SeaSlug: A high-uptime, long-deployment mobile marine sensor platform

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***Abstract*— This work describes a new autonomous surface vessel (ASV) for marine sensing applications. It provides the capabilities necessary for long-duration data-collection missions while having minimal upfront and operational costs. It has been optimized for both low-power and low-speed operation in order to meet long-duration mission requirements. Both air data and marine sensors as part of its standard sensor suite. Additional sensors can be integrated into external payload bays that provide both water and air access. Remote control and mission retargeting is provided by the open-source QGroundControl software. Xtend modems allow for long-range remote telemetry recording and analysis along with mission retargeting. This platform is validated by real-world autonomous tests demonstrating the feasibility of the L_2^+ control law. In these experimental tests, the SeaSlug was able to track a straight line to with an RMS crosstrack error of 0.98m and RMS heading error of 2.6°.**

I. INTRODUCTION

Comprising over two-thirds of the Earth's surface, oceans affect climate, animal populations, and human lives in a multitude of ways. Unfortunately, given its size, the ocean has always been difficult to study. This has been improved by the use of satellites to survey large swaths of ocean. However, they are limited by both cost and data collection abilities. The most effective method of data collection still remains manned excursions possibly augmented by robotic machinery or vehicles. These excursions can be effective but are limited by either cost or vessel and crew availability when studying sudden short-term events. Even when properly planned these excursions can be very expensive, on the order of thousands to tens of thousands of dollars per hour. This limits these research voyages to a small number of well-funded institutions.

Research into unmanned vehicles has been continuous since the early 2000s with several robotic platforms being developed since then. These platforms all attempt to lower costs and increase mission duration to minimize the important dollar-to-data metric. Lizhbeth [7] is one such platform with subsurface sampling capabilities through the use of a winch. It has been successfully used to collect data on algal blooms in lakes. SESAMO [3] is a similar platform that has successfully taken water samples in the open-ocean. To study fish populations in protected areas off of the Californian cost, a low-impact semi-submersible craft was developed by Laws *et al.* [8]. While these vehicles have been effective at their specific data collection goals,these platforms have neither the payload flexibility nor the endurance for the varieties of missions desired by marine scientists.

Fig. 1. An open-ocean test of autonomous control of the SeaSlug where the vehicle is controlling both heading and roll angle. Prominently displayed are its solar panels and radar reflector.

Improving both mission retargeting and mission endurance has been a focus of several research projects. Wind-propelled surface vessels with solar panels have been proposed for improving mission endurance [5]. They are generally designed with off-the-shelf catamarans and were not designed for sensor integration. Partially-mobile platforms, such as the autonomous self-mooring vehicle by Wood *et al.* [15], can achieve a high mission endurance by remaining moored most of the time. The tradeoff of this is the inability to perform missions where mobility is necessary or to operate in environments where mooring is not possible. The OASIS platform [6] is a very flexible ASV that can be used for mobile missions and includes a large payload capacity. Its power usage data was not discussed, however, nor was its payload flexibility. Commercial ASVs also exist, such as the Wave Glider [11] by Liquid Robotics. It is mechanically propelled by wave action with its onboard electronics powered by solar panels. There is limited space available for sensor payloads and they have no access to the water or atmosphere without modifications. Additionally the platform cannot be sold, only leased, and as such cannot be freely modified.

This work presents SeaSlug, an ASV platform designed for long-term marine observation deployments. It has been designed for studying both near-surface and atmospheric events. It has a large internal payload capacity in addition

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*This work was supported by a University of California Discovery Grant.

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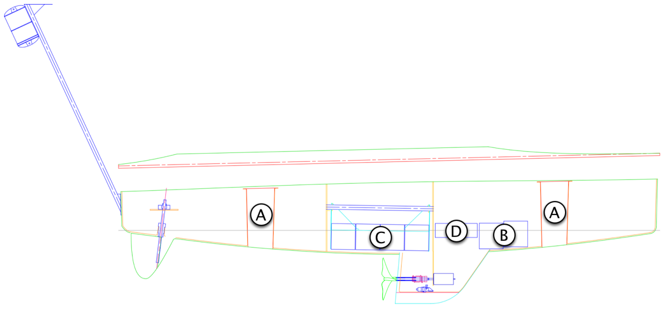

Fig. 2. The physical and electrical architecture of the SeaSlug. A: the sensor payload bays, B: the 12V battery bank, C: the 24V battery bank that is also the ballast, D: the water-tight electronics box for the autopilot.

