# The WHOI Jetyak: An Autonomous Surface Vehicle for Oceanographic Research in Shallow or Dangerous Waters

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***Abstract*—This paper illustrates the components, capabilities, and some characteristic applications of the Woods Hole Oceanographic Institution Jetyak – a small autonomous surface vehicle (ASV) designed for the collection of oceanographic data from shallow or dangerous waters. The Jetyak is the result of custom modifications to a Mokai jet-powered kayak, including an A-frame and sea chest for installation of instrumentation, servo-driven controls and an Ardupilot autopilot for autonomous operation, an onboard computer for instrument control and data logging, and radios for wireless operation and communications. With these modifications, the Jetyak's cost of replacement is less than $15,000 (excluding the cost of instrumentation payload).**

**The paper addresses the strengths and weaknesses of the Jetyak relative to piloted small boats and jetskis, autonomous underwater vehicles, and existing ASVs.**

**Preliminary data are included from some shallow-water and dangerous Jetyak field campaigns in order to illustrate applications to which the Jetyak is well or uniquely suited.**

## I. Introduction

The Woods Hole Oceanographic Institution (WHOI) Jetyak is an autonomous surface vehicle (ASV) designed to acquire traditional, high-quality oceanographic data in shallow or dangerous waters inaccessible to traditional surface craft. With a draft of less than 20 cm and an above-water height of less than 2 m, the Jetyak is capable of traversing very shallow waterways and beneath most overhead hazards (e.g. bridges, aqueducts, trees, etc.). With no humans on board and $15K (+ instruments) cost of replacement, the Jetyak can be deployed in situations where traditional human-carrying craft cannot. Figure 1 shows a WHOI Jetyak returning to Safety after collecting oceanographic data at the face of a calving glacier.

The Jetyak is the result of a suite of modifications and additions to a Mokai rotomolded polyethylene jet-powered kayak. It is capable of 8-10 hours of endurance and a maximum speed of 3.5-5.5 m/s (7-11 kts), depending on configuration. Hull modifications include an A-frame and sea chest for the attachment of in-water instruments. Control modifications enable the Jetyak to be radio controlled, and/or to autonomously follow pre-programmed latitude/longitude trajectories.

Section II provides background information on available options for oceanographic data acquisition in shallow and dangerous waters. Section III describes the WHOI Jetyak in detail.

Fig. 1. A WHOI Jetyak returns to safety after collecting oceanographic data at the face of Sarqarliup Glacier in Greenland.

Section IV illustrates the Jetyak's capabilities with results from some early scientific field work. Section V discusses avenues of ongoing engineering development for the WHOI Jetyak. Section VI concludes.

## II. Background

### A. Crewed Oceanographic Vessels

Most in-situ oceanographic data are gathered from crewed vessels. Initially, most Acoustic Doppler Current Profiler (ADCP) data were collected by deep displacement oceanographic vessels. Various methods have emerged [1] to allow shallow-water ADCP data collection, including data from the top of the water column. [1] presents a retractable ADCP boom-mount for use on small fiberglass boats, and shows estuary survey data collected from a small boat that would have been difficult or impossible to obtain using a deep displacement hull vessel or with a towed vehicle.

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WHOI's most popular boat for coastal oceanographic research is the 24' *Mytilus*. It is trailerable (but not shippable), has a shallow draft of 0.46 m (1.5 ft) and a daily rate (to WHOI projects) of $568 [2]. Decades of experience have led to fairly reliable engines and control systems on boats like the *Mytilus*. Comparatively, the Jetyak is more complex and less tested in marine environments. Thus, it is more prone to failures and requires more tinkering to achieve results. Small boats also have the advantage that they allow scientists on board to conduct in-situ interactive operations.

