SLOCUM: An Underwater Glider Propelled by Environmental Energy

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***Abstract*—SLOCUM is a small gliding AUV of 40 000-km operational range which harvests its propulsive energy from the heat flow between the vehicle engine and the thermal gradient of the temperate and tropical ocean. The design of both the glider and the thermal engine are discussed including the design genesis and approach, field trial results, concept strength, and limitations and potential use.**

***Index Terms*—AUV, glider, SLOCUM, thermal propulsion.**

I. BACKGROUND

IN 1978, a group at the Woods Hole Oceanographic Institution (WHOI) discussed adding horizontal propulsion to SOFAR floats [1]. These discussions created the nucleus of thinking that led to the SLOCUM design. Looking back, there are two interesting features of these discussions: they specifically addressed understanding circulation rather than hydrography; that is, a moving vehicle might provide more insight than a fixed mooring or a drifting, neutrally buoyant float; and many important system components were in place, a large neutrally buoyant vehicle with a substantial battery and an appropriate acoustic navigation and telemetry system.

These ideas were not realized in hardware, and in 1981 plans began to develop about simple, neutrally buoyant profilers which would periodically ascend to the surface and report position and data to the ARGOS satellite system. The result was the evolution of the ALACE and BOBBER profilers, [2], [3] and their successors, SOLO, APEX, and MARVOR.

The concept of vehicles capable of extended and controlled oceanic voyages remained alive and in 1988, during work on BOBBER, a new synthesis emerged; a practical design of a vehicle and engine able to cycle vertically using propulsion energy harvested from the thermocline was realized. The vehicle could move vertically through the ocean, using energy harvested from the environment. This is a simple concept of a heat engine which provides the buoyancy changing propulsion energy to drive the engine itself between the source and sink of heat at a useful speed. Immediately apparent was the possibility of converting the vertical displacements to controllable excursions, both horizontal and vertical, by arranging suitable lift and control surfaces and adding appropriate electronic control, navigation, communication, and sensor systems. That is the long-range glider, named SLOCUM after Joshua Slocum, the first solo global circumnavigator [4], [9].

The use of environmental energy for propulsion is obviously desirable, the three most realistic approaches are solar, wave, or thermal energy sources. Thermal energy was chosen since it is reliably and predictably available at all hours, it can be harvested while underway, and it exploits a reasonably simple engine design. Thermal propulsion has limitations; the most important is that the temperature gradient is not available globally.

A preliminary design was prepared and work started under contract with Henry Stommel at WHOI. Three major design initiatives were required: master the glider hydrodynamic design, demonstrate the thermal engine in the laboratory and field, and finally show both working together. The concept was an inexpensive vehicle suitable for long-range and endurance ocean exploration using a network of gliders. The design was to be suitable for making vertical and horizontal observations for ocean monitoring and surveying, for station keeping, and for seeking out, locking on, and surveying oceanic features. Of the three applications, the coordinated network of vehicles engaged in long-term ocean monitoring seemed the most attractive first goal.

II. GLIDER DESIGN

A prototype gliding vehicle was designed, constructed, and field-tested. The design process was facilitated by comparing in-water glider performance with a hydrodynamic simulator. The simulator was originally developed to model dirigibles and was modified for buoyancy-driven gliders by Henry Jex, System Technology, Inc. The glider, which glides both up and down, included an autopilot and flight recorder and was tested using a battery-powered buoyancy engine at Wakulla Springs, FL, in February 1991 and Seneca Lake, NY, in November 1991 [5], [6]. Both trials included a range of operating parameters using visual observation and internal records of heading, pitch, roll, pressure, and steering actuator position.

These gliders and subsequent WRC designs are steered by changing the position of the center of gravity with respect to the center of buoyancy, thus controlling both pitch and roll. The wing is arranged so that roll results in a yaw moment thus steering the glider. This design approach to steering was the result of concerns about reliability of through-hull actuators or shafts during extended operations and has been successful. The main battery is eccentrically mounted and supported on a carriage equipped with pitch and roll actuators. Most of the pitch moment is generated by the movement of fluid in the main buoyancy changer, and the moment due to controlled movement of the battery is used for fine adjustment of pitch angle. Pitch and roll are measured with gravity inclinometers, heading with a flux gate compass.