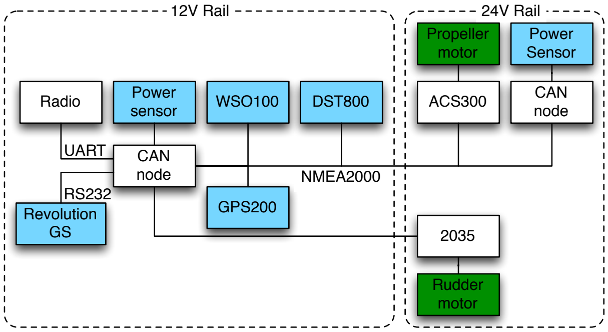

Fig. 3. System schematic showing onboard actuators (dark green) and sensors (light blue) along with their power source.

to externally-accessible and modular payload bays with both air and water accessibility. This modular design is extended to each onboard subsystem, as each communicates using a strictly-defined message set over a common bus. This facilitates both integration of additional hardware and repairs or alterations to existing subsystems. This bus utilizes the NMEA2000 protocol and therefore supports most off-the-shelf marine equipment. The SeaSlug is capable of long mission durations with a large onboard battery store and solar charging. Roll angle can be controlled by a moveable ballast, which allows increased solar efficiency by leaning towards the sun. A low-drag hull and high-efficiency propeller support a nominal operational speed of 3 knots (1.6 m/s). At this cruising speed the onboard batteries can provide 11 hours of continual use. Coding is done within MATLAB/Simulink, which allows for simulation-driven development using full-software and hardware-in-the-loop simulations. Groundcontrol software operating over a long-range wireless link provides telemetry recording, remote-control, and mission retargeting functionality.

II. PLATFORM ARCHITECTURE

Originally designed by Willow Garage and gifted to UCSC in 2009, the SeaSlug has been part of the Autonomous Systems Lab's (ASL) research effort to autonomously collect high-quality data at low cost. The physical design of the vessel remains, however all of the other subsystems have been replaced.

A. *Physical Architecture*

The hull has been optimized for low-speed operation in addition to energy scavenging capabilities. The result is a 5.9m length vessel with a narrow-beam design and a wide deck for solar panels. A 0.45m two-blade propeller mounted in the keel complements the narrow hull. With this design the SeaSlug has a cruising speed of 2 knots (1 m/s) with a maximum speed of 4.5 knots (2.5 m/s).

A mast is attached at the rear, angled aft and to port, and serves as an important structural element of the vessel. It provides both a mounting point for electronics and supports the vessel's self-righting abilities. A radar reflector mounted on the mast doubles as buoyancy, and when combined with the off-axis mounting of the mast, facilitates self-righting in the case of a capsizing. 91kg of ballast can be rotated at up to 90° in either direction around the longitudinal axis to right the vessel. This is in addition to the primary function of the ballast being to increase solar efficiency by maximizing solar panel exposure by commanding an appropriate roll angle.

Electronics are mounted in the large internal cabin within a waterproof container (D in Fig. 2). Two payload bays (labeled A in Fig. 2) provide space for additional sensors, both fore and aft, with air and water access. They are externally accessible and independent of the main cabin allowing for quick installation and removal of the payload. Internal space comprises an entire $0.3\text{m}\times0.3\text{m}$ column through the hull providing 0.1m^3 of internal space, with more available above the deck and below the hull. A standard marine CTD sensor (conductivity, temperature, depth) required minimal modifications for mounting within one of these payload bays.

B. *Electrical Architecture*

The SeaSlug has been designed with a modular control and electronics system in order to simplify ongoing development and maintenance operations. This modularity comes through the use of a central communications and power bus connecting all internal subsystems. Each one has a well-defined high-level communication interface such that any modifications within a single subsystem will not affect the others. This has already provided benefit when the rudder position sensor was changed from an analog position sensor to a high-precision magnetic rotary encoder and little downtime was incurred.

The central communications bus uses the NMEA2000 protocol [10]. This protocol provides two main advantages: it is easy to source marine sensors or controllers that support it and it is both electrically and physically designed for a harsh salt-water environment. Additionally its standard connectors can carry power so the same connector can be used between all onboard electronics.