Driving a straight line between waypoints in strong cross current in a small boat is difficult, with typical errors of 20 to 50 m, an order of magnitude worse than the Jetyak. Driver fatigue is frequently the limiting factor for small boat endurance, limiting operation to around 6 hours of accurate survey. Compared with the Jetyak, small crewed boats generally have a deeper draft, and their larger mass makes them more susceptible to damage when contacting terrain. Finally, crew safety dictates that small boats cannot enter dangerous waters (e.g. beneath a calving glacier, around unexploded ordinances, etc.).

The Jetyak works well as a small boat companion: the small boat conducts interactive operations requiring an operator while the Jetyak conducts repeated transects and surveys not requiring interaction. The small boat can also be used to launch and recover the Jetyak.

Coastal oceanographic data have also been collected by jetski-based systems, (e.g. ADCP and bottom depth in [3]). Jetskis outperform the Jetyak in breaking waves, especially in waves above 1 m, as a jetski operator can use the speed and manuverability of the jetski to drive around the most critical sections. Driven by an environmentally-exposed human pilot, and lacking an automatic control system, jetskis suffer at least the same fatigue and safety limitations of traditional small boats, and cannot automatically follow preprogrammed survey trajectories. Compared with jetskis, the Jetyak is larger and has significantly more space for installation of instrumentation.

### B. Comparison with AUVs

Autonomous Underwater Vehicles (AUVs) are another common survey platform in oceanographic research. They offer in-situ measurements (e.g. sampling of physical and chemical properties) and yield high spatial resolution data sets (e.g. photographs of the seafloor, and multibeam and sidescan sonar maps) even for deep water studies. They offer the robotic advantages of persistent precision control and access to dangerous targets of study (e.g. under ice) without endangering personnel. A wide variety of AUVs exists, featuring varying depth, endurance, payload, and autonomy capabilities.

Small AUVs (e.g. the Hydroid REMUS-100 [4], and Teledyne Gavia [5]) share significant applicability with the Jetyak. However, neither one is a replacement for the other. AUVs may operate at any depth (up to some structural limit), allowing them to follow bathymetry at a constant standoff, achieving high resolution sonar and photographic surveys even in deeper waters. The Jetyak, although unable to operate below the surface, derives three primary advantages over AUVs due to operating at the surface:

The Jetyak's **air-breathing gasoline engine** allows it to travel at up to 5.5 m/s. Top speeds of small AUVs are typically half that (e.g. REMUS 2.6 m/s [6] and Gavia 2.8 m/s [5]). As a result, the Jetyak is more capable than small AUVs when performing surveys in energetic shallow water flows such as tidal inlets). On site, the 5.5 m/s max speed and easy refueling allows for some transit during operations.

**Access to GPS signals** allows Post Processed Kinematic (PPK) or Real Time Kinematic (RTK) GPS to be logged with Jetyak survey data. This positioning information is critical for heave compensation in shallow water bathymetric surveys where swells and topography share similar spatial scales. IMUs capable of the same compensation over several hours are significantly more expensive than the rest of a small AUV system.

Remote operators may interact with the Jetyak over **high-bandwidth two-way radio**. This allows them to monitor mission progress in real time, and to command actions of the Jetyak's autopilot and onboard science computer.

### C. Existing ASVs

Considerable efforts have been expended in the development of ASVs in the past decade. A number of these are focused on high speed platforms for military, security, and offshore applications (e.g. see [7]) and primarily consist of gasoline powered outboard motors on larger (15-30 foot) vessels. The cost of these vessels is significantly higher than the Jetyak's because they are designed to operate over a much higher speed range - a possible advantage for operations with significant transit requirements.

Smaller commercial and academic ASVs exist whose performance specifications are similar to the Jetyak's, such as the twin hull Coimbra Squirtle [8], the twin hull ASV C-Cat 2 [7], and the single hull MIT SCOUT [9]. All three run propellors driven by electric motors, and reach a top speed of approximately 2.6 m/s. The Jetyak is similar to these vehicles, but has the advantages of higher top speed and reduced entanglement hazard due to its jet propulsion system. It also has a significantly lower cost than commercial systems and may be reconfigured in-house.

