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Acoustic-telemetry payload control of an autonomous underwater vehicle for mapping tagged fish

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Abstract

Autonomous underwater vehicles (AUVs) have demonstrated superior performance for tracking marine animals tagged with individually coded acoustic transmitters. However, AUVs engaged in mapping the distribution of multiple tagged fish have not previously been able to alter search paths to achieve precise position estimates. This problem is solved by the development of payload control software (Synthetic Aperture Override, SAOVR) that allows the AUV to maneuver with trajectories favorable for solving the tag's location from a synthetic aperture. Upon tag detection during a default mission search path, SAOVR (running on an embedded guest computer) seeks permission to take over navigation from the vehicle's native system after checking constraints of geography, timing, tag identification, signal strength, and current navigation state. Permitted maneuvers are then chosen from a template library and executed before returning the AUV to the point of first deviation for continued searching of other tags. Field evaluation on moored reference tags showed a high level of predictability in the AUV's behavior at SAOVR initiation and through maneuvers. Trials suggest that this logic system is highly beneficial to AUV use for fish telemetry in challenging environments such as narrow, deep fjords, or among reefs. Any mission programmed with the AUV's native software can be run with the SAOVR package to allow scientists to easily implement and manipulate synthetic aperture geometries without altering any of the software. Further modeling can help improve template design specific to expected movements of different fish species and relative to the designation of signal strength-defined execution thresholds.

Autonomous underwater vehicles (AUVs) have demonstrated superior performance for telemetering marine animals (fish and crabs) tagged with coded acoustic transmitters (Eiler et al. 2013). Telemetry, specified for this paper as acoustic tag detection by a hydrophone distinct from telemetry as messages between a remote vehicle and user, has become an important tool for ecological and stock assessment research. Telemetry typically utilizes fixed arrays of moored omnidirectional hydrophones to detect passage or general area of space use (Heupel et al. 2006; Reynolds et al. 2010; Eiler and Bishop 2016) or if closely spaced to calculate sequential fine-scale positions (tracks) by trilateration. (Cooke et al. 2005; Espinoza et al. 2011). Surface vessels are also used to sequentially occupy fixed listening stations (Ng et al. 2007), actively search an area for the tagged fish (Holland et al. 1999; Sims et al. 2001; Nielsen et al. 2012), or to follow a tagged individual (Wetherbee et al. 2004). Moored hydrophones are useful for experimental designs meant to synoptically detect the presence or passage of multiple tagged animals over long periods, but must defer to costly and laborious vessel-based tracking for information on animals beyond the array detection limits on the order of km. AUVs can perform some of these tasks (Grothues et al. 2008; Oliver et al. 2013; Haulsee et al. 2015; Breece et al. 2016), which then benefit from deeper, quieter hydrophone positioning (Eiler et al. 2013; Oliver et al. 2017). The application is further justified because other onboard sensors can provide proximal information on the surrounding habitat, making it possible to integrate fish telemetry data with geomorphic and environmental data (Grothues et al. 2010; Oliver et al. 2013; Haulsee et al. 2015, *see* Lennox et al. 2017 for a review of telemetry challenges and projections).

AUVs have previously been designed and used to track (follow) individual fish. One such solution involved the use of a REMUS-100 (Hydroid, Pocasset, MA) AUV proprietary native homing/docking system (Skomal et al. 2015). A short baseline system (SBL) hydrophone array in the nose cone determined the bearing and distance toward a large (~ 9 cm × 30 cm) native homing beacon, which was on a suitably large great white shark (*Carcharadon carcharias*) (Packard et al. 2013;

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Skomal et al. 2015). The AUV continuously turned the vehicle to track the shark, but used the AUV position as proxy for that of the shark (i.e., no tag positions calculated) and required additional assistance from a surface vessel to provide a position (Packard et al. 2013; Kukulya et al. 2016). The AUV would continuously turn toward the shark and occasionally collided with it (Skomal et al. 2015). That SBL does not decode individually coded ultrasonic fish tags. Another application used an IVER (Ocean Server, Fall River, MA) AUV with boom-mounted third-party stereo hydrophones (Lotek Wireless, Newmarket, Canada) to estimate sequential positions of a small (< 16 mm diameter) commercially-available coded tag on a small shark (leopard shark, *Triakis semifasciatus*) (Forney et al. 2012). Boom mounts required modification of the AUV control surfaces. Although the implementation was highly successful at estimating the shark's position as compared to the "known" position from a tracking boat, it is not clear that performance or predictability of that model was sufficient to let the AUV leave the surface, where initial tests were made. The position of a single tag was iteratively estimated from possible initial solutions provided by an angle estimate from the stereo system and refined using a particle filter model. Thus, the vehicle would make constant subsequent course corrections to maintain proximity without ramming the shark but while also recording the position estimates (Clark et al. 2013; Xydes et al. 2013). Although the focus was on a single individual, this advancement allowed the use of small, individually coded and commercially available acoustic tags appropriate to use on many species. This work was furthered to include two stereo vehicles, which expands the geometry of the locations over which detections are simultaneously made for determining position from signal time-of-flight differences (Lin et al. 2013, 2014; Shinzaki et al. 2013). The AUVs need to be in contact with each other to coordinate movement, avoid collision, and combine the data that they collect independently so that the fused data can be used in a particle filter model to estimate position. Estimates are further refined by incorporating data broadcasted by SmartTags incorporating inertial guidance systems (together with a video logger and timed release, Lin et al. 2016). Such SmartTags move the project back into the restrictions of large animals with external tags addressing short-term (hours to days) questions. The extent of the problem is exemplified by an attempt to use as many as three autonomous surface vehicles, simultaneously coordinated by real time communication with a remote mission center, to form geometries useful for positioning (Zolich et al. 2017).