Power is provided through independent 12V and 24V power rails and are labeled B and D in Fig. 3. A 12V battery provides the standard voltage to the NMEA2000 bus. This lower-capacity battery bank powers almost all onboard electronics using a 98Ah marine gel battery. The actuators, requiring substantially more power, run off the larger 24V power rail. This is powered by 4 220Ah 6V sealed lead-acid

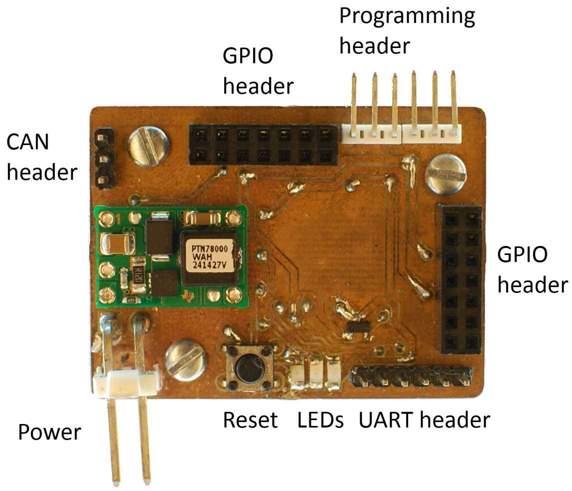

Fig. 4. The CAN interface board used as the main computer and for integrating electronics as another CAN node on the NMEA2000 bus. The 5V switching regulator is the small visible circuit board.

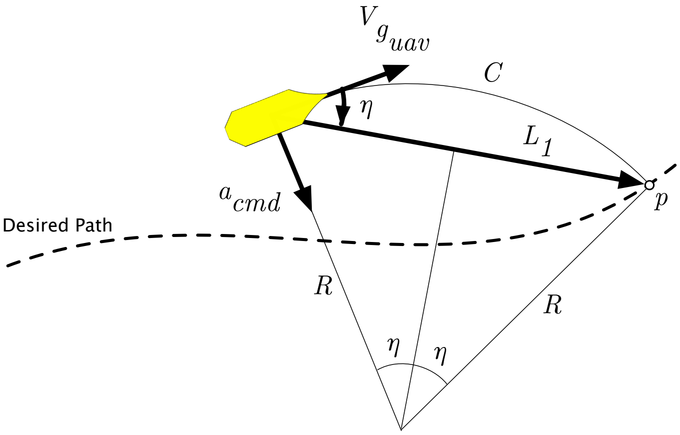

Fig. 5. The geometry behind the L_2^+ control law. p is the aim point dictated by the L_1 look-ahead vector. a_{cmd} is the resultant acceleration necessary to intercept p.

batteries. 24V was used here as it is high enough to provide the desired power to the actuators and it is a standard voltage compatible with most motor driver electronics. Onboard environmental sensors include a water sensor (Airmar DST800) and an air/wind sensor (Maretron WSO100). A GPS receiver and an inertial measurement unit (IMU) provide navigational data. Global position, ground speed, and course-over-ground are captured at 5Hz by Maretron's GPS200 GPS unit and True North's Revolution GS digital compass provides absolute heading, pitch, and roll at 28Hz.

A controller board has been designed for interfacing peripherals with the central NMEA2000 bus (shown in Fig. 4). With this board any sensor or input can be readily converted to operate as a CAN node. It is small, measuring 38mm by 51mm, so that it can be used in small watertight enclosures. Both 3.3V and 5V voltages are available from an onboard switching regulator that can be powered by either the 12V or 24V battery bank. Up to 40MIPS of processing power is provided by a dsPIC33F processor. This is powerful enough to run the primary control algorithms necessary to control the vessel. Additional sensors include an input voltage sensing circuit for monitoring battery life and a temperature sensor for detecting over-temperature operation. A pair of headers expose remaining pins following the "shield" expansion board pattern popularized by the Arduino platform [1]. This shield design simplifies integration of additional hardware by providing a standard pinout and mounting pattern. This board is currently used to run the primary computer and for integrating the 24V power sensor with the NMEA2000 bus.

C. Software Architecture

The onboard computer runs C code generated by MATLAB/Simulink. Using these tools allows for simpler design and testing than would be available in a pure-C environment. Their large standard library includes time- and frequency-domain control systems functionality that also simplifies coding. This C code generated by Simulink is supplemented by additional low-level code for peripheral drivers.

The controller is programmed using an active-loop design where each loop executes in exactly one time step and idles in between. Real-time guarantees are met by a central control loop that runs at 100Hz, consistent with sampled data systems using discrete control.