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Pitch and roll control range is ±40°, achieved by translating and rotating the main battery pack. The center of buoyancy is approximately 4 mm above the center of gravity in a glider in horizontal equilibrium, therefore the 12-kg battery must be displaced approximately ±12 mm. Axial displacement uses a lead screw and lateral displacement result from rotation of the asymmetric battery. The yaw moment for steering is achieved by mounting the wings aft of the center of buoyancy, and when rolled, the lateral component of lift creates a yaw moment. Steering is well behaved with a minimum turn radius of approximately 7 m.

1991 glider specifications:

Length	3.2 m
Diameter	0.165 m
Displacement	40 kg
Hull	aluminum alloy 6061-T6
Collapse depth	2600 m
Wings:	Configuration: straight cruciform, swept planform: vertical 0.036 m^2, 66° swept back, 3.9 AR, horizontal 0.067 m^2 each, 43° degree swept back, 1.6 AR, thickness 15.9 mm.

The field trials showed good agreement between actual and predicted performance down to a stall angle of 8°, stable performance, excellent recovery from perturbation, and zero pitch oscillation.Horizontal speed was 0.25 ms^{-1} at 40° dive-angle with a buoyancy drive of ±50 g.

Many observers are surprised by the steepness of the optimal dive angle of approximately 40°; however, field measurements and simulator results both show a broad optimum of 30° to 45°. The design goal is maximum horizontal speed for a given engine, i.e., a given buoyant force, and the buoyancy charge is replenished without penalty every cycle, that is, there is a free refueling every cycle, and the best balance is to dive steeply and move quickly to the next refueling. In a battery-powered glider, every reduction in drag results in improved performance. In the thermally powered SLOCUM, design steps toward desirable drag reduction can be balanced against steps to increase engine size and output [7].

III. THERMAL ENGINE

The engine propels the glider by changing vehicle buoyancy. Heat is absorbed from the warm surface water and rejected to the cooler, deep water during the vehicle's transit through the thermocline, and causes a change of state of an internal working fluid which undergoes a volume change upon change of state. The resulting volume change of the fluid provides an adequate change in buoyancy of a vehicle of constant mass to enable it to ascend and descend at a useful speed. This variable buoyancy, derived from environmental energy, is the sole source of glider propulsion power.