The ability to autonomously track individuals in meter-scale resolution over periods of hours on short (several seconds to minutes) time-scales is very important for quantifying movements descriptive of specific behaviors such as foraging and social interactions that help us understand the ecology of large fishes (White et al. 2016). This is especially important for addressing the potential for fish to leave the typically small coverage of multi-hydrophone trilateration arrays set up for such experiments. However, it is less useful for addressing questions related to synoptic distribution of multiple (and potentially smaller) fish over long time scales that may still require high resolution but over wide areas. These include questions related to distribution in dynamic habitat, migration, home range, and ecologically meaningful personalities (Heupel and Webber 2012). Propeller-driven and glider AUVs have previously been used to detect the presence/absence or sub km-scale position of multiple fish along a search path (Grothues et al. 2008; Oliver et al. 2013; Haulsee et al. 2015; Breece et al. 2016). Such "mapping" differs fundamentally from "tracking" applications and tag positions are typically estimated in post-processing, often to the precision defined by the tag/hydrophone detection radius. Refined position estimates can be made through mapping of the sound-pressure level (SPL) field (Grothues and Davis 2013) or by synthetic aperture (Grothues et al. 2008). Synthetic apertures are formed when the timestamps of a set of recorded tag signals (typically between 8 and 20 detections over several minutes) are post-synchronized by cumulative subtraction of the signal interval so that the timestamp remainders represent the differences (measured to < 0.0001 s precision) in signal flight-time owing to a change in receiver location. (Note that synthetic aperture formation for acoustic telemetry differs from RADAR and SONAR in that receive and transmit functions are decoupled and are not meant to create an image.) Tag locations from subsequent detections made along a path using time-of-arrival-differencing (ToAD) are then calculated as if from a moored multi-hydrophone array (Nielsen et al. 2012). These are potentially much more precise than SPL-estimated positions and moreover allow for solutions outside of a synthetic aperture's parabola. The quality of synthetic aperture position estimates is dependent first on the precision of the timing and on geometry of the aperture based on theory of minimizing the intersect area of possible reception spheres or circles (termed dilution of precision, Schau and Robinson 2003; Pascazio and Fornaro 2013). Geometry is confirmed in practice as the most consistent determinant of quality in estimates from moored array hydrophone positioning systems (Meckley et al. 2014; Romain et al. 2014; Steel et al. 2014; Guzzo et al. 2018) and for those made by a towed hydrophone (Nielsen et al. 2012).

AUVs engaged in multi-fish mapping have not previously been able to alter search paths en-route, as do surface vessels, to refine position estimates by creating geometrically favorable apertures. This problem is solved by the development of payload control software that allows the vehicle to alter its pre-programmed movements based on information from an integrated telemetry hydrophone. The engineering task is challenged by uncertainty in the signal-receive behavior in unknown field conditions, by uncertainty regarding the clustering or dispersal of multiple tagged animals with overlapping detection range, by geographical or bathymetric constraints, and by operational constraints related to AUV mission duration, timing, and AUV deployment and recovery (Grothues et al. 2010; Eiler et al. 2013). Specifically, course deviations should be predictable as to where they maneuver relative to the tag to achieve the desired synthetic aperture, they should not trap the vehicle in a feedback loop, they should not allow the AUV to run into known underwater obstacles such as shoals or walls (White et al. 2016), or execute while the support vessel is in proximity for deployment or recovery, and should not allow it to exceed an expected mission time. That way, unattended AUVs can be met by their recovery vessels at pre-planned positions/time slots. Some vehicles, especially one-off custom designs used by their creators but also the popular-level IVER vehicles (e.g., Ocean Server), run an open source platform that makes integration easy. In others, (e.g., Hydroid REMUS class, Bluefin Robotics Artemis class), a further engineering challenge is posed in that the access to native navigation systems is proprietary. Whether or not access to the primary navigation system is open, mission parameters should be easily manipulated by biologists in the field in a way that protects the primary navigation system and priorities from unintended consequences and during non-tracking missions. Thus, a standalone module that can be enacted or turned off and that isolates the programming of override maneuvers to well defined and allowable cases while checking for and reporting faults, will advance the application of this tool.

The purpose of this paper is to describe the development, implementation, and field-testing of a payload control program, Synthetic Aperture OVerRide, (SAOVR) that utilizes an available bridge between the native proprietary software of a commercially available AUV and an onboard guest computer that monitors a hydrophone/processor. Safe and predictable maneuvers respond to novel detections of acoustic tags even given that we know nothing about how the proprietary native system operates. Any mission programmed with the AUV's native interface software can be run with the SAOVR package to allow scientists to easily implement and manipulate maneuvers of their own geometry/design without altering any of the software. The maneuver geometry can be defined anew by any user of the SAOVR package. We further describe the way in which the software can be manipulated for application to other (including open source) vehicles and potentially applied to other goals and sensor systems. The design and performance of specific maneuvers used during payload control-enabled missions are a separate issue from the design and implementation of the payload control logic and its testing and therefore described and assessed separately.

Materials and procedures

System overview

The REMUS-100 (Hydroid, Pocasset, Massachusetts, U.S.A.) is a person-portable (1.6 m length × 0.19 m diameter, 43 kg) torpedo-shaped propeller-driven AUV capable of speeds to 2.4 ms^{-1} (Fig. 1). It supports a number of sensors for physico-chemical, bathymetric, and biological oceanographic studies (Moline et al. 2005). A single coaxial omnidirectional hydrophone (WHS 3050, Lotek Wireless) is custom-mounted on the nose as a reconfiguration of an over-the-shelf design used in moored arrays (Grothues et al. 2010). The hydrophone processor detects and interprets code-division-multiple-access (CDMA) coded signals from any MAP series acoustic transmitter (Lotek Wireless) broadcasting in the 76 kHz band. This transmitter series has a code space of about 80,000 identification codes as well as pressure, temperature, and motion signals from optional tag sensors. The AUV also carries a factory-installed embedded guest PC operating on Windows XP. The guest computer and a communications protocol for input/output to the native system (described below) is an option marketed by Hydroid. It was

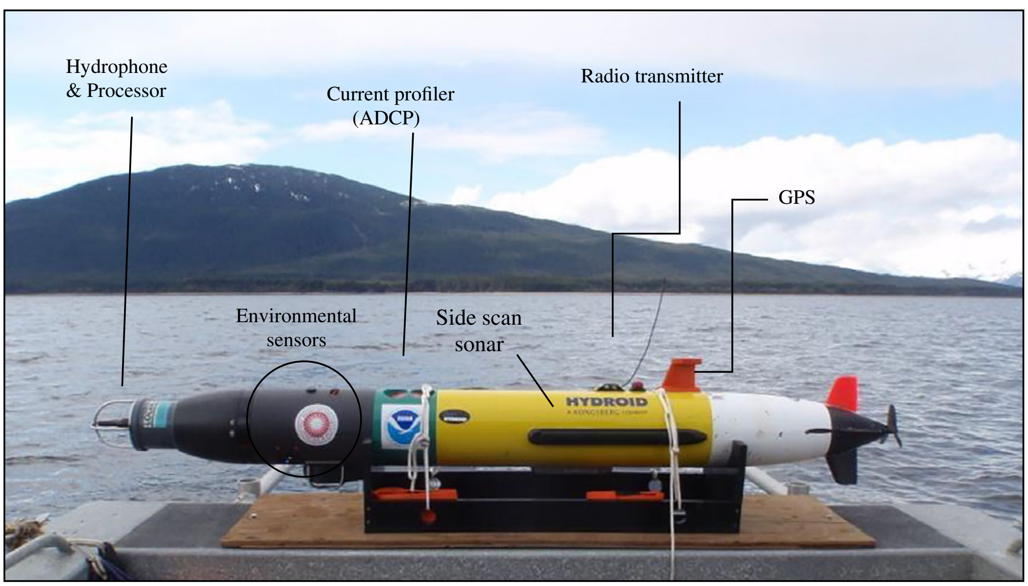


Fig. 1. The REMUS-100 AUV fitted with a coaxial Lotek WHS 3050 hydrophone/processor.

