AUV Experiments in Obstacle Avoidance

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Abstract **– Reactive Obstacle Avoidance (OA) is an important step in attaining greater autonomy in Autonomous Underwater Vehicles (AUV). For AUVs that conduct underwater surveys, avoidance of uncharted obstacles can improve vehicle survivability. This paper discusses initial experiments at the Center for AUV Research in obstacle detection and avoidance using the Naval Postgraduate School ARIES AUV with the Blueview Blazed Array forward looking sonar. It includes a discussion on evaluating OA optimality, autopilot control design and sonar image processing. It concludes with a description of successful results from a recent demonstration.**

I. INTRODUCTION

Autonomous Underwater Vehicles (AUVs) have become important tools for assessing the environment. Whether it is assessing a naval mine threat or the collection of oceanographic data these vehicles provide users a better understanding of the ocean. A limitation of many AUVs is the inability to avoid potentially dangerous obstacles in their path. There are many situations where a vehicle could benefit from the ability to identify and avoid obstacles and navigational hazards. These include: A sharp rise in the ocean floor, a dredged harbor lane, an obstacle proud of the ocean floor and ships maneuvering on the ocean surface.

Recent advances in sonar technology have enabled the development of relatively low-cost, low-power, Forward Looking Sonar (FLS) that can provide the sensing for an AUV obstacle avoidance (OA) capability. This paper discusses five topics: first, the sonar and AUV systems involved in the experimentation, second, the development of a framework to evaluate the optimality of avoidance maneuvers, third, design consideration in the development of the autopilot controller for obstacle avoidance, fourth, the image processing necessary to detect, measure and track an obstacle and fifth, initial experimental results.

II. SONAR DESCRIPTION AND VEHICLE CONFIGURATION

NPS ARIES (Fig. 1) is an AUV designed for experimentation and testing of new navigational concepts and sensor systems. For communications it features Freewave 900MHz and 802.11a/b WLAN radio communications, a Benthos Telesonar Underwater Acoustic Modem and an Ashtec GPS receiver. For navigation it has the Kearfott Gyro System, the Systron

Fig. 1. NPS ARIES AUV

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14. ABSTRACT
Reactive Obstacle Avoidance (OA) is an important step in attaining greater autonomy in Autonomous Underwater Vehicles (AUV). For AUVs that conduct underwater surveys, avoidance of uncharted obstacles can improve vehicle survivability. This paper discusses initial experiments at the Center for AUV Research in obstacle detection and avoidance using the Naval Postgraduate School ARIES AUV with the Blueview Blazed Array forward looking sonar. It includes a discussion on evaluating OA optimality, autopilot control design and sonar image processing. It concludes with a description of successful results from a recent demonstration.

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Donner Motion Pack Inertial Measurement Unit (IMU) and the Honeywell HMR3000 tri-axial magnetometer. For sensors it has the Blueview Technologies Blazed Array FLS, a 600KHz RDI Doppler Velocity Log, a Deep Sea Power and Light underwater camera and a pressure cell. For a more thorough description see [1].

The Blazed Array by Blueview Technologies was the sonar system used with ARIES. It uses broadband transmitters and receivers with time-frequency decomposition to encode imaging information. This technique greatly reduces hardware requirements since all of the information is distributed and collected through one broadband signal channel. The sonar has a center frequency of 450 KHz. The arrays can be configured in either a vertical or horizontal configuration. For the initial experiments, an emphasis was placed on avoiding obstacles proud of the ocean floor so the arrays were mounted vertically on the bow of ARIES.

Fig. 2 illustrates the nominal projection of sound from the arrays with the vertical mounting. Using a line normal to the vertical surface of the stave as a reference, the high frequencies emanate downward at approximately 22.5 degrees and the low frequencies at 45 degrees. Each stave also has approximately 12 degrees of horizontal aperture.

