Implementation of Energy Harvesting System for Powering Thermal Gliders for Long Duration Ocean Research

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Abstract— **The exploration of the Earth's oceans is aided by autonomous underwater vehicles (AUVs). AUVs in use today include floats and gliders; they can be deployed to profile salinity, temperature and pressure of the ocean at depths of up to 2 km. Both the floats and gliders typically control buoyancy by filling and deflating an external bladder with a hydraulic fluid delivered by an electrical pump. The operation time of an AUV is limited by energy storage. For floats, such as the Argo float, the operating duration is approximately 5 years with the capability to dive once every 10 days. For electric gliders, such as the deep G2 Slocum, the mission duration can be up to one year with lithium primary batteries. An energy storage system has been developed that can harvest energy from the temperature differences at various depths of the ocean. This system was demonstrated on an Argo style float and has been implemented in a thermal version of the Slocum glider. The energy harvesting system is based on a phase change material with a freeze thaw cycle that pressurizes hydraulic oil that is converted to electrical energy. The thermal Slocum glider does not use an electrical pump, but harvested thermal energy to control buoyancy. The goal for the thermal Slocum glider is for persistent ocean operation for a duration of up to 10 years. A thermal powered glider with an energy harvesting system as described can collect conductivity, temperature, and pressure data and deliver it to the National Data Buoy Center (NDBC) Glider Data Monitoring System and the World Meteorological Organization (WMO) Global Telecommunications System (GTS). Feeding into operational modeling centers such as the National Centers for Environmental Prediction (NCEP) and the U.S. Naval Observatory (NAVO), this data will enable advanced climate predictions over a timespan not currently achievable with present technology. Current testing of the thermal powered Slocum glider is to determine the durability of the technology and quantify the glider system design. Previous issues with this technology included energy storage system management and glider mechanical limitations. Our objective is to learn how to fly an energy harvesting thermal glider that interacts with the ocean environment efficiently. We would also like to establish the latitudinal range of operation. This thermal powered Slocum glider, dubbed Clark, after the famous explorer duo Lewis and Clark, has been deployed off of St. Thomas for flight dynamics and durability testing. The following paper will discuss the deployment and testing of the thermal powered Slocum glider. We will also discuss the advantages of ocean energy harvesting technology for oceanographic research.**

Keywords—glider, thermal glider, thermal recharging

I. INTRODUCTION (*HEADING 1*)

Stemming from a technology development cycle in the early days of the National Oceanographic Partnership Program (NOPP), Rutgers University has maintained a close working relationship with Teledyne Webb Research Corporation (TWRC), often serving as a testbed for new designs, improvements, or enhancements to the Slocum glider. The first prototype of this glider was deployed off the coast of New Jersey in 1999, and Rutgers purchased their first commercially available Slocum Electric glider in 2003. By 2007, Slocum gliders had been declared a viable technology for sustained ocean observations [1]. With the largest fleet of Slocum gliders in the world outside of the U.S. Navy, Rutgers has gained valuable operational experience from over 400 deployments around the world. A first-ever Slocum-TREC (Thermal RECharging) deep ocean glider has been developed through a partnership between Teledyne Webb Research Corporation (TWRC) and the National Aeronautical Space Administration's Jet Propulsion Laboratory (NASA-JPL) for the Office of Naval Research (ONR). Slocum-TREC is a thermal-class glider that can harvest energy from the ocean thermoclines. A photo of the Slocum-TREC "Clark" is shown as Fig. 1. The Slocum-TREC ocean glider was deployed on June 9th 14 miles off the coast of St. Thomas, U.S. Virgin Islands. The goal of Slocum-TREC is to demonstrate the feasibility of the thermal buoyancy drive and TREC energy harvesting system to power deep ocean floats that can operate autonomously for periods of up to 10 years.

