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Towards the optimal operation of a thermal-recharging float in the ocean

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ABSTRACT

A large number of profiling floats are currently in use around the world oceans to monitor oceanographic conditions. Generally, floats are in motion by the buoyancy force, and missions of data collection, storage, and communication are carried out relying on Lithium-ion batteries. Chao et al. developed the TREC float which is operated on batteries rechargeable from the ocean thermocline. It uses a patented TREC (Thermal RECharging) engine which is a thermo-mechano-electric converter utilizing a Phase Change Material (PCM) system for energy harvesting. Data are desired from a target area, but the floats have lacked a way to stay on target, carried away from it by ocean currents. An alternative solution is proposed in the present study combining a profile float (the TREC) with small thrusters to allow for location correction. The main purpose of this study is to solve an optimal energy allocation problem through the numerical analysis of the nonlinear correlation between energy harvesting and consumption. A powered TREC is designed by sizing a feasible thruster to translate back to the target area. A parameter study on energy allocation is carried out with various types of translation motion (vertical, horizontal, and rotational for *Options V, H,* and *R*), and the geometry of the float (spherical and cylindrical end shapes for *Options S,* and *C*). Option R is the most promising candidate under the design requirements, though it must be noted that the location correction phase takes much longer due to the rotation time.

1. Introduction

The main objective of the present work is to carry out a feasibility study to provide optimal mission profile for the float powered by thermal rechargeable battery. While the energy is harvested from the float diving between the surface and 1 km down in the ocean, the float is drifted away from the target location due to random ocean currents. A propeller thruster is installed to control the position of the float and travel back to the target location. The present study will investigate nonlinear relationship between the energy harvesting and consumption in terms of the float shape, float orientation in motion, ocean current speed, the number of float dives, drifting distance, and efficiency of the thruster.

The oceans cover 2/3 of the earth's surface and play an important role in maintaining the health of the earth's biosphere, but exploring the ocean in detail has practical problems. The exploration of deeper regions is even more difficult. The common approach uses moving ships, a mooring platform, or the autonomous underwater vehicle (AUV). The mooring platform is stationary at a fixed location where the sensors are attached along the wire connected to the anchor on the seafloor. These are relatively expensive and limited their numbers.

On the other hand, recent development of autonomous underwater vehicles (AUVs) makes it possible to extend the ocean exploration beyond ship tracks and fixed mooring locations. A float can move up and down the ocean while being drifted horizontally by ocean current. Currently, there are close to 4000 floats already as part of the international Argo program (http://www.argo.ucsd.edu, see Fig. 1). Floating sensors that communicate by satellite have proven their worth in the Argo project that explores ocean temperature and salinity worldwide.

Currently, the Argo floats are all powered by primary batteries and therefore can make a limited number of dives between surface and 2000 m. The average life of the latest model Argo floats are around 3.7 years, but the exact lifetime for a particular float depends on the depth of the mission profile and the surface water density. The average Argo floats with lithium battery operate on the order of 200 cycles with surfacing frequency ranging from every few hours to 10 days. The short battery lifetime and high cost for battery replacement/recharging are probably the single most limiting factor to prevent the use of gliders and/or AUVs away from the ship or coast. To combat energy limitations, Viet devel-

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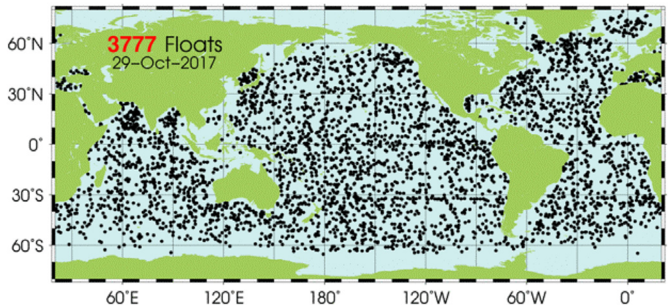

Fig. 1. The latest picture of the Argo array (Argo, 2017).

oped a floating energy harvester using the piezoelectric effect to harvest the energy from intermediate and deep water waves (Viet et al., 2016). Nakamura proposed the SKWID concept as a new type floating wind turbine for low cost energy capturing from the ocean (Nakamura et al., 2013). The innovative Thermal RECharging (TREC) engine was designed by Chao et al., which uses a thermo-mechno-electrical converter to harvest energy from the temperature differences between warm surface water and cold deep waters (Chao, 2016). It uses pre-selected phase change materials (e.g., pentadecane, $C_{15}H_{32}$) that exhibit substantial thermal expansion during the solid-to-liquid phase transition when experiencing significant temperature changes (e.g., 10^oC). This mechanical expansion will create pressure difference, which is subsequently used to drive an generator to produce electric power. The generated electric power is stored in recharging batteries or super-capacitors. Wang investigated the feasibility of using solid/liquid PCM to harvest environmental thermal energy associated with temperature differentials (Wang et al., 2017).