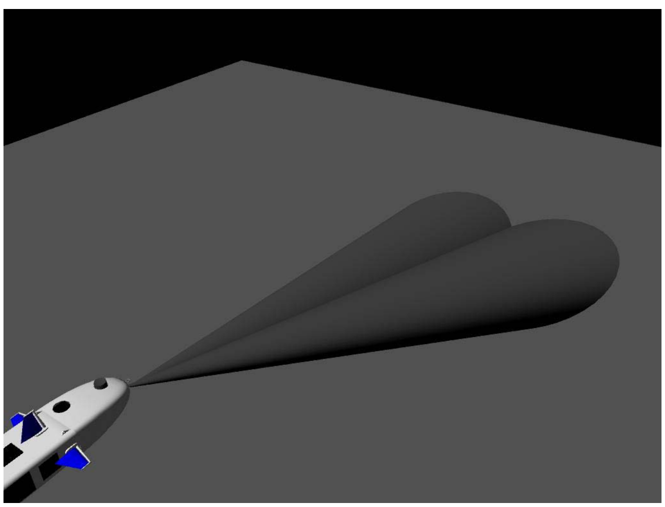

Fig. 2. Projection of the Blazed Array Sonar

Fig. 3 is an example of two images from the Blazed Array mounted on the NPS ARIES. The sonar transducer attached to the AUV is located at the top left corner of each image. The strong linear return in each of the images is typical of a flat ocean floor without obstacles. The volume above the ocean floor is the ensonified portion of the water column and is bounded by the upper and lower frequency of each sonar stave. For our application, the sonar is set to a medium low resolution which results in an image size 491x 198 pixels with an effective range of approximately 80 meters. This resolution permits a 1 Hz sonar update rate which is reasonable for the OA experiments.

Equations (1 and 2) represent the distance calculations from the nearest and farthest sonar beams (respectively) as they reflect off a featureless ocean floor. Θ_T is the total angle measurement taking into account the sonar mounting angle (Θ_a) and the vehicle pitch at time t, ($\Theta(t)$). $d_1(t)$ is the distance forward of the vehicle with to the low frequency return and $d_2(t)$is the distance forward of the vehicle to the high frequency return.

$$d_1(t) = h(t) * \tan(\Theta_T) \quad (1)$$

$$d_2(t) = h(t) * \tan(\Theta_T + 22.5) \quad (2)$$

$$\Theta_T = 45 + \Theta_a + \Theta(t) \quad (3)$$

III. HARDWARE AND SOFTWARE ARCHITECTURE

A principle feature of ARIES is its flexibility for housing new hardware and software for testing new methodologies in underwater robotics. There are three components of the Blazed Array sonar: the arrays, the electronics and a PC-104 computer for image

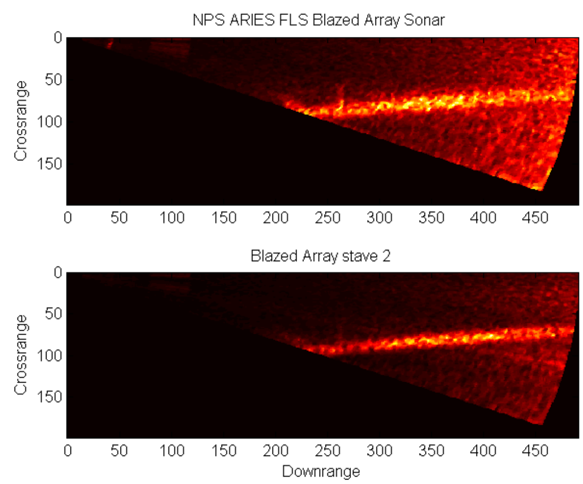

Fig. 3. Blazed Array Sonar Image Examples for Flat Ocean

storage and processing. The original bow design was modified to mount the arrays. To maintain hydrodynamic efficiency, a flexible polyurethane nose was constructed to house the arrays. This minimizes signal attenuation and provides a degree of protection. The construction of the nose permits the arrays to be oriented either in the horizontal or vertical position.

The power and control signals are passed through a water tight bulkhead and attached to the electronics. From there, images are saved and processed using a Windows based PC-104 computer. A graphical depiction is given in Fig. 4.

V. EVALUATING OPTIMAL AUTOPILOT CONTROL FOR REACTIVE BEHAVIORS

Currently many AUVs use side scan sonar to survey an area. These vehicles frequently navigate using a fixed altitude command to provide consistency in the sonar images. Typically there is a sonar gap underneath the vehicle known as the "near-nadir" region. Altitude navigation is normally close to the ocean floor in order to reduce this gap.

An optimal reactive avoidance strategy can be defined as the minimization of Cross Track Errors (CTE) from the intended original path. For vehicles surveying the ocean with sonar systems, minimizing CTEs in the vertical plane is desired since this minimizes gaps in the near nadir region. Minimizing CTEs in the horizontal direction is desired since stable heading results in consistent side scan images. This general optimization problem can be defined as the minimization of the AUV CTE subject to constraints.