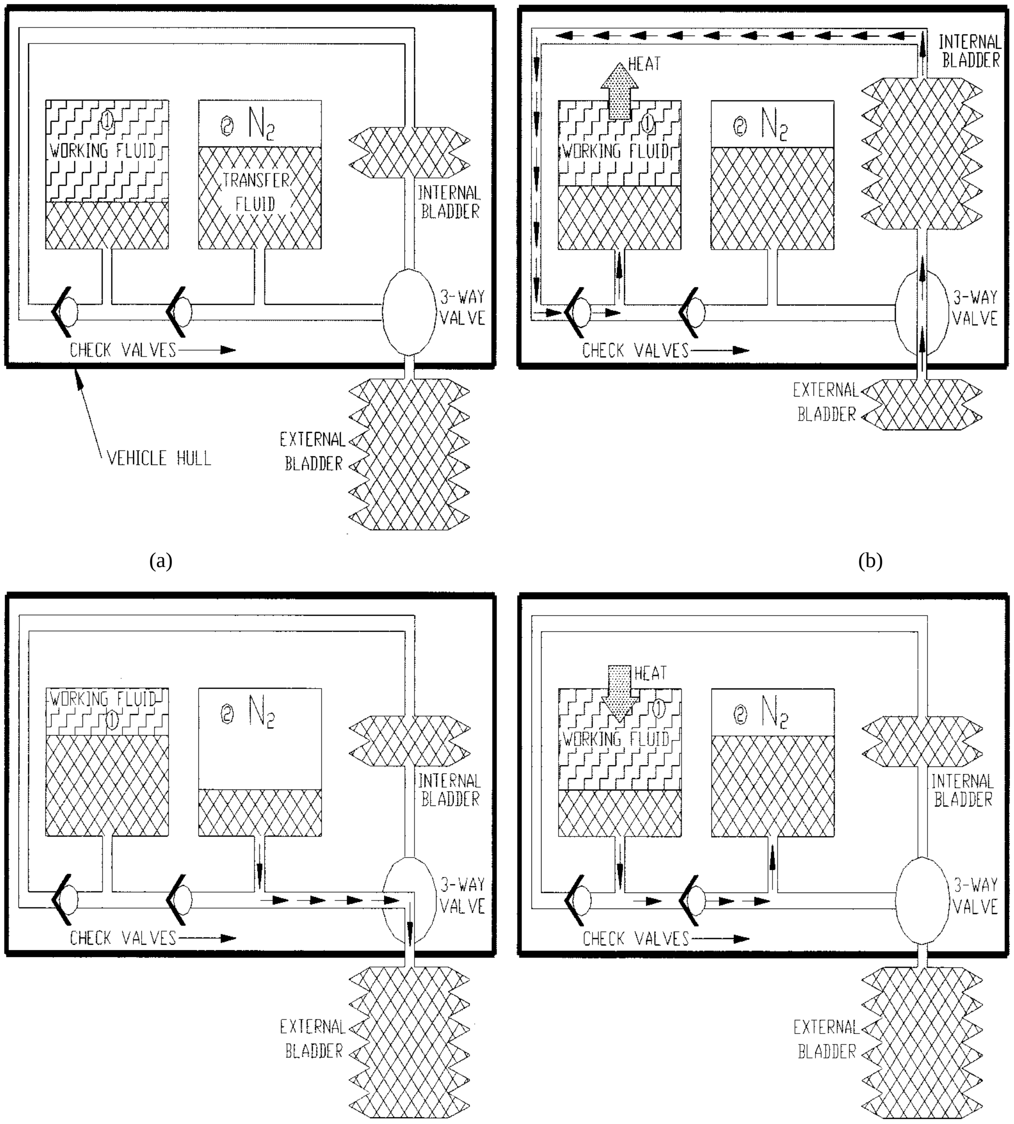
Heat engines using liquid-vapor state change are familiar, however, in SLOCUM the less familiar change between liquid and solid is used. Most liquids contract on freezing, and the expansion on melting exerts a large pressure well-matched to oceanic pressures. The four stages of the thermodynamic cycle are shown in Fig. 1.

Environmental energy is harvested by heat flowing into and out of the working fluid in chamber (1), which expands on freezing and contracts on melting. The resulting work is transmitted around the system by the transfer fluid, typically ethylene glycol. Chamber (2) is an energy storage accumulator, with the transfer fluid pressurized by nitrogen at a pressure greater than the maximum external ocean pressure.

- Fig. 1(a) shows the vehicle in stable thermal equilibrium in the warm surface water, N_2 compressed, external bladder inflated, and working fluid expanded.
- Descent begins by opening the three-way valve [Fig. 1(b)], venting the external bladder to internal bladder. The pressure differential for this flow is created by maintaining the hull interior slightly below atmospheric pressure. As the vehicle reaches cold water, heat flows out of the working fluid, which freezes, contracts, and draws in glycol from the internal reservoir.
- The beginning of ascent [Fig. 1(c)], results from opening the three-way valve, the pressurized glycol in the accumulator moves to the external bladder and the vehicle changes from negative to positive buoyancy. The working fluid is frozen and has minimum volume.
- During ascent [Fig. 1(d)], the vehicle ascends to warm waters, heat flows into the working fluid, which melts and expands, and glycol flows to recharge the accumulator. The vehicle arrives at the surface in the same equilibrium as it started at in Fig. 1(a), the cycle is complete.

Some strengths and limitations of the engine design are clear immediately. This schematic shows the simplicity of the design. The three-way valve is necessary to control the operational timing, including stopping at intermediate depths, and the two check valves are the only additional dynamic complexity. The thermal cycle has very low efficiency, approximately 3%, due to the small temperature differences. The low efficiency itself is not a handicap since there are large sources and sinks of heat, however, the low efficiency means a large heat flow relative to the useful work done. During typical operation, the peak heat transfer rate is approximately 40 W driven by a small temperature difference. Freezing presents a difficult heat path since a layer of frozen working fluid builds on the inside surface of the engine nearest the surrounding water and inhibits further convective heat transfer. When melting, this outer layer transforms to liquid first and convection aids in melting the frozen interior of the working fluid. To facilitate timely heat transfer the working fluid is contained in external tubes, Fig. 2. Heat transfer is facilitated by adding conductive radial washers or random spirals to the working fluid.

