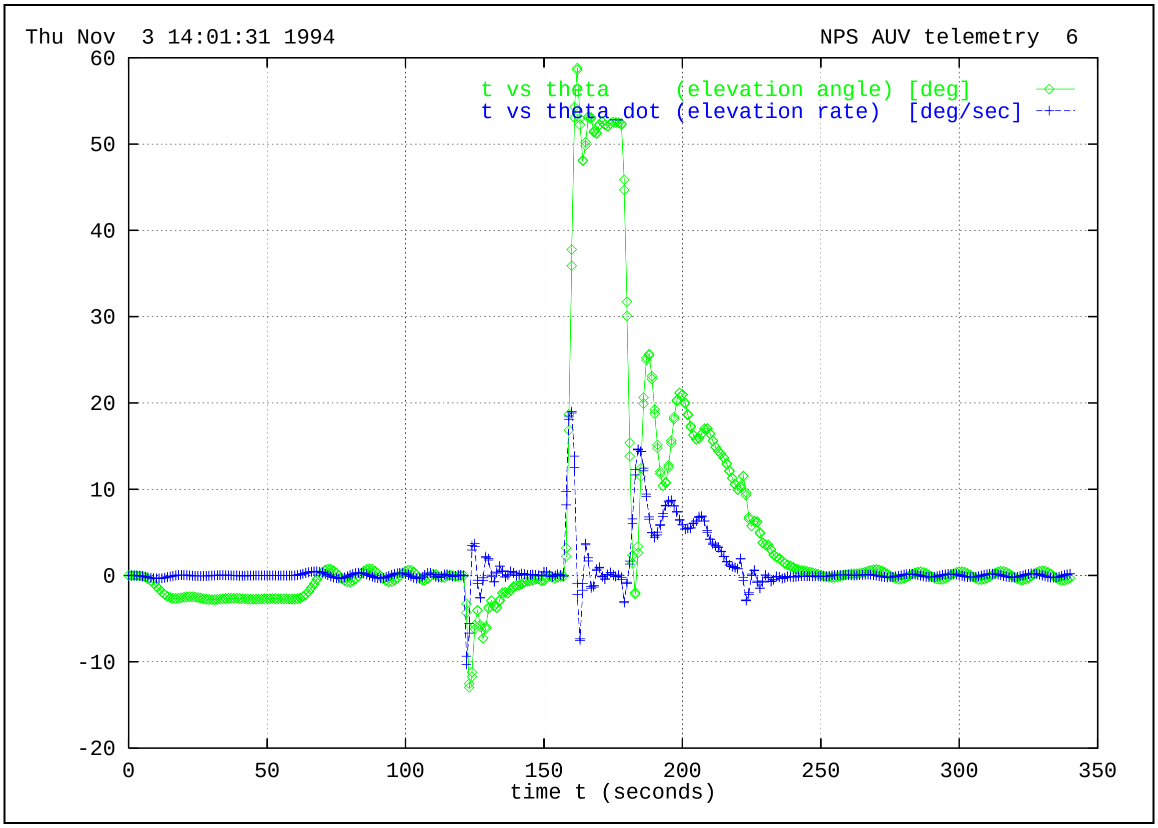

Figure 9.8. World pitch Euler angle θ and derivative versus time ***t***.

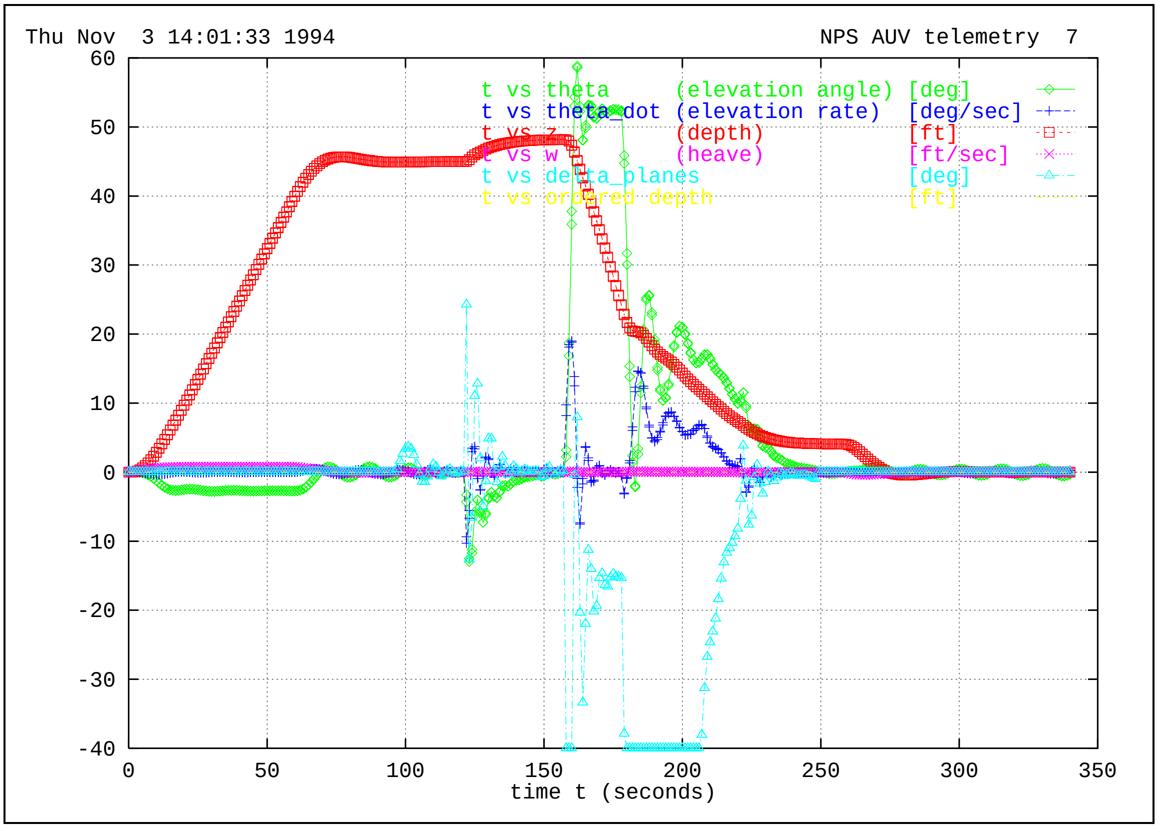

Figure 9.9. World theta Euler angle θ and related variables versus time ***t***.