factory-retrofitted to the test REMUS-100 (in operation since 1996), but most new REMUS vehicles are near-custom configured and could be included for buyers of newer vehicles at procurement (Hydroid pers. commun.). Functions of the native and guest computers are accessible through an external laptop via the AUV's virtual interface program (VIP) when the vehicle is on the bench.

Software

The SAOVR electronics package is built on the guest PC's XP system. From a technical perspective, this is not as desirable as a real time operating system (RTOS) in terms of performance guarantees (Janka 2012), but it allowed the use of the Windows serial RS232 COM library and the Windows threading and synchronization libraries, as well as the C++ Standard Template Library (STL). The embedded Windows PC was also already required to run the hydrophone/processor's native interface software (MAPHost). The SAOVR package is written in C++, totals just under 2200 source lines of code, and runs on four threads (detailed below).

The SAOVR package is separate from the native AUV control package, with which it communicates via RS232 (Fig. 2). The AUV control package is responsible for executing missions (here forward "default mission" or "search path") designed and pre-programmed in the Hydroid VIP. A link between the proprietary AUV control package and the guest computer implements Hydroid's REMUS REmote CONtrol (RECON) protocol. This communications protocol streams ASCII messages at a constant 9 Hz rate to the guest computer regarding vehicle status (operating mode, geoposition, depth, altitude over bottom, heading, attitude, speed, propeller rps, and goals). It also allows a limited selection of text messages back from the guest computer to the native control package requesting new vehicle speed, depth, and heading (overrides) and a command to return to last or new nearest default path point. RECON allows these override requests to be made at any time; however, the AUV control package may reject the requests based on prioritization, such as "abort" commands due to low battery. The nature of the prioritization code is proprietary and unknown to us, but is sensitive to user settings through the native VIP such as what constitutes a "low" battery.

SAOVR logic

For testing purposes, override maneuvers were either point-forward or base-forward equilateral triangles bisected by the current AUV bearing each with two different duration parameters (90 or 180 s). In practice, any geometry can be applied; the rationale for these particular maneuver shapes will be described in a subsequent paper. Upon mission start, the SAOVR program listens passively to the hydrophone/processor's data stream (provided by MAPHost software as a csv file) while the vehicle executes its default search path. Upon tag detection, SAOVR logs the event and seeks permission to take over navigation based on several constraints: (1) Has the vehicle cleared its initial launch area? (2) Has the tag been previously detected in this mission? (3) How long ago? (4) Is the vehicle already in override mode for another tag? (5) Is the vehicle close enough that a maneuver might be successful in producing a useful path geometry relative to the tag? and (6) Is the vehicle in a safe area for course deviation? Questions

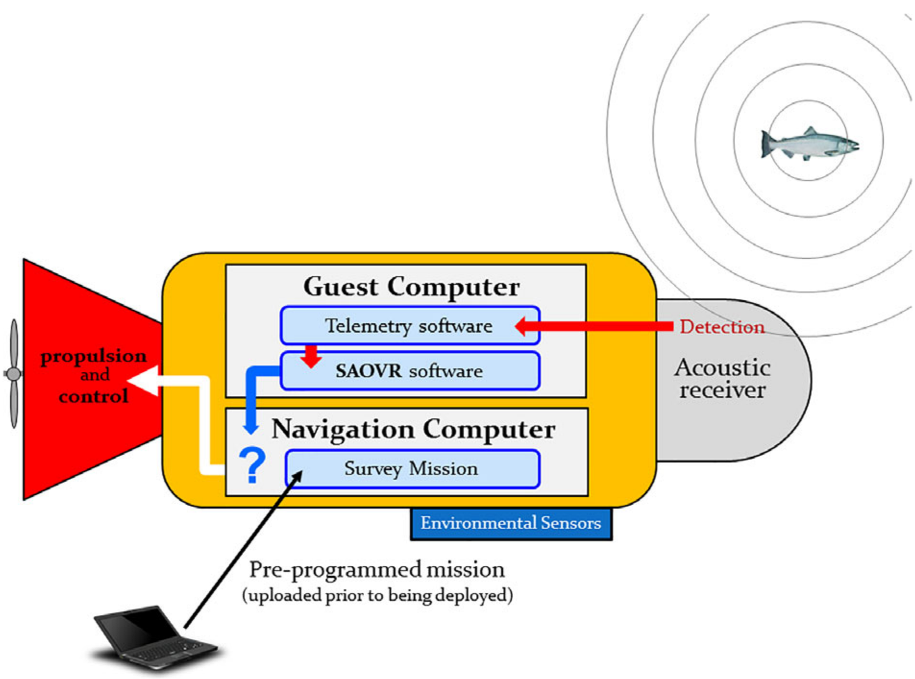


Fig. 2. Flow control in the REMUS-100 with RECON and integrated hydrophone.

1, 3, and 4 are answered by code that checks a timer (cooldown period) against the program's event log to determine the time elapsed since the last maneuver or other constraint was issued. Question 2 is answered by checking tag identities in the program's event log. Question 5 is answered by checking the SPL of the received tag signal against a standard acceptable level set by the user. For our test purposes, this SPL was developed from a distance-vs.-SPL regression (detailed below). Question 6 is answered by comparing the current position of the AUV (retrieved from the RECON protocol text message stream) to all possible positions within "exclusion zones" set by the user in advance. If permission is granted by a unanimous "yes" to all questions, the program checks the tag identity for assignment to a particular maneuver template in an on-board library. For each inflection point in the template, the SAOVR package computes a new heading command based on the current position and the chosen maneuver geometry, specified by heading deviation, speed, and time—where the product of the latter two variables is equated to distance. These commands are then passed to the AUV control package and executed.