Energy-harvesting ASVs have been developed for long-duration applications. Examples include the AUSI/IMTP solar powered AUV [10], the ASV C-Enduro, which uses an onboard wind turbine and solar panels in combination with a diesel generator [7], and the Liquid Robotics Wave Glider, which harnesses both solar and ocean wave energy [11]. The significant cost of these systems can be justified for applications requiring extreme endurance. Solar powered AUVs have similar advantages and disadvantages (vs. the Jetyak) as their battery-powered cousins. Due to the 4 m draft of their wave energy harvester, Wave Gliders are ill-suited to shallow and flat water applications. The C-Enduro is similar to the small electric ASVs discussed above, but with higher cost and endurance.

## III. The WHOI Jetyak

### A. Overview

The WHOI Jetyak is an ASV built by customizing a Mokai jet-powered kayak. The base vehicle from Mokai costs

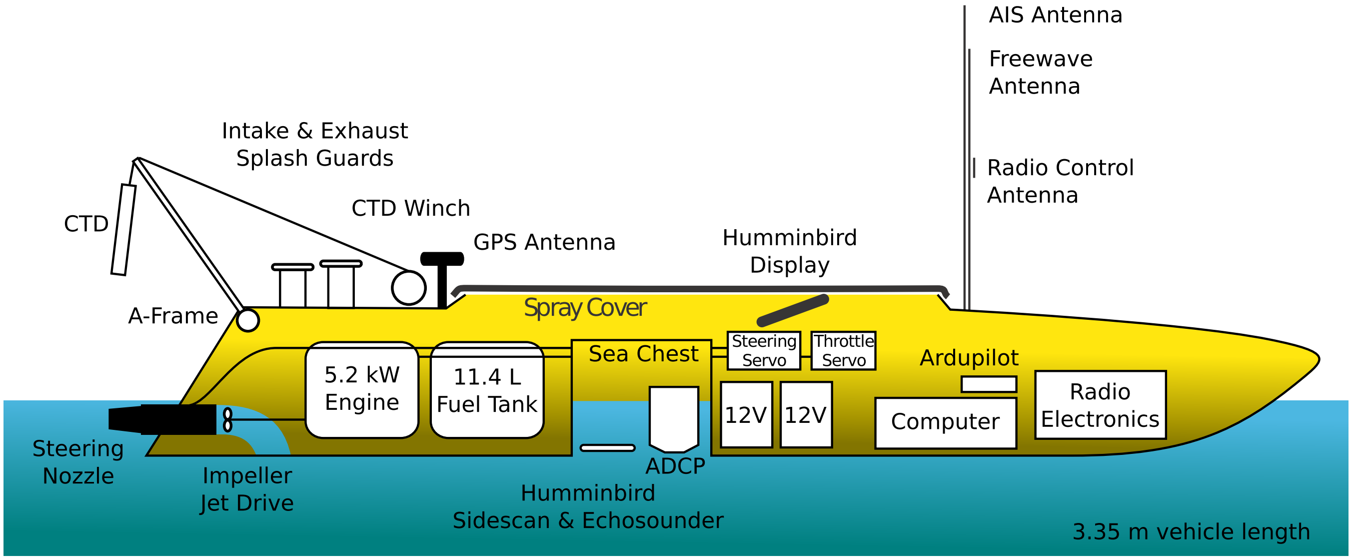


Fig. 2. This schematic shows the components that make up the WHOI Jetyak. Additional components are added/substituted as needed for particular experiments. Descriptions of the components appear throughout Section III.

approximately $6,000, including the 5.2 kW (7 horsepower) Subaru EX21 engine, and 11.4 L (3 gallon) gasoline tank. The hardware modifications (including components and time) bring the total cost of replacement for the Jetyak to less than $10,000. The Jetyak is 135kg, 3.35 m long, and has a top speed of 5.5 m/s. Figure 2 shows in schematic form the components that make up the Jetyak. The remainder of this section describes the custom modifications and installations that transform the Mokai vehicle into the Jetyak ASV. Note that multiple WHOI Jetyaks have been built and deployed in various configurations.