The onboard controller includes two-way communications with a remote groundstation for telemetry recording and other functions. QGroundControl [16] provides this functionality using the open MAVLink [12] communications protocol. Both were developed as part of the PIXHAWK project [13] at ETH Zurich. Originally designed for use with micro air vehicles (MAVs), they have both been turned into successful open-source projects that can support a variety of vehicle types. This has led to them being adopted by a multitude of autonomous vehicle projects including the ArduPilot Mega [2], pxIMU [13], and SLUGS [9].

MAVLink provides several features that make it worthwhile as the communications protocol. It is supported by several groundstation programs targeting different platforms and can be easily modified to support additional message types. Libraries are available for both C and Python. The C library is used aboard the autopilot while the Python version is used for PC-side communications and data processing outside of QGroundControl.

QGroundControl was chosen as the groundstation software due to its variety of features and interoperability with MAVLink. Received telemetry can be recorded or displayed using a myriad of visualization tools including maps, gauges, and graphing widgets. QGroundControl can also transmit to the vessel new parameters and missions, allowing for gain tuning or mission retargeting while in the field. Manual control is also performed through QGroundControl via a USB joystick.

III. CONTROL ARCHITECTURE

The main control law used aboard the SeaSlug is the L_2^+ controller [4] adapted for surface vessels. This algorithm builds on the L_1 control law originally developed and analyzed for unmanned aerial vehicles (UAVs) by Park *et al.* [14]. The L_1 control law uses a fixed look-ahead distance to determine an aim point, p, along the desired path as shown in Fig. 5. The desired trajectory towards this aim point is the arc, C, that is described by an angle, η, dependent on the vehicle's velocity vector and the L_1 vector. Tracking this arc is down by the calculation of a necessary lateral acceleration. This is then mapped into a commanded roll angle when controlling a UAV. As the vehicle moves, its aim point moves along the path staying an L_1 distance away.

The L_2^+ control law makes several modifications to the L_1 algorithm that are necessary for it to be useful in the targeted operational environments. The primary modification is additional logic for when the vehicle is farther than the look-ahead distance from the waypoint track, which had previously been unspecified. This new logic makes it possible for the vehicle to be at an any initial point and still intercept and follow the desired path. This new behavior also led to the addition of both initial-point and return-to-base functionality.

The original L_1 control law used a fixed length for the look-ahead vector, which could cause instability at high speeds, as the effective gain is proportional to the vehicle's groundspeed [4]. Altering this distance to be a function of groundspeed solves this problem and the gain then stays constant, ensuring stability at all speeds. This was a necessary modification for operation in environments where the vehicle's groundspeed could change drastically, such as from wind in the case of UAVs.

In the original formulation of the L_2^+ algorithm the path to the aim point is commanded as a lateral acceleration. This was appropriate for UAVs that can directly control lateral acceleration, but is inadequate for ASVs which cannot. To support vehicles that cannot command a lateral acceleration, the radius of the turn is instead used to calculate a desired yaw rate. Then the necessary control surface command can be calculated using a model of the vehicle kinematics. The kinematic model for the SeaSlug described in Sec. IV-A.1 was used to calculate a mapping between yaw rate and rudder angle.

IV. SYSTEM PERFORMANCE

A. *Modeling*

1) Kinematics: The vessel kinematics follow the simple inverse-bicycle model illustrated in Fig. 6. This model is the generalization of a vehicle that can only propel itself along its longitudinal axis with a steering actuator at the rear. Its governing parameter is the distance between the center of rotation of the vehicle and the center of force from the steering actuator. For a ground vehicle this is the wheelbase: the distance between the axles. For a marine surface vessel, it is the distance between the center of rotation of the vessel and the center of pressure of the rudder. This leads to the following equations of motion:

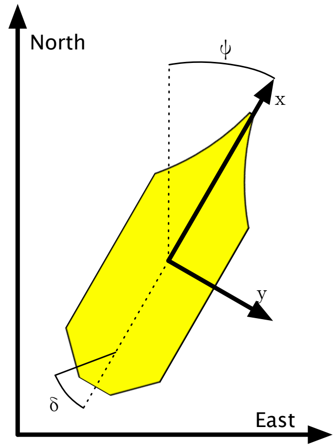

Fig. 6. Diagram of the geometry behind the inverse-bicycle model. δ is the rudder angle and ψ is the vessel's heading.

$$\begin{bmatrix}\dot{N}\\ E\\ \psi\end{bmatrix} = \begin{bmatrix} v_g \cos\psi \\ v_g \sin\psi \\ \frac{v_w \tan\delta}{L}\end{bmatrix} + \begin{bmatrix} v_{c_N} \\ v_{c_E} \\ 0\end{bmatrix} \tag{1}$$

N, E, and ψ are the north- and east-position and heading of the boat. v_g and v_w are the ground and water velocities of the vessel and v_c is the ground speed of the current. Note that the ground velocity is simply the vector sum of the water velocity and the current: $v_g = v_w + v_c$.