The SAOVR package is inactive on the AUV unless it is invoked prior to a mission through the VIP. Thus, it does not interfere with any other missions and will not cause a mission abort because it does not find the optional hydrophone attached. Prior to invoking the program, the user supplies the override parameters as a series of simple ASCII (*.txt) files to a program folder using the Windows drag-and-drop interface (Fig. 3). In broad terms, the operation of the SAOVR package then follows with a series of steps: (1) Run the startup algorithm to initialize the system state (i.e., obtain current position, depth, speed, etc.), (2) provide a keep-alive message (via the "keep-alive" thread) every 2 s to the AUV control stack at all times, throughout the default mission and any overrides, (3) concurrently, keep internal state of the AUV heading and vehicle status via the "status reader" thread, (4) after an appropriate startup delay, wait for an acoustic tag signal to be logged by MAPHost and passed to the SAOVR program via the "tag listener" thread, (5) if a tag is heard, all applicable cooldowns have expired, and the vehicle is not in an exclusion zone, wake the "main thread" to invoke a full override and execute the maneuver specified for that tag, or the default maneuver in the expectation of creating a good aperture, (6) at the end of the override maneuver, release control of the vehicle. The vehicle will then return to either the nearest point on the default mission trackline or the location at which the override was invoked, depending on the setting. (7) After all appropriate cooldown timers have expired, return to step (2). The logic flow of these steps are diagrammed in Fig. 4 and detailed below.

Startup algorithm

The purpose of the startup algorithm is twofold: first, to initialize the system to a known state, and second, to provide a final sanity check of the override parameters for the user, who may be making adjustments to the aperture parameters in the field. First, the log file is opened. Even if the startup algorithm fails, the error message will be written to both the log file and the console to allow users to take appropriate action. Second, the COM port to the RECON stack is opened. A mutual exclusion object (mutex) controlling access to the port is also initialized. Next, the aperture and parameter files are parsed and printed to the log. Any parse error will result in termination of the program with an informative error message saved in the log. Printing the parsed aperture files and parameters to the log allows the user to perform a final sanity check before putting the vehicle in the water. The "tag reader" thread is started next. As a safeguard, the tag reader thread will cause startup to pause until it finds the file that will log any tag detections made by MAPHost. Finally, the "keep-alive" and "status reader" threads are started, and the system enters a wait state until it detects that the AUV has started its pre-programmed mission.

Command file parsers

The command file parsers are responsible for finding and parsing parameters supplied to SAOVR. Two optional parameters allow the user to override the default startup cooldown and SPL cutoffs. An additional optional parameter allows the user to define exclusion zones—circular areas in which no overrides will be executed. Two mandatory parameters are a lookup table file that is keyed by tag ID and provides the aperture that should be executed for that tag (below), as well as at least one aperture file, which becomes the default for all other tags.

Startup delay

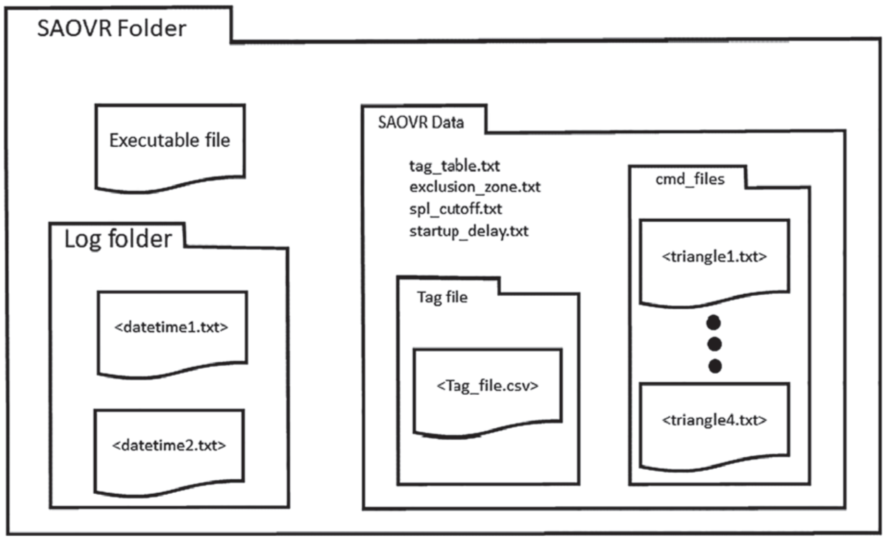
In order to facilitate uninterrupted mission startup, the SAOVR software can be configured to ignore all overrides that would otherwise be triggered for a specified number of seconds after the vehicle is commanded to start the mission. This parameter is optional with a default value of 60 s and was set to 320 s for test missions.

SPL cutoff

The SAOVR software can be configured to trigger overrides only when tags above a certain SPL threshold are reported by MAPHost's csv file output (in the "Power" column). Threshold values for testing were chosen based on a regression of SPL-vs.-distance as calculated from AUV passes near moored reference tags (Fig. 4). Editing this value in the template file (Fig. 3) allows the user to configure the vehicle to respond to tags with some predictability relative to distance from the tag and thus to influence the success of a maneuver in creating an aperture useful for solving the tag position.

Exclusion zones

In order to avoid executing maneuvers in areas where a maneuver may put the vehicle at risk of damage, the user defines exclusion zones as circular areas in which the vehicle




```
%triangle1.txt
%Cooldown period for this particular aperture, in seconds
120
%Turn to make the first half-leg of the triangle (90 deg)
% 1.8 knots = 0.926 m/s, so 10 meters requires 10.8s
10.8
>ALTER HEADING 90
#C,Depth,Altitude,30.0
#C,Speed,1.8 knots
%Turn to make the second leg of the triangle (-120 deg)
%10 meters requires 22.5s
~ continues
```

```
%tag_table.txt
% First line of this file is the global cooldown time in seconds, then each
% additional line is a tag ID (-1 means 'default') and an associated file
% describing the aperture to run (or the IGNORE command)
90
-1 SAOVR_data\\cmd_files\\triangle1.txt
3600 SAOVR_data\\cmd_files\\triangle2.txt
4020 SAOVR_data\\cmd_files\\triangle4.txt
1028 IGNORE
```

Fig. 3. Windows OS folder structure for interfacing with SAOVR and two examples of user-edited text files; (1) an aperture template file (triangle1.txt) with local cooldown and deviation angles and leg durations, and (2) the look up (tag_table.txt) by which the "tag reader" thread assigns a particular detected tag to an appropriate aperture template file. The global cooldown also is assigned here. Lines starting with "%" are comments not read by the software and may be used to annotate the file.

will not respond to any overrides that would otherwise be triggered. These are provided in a text file before startup by a center point (decimal degrees latitude and longitude) and a radius (in meters). A rectangular exclusion zone is easily approximated as a series of circles with widely overlapping radii. As the current AUV position is constantly updated by the "status reader" thread, the distance between the current position and the center of each provided exclusion zone is checked using the Haversine function to compute the distance on an elliptical surface. Note that "exclusion" refers explicitly to the case of override initiation. The AUV may transit the zone as part of the default mission path or may enter it as part of an override maneuver initiated in an open zone. Thus, the placement of an exclusion zone should consider the extent to which any of the possible template maneuvers (see below) might penetrate the zone and should allow such a buffer.