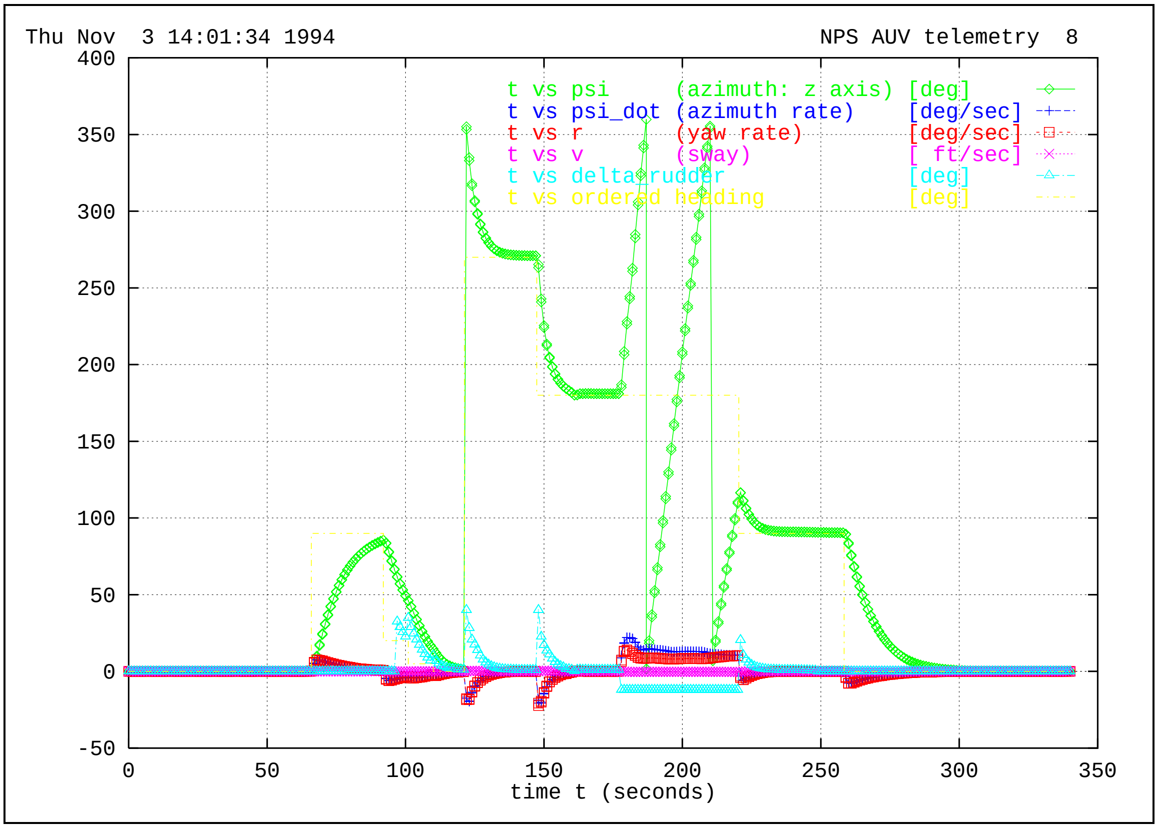

Figure 9.10. World yaw Euler angle ψ and derivative versus time ***t***.

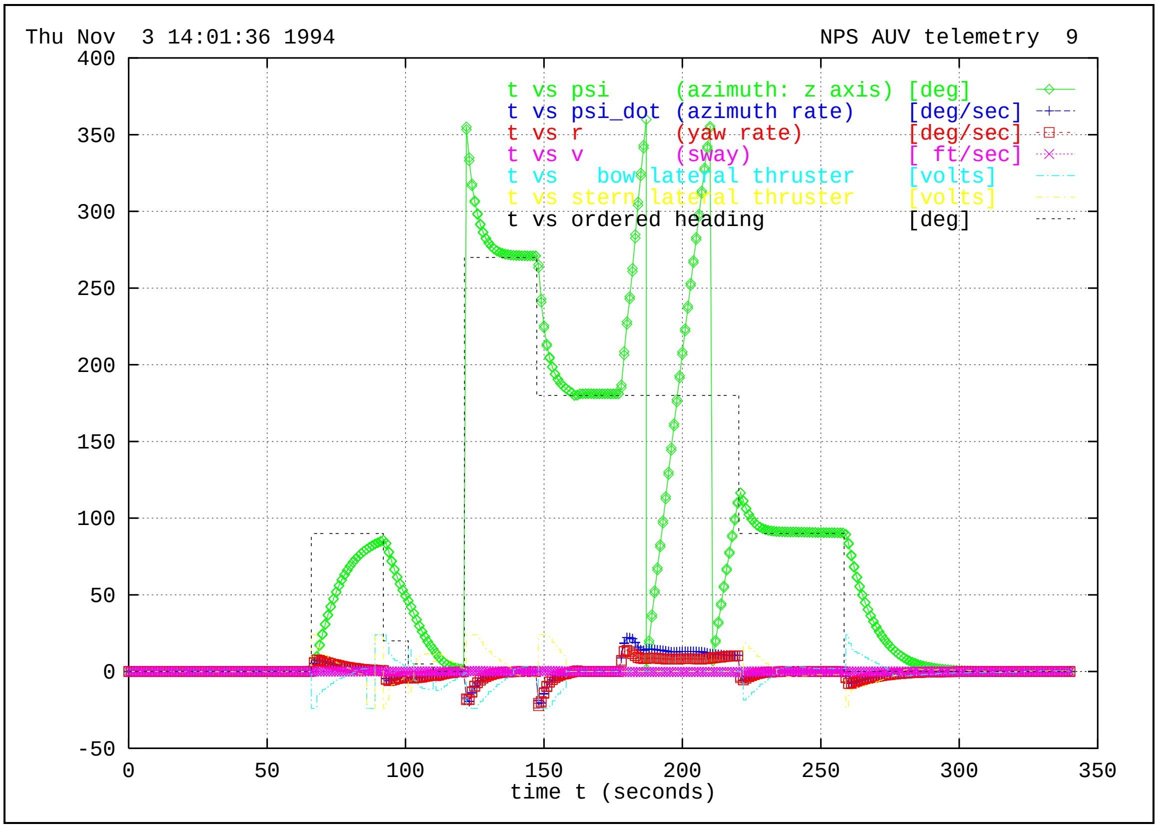

Figure 9.11. World yaw Euler angle ψ and lateral thrusters versus time ***t***.