For this model it was assumed that there was no side-slip through turns. This is reasonable given both the speed of the vessel and the resistance offered by its weighted keel. The controlling parameter L, the distance between the center of rotation of the vessel and the average center of pressure of the rudder, was found to be 3.27m for the SeaSlug.

2) Dynamics: The dynamics of the vessel are largely ignored within the simulation model. Given that the primary actuator is the rudder, both the pitch and roll should have a negligible effect on steering. Pitch will only vary when traversing waves and should only affect the vessel over short timespans. Roll is similar, though it does change when the vessel is turning at higher speeds and may affect the rudder dynamics.

The rudder dynamics have been modeled using data from several experimental tests. These included tests with manual control where step changes in rudder angle were commanded at various velocities. This data revealed that the vessel speed had a negligible effect on the rudder response. The rudder was therefore modeled as a simple first-order lag:

$$\frac{\delta_{\text{act}}}{\delta_{\text{cmd}}}(s) = \frac{\tau}{s+\tau} \tag{2}$$

A least-squares fit was done over the data collected over several test runs and τ has been found to be 0.7s, which was found to model the rudder response well.

B. *Simulation*

Simulation has played a large role in the development of the SeaSlug and is included in every step of the development

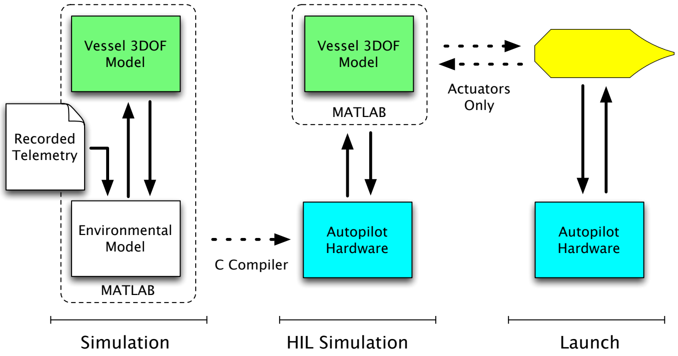

Fig. 7. The testing and development process of SeaSlug. There are four separate stages of simulation before a live test is done: full simulation, HIL, HIL with actuator feedback using small-scale subsystems, and then finally onboard testing.

workflow as shown in Fig. 7. The first simulation step is performed entirely on a PC and runs the same controller algorithms as that onboard the vessel. The next stage of testing involves hardware-in-the-loop (HIL) using the same hardware controller board that controls the SeaSlug. The simulator then runs only the environmental portion of the simulation with the controller executing as if it was interacting with actual hardware actuators. This data is interfaced with Simulink using a UDP connection, which is then converted in software to RS232 before being transmitted to the controller.

An additional HIL testing mode has been created that includes data from the actuator sensors, allowing for testing of the main controller with real actuator dynamics. In this mode the rudder is operated in the same way as it would be during a live test. The propeller is excluded from this mode as its sensor feedback is currently unused. While this mode was designed for operation onboard vessel while in dry-dock, it can also be used with any systems that have the same inputs and outputs as the vessel's systems. A small model of the vessel's rudder and propulsion subsystem has been constructed for in-lab testing of these systems.

With these additional HIL modes, the development process is shown in Fig. 7: full-simulation in Simulink, HIL simulation, HIL simulation with feedback using small-scale subsystems, and finally HIL simulation aboard the vessel while in dry-dock.

C. *Experimental Tests*

Experimental tests, both under manual and autonomous control, have been performed in the Santa Cruz harbor. Fig. 8 shows the vessel under autonomous control traversing a series of waypoints and then returning to its original location. Fig. 9 shows the heading and crosstrack error throughout the test. Heading and crosstrack errors spiked during waypoint transitions but then quickly approached zero. For the 3rd waypoint leg, involving a heading change of 10°, the RMS heading error was 2.6°. For this same leg the RMS Crosstrack error was 0.98m.