Tag lookup table

The tag lookup table, also a user-edited text file, allows the user to define how the SAOVR package will respond to individual tags, as well as to set a default aperture and identify any tag codes that should be ignored. The table is keyed on the tag code and points to an aperture file (Fig. 3).

Aperture template files

Each aperture template text file uses a simple series of commands to define the geometry of the aperture (Fig. 3). The user

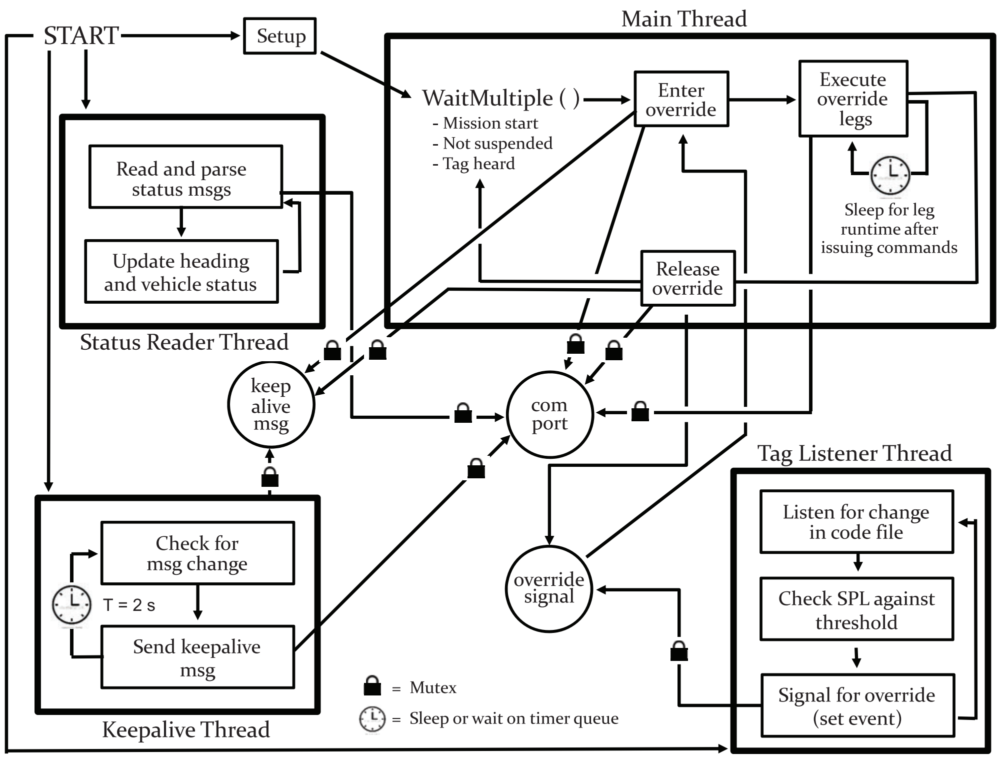


Fig. 4. Flow diagram showing control of communication within and among threads of SAOVR under prioritization by mutual exclusion objects (MUTEX).

may manipulate depth, speed, time, and relative heading over an arbitrary number of legs in order to create complex maneuver geometries. These files are internally translated to appropriate RECON messages on startup. The new heading for a leg is computed by SAOVR by taking the current vehicle heading provided by the "status reader" thread, adding or subtracting the relative heading, then adding 360 and taking the result modulo 360 to ensure a positive result.

Cooldown timers

In order to prevent the vehicle from executing maneuvers ad infinitum in a tag-rich environment, the user must supply two types of cooldowns. The first is a global cooldown (240–480 s during testing), which tells the vehicle how long to wait before it can execute another override. The second is a tag-specific cooldown, provided in the aperture template file (Fig. 3), which tells the vehicle how long to wait before executing another override for that particular tag. Generally, the global cooldown is responsible for keeping the vehicle on-mission, so that the same tag does not trigger repeated overrides from the same location within a given mission or pass, while the local cooldown can be used to tune the behavior for specific tags. For example, tag codes associated with species which are known to be primarily stationary (e.g., crabs) may have very large cooldowns, perhaps even longer than the expected lifetime of the mission, to prevent spurious apertures from being executed when a single aperture is sufficient to collect the required data. Conversely, shorter cooldowns can be used for more mobile species that might subsequently (within a mission) be encountered in different locations.

Keep-alive message thread

In order for the control stack to continue executing the pre-programmed mission, it must receive a keep-alive message at least every 5 s. This is imposed by RECON and cannot be modified by the user. This message is usually provided by the AUV navigation control through RECON, but, in order to implement overrides, the SAOVR package must take over this duty. The nature of the keep-alive message varies with the state of the AUV, but the SAOVR package provides an appropriate keep-alive every 2 s. This allows the software to miss a single message (for example, due to the inability of the "keep-alive" message thread to successfully do a non-blocking acquisition of the COM port mutex) and still keep the vehicle functioning, so long as two messages in a row are not missed. In testing, the keep-alive thread was never observed to miss sending a keep-alive message.

Status reader thread

The purpose of the "status reader" thread is to receive periodic (9 Hz) status messages as specific ASCII text strings from the AUV through the RECON com port and update the internal state accordingly. The three most important pieces of information provided by the vehicle are the current heading, current position, and vehicle state (pre-launch, in-mission,

mission suspended, mission over, override enabled). Depth and speed are also transmitted. Because the vehicle can enter a variety of states in which override is not allowed (e.g., stuck on surface, acquiring GPS), it is necessary to track vehicle state. This also allows verification that overrides have been correctly enabled. The "status reader" thread prints one message per second to the console to allow debugging, and one message every 45 s to the log file to keep the file at a manageable size, while still allowing reconstruction of the mission in the result of abnormal termination.