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Fig. 1: Photo of the Slocum-TREC Glider "Clark"

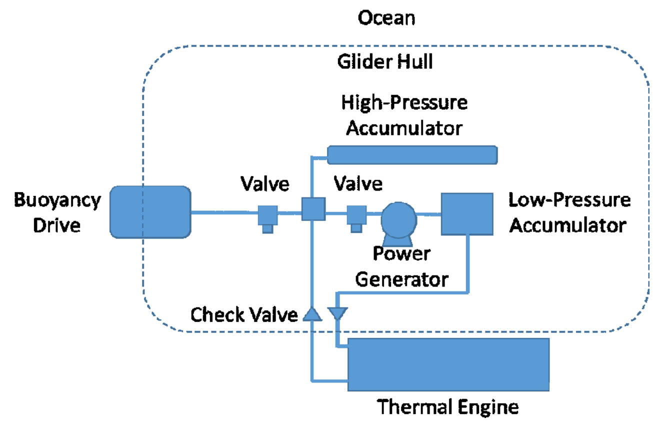

Fig. 2: Functional schematic of Slocum-TREC energy harvesting and thermal buoyancy drive

II. Background

A. Glider Configuration

The Slocum-TREC glider is currently configured to operate with one scientific instrument to measure conductivity, temperature, and depth (CTD). Thermal-class gliders use a thermal engine to directly drive a buoyancy pump that controls the ocean glider's depth and ascent rate. It is capable of diving to 1200 meters and is currently programmed to dive up to 4 times a day. This ocean glider is not limited by battery energy storage.

1) Energy Harvesting System

A functional schematic of the Slocum-TREC energy harvesting and thermal buoyancy drive is shown as Fig. 2. As the glider travels through an ocean thermocline, a phase-change wax in the thermal engine undergoes a freeze-thaw cycle. As the phase-change wax is thawed, the expansion of the wax pressurizes the hydraulic oil in the thermal engine. As the hydraulic oil is pressurized, the energy from pressurization is captured in a high-pressure accumulator. The energy stored in the high-pressure accumulator can then be discharged to the gliders buoyancy drive to provide propulsion [2]. The energy storage in the high pressure accumulator can also be discharged to a power generator to be converted to electrical energy [3]. The electrical energy is used to provide electrical power to the glider to support hotel loads, science and communications. After the oil storage in the high-pressure accumulator is discharged, it is collected in the low-pressure accumulator and fed back to the thermal engine during the phase-change wax freeze cycle.

2) Field test, Energy Harvesting

The energy storage battery voltage of the TREC system during ocean testing is shown as Fig. 3. The TREC energy storage system is configured of two batteries, one battery is being charged by the energy harvested from the ocean by the TREC system, the other is used to provide electrical power to the Slocum-TREC ocean glider. The energy storage batteries are cycling between 13.2 and 13.4 Volts. These battery voltages correspond to approximately 40 to 75% state-of-charge (SOC). Operating the batteries in this SOC range will maximize battery cycle life to meet the program goals of 10 years of operation. The battery set points are controlled from land and can be changed to operate in a SOC range required by a specific mission. An example of a power generation cycle for the TREC system during ocean testing is shown as Fig. 4. A typical generation cycle runs between 40 to 45 seconds. The maximum charge power is approximately 220 Watts. The average energy generated by the TREC system per dive is approximately 1.8 Wh. The estimated energy storage is approximately 1.7 Wh/Dive, this includes the efficiency of the batteries under these charge conditions. In the present operating mode, a battery could deliver approximately 70 Wh electrical energy every 80 generation cycles. This energy can be delivered at power levels as high as 800 Watts. This capability can enable the operation of high-power science instruments on a Slocum-Class ocean glider with the persistence of years of operation.