Gas transmission across the accumulator bladder is an important design issue. The glycol must pressurize the nitrogen gas in the accumulator without gas transfer. If gas dissolves in the glycol, it will eventually come out of solution as a bubble in



(a) (b) (c) (d)

Fig. 1. SLOCUM thermodynamic cycle. (a) Equilibrium conditions at surface before descent. (b) Descent with heat flow to water. (c) Beginning of ascent. (d) Ascent, heat flowing from water, returned to equilibrium as in (a).

the low-pressure part of the system, and a significant gas accumulation over a five-year autonomy will compromise the closed system. Three solutions have been successful: use of metal bellows, use of flexible synthetic bladders of very low gas transmission, and floating piston separators.

IV. Operational Experience

Three thermally powered vehicles have been built and successfully tested in the field. The first was a vertical profiler vehicle to test the propulsion concept in an ocean environment without the complication of gliding. The second and third were fully autonomous tests of a thermally powered glider in a lake with a vertically compressed thermocline.

A vertical profiling vehicle powered by a thermal propulsion engine was deployed from the Sea Education Association training vessel Corwith Cramer October 1995 in the Sargasso Sea. The unit successfully transmitted 120 consecutive temperature profiles to a depth between 1250 and 1400 m over 240 days before failure [8]. The exact cause of failure is unclear, however, thermal engine operating parameters, battery voltage, and sensor operations were normal throughout the entire deployment.

The first complete combined glider plus thermal engine was tested in the seasonal thermocline of Seneca Lake, NY, during August 1998. Thermal conditions were 18° at the surface and 5° at 80 m. Dives were to 125-m depth and glide angles from 10° at 40° with horizontal speeds of 0.15 to 0.22 m/s. Fourteen sequential fully autonomous dives were logged with thermal propulsion. Horizontal displacement was logged using GPS fixes just before descent and immediately on surfacing. The autopilot maintained heading along the center of the narrow lake and was able to correct a 90° heading error in 25 m of vertical excursion.

The August 1998 test was the first demonstration of autonomous thermally propelled gliding, however, the control, navigation, and communication capability were minimal. A