Tag listener thread

The "tag listener" thread is responsible for reading the tag codes output by MAPHost. While there is a slight delay as the hydrophone processes the signal and sends it over a secondary COM port to the MAPHost software, and another slight delay while the MAPHost software outputs the decoded result, the delays were found to be small enough that they did not affect mission operation. The tag listener thread also checks the SPL against the threshold chosen by regression against distance and listed in the SPL cutoff text file (Fig. 5).

Main thread

Finally, the "main" thread is responsible for executing the overrides themselves. It places itself in a wait state until it receives signals that the mission has started and a tag has been heard, and all appropriate cooldown and exclusion zones are respected. It then wakes, reads the appropriate override commands from the Tag Lookup Table and passes the corresponding depth, speed, heading, and time commands as text strings to the AUV navigation control via RECON's RS232 port.

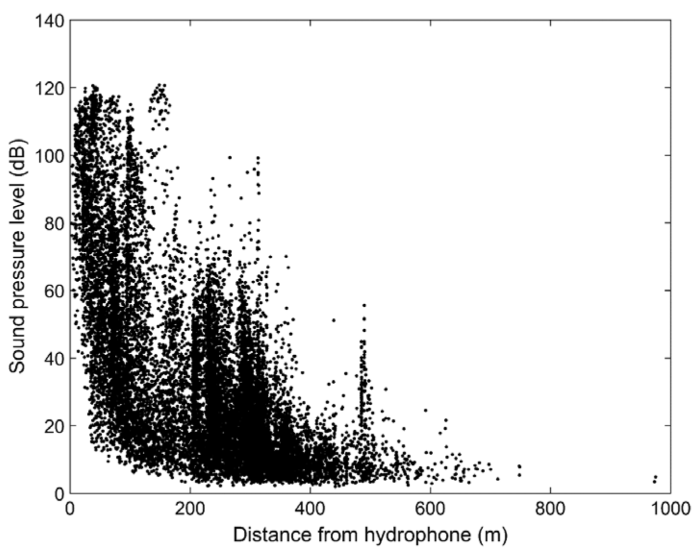


Fig. 5. Scatter of sound pressure level (SPL) vs. distance from reference tags (*n* = 12, same model) at known positions from a test array in Port Walter, AK. The mode spikes (e.g., at 150 m, 300 m, and 500 m) arise because the AUV repeatedly approaches and departs several moored tags from a common baseline distance with fluctuations owing to variation in the timing of maneuver initiation for one or any other tag in the vicinity.

Validation

In-water validation was iterative. Test missions occurred in Great Bay, NJ and in Auke Bay and Port Walter, AK (Table 1). Test missions were run through an array of 2–6 moorings that each supported two active acoustic tags at fixed depths below the surface. Tags were model MA-TP16-33 and broadcast at 2 s intervals with source level 155 dB re 1 μPa @ 1 m. Moorings in Great Bay and Auke Bay were spaced so that tag signals from different moorings would not likely be detected from a common point along a mission path. This emulated the condition of tag detections after cooldowns had expired. However, the positioning of selected moorings in Port Walter, AK (with at least one mooring situated near the baseline path while another was ~ 100 m perpendicular to the path) and the two tags on a given mooring made it possible for multiple tags to be detected simultaneously. This emulated the conditions when multiple fish were detected together and cooldown timers were in effect. Additional reference tags were dragged behind a vessel during later tests (Table 1).

Results and discussion

Every test mission confirmed that SAOVR took control of the vehicle. No missions occurred where either the hydrophone's native record or the SAOVR event log showed a novel tag detection that was not acted on by SAOVR unless it was specifically constrained not to by cooldown, timer, low SPL, specific tag exclusion, or geographic exclusion. However, the potential for such an error was identified. In the case of numerous tags being detected and recorded to file, it is possible for the guest operating system to restrict access to the MAPHost output CSV file (note that this is not a SAOVR function but a Windows OS access conflict). This was observed when tag detections in the MAPHost record were unidentified in the SAOVR event log along with an error message for accessing the MAPHost text file. This is not problematic in practice because, in such a target-rich environment, the AUV will already be executing SAOVR for other tags, which will produce geometries useful for calculating the position of other novel tags recorded in the same detection space.

During test Missions 1 and 2, both cooldown timers were inadvertently set assuming units of seconds (not the requested milliseconds) and thus expired too soon. In retrospect, this tested the null state of the cooldown timer. Upon first tag detection, the AUV initiated a maneuver followed by a series of subsequent maneuvers even before the previous maneuver was completed, resulting in a complex path geometry (Fig. 6). The local tag feedback loop could have been broken by a properly formatted global cooldown timer. With the safety of a global cooldown timer in effect to keep the AUV from wandering, this kind of behavior might be useful to some applications. Randomness is introduced to the initiation direction of each subsequent maneuver (taken off the current heading) through the movement of a tagged fish at liberty or through

Table 1. List of test missions in Auke Bay (AB), Port Walter (PW), and Big Port Walter (BPW), Alaska.

							Cooldown (s)			
Mission	Date	Location	SAOVR	Objectives	Legs	Targets	Startup	Global	Local	SPL restriction (dB)
M1	42016	AB	No	General operational test	1	4				
M2	042116A	AB	Yes	SAOVR test (cooldown)	1	4	360	180	120	
M3	042116B	AB	Yes	SAOVR test (exclusion zone)	2	4	360	180	180	
M4	42216	AB	Yes	SAOVR test (SPL cutoff)	2	4	360	180	180	
M5	42516	AB	Yes	SAOVR test (cooldown)	2	4	960	360	180	40
M6	042916A	PW	No	Survey with reference tags	1	8				
M7	042916B	PW/BPW	No	Survey with reference tags	2	10				
M8	50216	PW	No	Survey with reference tags	1	8				
M9	50316	PW	No	Survey with reference tags	4	8				
M10	51216	PW	No	Survey with reference tags	2	10				
M11	51316	PW	No	Survey with reference tags	2	10				
M12	051416A	PW	Yes	Survey with reference tags	4	2	320	420	240	15
M13	051416B	PW	Yes	Survey with reference tags	4	10	320	420	240	15
M14	051516A	PW	No	Survey with reference tags	4	10				
M15	051516B	PW	Yes	Survey with reference tags	4	10	320	420	240	15
M16	051616A	PW	Yes	Survey with reference tags	4	10	320	420	240	15
M17	051616B	PW	Yes	Survey with reference tags	4	10	320	840	480	15
M18	51716	PW	Yes	Survey with reference tags	4	10	320	840	480	15
M19	51816	PW	Yes	Survey with reference tags	4	10	320	840	480	15
M20	51916	BPW	Yes	Survey with free-ranging fish	8	4	320	420	240	15
M21	52116	BPW	Yes	Survey with free-ranging fish	4	5	320	420	240	15
M22	052416A	BPW	Yes	Survey with free-ranging fish	6	6	320	420	240	15
M23	052416B	BPW	Yes	Survey with free-ranging fish	6	7	320	420	240	15
M24	052516A	BPW	Yes	Survey with free-ranging fish	5	7	320	420	240	15
M25	052516B	BPW	Yes	Survey with free-ranging fish	3	11	320	420	240	15
M26	52616	PW	Yes	Survey with free-ranging fish	8	8	320	420	240	15