### B. Construction

*1) Hull Modifications:* A rigid A-frame has been added to the back of the vehicle, allowing attachment of instrumentation. The A-frame may be folded down for transport.

A section of the hull bottom has been replaced by a custom sea chest. The sea chest, pictured in Figure 3, allows instruments to hang into the water without sampling from the vehicle wake, without causing a yawing moment while the Jetyak is under way, and without presenting a significant snag hazard. The sea chest is sealed to the hull using 3M Scotch-Grip rubber and gasket adhesive #847.

### C. Engine Modifications

Two major modifications have been made to the 7 horsepower 4 stroke Subaru engine. First, a painless flywheel clutch [12] has been added to allow the Jetyak to remain stationary without stopping the engine. Second, chimneys have been installed over the engine compartment air intake and exhaust to prevent water from washing into the engine. Prior to their installation, a single wave could wash water into the intake, stopping the engine, and requiring extensive maintenance to return the engine to working order. The chimneys have helped greatly with this, but corrosion of the fuel injection/carburetor system is still a issue, and requires preventive maintenance. This is true of jetski engines as well.

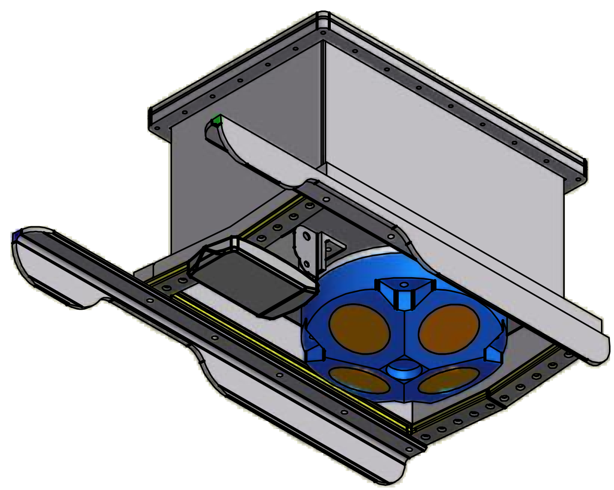

Fig. 3. A custom sea chest, shown here from below, is installed in the hull of the Jetyak to house instruments (e.g. sidescan and ADCP sonar heads as shown).

*1) Control Modification:* The Jetyak's manual throttle and steering controls were replaced with a custom servo-driven system. The system includes servos for steering and throttle, both mounted inside waterproof rigid PVC enclosures and secured inside the Jetyak cockpit on the underside of the starboard deck. Power and signal to the servos are connected via a waterproof six-pin Switchcraft bulkhead connector. The servos connect to the original Mokai linkage terminations via custom adapters.

For steering, the jet duct (pictured in a full turn to port in Figure 4) is driven in the original Mokai push-pull configuration with a Seiko PS-050 High Torque servo. The throttle linkage is controlled with Hitec HS-M7955TH servo, connected in a single pull with spring-driven return. The cable sleeve is fixed to the hull by a small bracket. All hull penetrations are sealed with marine grade room temperature vulcanization silicone to prevent leakage.

Fig. 4. A custom servo-driven control system utilizes full steering throw of the jet duct. Here, the duct is pictured as in a turn to port.

Note that Mokai is now advertising electronically controlled steering and throttle in its newest products [13].

*2) Navigation and Control:* The servo-driven control system takes inputs from an Ardupilot Mega 2.5 (APM). The APM either acts as a simple pass-though for human pilot commands sent by a handheld hobbyist radio transmitter, or generates servo commands autonomously as an autopilot. The APM was chosen as the Jetyak's autopilot because of its low cost, capable sensor suite (including GPS), existing open-source autopilot firmware, and existing mission planning software. Detailed descriptions of the APM hardware and many of its various uses are available online [14].