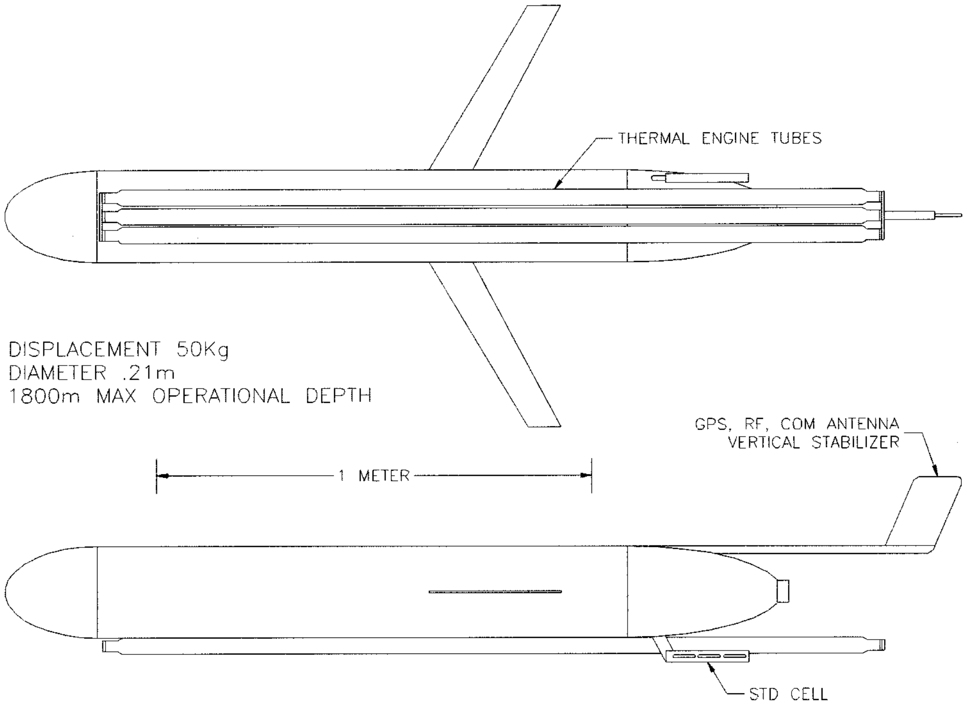


Fig. 2. Outline of SLOCUM glider.

substantial development program resulting in two vehicles with capable micro-controller and GPS reception, local and global satellite communication when surfaced, CTD sensor system, and internal dead reckoning navigation, based on software developed for the MIT Odyssey AUV.

One vehicle, optimized for coastal operation using a battery-powered buoyancy charger, was deployed during July 2000 at the Rutgers LEO15 site and patrolled continuously for 10 days, and returned 5280 CTD profiles. There are numerous measurement systems deployed at LEO15 and we were able to both confirm the quality of the CTD profiles and compare the transport estimate made with the glider, i.e., difference between GPS and dead reckoning, and the CODAR and ADCP measurements. This deployment quantified the performance of the control, navigation, communication, and measurement subsystems, and the software was transferred to a thermal glider using similar subsystems.

The second vehicle, a thermal glider, was operated at Seneca Lake in August 2000. The thermal propulsion performed well and predictably, however GPS reception was marginal due to inadequate elevation of the tail fin antenna. This was corrected by redesign in the mounting of the external engine components from the top to the bottom of the glider; the resulting larger surface pitch angle increased the antenna elevation. During a further deployment at Seneca Lake, October 2000, the thermal glider moved freely through the lake seeking navigational waypoints. This design is undergoing numerous detail refinements, with deployment near Bermuda planned.

V. DESIGN

The second thermal glider, Figs. 2 and 3, uses a cylindrical aluminum alloy mid section 0.21 m diameter with two internal stiffener rings, an elliptical nose closure, and a flooded tail fairing. The three external tubes contain the engine working fluid. This engine mounting imposes a drag penalty that can be reduced in future designs, however the flexibility and rapid heat transfer have been worthwhile in the developmental stages, and lake operation requires a faster heat transfer than ocean deployments.

The wings are symmetrical for gliding both upward and downward, laboratory data and field experience for symmetrical operation at Reynolds no. $\sim 3 \times 10^4$ is uncommon, the available data shows that thin flat wings with sharp leading edge have very good performance in this application. Simple 2-mm thick carbon laminate wings are used. The tail fin is a sandwich structure 2.8-mm thick and contains the three antennas; GPS, line-of-sight LAN, and ARGOS. A large sweep angle for the wings and tail, 45°, is desirable to reduce weed accumulation. When surfaced, the tail is elevated by inflating a 1.5 L air bladder inside the flooded tail fairing, air is pumped from and vented to the hull interior. With this inflation the tail fin is well elevated in moderate sea states. The LAN communication has been effective to 21-nm maximum range from an elevated shore antenna.

Movement of thermal engine fluids is controlled so that during gliding fluid movement creates minimal moments that would affect pitch or roll, and at surface and deep inflection the fluid movement provides the pitch moments required, the battery actuator acts as a secondary pitch adjustment.

Fig. 3 shows the balance of forces during upward gliding. The hydrodynamic forces are typically 0.6% of the gravitation weight and buoyancy forces. This is unlike air gliders where the buoyancy forces are negligible, it is analogous to a gliding dirigible or submarine. The dominance of gravity forces means the attitude is very stable, with swift recovery from perturbation,