A major advantage of the TREC engine over the Li-battery is that the float mission lifecycle can be increased by at least an order of magnitude, not to mention the cost saving to recover/replace/redeploy those dead floats and the reduced environment impact of leaving dead batteries at sea. The TREC engine used to power the float using only about 10 kg of PCMs to generate about one watt-hour of energy every time when it dives between the warm surface waters and cold waters at depths. The results from the TREC prototype tested in the ocean suggest that a minimum of 1 kJ can be harvested from a dive down to $1,000$ m in depth using 1 kg of PCM.

On the other hand, data from a localized region needs to be monitored by the float, which is constantly drifting off target due to random ocean currents. An effort to add a propulsion system to the float is made in the present study to re-locate the float by correcting the drifting distance. A propeller type thruster could be considered as an efficient way to generate propulsive force. Associated energy consumption should be provided by the recharged batteries and is investigated through a numerical study which formulates nonlinear relations of the amount of energy harvesting, resistance with respect to the float orientation during the motions, flat geometry, ocean current speed, and the thrust level of the propeller thruster. The development of such a simulation capability is both valuable in its own right and essential for efficiently designing and scaling the TREC engine for specific applications through the laboratory experimentation.

Two types of the float with the end structure of sphere or cylinder shape are considered for the comparison of energy efficiency and mission completion time of the position correction. Option S denotes the float with the sphere, Option C is used for the float with the cylinder. Three orientation positions are considered during the translation phase, horizontal, vertical, and rotational, notated as *Options H, V*, and *R*, respectively. The motion of Option SV represents the float with the sphere end structure moving in the vertical orientation. More detailed explanation will be presented in the section 2.2. Shapes of the float and orientations and Fig. 5. The overall efficiency of the thruster is inferred based on the commercially available thrusters used in UAVs. Analysis is conducted using a combination of Computational Fluid Dynamics (CFD) and various optimization techniques in order to achieve the following objectives.

- Predict hydrodynamic forces acting on the float at various cruising speeds with respect to float shape and orientation during the horizontal and vertical motions.
- Estimate the total energy consumption during location correction and determine feasibility for a design constrained by a limited energy capacity.
- Decide upon a feasible thruster to complete location correction in cruising energy requirements, based on the resulting estimations.

The organization of the paper is as follows. In Section 2, introduction of the rechargeable float is made with the discussions on the thermal energy harvesting using the TREC engine and the target mission profile for the location correction. The estimation of the ocean background current is made based on the 18-month long field-test results. Numerical methods to analyze the float motions are discussed in Section 3 to compute the amount of resistance for the floats different in shape (i.e., sphere vs. cylinder ends), orientation during the vertical and horizontal motions. For the location correction phase through the horizontal motion, the terminal velocity and the traveling time are estimated for the floats moving with the motions of *Options V, H*, and *R*. Rotation time for the float with the *Option R* is also calculated. Finally, in Sections 4 and 5, the net energy is calculated by predicting required prop-input and prop-output energy in consideration of efficiency of the thruster.

2. Rechargeable floats

The mechanics of energy harvesting of the TREC engine is shown in this section, followed by the specifications of the float powered by the TREC engine. Float shape and the entire mission profile are given in detail in consideration of the ocean currents.

2.1. Thermal energy harvesting

The TREC engine is a patented, thermo-mechano-electric converting device shown in Fig. 2. It uses pre-selected phase change materials (e.g., pentadecane, $C_{15}H_{32}$) that exhibit substantial thermal expansion during the solid-to-liquid phase transition when experiencing significant temperature changes (e.g., 10^oC), where the ideal operating temperature ranges between 8^oC to 16^oC.

The PCM changes the volume depending on the surrounding temperature, i.e., it contracts the volume at low temperature down the ocean (∼ 1 km down) and expands at normal temperature near the ocean surface. This mechanical expansion will create pressure difference, which is subsequently used to drive an electric generator. The generated electricity is stored in recharging batteries or supercapacitors to produce power. Materials research performed thus far indicated that substances similar to pentadecane could provide adequate performance across a number of oceanic temperature regimes.

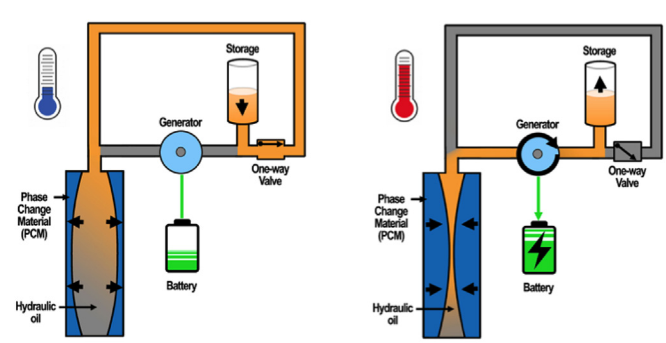

Fig. 2. Schematic of the TREC engine (Seatrec, 2017).