The Mission Planner software allows a user to pre-program a mission for the Jetyak to execute autonomously. The ability to import custom maps allows high resolution satellite imagery to be used as a survey planning guide. This is particularly useful in areas with variable bathymetry. Preprogrammed missions consist primarily of trajectories connecting latitude/longitude waypoints, but may also include various other directives. Mission Planner can also communicate with the APM in a convenient "follow me" mode, allowing the Jetyak to follow a mothership autonomously (e.g. during transit). Details of the Mission Planner software are available online [15].

The Jetyak APM runs the community-written APM:Rover firmware, designed to pilot a wheeled rover using steering and throttle commands. Testing showed that without modification, the rover firmware could be tuned to control the Jetyak. Track-following is implemented by commanding steering angle based on proportional, integral, and derivative (PID) feedback of cross-track position error. Speed control is implemented by commanding throttle changes based on PID feedback of speed measured by GPS (relative to ground). Track-following performance is illustrated in Figure 5.

The left panel of Figure 5 shows the commanded and actual trajectories of the Jetyak from Wasque Shoals off of Martha's Vineyard in July 2014. A 1 m/s tidal current was running from the Southwest during the collection of these data. The Jetyak began at the Northwest corner of the survey grid. Overshoot is visible in the turns at the ends of the down-current legs. Strange behavior is visible in the final turn (Southeast corner), and may have been due to the breaking waves observed over this very shallow region of the survey.

The right panel of Figure 5 shows normalized histograms of the cross track position error (measured at constant frequency) over the East-West legs of the data set, including overshoots at the ends of the down-current legs. Traveling East (red histogram), the mean and median cross track errors are -0.73 m and -0.16 m (negative indicates vehicle too far to port), while the RMS error is 2.77 m. Traveling West (green histogram), the mean and median cross track errors are 1.37 m and 1.45 m, while the RMS error is 1.94 m. The effect of the persistent current from the Southwest on the APM's simple PID controller is evident both in the track line plot and in these statistics.

*3) Communications:* An external radio communications mast is mounted on the Jetyak deck, towards the bow. The splash-proof mechanical assembly is cable-stayed to the Jetyak hull, but also quickly detachable for low profile transport. The mast contains a Spektrum AR6255 6 channel receiver, a Freewave 900 MHz radio modem, and an Automatic Identification System (AIS) antenna.

The Spektrum receiver provides traditional radio control of the Jetyak using a compatible handheld transmitter.

The Freewave provides both ethernet communication to the data acquisition PC, and 57K baud serial communication to the APM. This allows for adaptive survey and real time quality control, greatly improving the quality of data gathered. The Freewave radio is functional up to approximately 2-3 km range, depending on conditions and ground station antenna placement.

In place of the Freewave radio, the Jetyak has been fielded with a ($100) 3D Robotics 900 MHz, 100 mW data radio pair for communication with the APM and a ($70) Ubiquiti 2.4 GHz wifi transceiver for communications with the data computer. These hobbyist/consumer systems are functional only up to approximately 1km range, but are less expensive than the ($3,000) Freewave radio.

The AIS tracking functions up to approximately 5-8 km range.

*4) Onboard Computer:* The Jetyak data acquisition computer varies with the preferences of the users. It can range from a completely decoupled system to one that is fully integrated with the onboard navigation and control system. To date, the WHOI Jetyaks have been deployed with two distinct systems. One is an automotive-grade i7-x64 PC running windows, used to control the acoustic systems (ADCP and sidescan sonar). Using remote-desktop software and the communications systems described above, one can use commercial visualization software for realtime remote display of bathymetry and ADCP data. A second system, based on a more physically compact Mac Mini computer running Linux, has been used for controlling hardware that does not require commercial (closed source) drivers and visualization tools. Again, remote-desktop software allows users on shore or in a chase boat to monitor the quality of the data being collected. In both cases, the APM can be connected over a serial port to the science computer, allowing for more complex autonomy and/or operator interaction during missions. For example, the science computer can monitor which waypoint the Jetyak is moving toward and can instruct the APM to stop forward progress while a CTD (winch) deployment takes place.