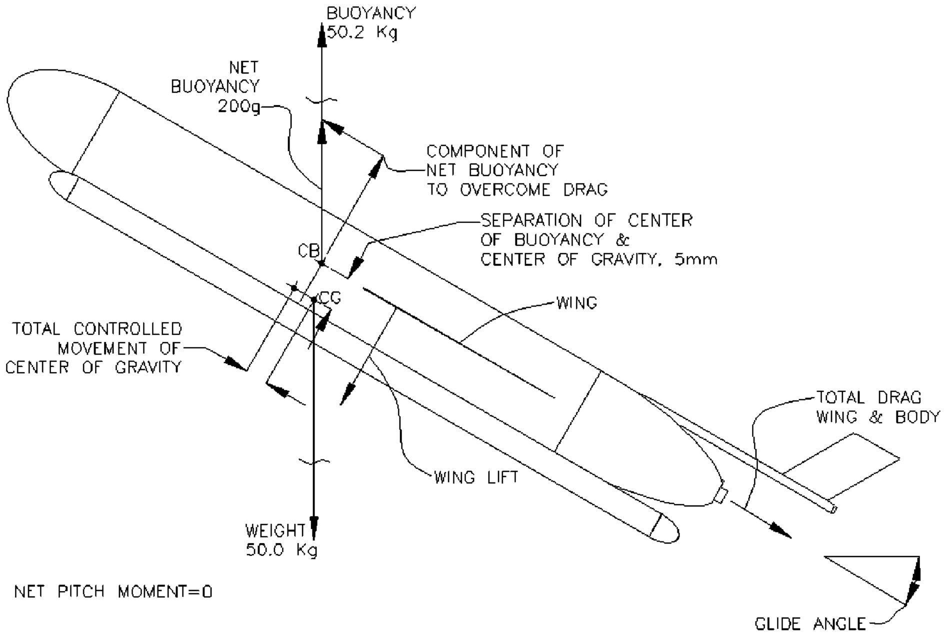


Fig. 3. Force balance diagram of forces acting on glider, angle of attack not included.

Fig. 4. SLOCUM glider in operation, shown is the prototype version with thermal engine mounted on top of the hull.

and rapid initiation of efficient gliding after leaving a rough surface. With the battery powered coastal design operation in water depths of 3 m is practical.

The flooded tail also enclosed an acoustic transducer used for relocation and telemetry, a weight jettison activated by mission overtime or overpressure, and a CTD sensor. The CTD, a nonpumped Sea-Bird Electronics (SBE) design aimed at combining accuracy, low drag, a faired profile to reduce weed accumulation and ruggedness, particularly desirable during handling. Standard SBE components are mounted inside a vented titanium enclosure.

The overall design strategy emphasizes moderate manufacturing costs, simple maintenance, and operation with a small team. Small boat operations with one or two people are routine.The wings are detachable for transport, are sufficiently flexible to withstand considerable abuse, and are easily replaceable in the field. Fig. 4 shows the SLOCUM glider in operation.

VI. AOSN OPERATIONS

Throughout the conceptual and design stages, SLOCUM has been intended as a simple, inexpensive, and easy to use AUV aimed at operating in groups or fleets in a coordinated network. Its natural sawtooth profile and great range is well suited to monitoring the physical properties of the upper ocean on a large scale for extended periods. SLOCUM or its environmentally powered successors may be an important tool in large-scale networks for observation and monitoring of the ocean interior [10]. Application for SLOCUM networks are:

Monitoring Grid: A fleet of SLOCUMS could be deployed over an ocean basin so that each occupies a 7° by 7° square. Each glider would sample and report on the water column in that square for five years. They would be periodically visited by roving master gliders which can, among other things, verify the calibration of their sensors by performing similar measurements at the same time *in situ*. Such long-term monitoring over a relatively dense grid would enhance the capability to monitor and model very large ocean areas.

Feature Tracking: The vehicle's ability to move horizontally and vertically gives it the ability to seek out, explore, and adaptively and interactively track features of interest as they move and evolve over time. The SLOCUM glider could be part of a monitoring grid deployed in an area where a feature such as an eddy or front would be likely to traverse. Upon detection of the feature, the gliders could move with it and sample its internal structure, providing a description of the life cycle, perhaps for several years.

Station Keeping: Deep ocean moorings are expensive to deploy and maintain, and have limited lifetime. The SLOCUM glider could perform as a five-year virtual mooring by profiling repeatedly in the same location.

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