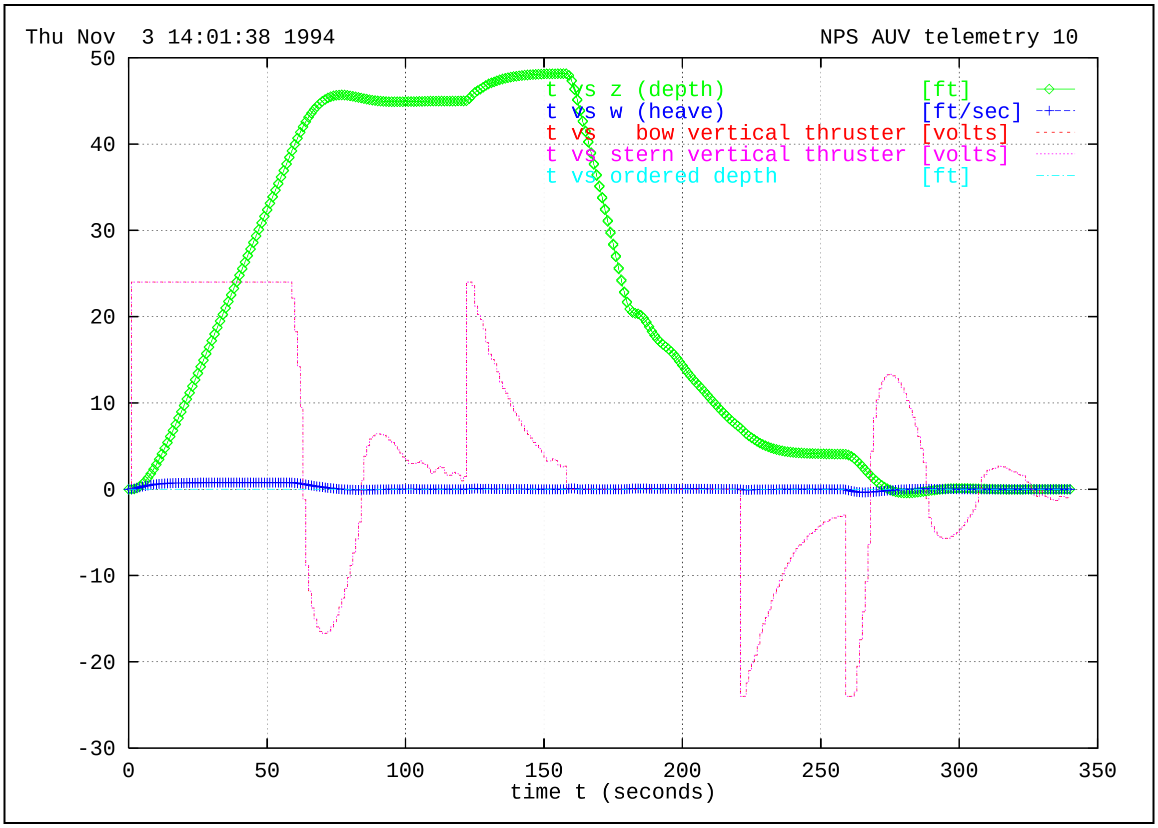

Figure 9.12. World depth coordinate ***z*** and related variables versus time ***t***.

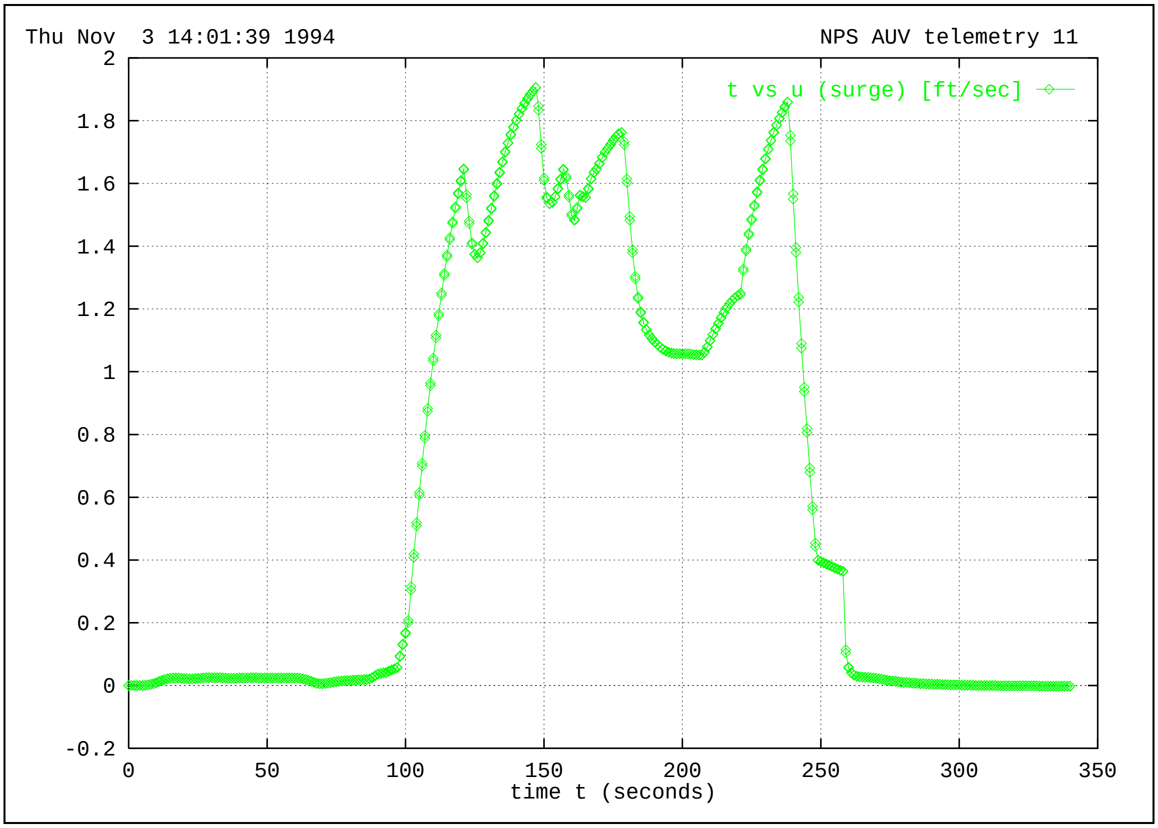

Figure 9.13. Body longitudinal surge velocity ***u*** versus time ***t***.

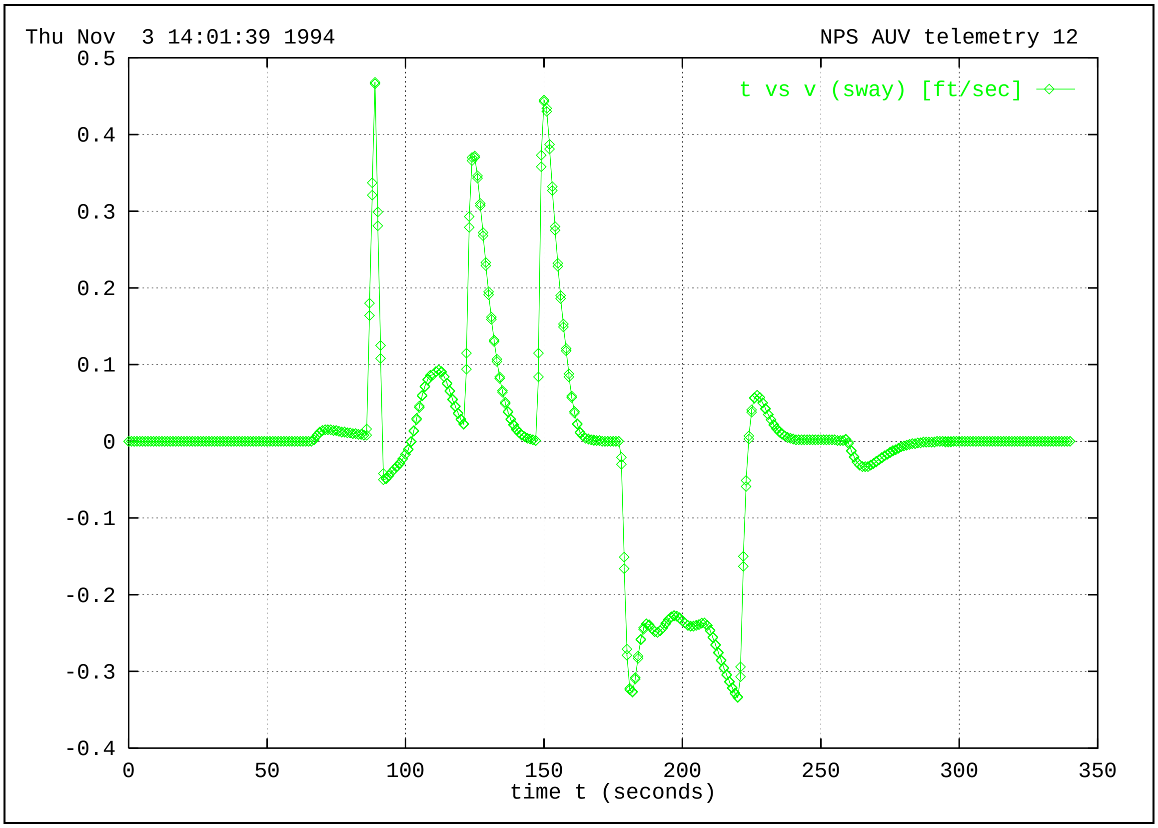

Figure 9.14. Body lateral sway velocity ***v*** versus time ***t***.