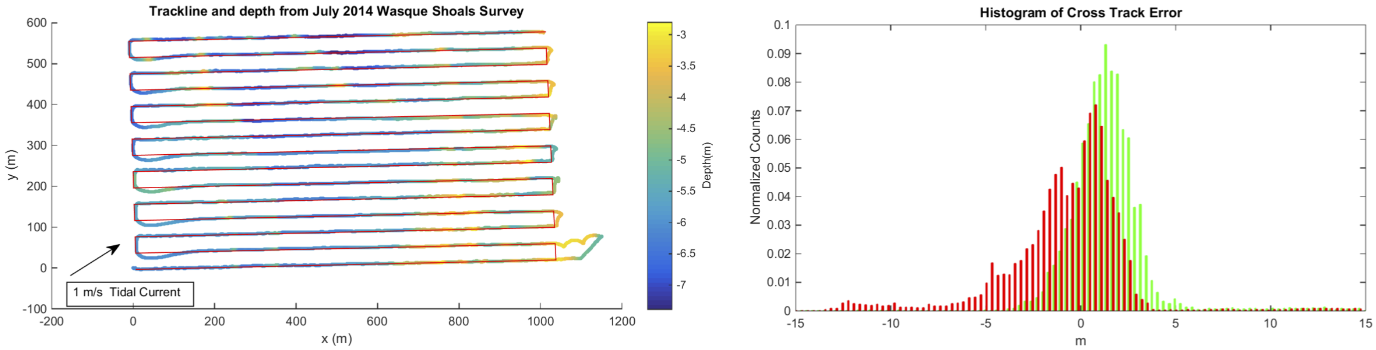


Fig. 5. The Jetyak's ability to follow commanded track lines is illustrated (left) by these data collected off of Martha's Vineyard. The commanded track is shown in red. The actual vehicle trajectory is represented by dots whose color indicate measured bottom depth. X and Y are aligned with East and North, respectively. Cross track position error histograms are shown (right) in red for Easterly travel and in green for Westerly travel. There was a 1 m/s tidal current running from the Southwest.

*5) Transportability:* The Jetyak may be loaded into the back of an extended bed pickup or cargo van by two adults. It is also shippable by air, provided that the engine is drained of all fuel.

## IV. Field Results

This section provides a few examples of scientific data collection already performed with the Jetyak. Scientific results are not fully developed here. Rather, these examples are intended to illustrate the unique capabilities of the Jetyak and the field data collection it enables.

### A. *Coastal Bathymetric Change Surveys*

The Jetyak has been used to track bathymetric change of medium scale (100 m wavelength by 3 m high) tidal sand waves, and to conduct ADCP surveys of the flow over these bedforms. This kind of tracking is important for understanding coastal ecosystems as well as for conducting unexploded ordinance mitigation. The Jetyak has been used in this capacity in two study areas off of Martha's Vineyard, MA - Long Point surf zone and Wasque Shoals.

Preliminary results from Wasque Shoals appear in Figure 6. They indicate northeasterly dune migration, evident in three overlaid bathymetric maps created with data from three separate Jetyak surveys.

These data could not have been collected by an AUV due to the shallow depths and energetic flows (including some breaking waves). A small boat (e.g. the *Mytilus*) or jet ski would be able to operate in the area, but without the precise line-following of the Jetyak - important for achieving efficient coverage of the shallow survey area. Note that the line-following example in Figure 5 is from the July 2014 survey in Figure 6.