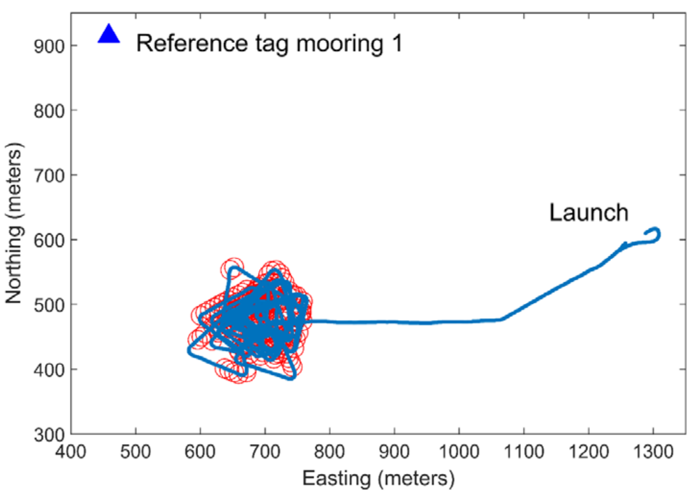


Fig. 6. Plan view of the AUV's path (solid line) during Test Mission 1 on 21 April 2016 including left-deflection "point forward" triangular override maneuvers without a proper cooldown period. Open red circles denote the position along the AUV's path when tag ID no. 15821 was detected. Easting and Northing are truncated (easting -519000, northing -6470000) UTM Zone 8 V.

variation in the interval between received (rather than broadcast) tag signals. If a user wanted to create a loiter for specific tags near a detection position in order to gain side scan sonar imagery from many different angles, but without coding complex geometry, they could shorten the local cooldown and set a global cooldown that would break it out of the loop. Cooldown parameters were correctly entered in all subsequent missions and performed as expected, both on local and global settings.

Predictability as a function of SPL threshold was tested specifically during Mission 3 and monitored on all subsequent missions. Minimum SPL was set initially at 44 dB and thereafter at 15 dB based on an expected distance-to-tag of about 400 m and 900 m, respectively (Grothues and Davis 2013). The position at which the AUV executed an override for a given tag along a repeated search varied by meters (Fig. 6). In practice for ecological studies, a higher SPL threshold should be set to let the AUV approach closer before initiating navigation override. This would have increased the chance that a maneuver would envelop a tag, which provides the best synthetic aperture. In the current case, the low threshold was