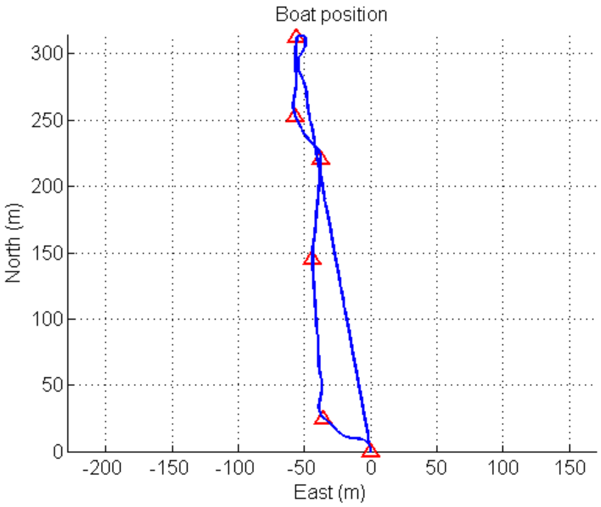

Fig. 8. Vessel path during an autonomous test run. Waypoints are shown as triangles with the desired path being straight lines between them. At the end of the waypoint run, the vessel returns to the origin.

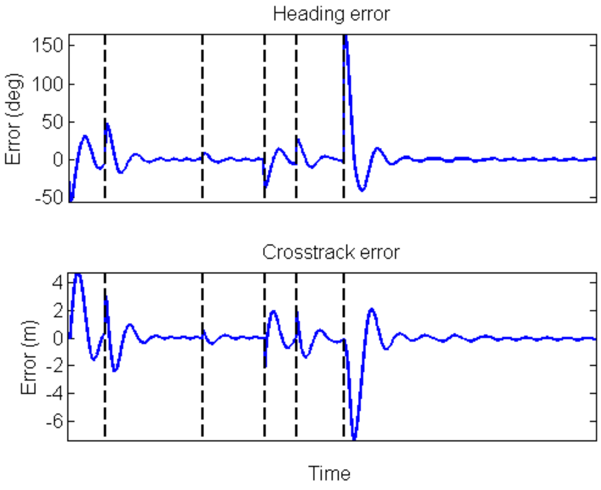

Fig. 9. Vessel crosstrack and heading error during the same test run as in Fig. 8. The vertical dashed lines indicate waypoint transitions.

Power usage during a manually-controlled test run of 1.25 hours is shown in Fig. 10. During this test the commanded throttle was varied to demonstrate the range of power usage. Power use varied between 400W and 750W with the propeller running between nominal and maximum speed. Over the course of the entire test run the measured power drain was about 10% for both battery banks. From this the calculated runtime at cruising speed is approximately 11 hours.

V. CONCLUSIONS & FUTURE WORK

A. *Conclusions*

This work presented the SeaSlug as an unmanned long-duration marine sensor platform. Preliminary experimental results were presented that validated its autonomous capabilities. The L_2^+ control law was shown to provide acceptable results for ASVs with an observed crosstrack error during line-following tests with an RMS crosstrack error of

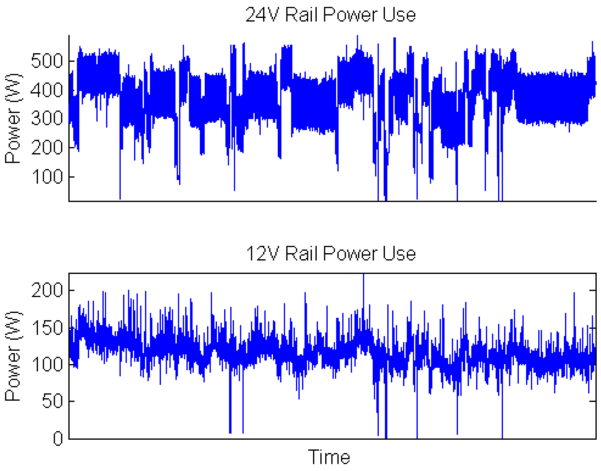

Fig. 10. Power usage during a manual control test run in the Santa Cruz harbor for both the 12V electronics battery bank and the 24V main battery bank.