In addition to the Martha's Vineyard locations, the Jetyak has been used to conduct bathymetric change surveys to understand cross-shore sediment transport processes on the shoreface attached ridges offshore of Fire Island, NY (February and May 2104). While the Jetyak was deployed, operated, and recovered from shore for the Martha's Vineyard surveys, it was deployed, operated, and recovered from the *RV Connecticut* for

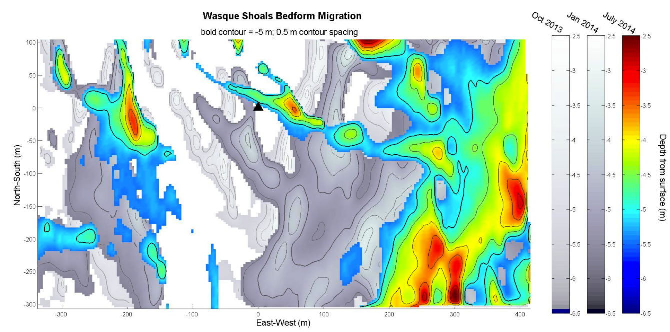


Fig. 6. Data from three Jetyak surveys over a nine month period show dune migration in Wasque Shoals off of Marthas Vineyard, MA. The most recent survey is color contoured, and the older surveys are gray shaded. The bedform bathymetry was contoured to a maximum depth of 5.5 m from the mean tidal elevation. The surface below 5.5 m (not shown) is relatively flat with a maximum depth around 6.5 m. The dunes are primarily migrating northeast with a rate of 15 m/month, and also rotating slightly in response to flood tide dominated currents and waves from the South West. The triangle depicts an instrument frame that was buried by a dune in January, 2014 and is becoming unburied in July, 2014.

the Fire Island surveys. The Jetyak autonomously conducted surveys of approximately eight hours duration while the ship deployed and recovered moorings with only minimal interruptions to tend the Jetyak.

### B. *Sarqarliup Glacier, Greenland*

In July of 2013, a WHOI Jetyak was used for 5 days to collect data from along the ice front of Sarqardleq Glacier, Greenland (68.9 N, 50.4 W). The vehicle, pictured in Figure 1, carried a winched CTD with turbidity sensor, ADCP, multi-beam sonar (used for mapping both the fjord bathymetry and ice front), SICK laser, and a GoPro camera.

Figure 7 shows preliminary multibeam sonar data from two vehicle trajectories (in black) across the ice face, one with the multibeam sonar pointed toward the ice, 45 degrees up from nadir (returns shown in white), and one with the multibeam sonar pointed straight down (returns shown in brown). Figure 8 shows a portion of the Jetyak's multibeam sonar map of the ice face over gridded fjord bathymetry collected in a prior field season by small boats and a REMUS AUV.

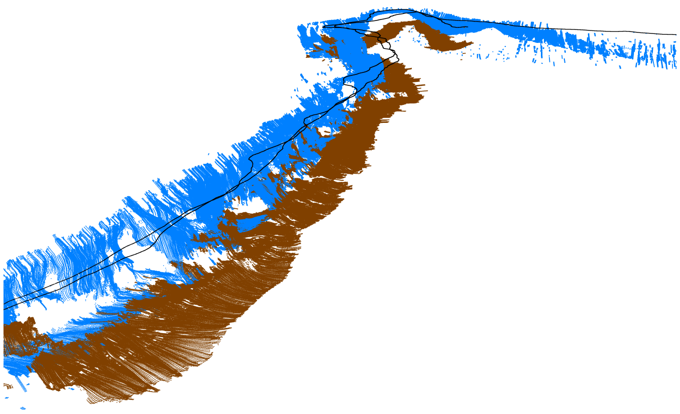

Fig. 7. Multibeam sonar returns are shown along with the two vehicle trajectories along the glacier face from which they were collected.