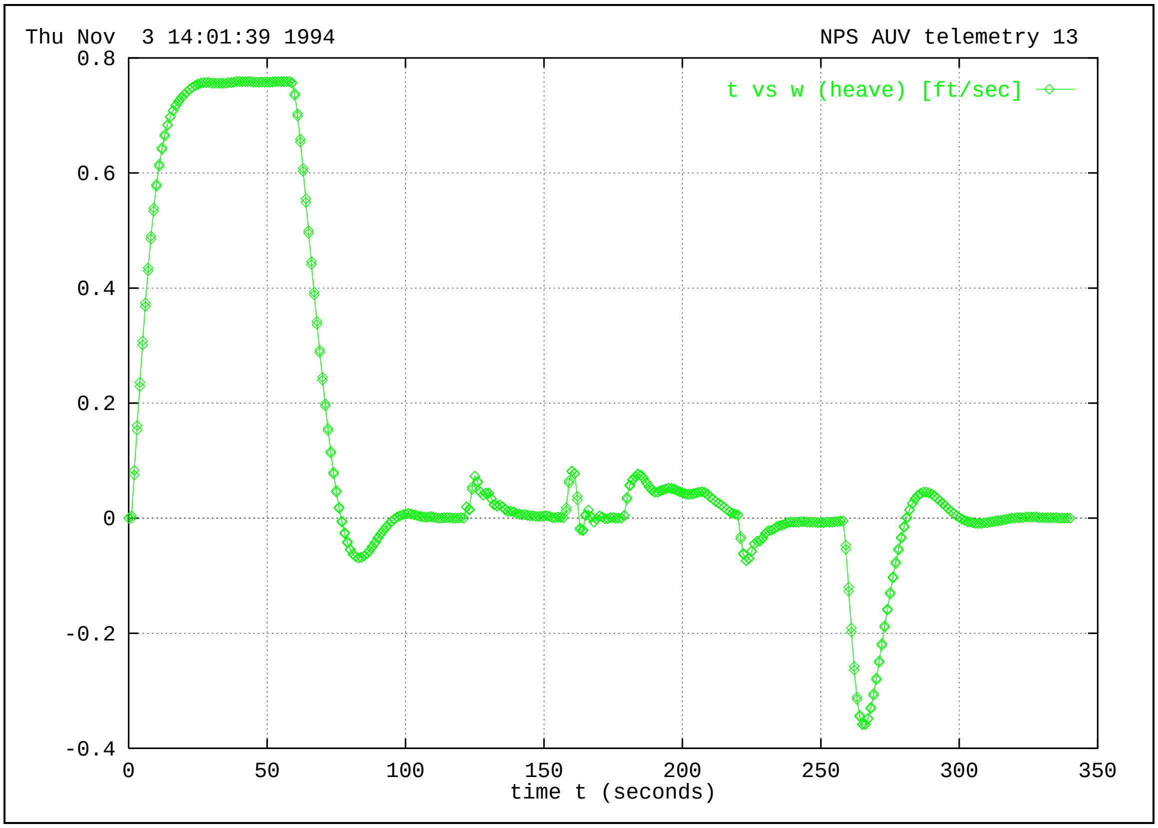

Figure 9.15. Body vertical heave velocity ***w*** versus time ***t***.

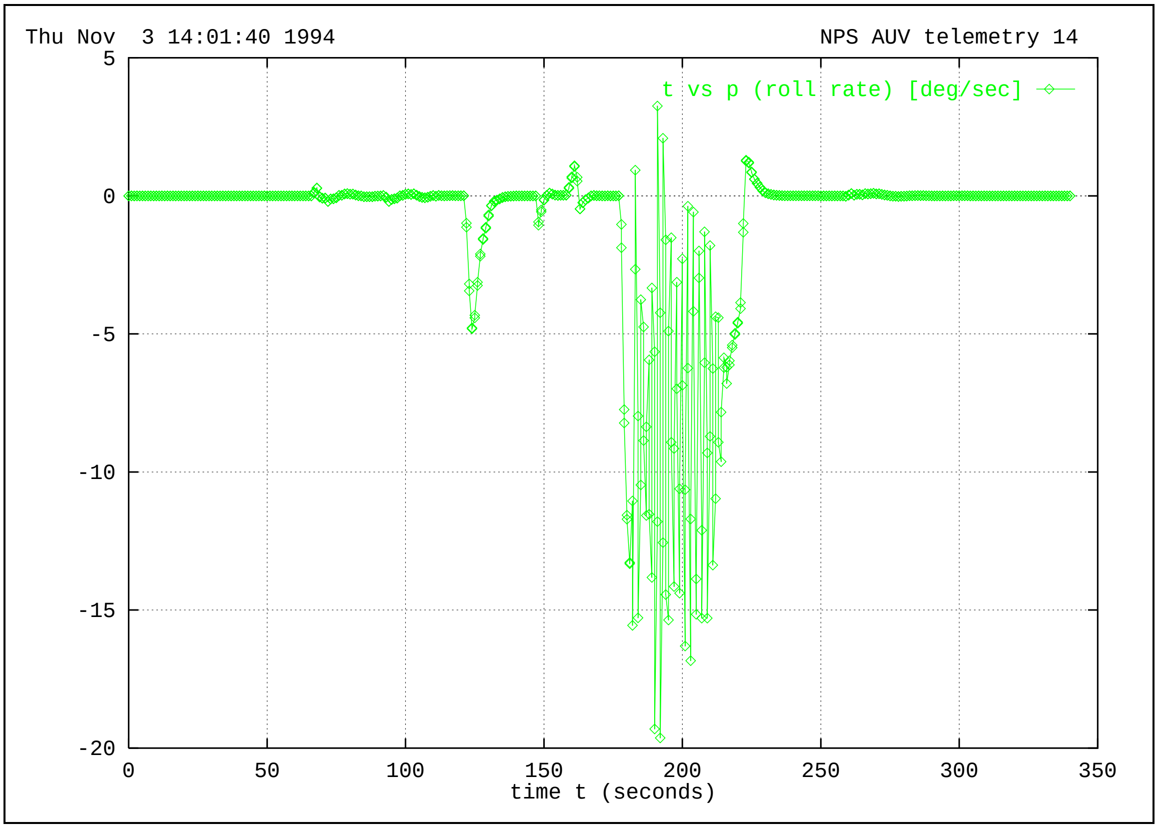

Figure 9.16. Body longitudinal rotation roll rate ***p*** versus time ***t***.