0.98m. Observed power use showed a battery-only runtime of 11 hours, which is sufficient for planned short-duration missions. With solar charging enabled, this can be extended to a full 24 hours with no alteration to the onboard hardware or controller. Future work will lengthen this to the desired indefinite runtime.

B. *Future Work*

Near-term improvements to the SeaSlug platform focus on improved modeling of the vessel. Data from additional experimental tests will be used with an Extended Kalman Filter to find improved values for existing parameters. The vessel's kinematic model will be expanded to include the propeller dynamics using this same data. At this point velocity control can then be introduced to the control system.

Energy scavenging will receive improvements in order to extend the power capabilities to support indefinite-length deployments. Standard marine solar panels will be added, providing approximately 1kW of power at peak. Additionally power connections will be extended to the payload bays enabling integration of larger, more power-hungry sensors. A connection to the NMEA2000 bus will be routed to the payload bays as well to allow payload sensors access to the central data logger.

In order to operate for long durations in a busy environment, collision avoidance logic will be necessary. Both active radar and an AIS transceiver will be added for detection of other vessels. These sensors will feed into a high-level planner running on an additional computer which will then provide command inputs to existing controller.

ACKNOWLEDGMENT

This work was partially funded by a generous donation from Willow Garage and a grant from the University of California Discovery Grant program.

REFERENCES

[1] The Arduino homepage. `http://arduino.cc`.

[2] The ArduPilot project. `http://www.diydrones.com/notes/ArduPilot/`.

[3] M. Caccia, R. Bono, G. Bruzzone, G. Bruzzone, E. Spirandelli, G. Veruggio, and AM Stortini. Design and exploitation of an autonomous surface vessel for the study of sea-air interactions. In *Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference on*, pages 3582–3587. IEEE, 2005.

[4] R Curry, M Lizarraga, G Elkaim, and B Mairs. L_2^+, an improved line of sight guidance law for uavs. *American Control Conference*, June 2013.

[5] G. Elkaim and CO Boyce. An energy scavenging autonomous surface vehicle for littoral surveillance. In *Proceedings of ION Global Navigation Satellite Systems Conference*, 2008.

[6] J.R. Higinbotham, J.R. Moisan, C. Schirtzinger, M. Linkswiler, J. Yungel, and P. Orton. *Update on the development and testing of a new long duration solar powered autonomous surface vehicle*. IEEE, 2008.

[7] G. Hitz, F. Pomerleau, M.-E. Garneau, C. Pradalier, T. Posch, J. Pernthaler, and R.Y. Siegwart. Autonomous inland water monitoring: Design and application of a surface vessel. *Robotics Automation Magazine, IEEE*, 19(1):62 –72, march 2012.

[8] K.E. Laws, C. Bazeghi, S.C. Petersen, and J.F. Vesecky. An autonomous sensor platform vessel for marine protected area monitoring. In *Geoscience and Remote Sensing Symposium,2009 IEEE International,IGARSS 2009*, volume 4, pages IV–991 –IV–994, july 2009.

[9] M Lizarraga. Design, implementation and flight verification of a versatile and rapidly reconfigurable uav gnc research platform. 2009.

[10] Lee A. Luft, Larry Anderson, and Frank Cassidy. Nmea 2000: A digital interface for the 21st century. Technical report, National Marine Electronics Association, Jan 2002.

[11] J. Manley and S. Willcox. The wave glider: A persistent platform for ocean science. In *OCEANS 2010 IEEE-Sydney*, pages 1–5. IEEE, 2010.

[12] Lorenz Meier. Mavlink: Micro air vehicle communication protocol. http://qgroundcontrol.org/mavlink/start.

[13] Lorenz Meier, Petri Tanskanen, Lionel Heng, Gim Hee Lee, Friedrich Fraundorfer, and Marc Pollefeys. Pixhawk: A micro aerial vehicle design for autonomous flight using onboard computer vision. *Autonomous Robots*, pages 1–19. 10.1007/s10514-012-9281-4.

[14] S Park, J Deyst, and J How. A new nonlinear guidance logic for trajectory tracking. *AIAA Guidance, Navigation and Control Conference and Exhibit*, Jan 2004.

[15] S. Wood, M. Rees, and Z. Pfeiffer. An autonomous self-mooring vehicle for littoral & coastal observations. In *OCEANS 2007-Europe*, pages 1–6. IEEE, 2007.

[16] ETH Zurich. Qgroundcontrol: Ground control station for small air land water autonomous unmanned systems. http://qgroundcontrol.org/.