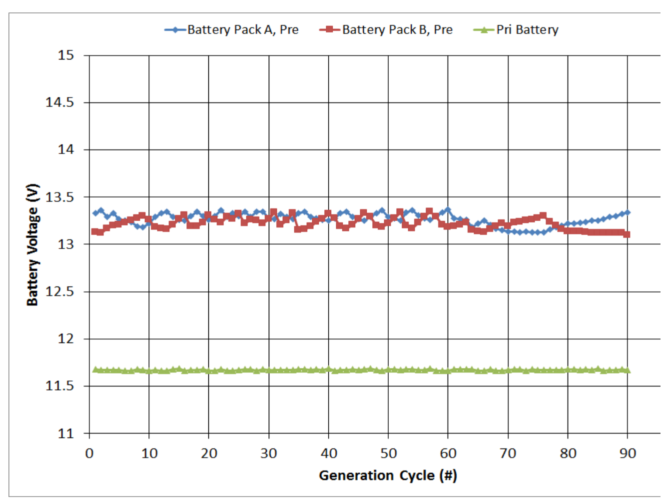

Fig. 3: Energy storage battery voltage of TREC system

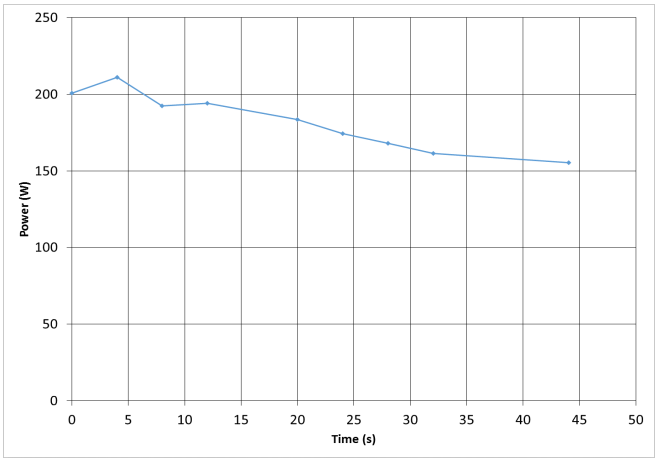

Fig. 4: TREC system energy generation cycle

B. Ballasting and Flight Dynamics

Engineers from TWRC, NASA-JPL, and Rutgers combined their expertise at the University of the Virgin Islands (UVI) in St. Thomas, USVI to assemble, ballast, and deploy the Slocum-TREC for a long duration test flight. The importance of stringent control of ballast is exacerbated by the buoyancy drive; too light and the glider cannot dive to the depths and temperatures it needs to reach to achieve a thermal charge, too heavy and the glider is unable to surface, which ultimately leads to the expulsion of an ejection weight and the end of the mission, requiring an emergency recovery.

Flight characteristics are generally similar to standard electric gliders, but volume and structural differences change the dynamics, giving the Slocum-TREC its own signature flight pattern and nuances. Ballasting was conducted in Brewers Bay, a relatively sheltered patch of water adjacent to UVI's dock, with only a moderate predominate wave and current field. Reliant upon the CTD attached to the Slocum-TREC, data were obtained, density calculations were made, and ballast was adjusted accordingly. Fine adjustments were made at sea, once flight parameters were analyzed following a test dive, by adding small ballast weights externally to achieve a symmetrical yo (dive and climb) pattern. Total symmetry in the yo could not, however, be obtained due to water mass layering. The decision was then made to aim for symmetry in the top water mass, allowing the glider's vertical velocity to slow in the deep water masses; the effects of which are mitigated by compaction of the carbon fiber hull resulting in a lesser volume, and therefore less buoyancy. Further flight dynamics adjustments required recovery and needed to be performed in the lab. Specifically, an inherent roll was noticed that would switch signs from the average on the dive and climb; rolling slightly to port on the dive and hard to port on the climb; this can be seen in the top plot of Fig. 5. A detailed inspection and measurements in the lab uncovered a slight twist between the hull and the thermal engines, effectively turning the entire glider into a rudder. The twist was corrected, and roll has been steady at less than -2 degrees as seen in the bottom plot of Fig. 5.

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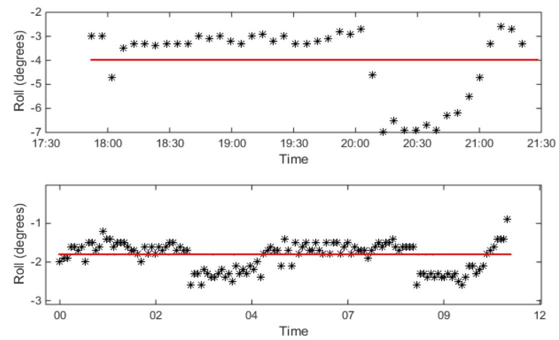

Fig. 5 – Roll before and after fixing the twist in the hull. Red is average roll; -4 degrees prior and less than -2 after.