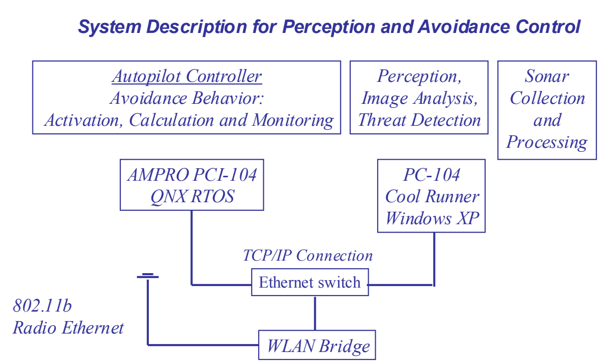

Fig. 4. System Description for Perception and Control

This can be mathematically defined as a line integral *f(x,y,z)* with respect to arc length *C*. The arc is a segment of the path from waypoint *a* to *b* and defined by the vector ***r*** in (4). Assume that the curve is continuous and is given by the parameter *t* in (5). The line integral is given in (6 and 7) where *ds* is the magnitude of *dr* (8).

$$r(t) = g(t)i + h(t)j + l(t)k \qquad a \le t \le b \tag{4}$$

$$x = g(t),\ y = h(t),\ z = l(t) \tag{5}$$

$$A = \int_C f(x,y,z)ds \tag{6}$$

$$A = \int_a^b f(g(t),h(t),l(t))\sqrt{(\frac{dx}{dt})^2 + (\frac{dy}{dt})^2 + (\frac{dz}{dt})^2}\,dt \tag{7}$$

$$ds = \|r\| dt \tag{8}$$

The total avoidance behavior along one waypoint track can be described as a finite number of piecewise smooth curves where each departure from the waypoint track is an obstacle avoidance behavior. Each piecewise curve is ensured to be greater or equal to zero by taking the absolute value (9). Each avoidance is also bounded by a start and endpoint (*a*,*b* respectively).

$$CTE_0 = \int_{c_1} |f|\ ds + \int_{c_2} |f|\ ds + \int_{c_3} |f|\ ds + \ldots + \int_{c_n} |f|\ ds \tag{9}$$

The entire navigation route can likewise be summed (10) to obtain a metric for how the vehicle navigated through an obstacle field. Surveying the entire area and minimization of the total avoidance is the navigation goal.

$$CTE_T = \sum_1^n CTE_n \tag{10}$$

where

n = number of navigation waypoints

There are at least four constraints associated with the minimization goal, they are:

1. Successful navigation around the obstacle
2. Smooth continuous navigation
3. AUV limitations in turning radius in the horizontal and vertical planes
4. Minimizing AUV changes in pitch and heading commands to maintain optimal sensory orientation

It is, of course, imperative that the vehicle miss the obstacle. To ensure that the vehicle misses the obstacle, a minimal "protection sphere" is artificially placed around the obstacle. For an obstacle on the bottom, the protective area would be a half sphere above the ocean floor. Equation 11 gives the standard equation for a sphere of radius *a* centered at (x_0, y_0, z_0). The variable *a* corresponds to a scalar representing the protection buffer plus the maximum radial distance from obstacle center and (x_0, y_0, z_0) is the center of the identified obstacle. Equation 12 represents the avoidance behavior where the AUV navigation path does not intersect the obstacle protection sphere boundary.

$$(x-x_0)^2+(y-y_0)^2+(z-z_0)^2=a^2 \quad (11)$$

$$\left(f(x,y,z) \quad (x-x_0)+(y-y_0)+(z-z_0)=a^2\right)=\varnothing \quad (12)$$

The vehicle maneuverability is a constraint on the optimization problem. There are limitations in the turning radius in the vertical and horizontal directions. In the vertical plane, there is a maximum pitch angle which an AUV cannot exceed. Without the ahead looking sonar, and at a given fixed navigation altitude there is a minimal size where an obstacle proud of the ocean floor becomes a navigational hazard. Fig. (5) shows simulation results to demonstrate the limits in ARIES ability to avoid an obstacle proud of the ocean floor. With ARIES navigating at three meters altitude, without taking into consideration lags in sensor reporting, and without a FLS, an obstacle greater than 5 meters high would result in a collision. Any ocean bottom slope increase of greater than approximately 35 degrees would result in a collision.

Another set of constraints relate to optimal sensory orientation. Maintaining a pitch close to zero ensures that the FLS can reliably provide feed forward input to the controller. Minimizing the changes in heading due to avoidance maneuvers in the horizontal plane ensures consistency in the collection of side scan sonar imagery.