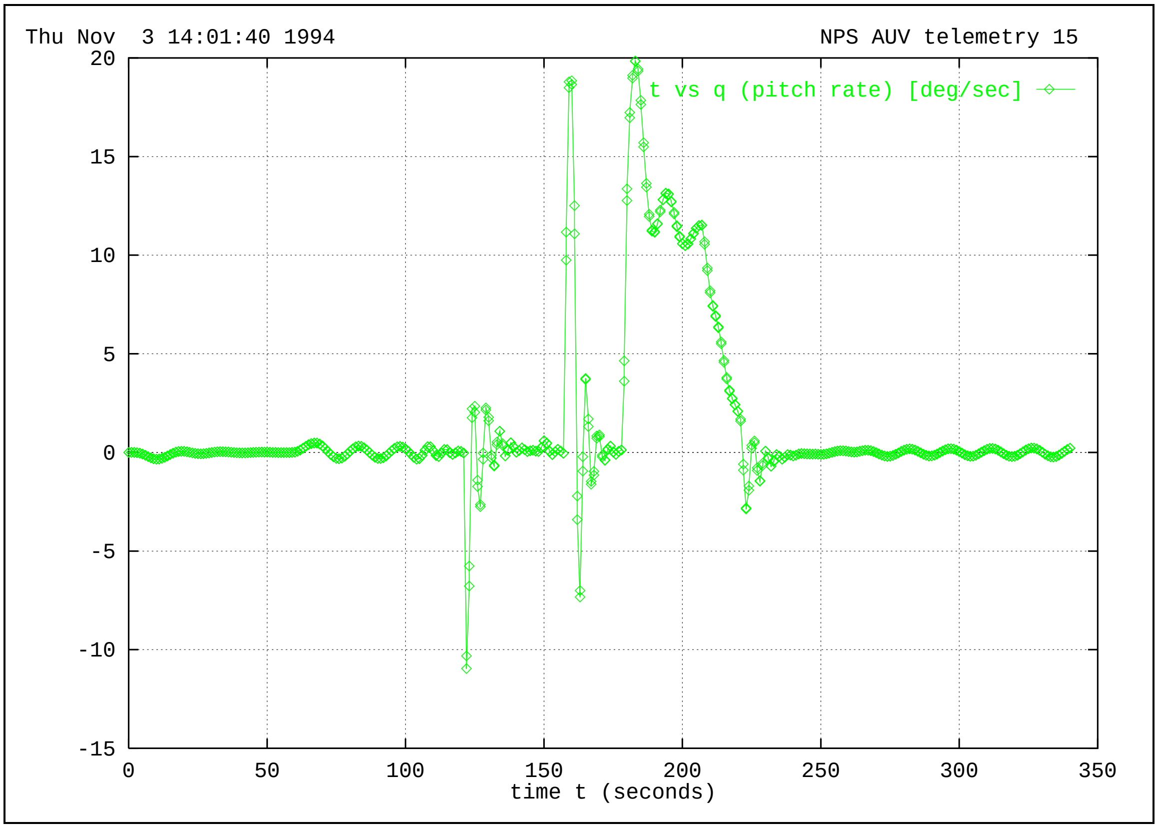

Figure 9.17. Body rotational pitch rate ***q*** versus time ***t***.

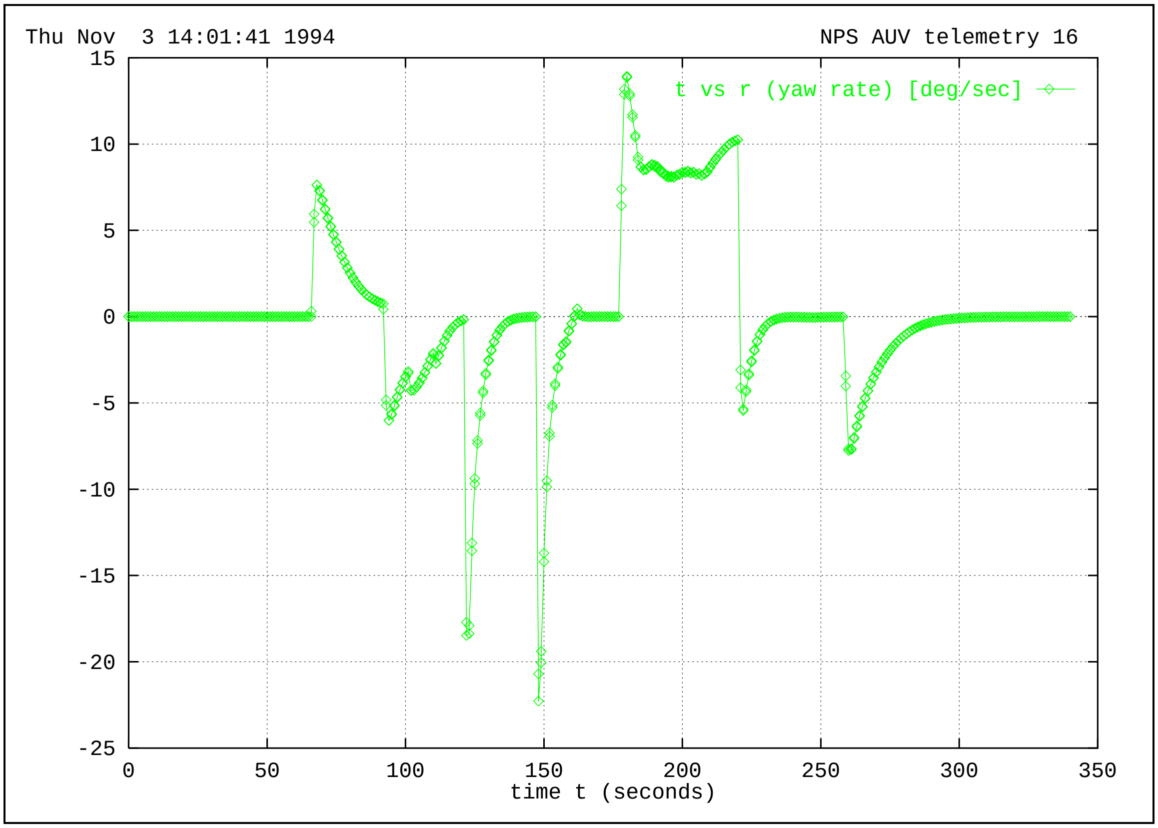

Figure 9.18. Body vertical rotation yaw rate ***r*** versus time ***t***.