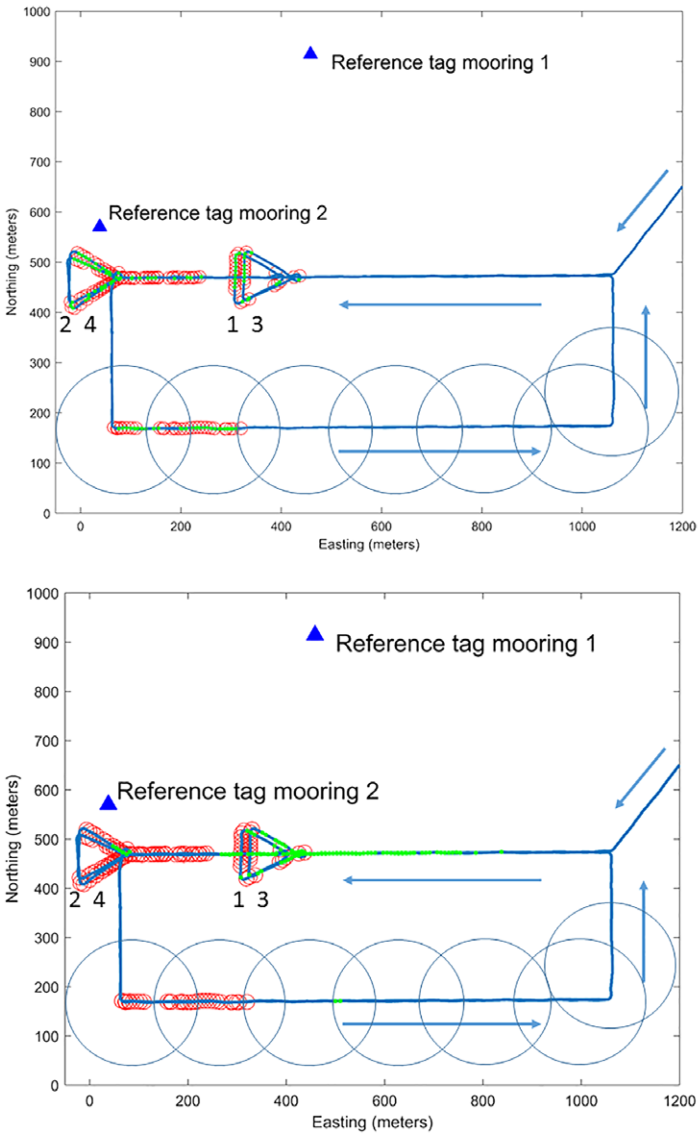


Fig. 7. Plan view of the AUV path (solid blue line) during Test Mission 3 on 25 April 2016. Arrows denote direction of travel from launch and twice around circuit. Two override maneuvers were completed on each lap at similar positions (sequence denoted by numbers 1–4) in response to detections from tags at mooring 1 (maneuvers 1 and 3) and mooring 2 (maneuvers 2 and 4). Note that tag detections were also made during maneuvers for tags on mooring 1, and although the previous maneuvers were not initiated for a tag because the AUV was already in a maneuver or in cooldown, the detections made can contribute to the formation of synthetic aperture for the secondarily detected tag. In the upper panel, open red circles denote the position along the path where tag ID no. 10435, at 25 m depth on mooring 2, was detected. Green dots show the location where tag ID 15085, at 50 m depth on the same mooring, was detected. The similarity in detection patterns illustrates the predictability of detection zone and maneuver execution in a given acoustic environment, and why a maneuver executed in response to detection of the first tag serves synthetic aperture formation for the second. In the lower panel, the effect of the history of detection from Tag ID 15821, (green dots, on mooring 1 at 25 m depth) on the position of allowable executions for Tag ID 10435 (red circles, mooring 2), is shown. There were five types of restriction controls in place, (1) a launch countdown to preserve boat and AUV safety (enforced but not invoked since the tags were well out of detection range at launch), (2) an SPL restriction visible in the lower panel as a long run in for tag 15821 (green) (3) a tag cooldown, a (4) global cooldown and (5) geographic exclusion zone. Detections were made on the eastbound return legs but overrides were suppressed due to the enforcement of an exclusion zone programmed as a sequence of circular zones (open gray circles) for that entire leg. Easting and Northing are truncated (easting -519000, northing -6470000) UTM Zone 8 V.

necessary to allow overrides from tags on distant moorings (which would never be enveloped given the maneuver templates used) for the purpose of testing synthetic aperture performance (treated separately). The particular SPL threshold should be set based on expectations of the performance of the tags in use for a project given a known signal repeat rate and strength. Performance in the case where a variety of tag models are expected in a search area can be enhanced by keying different tag models to different maneuver sizes (aperture templates) even if the threshold SPL is constant. The SPL threshold can be overruled by enforcement of a cooldown period. If a novel tag is detected soon after the maneuver for a prior tag is initiated, it can be temporarily ignored. This may move the vehicle closer to the next tag so that its override maneuver happens at a different distance relative to the tag (and possibly even after passing it) (Fig. 6). All of the detections can still be used in the synthetic aperture calculation. Consecutive novel tags within a maneuver all benefit from the same maneuver.

Exclusion zones were first tested during Mission 3. Exclusion zones were implemented in all test missions thereafter in response to real concerns about vehicle safety in the confines of the deep, steep-sided fjord where a case study examined salmon emigration. Geographic exclusions were never violated despite the presence of towed and moored test tags and tagged fish at liberty as observed during Mission 3 (Fig. 7).

This work produced an open source software package that provides an easy-to-use and stable method for implementing payload control for telemetry on REMUS class AUVs with RECON. The package is freely available at GitHub (https://github.com/sharkiteuthis/REMUS-Control-Framework-Public). The architecture can be duplicated for use on other vehicles mounting Lotek hydrophones, including open source vehicles without RECON, because decisions culminate in ASCII string commands that can be easily tailored to other systems.

Several important caveats need discussion as they relate to further work. First, the software cannot currently be implemented for use on acoustic fish tags from other vendors. While it would be straightforward to modify the current software to monitor an exported log file other than the one produced by MAPHost, it is important that a tag manufacturer includes such a near-real time option with their hydrophone/processor interface software. Alternatively, the package could be altered to allow the "tag reader" thread to access the secondary COM port to receive signals directly from the hydrophone's native processor (though that might be binary and require interpretation). Also, override maneuvers offer diminishing returns if a synthetic aperture cannot be calculated. This happens when the timing of the signal pulse train is randomized to prevent code-collision; the interval to subtract from successive timestamps of a collection of received signals cannot then be known. Even in the absence of randomization, the signal architecture of some tag types dictates both long signal duration and signal spacing so that relatively few signals may be recorded within an aperture and with greater individual error in arrival time as the signal train spreads (*see* Grothues 2009). Furthermore, SPL is not logged by all types of receivers and thus could not contribute to decision making. However, it would be feasible to use the payload control for other tag types (including tags with pseudo-randomized signal intervals) simply to cause the AUV to loiter or further search locally. This is similar to the way that oceanic predators hunt for patchy prey (Humphries et al. 2010) and it has been applied in terrestrial robots (Saldivar 2012). In that case, a detection kernel density calculation might narrow a position estimate to improve measures of the local habitat from other sensors, including side scan sonar (*see* Grothues et al. 2017).

The logic flow for this software allows great flexibility in designing sampling strategies. Because tags are keyed to different maneuver templates (including no maneuver), a single mission can serve to map the distribution of multiple species with maneuvers appropriate to each, for example, large fast maneuvers for fast-moving sharks with large loud tags, small maneuvers for sedentary flounders or crabs with smaller, quiet tags, or schooling fish with clustered distribution, and even ignoring reference or dropped tags. The user simply edits the requisite text files in any text editor and saves them in a designated folder in the familiar Windows environment prior to startup. The maximum possible mission time is bounded as the default mission time plus the product of the number of tags at liberty and the duration of their designated maneuver and will be less than that unless tags are detected at equal spacing and always as cooldowns for previous detections have expired. The expected recovery location is never changed and the vehicle does not roam or follow fish beyond specified search areas.

We close by treating the potential for expansion of this software or its logic to other sensor applications, using active acoustics (SONAR) as a proximal example of interest to fisheries investigations (*see* Grothues et al. 2017). In that case, the sensor (transducer) also incorporates a hydrophone and writes properties of the received signal echo to a file. In the case of "fish finder" SONAR, this will be reverberated waveform and strength data, and in the case of side scan sonar as used on the current test vehicle, this will be georeferenced imagery stored in long-track segments called tiles. In either case, some sort of sonar interpretation output (not raw data) must be available to SAOVR. For example, if MATLAB were also running on the guest or integrated system and had access to the drive where sonar data was being written, then an image processing routine would query tiles (with some lag) or signal reverberation characteristics (with less lag because a whole tile is not necessary) and write a decision to a text file. Note that the MATLAB signal-processing algorithm in this hypothetical example is analogous to and replaces the processing and output that Lotek's MAPHost does; it is not an "additional" piece. The user would tell SAOVR what kind of logged value (for example binary) to expect in an analog to the tag lookup file checked at some short regular interval. After that, all the logic and code remains the same. Note that the maneuver would not be executed for the same purpose (e.g., for positioning the reflector, which is already done by side scan sonar's geotiff print routine), but rather to increase sampling time in the vicinity or obtain different imaging angles in order to confirm, identify, or better describe a target.

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Conflict of Interest

None declared.

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