III. Results

A. Characterization of physical structure – salinity, temperature, and density off the U.S. Virgin Islands

The Slocum-TREC is equipped with a Seabird Electronics (SBE) 41 CP CTD - a low power, 1 Hz continuously profiling flow-through cell CTD originally designed for profiling floats that has proven effective over long periods of unattended operations [4]. This allows for the continual collection of conductivity and temperature data, providing a clear picture of the physical structure of the water column. Initial analysis of the CTD data raised some concerns related to the calibration of the instrument, as results were atypical of the deep water column structure commonly seen in other areas. Once instrument calibration was verified by TWRC, a closer look was taken at the climatology of the area via the Caribbean Coastal Ocean Observing System (CariCOOS.org), a Rutgers partner through the Integrated Ocean Observing System (IOOS). The atypical structure is a subsurface peak of high salinity water nearly 37 psu sitting at a depth of almost 200 m known as the Subtropical Underwater (SUW) mass. The SUW is almost 2 psu higher than the deep water masses in the area, but is more than 15 degrees C warmer, ensuring a stable water column with no density inversions (Fig. 6). The lower salinity top water layer is known as the Caribbean Surface Water (CSW) mass, and, when time shifted, shares a decent correlation to the outflow of the Orinoco River basin in Venezuela [5]. Further freshwater input to the area comes from North Atlantic surface waters and the immense outflow of the Amazon River basin, resulting in a significantly less dense surface water in the top 100 m approximate depth [6]. The CSW exhibits a strong seasonal cycle between the summer and fall in both the depth and intensity of the halocline, corresponding to the lack of or abundance of freshwater input from South America [5]. It is this water mass and its fluctuations that makes its way onto the shelf and impacts marine life in and around the islands. The Slocum-TREC boasts its advantage as a superior platform for sustained ocean observing operations focusing on these types of measurements, as it has the ability to profile continuously for years while actively controlling its location as opposed to Lagrangian-style floats that must ride the predominate currents. Several seasonal cycles could be observed on a single Slocum-TREC deployment, closing data gaps and possibly raising correlations to related climatic cycles.

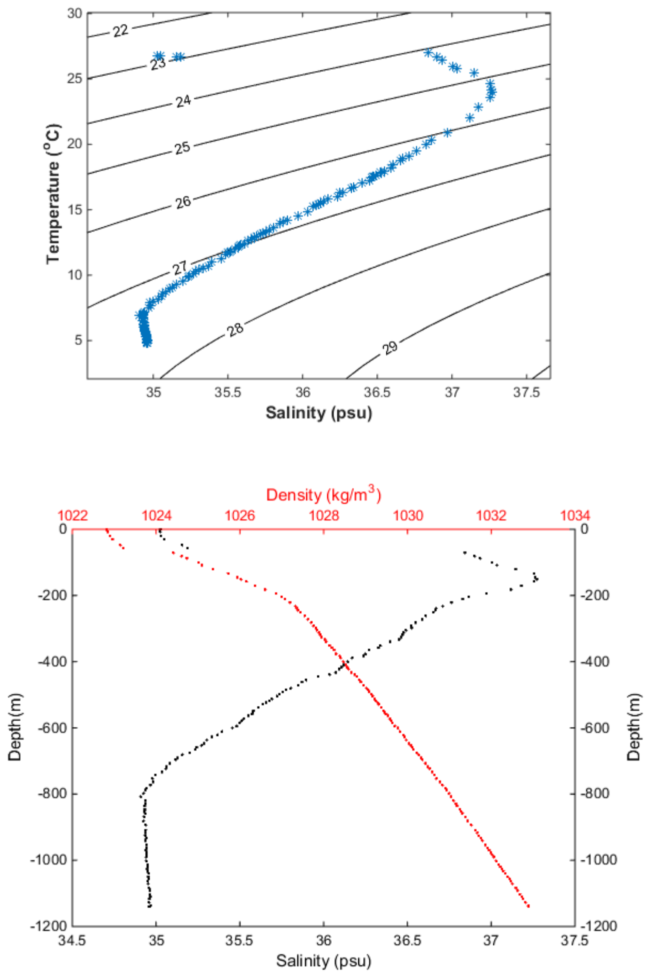

Fig. 6 – T-S diagram, salinity field and density structure showing water column stability. All data transmitted back from "Clark".