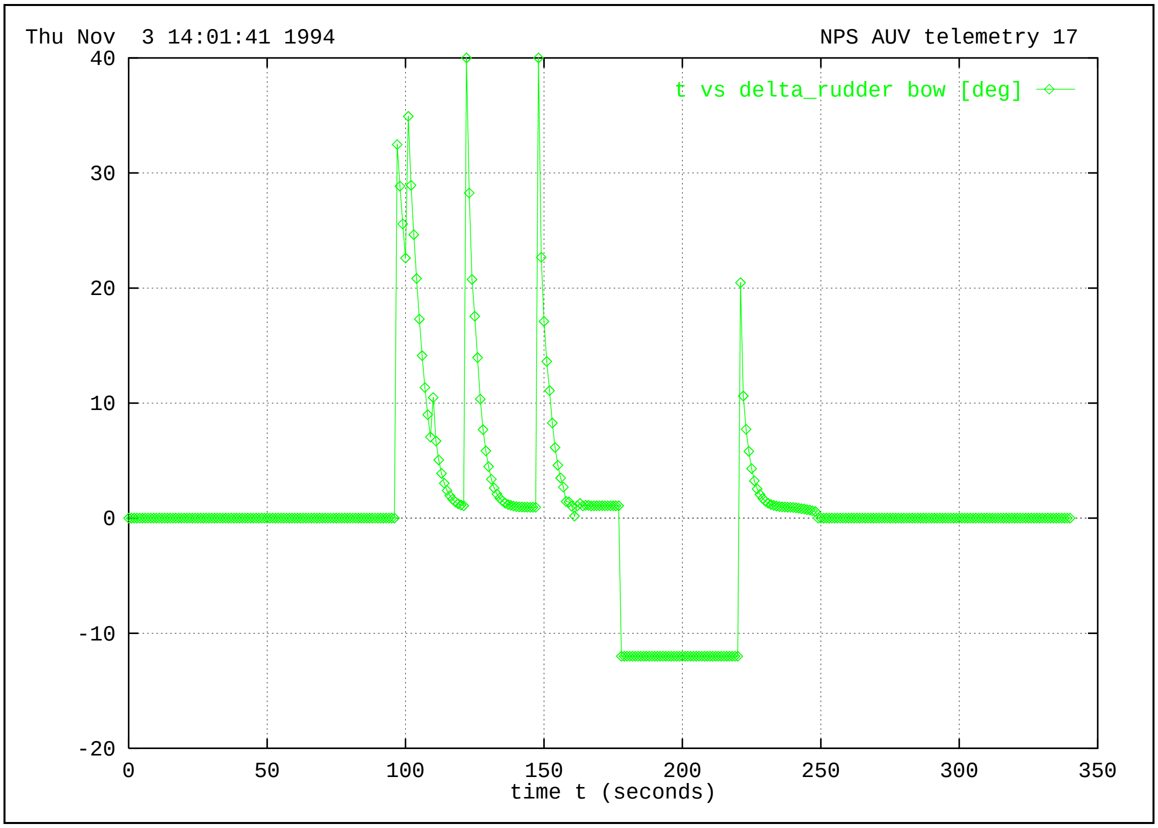

Figure 9.19. AUV bow rudders rotation (stern rudders opposed) versus time ***t***.

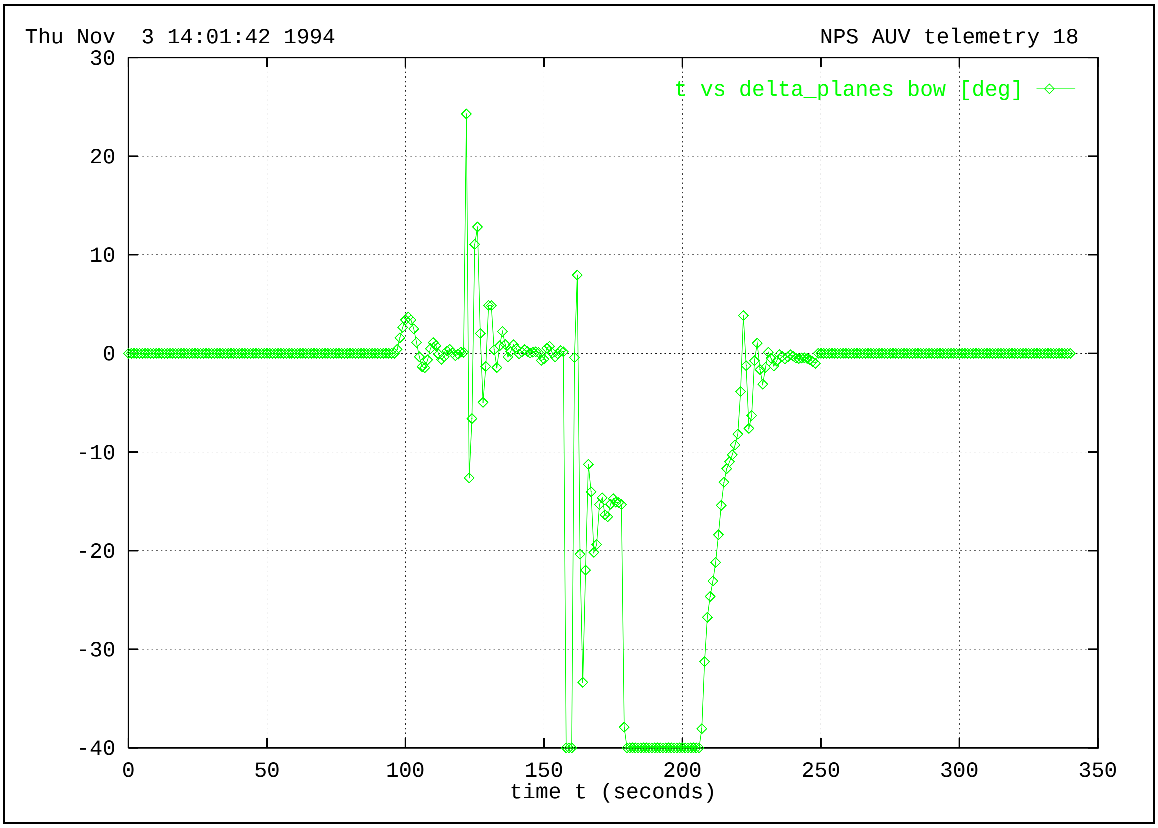

Figure 9.20. AUV bow planes rotation (stern planes opposed) versus time ***t***.

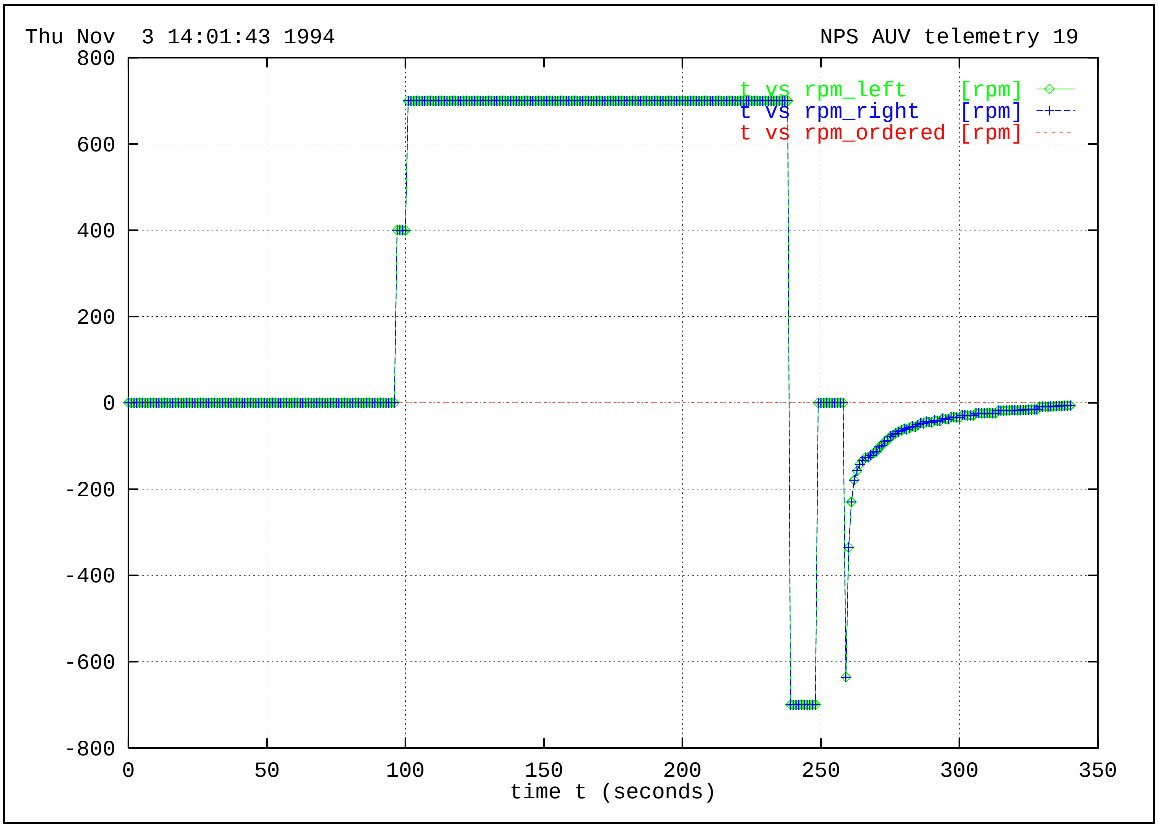

Figure 9.21. AUV port and starboard propeller speed versus time ***t***.