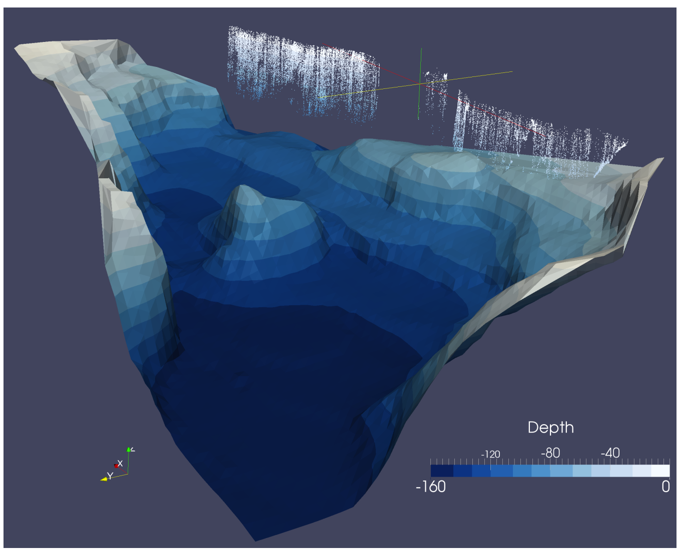


Fig. 8. A portion of the ice face multibeam sonar returns are shown above gridded fjord bathymetry

Venturing near the edge of a marine terminating glacier is extremely dangerous due to ice calving, and traditional small boat assets are not able to perform data collection near the glacier face because of danger to the crew. Some measurements have been obtained by lowering instruments from helicopters, but large helicopters are very expensive, and readily-available drones cannot carry the necessary payload. The WHOI Jetyak allows researchers to collect several hours of data near the ice front in a cost-effective way and without endangering personnel.

### *C. River Surveys*

The Jetyak has also been used to perform bathymetric, sidescan, ADCP, and CTD surveys in the Connecticut River, and between piers in New York Harbor.

## V. Ongoing Work

The next generation of the WHOI Jetyak aims to expand the autonomy of the Jetyak by enabling operations in trafficked regions without the input of human operators. The Jetyak will use GPS and marine charts for navigation and AIS and a Lowrance 3G Marine Radar for obstacle avoidance according to the International Regulations for Preventing Collisions at Sea (COLREGS). It will be capable of transiting to a research site of interest and performing a scientific mission without human input or oversight. The cost of operation will then approach the cost of fuel, and the frequency of data collection can be dramatically increased (e.g. to even daily local surveys) at negligible costs. The ability to move through dynamic and unknown environments will also open up new types of operations, such as using the Jetyak as a data, communications, and navigation relay point for AUV operations.

## VI. Conclusion

This paper has illustrated the components, capabilities, and some characteristic applications of the WHOI Jetyak – a small ASV designed for the collection of oceanographic data from shallow or dangerous waters. The Jetyak is the result of custom modifications to a Mokai (gasoline) jet-powered kayak, including an A-frame and sea chest for installation of instrumentation, servo-driven controls and an APM autopilot for autonomous operation, an onboard data computer, and radios for wireless control and communications. Including these modifications, the Jetyak's cost of replacement is less than $15,000 plus the cost of instrumentation payload.

Compared with human-piloted small boats and jet skis, the Jetyak is better at following survey track lines, and may do so without the duration constraint of pilot fatigue. Further, the Jetyak may operate in waters too dangerous for crewed vessels (such as along a glacier face as in Section IV-B). However, there are many advantages of having a scientist in-situ that the Jetyak can at best approximate.

Compared with AUVs, the Jetyak shares many of the advantages and disadvantages of a robotic system. However, it is not as well suited to operations in waters deeper than approximately 10 m (depending on desired instrumentation). The Jetyak is constrained to operate at the surface, and thus produces lower-resolution bottom surveys as water depth increases. However, the Jetyak's gasoline engine and access to through-the-air radio communications (including RTK and/or PPK GPS) are advantages that make the Jetyak better suited than AUVs to shallow water operations, where wave action can pose a hazard to the vehicle and degrade data quality.

Compared with existing ASVs, the Jetyak presents a reduced propulsion entanglement hazard. It is smaller, more easily portable, shorter-range, and less expensive than other gasoline-powered ASVs, yet offers a more energetic capability than solar/electric ASVs. The Jetyak is also an open design, allowing ongoing development and additions as compelled by evolving scientific motivations.


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