B. *Quantification of system design and limitations*

While the Slocum-TREC is currently deployed and fully operational, there are several components of the system that still require quantification. The thermal power generation and energy storage system developed by JPL has been thoroughly tested, measured, and documented, and is described above in detail. Thermal harvesting and power generation has, in fact, been so efficient that the Slocum-TREC has been shunting excess energy, and CTD horizontal resolution has been increased to sample on every dive. The overachieving nature of this system will likely lead to further design improvements as more energy intensive instruments can be integrated to further enhance ocean sampling. Initial musings include increasing sampling resolution in water masses of interest, along with integrating a pumped CTD such as the SBE GPCTD to improve thermal lag calculations in high vertical resolution sampling of strong thermoclines. The latitudinal limits of operation, however – how far north or south the glider can operate while continuing to obtain a thermal charge – are more difficult to discern. The glider requires a thermal difference of at least 12 degrees C between the surface and its maximum dive depth of 1200 m, spending approximately 120 minutes at <8 degrees C for the wax to freeze, plus an additional 120 minutes at >20 degrees C for the wax to melt in order to obtain a thermal charge. While oceanographic models may assist in determining general latitudinal limits, this can change in the short term as currents meander or eddies form and migrate. On a larger time scale, latitudinal limits may expand in the future as oceans continue to warm. One pressing limitation that the Slocum-TREC team has not addressed is a concept familiar to many who have conducted long duration oceanographic studies – biofouling. Ablative paints and other standard antifouling methods have proven ineffective over long durations, and newer technologies such as those resembling shark skin coatings are not yet commercially available. By continuously harvesting thermal energy, the Slocum-TREC has solved the propulsion and energy budget limitations, perhaps thrusting biofouling to the forefront of the list of issues facing long duration ocean sampling.

C. *Data Flow and Implications for the Future*

Currently, data collected by the Slocum-TREC "Clark" is transferred via the Iridium satellite constellation and routed directly to TWRC. This is then synced to a server at Rutgers where data is displayed on the web in near real-time. From Rutgers, this data is ported into the Global Telecommunications System (GTS) for ingestion into oceanographic models by operational modeling centers such as the National Centers or Environmental Prediction (NCEP) and the U.S. Navy (NAVO). NCEP's mission statement refers to delivering climate products essential to protecting life, property, and economic well-being, immediately vesting their interest in the expansion of the collection of accurate, high resolution ocean data. Through the GTS, data collected by gliders, floats, and other assets can be assimilated into models such as the Real-Time Ocean Forecasting System (RTOFS), a global operational model based on an eddy resolving 1/12° global HYCOM (Hybrid Coordinates Ocean Model) developed by the U.S. Navy [7]. Future plans for RTOFS include inputs to hurricane and climate forecast systems, further emphasizing the need for high resolution data collection in sparsely sampled areas. The strengths of the Slocum-TREC become apparent in this context, showcasing the ability to routinely gather high resolution data that can be regularly transmitted ashore for a cost that diminishes throughout the life of the glider. Daily assimilation into models can assist with improving ocean, terrestrial, hurricane and climate forecasting at a level that is unparalleled by any other oceanographic platform.

IV. CONCLUSIONS

Thus far, the Slocum-TREC deployment has been a resounding success. "Clark" has been continually operating in the Virgin Islands Trench, sending full-profile data ashore in user-configurable intervals of anywhere from 6-12 hours; further adjustable if desired. The ocean glider operators, dubbed pilots, since the glider does "fly", are currently in the process of optimizing and adjusting flight and energy storage parameters. The first stage of endurance testing will be complete after 90 consecutive days of deployment. The goal for the second stage of endurance testing is for continued operation greater than 200 days. After the second stage of endurance testing, the glider's flight and energy system data will be evaluated and an extended mission will be proposed. The third mission will likely traverse the Atlantic, including paths suggested by Rutgers undergraduates studying the global ocean models and working on detailed path-planning projects, allowing "Clark's" success to transcend the engineering community and enter the educational community as well.

ACKNOWLEDGMENTS

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