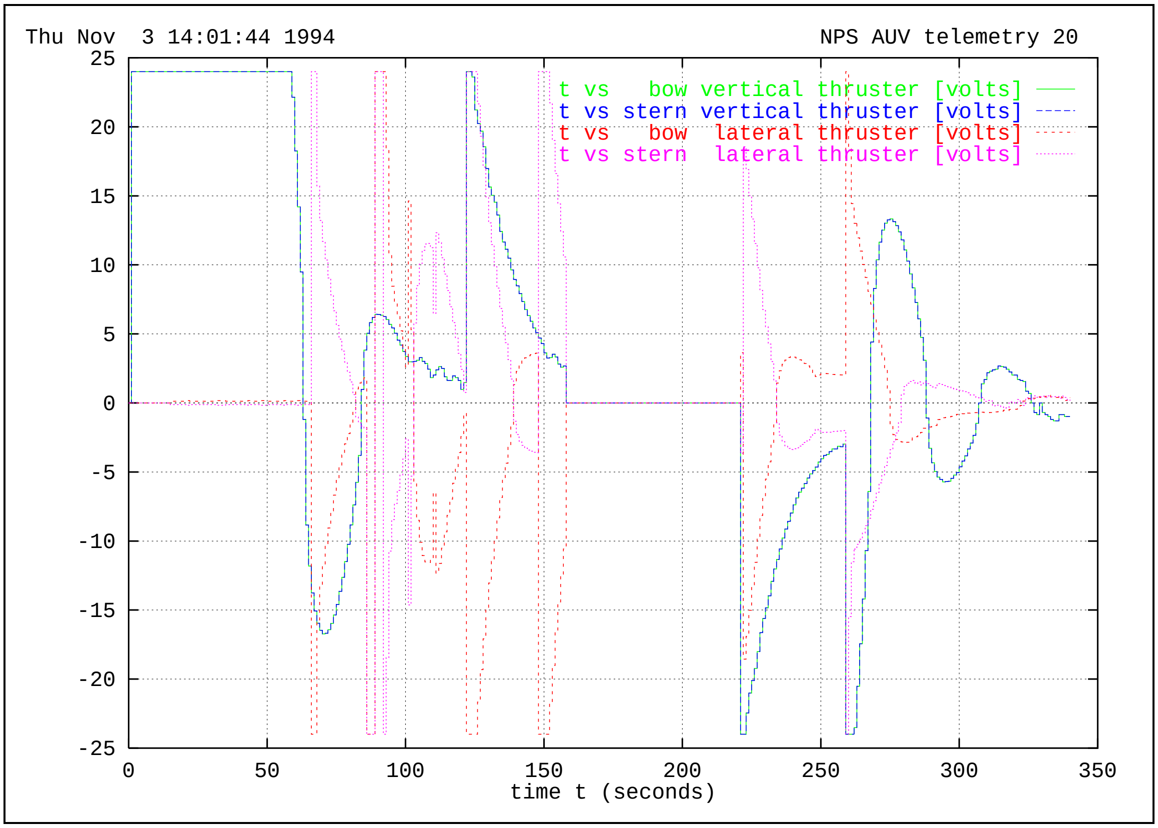

Figure 9.22. AUV vertical and lateral thruster control voltages versus time ***t***.

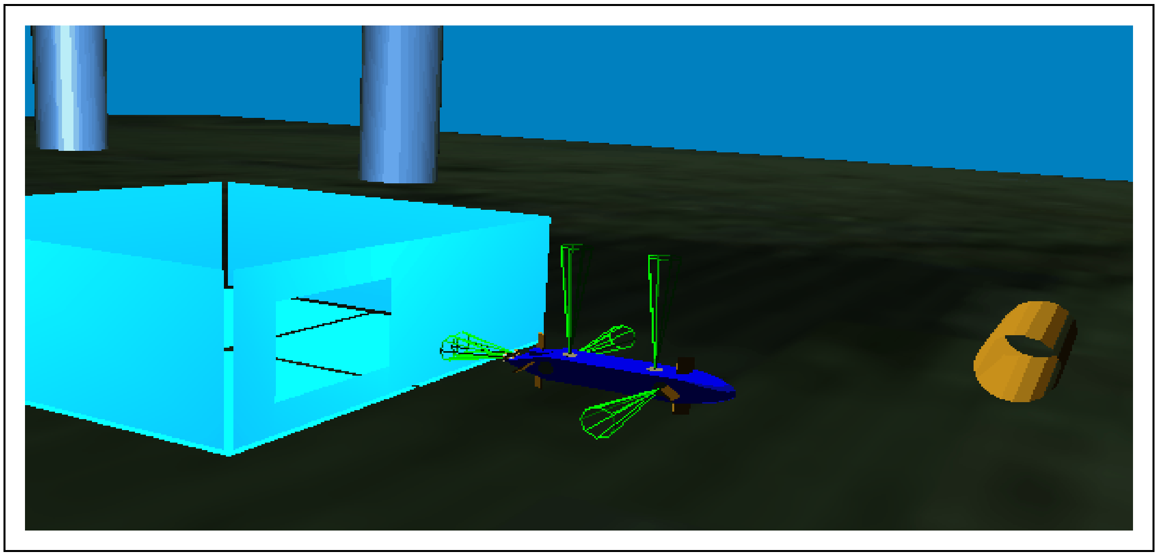

Figure 9.23. AUV initial turn and depth change from the test tank to the torpedo tube using all thrusters, propellers and planes.

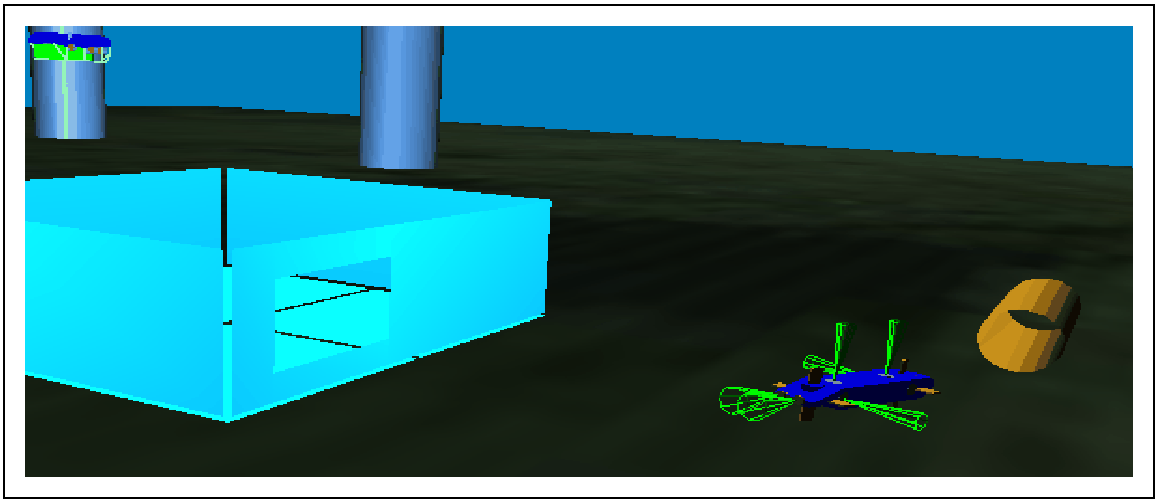

Figure 9.24. AUV nearing entry to torpedo tube. Note counterintuitive (but correct) opposition of lateral thrusters to propeller and rudder control, damping yaw rate ***r*** and preventing overshoot.

D. NETWORK TESTING AT *The Edge*

Distribution of underwater virtual world components enables scalability and real-time response, both for robot world models and for people. The distributed implementation of the underwater virtual world (Brutzman 94e) was tested and demonstrated for six days as part of *The Edge* exhibition at the SIGGRAPH 94 conference, held in Orlando Florida (Brutzman 94b, 94c). We estimate that 2,000 of 32,000 SIGGRAPH attendees stopped at our underwater virtual world exhibit to observe a robot mission and learn about the project. Robot interactions in the virtual world were also multicast over the MBone with worldwide scope (ttl 127) using audio, video and DIS channels.

The forty reviewed exhibits in *The Edge* were representative of leading computer graphics applications in the world. *The Edge* was intended to include shared experiences, simulation, training, education, virtual environments, high-bandwidth networked graphics, telepresence and telerobotics. The underwater virtual world project has components and relevance in each of those areas. Our objective was to inspire and stimulate attendees to consider a myriad of opportunities previously considered infeasible. Feedback comments from visitors, SIGGRAPH organizers and the press (Meyer 94) were uniformly enthusiastic.

One technical goal during this demonstration was to evaluate netwoRk loading. Bandwidth budget plans called for an average bandwidth of 225 kilobits per second (Kbps) is available (i.e. 25% of a 1.5 Mbps T1 Internet connection). This bandwidth budget included 128 Kbps for locally generated video/graphics, 64 Kbps for a shared audio channel and 15 Kbps for sending DIS PDUs. 128 Kbps is the default bandwidth for world-wide multicast video programs and equates to 1-3 frames per second. Lower or higher bandwidths and a corresponding change in frame rate are feasible.

DIS Entity State PDU size for the NPS AUV is larger than the nominal DIS PDU default, since three articulated parameters are attached to each AUV PDU for sonar, plane surface, propeller and thruster values. DIS protocol bandwidth for the

SIGGRAPH demonstrations were based on these PDUs being multicast at full virtual world update frequency of 10 Hz.

$$\begin{aligned} DIS\ bandwidth &= (multicast\ PDU\ update\ rate)\ [PDU\ size] \\ &= (10\text{ Hz }\ update\ rate)\left[\frac{1152\text{ bits}}{PDU} + 3\left(\frac{128\text{ bits}}{\begin{array}{c} articulated \\ parameter \end{array}}\right)\right] \\ &= 15.36\text{ Kbps} \end{aligned} \tag{\textbf{9.1}}$$

This full update rate of 10 Hz was used to relay every possible nuance related to physical motion of the highly dynamic autonomous underwater vehicle. By way of contrast, a standard Entity State PDU with no articulated parameters being relayed at the maximum standard interval of 5 seconds produces only a 0.23 Kbps bandwidth load.

Another important way of making virtual worlds widely available is developing an information infrastructure where potential virtual world participants have the network capabilities to participate. Toward this end we have utilized MBone in a number of scholarly conferences. Objectives are usually twofold: learn how to use global videoconferencing more effectively, and assist potential collaborators in learning more and connecting. We have achieved a steady series of successes at a variety of sites including 1993 U.S. Geological Survey Menlo Park scientific visualization workshop, the International Advanced Robotics Programme (IARP) Mobile Robotics for Subsea Environments 94 (Brutzman 94a), IEEE Autonomous Underwater Vehicles 94 (Brutzman 94d), GLOSAS Global Lecture Hall of July 94 (McLeod 94), and SIGGRAPH 94 (Brutzman 94b, 94c). Effectiveness of these techniques has been formally evaluated (Gambrino 94) with typically positive and enthusiastic results (Macedonia, Brutzman 94). It is our belief that use of MBone in a variety of media will continue to grow at a slow but exponential rate, and it is our experience that familiarity and practice overcomes limitations associated with bandwidth restrictions.

The combined use of socket connectivity, MBone audio/video/graphics/PDUs, the DIS protocol and World-Wide Web (WWW) functionality means that the underwater virtual world is an excellent application to take advantage of a high-bandwidth information superhighway, further extending the capabilities of multiple researchers. The network approach allows many individuals dynamic remote access, and distributing components minimizes dependence on unique (or hard-to-replace) hardware and software. The DIS protocol permits compatible interaction with other virtual worlds over the Internet. Providing hypermedia access via publicly available WWW browsers such as *Mosaic* makes a complete variety of pertinent archived information available to anyone. Such information media include images, papers, datasets, software, sound clips, text and any other computer-storable media. This supports another long term objective of the project, which is to continue extending the scope of virtual world entities and simplifying virtual world interfaces in order to become useful as an exemplar application for education. Thus an infrastructure is evolving whereby virtual worlds can support remote scientific collaboration and education, both regionally and globally.

E. SUMMARY AND FUTURE WORK

This chapter showed experimental results in hydrodynamics, Internet-wide network loading and remote collaboration. Hydrodynamics behavior of an underwater vehicle is shown to be highly complex and dependent on a large number of interacting variables. Temporal plots permit precise analysis of results, but real-time 3D graphics playback is required for overall evaluation and insight. From a network perspective, the Internet is currently capable of supporting the variety of high-bandwidth information streams needed for full virtual world connectivity. Tested streams include point-to-point telemetry sockets, audio, video, graphics, DIS PDUs and archived multimedia. Addition of arbitrarily large numbers of virtual world viewers is shown possible through use of the MBone for time-sensitive information such as audio, video and DIS position updates.

Future work on experimental results is extensive because use of the underwater virtual enables many new capabilities. Top priority is to reintegrate execution level software in the actual vehicle and reproduce virtual world results in the real world.

Regrettably, the long break in 1994 AUV testing due to hydrogen explosion repairs has precluded running any of these missions in the water. This lack of validating test data duplicating virtual world missions in the real world has precluded performing a "Turing Test" of virtual world operations. A top priority for 1995 is to stabilize the equipment rebuild and upgrade the execution level robot control program to use new hardware interfaces. At that point virtual world test results are expected to be completely validated against identical missions run in the test tank.

Collaboration with other underwater robotics and virtual world researchers is highly desirable in order to scale up the scope of the underwater virtual world. A formal validation and verification confidence assessment can improve project implementation and may help formally clarify the fundamental requirements needed for global internetworked large-scale virtual worlds. Exciting future possibilities include use of the underwater virtual world as an educational tool, as a testbed for new AUVs, and as a means for providing context amidst the gigantic mass of information content which is being connected via the Internet.