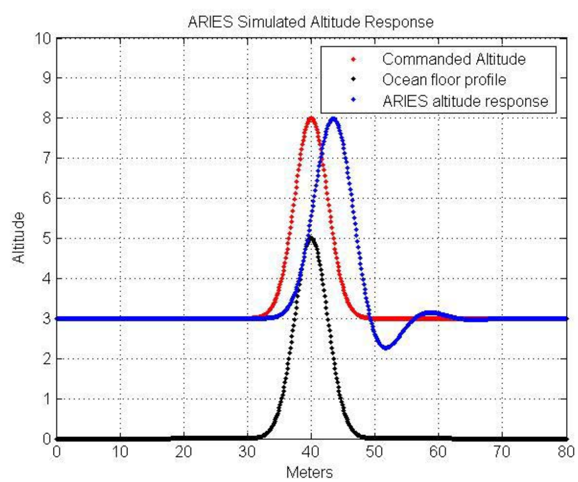

Fig. 5. Simulated Altitude Response of ARIES

Equations 13 and 14 represent the goal of minimizing the rate of change for pitch and heading during active avoidance maneuvers and summing that over the total avoidance maneuvers and navigational waypoints.

$$\sum_{WP=1}^{p}\sum_{OA=1}^{m}(Min\sum_{n=a}^{b}\frac{\partial\theta_n}{\partial t}) \quad (13)$$

$$\sum_{WP=1}^{p}\sum_{OA=1}^{m}(Min\sum_{n=a}^{b}\frac{\partial\psi_n}{\partial t}) \quad (14)$$

In summary, there are many ways to define avoidance optimality; typical formulations include time and energy optimization. For AUV survey vehicles that place a premium on maximizing area coverage, one measure of optimality is minimizing the total cross track error throughout the navigational profile. This framework can be used to compare reactive avoidance strategies to investigate the best choices for different situations.

VI. AVOIDANCE NAVIGATION IN THE VERTICAL PLANE

For initial experimentation, emphasis was placed on the vertical avoidance of an obstacle that was proud of the ocean floor. This was based on a prioritized list from the Office of Naval Research (ONR) and U.S Navy AUV operators. (Note: This can be used to make some simplifying assumptions about quantifying the optimality of the reactive avoidance behavior, namely that only motion in the vertical plane is considered.)

An AUV typically senses altitude and measures speed over ground using a Doppler Velocity Log (DVL). For a vehicle in continuous forward motion, without a FLS, (as described earlier) there is a gradient threshold where the DVL is no longer adequate to maintain altitude. This is important in that it identifies the height parameter in FLS image processing for classifying a feature as a navigational hazard[1].

There are many different methods for embedding an obstacle avoidance behavior in the autopilot. Examples include: Artificial Potential Fields [2], Histograms [3,4] and Fuzzy Logic [5]. For the initial testing simplicity was considered most important. Heminger [7] concluded that a Gaussian-based additive function (Equations 15–20) was a reasonable solution for a range of vertical avoidance scenarios.

$$AltCom = Alt + Max\,Height * e^{\frac{-(x-x_i)^2}{2*\sigma^2_x}} \quad (15)$$

$$Alt = Default\ Altitude\,Command \quad (16)$$

$$Max\,Height = Obstacle\,Height + Safety\,measure \quad (17)$$

$$x = \ AUV\ Position\ Along\,Track \quad (18)$$

$$x_i = Obstacle\,Position\ Along\,Track \quad (19)$$

$$\sigma_x = Variance\ Along\,Track \quad (20)$$

[1] Previous research by Healey [6] has characterized the limitations of the REMUS AUV to react to steep increases in an ocean floor. In simulation, at three knots the smaller vehicle was unable to maintain altitude when the increase in the ocean floor slope was greater than 45 degrees.

Fig. 6 shows a diagram of the feed forward controller. ARIES uses a Sliding Mode Controller (SMC) for altitude, depth and heading. A SMC requires a linear combination of state variables to be used for the identification of a sliding surface. The goal is to drive the surface to zero. A control law is defined using Lyapunov methods by defining a positive definite function. During an ARIES navigation run, when an obstacle was detected, the size and position relative to ARIES was forwarded to the controller. The Gaussian derived altitude command was calculated by an avoidance function based on the height of the object and this, in turn was passed to the SMC as an altitude command.

VII. OBSTACLE DETECTION AND SONAR IMAGE PROCESSING

The goal is to detect obstacles that represent a threat to the AUV. In general, the goals of the image processing are as follows:

1. Identify the ocean floor.
2. Establish a Region Of Interest (ROI) search space
3. Search the ROI for obstacles
4. Identify and track obstacles
5. Provide measurements to the autopilot controller
    a. Distance of obstacle from ARIES
    b. Height of obstacle
    c. Centroid of obstacle

The first step is gathering statistics on each image to determine a threshold value. The threshold value is used to create a binary image where values less than the threshold are set equal to zero and values equal to or above the threshold are set to one. The next step is to erode the images. Erosion of the binary image sets each pixel to the minimum of a 3x3 region where the pixel is the center point of the region. This is done to give a finer definition to the structural returns from the sonar.

An important step in the process is the use of a transform to identify the pitch of the ocean floor. It is used to isolate linear features within the sonar image. As seen in Fig. 3, a typical sonar image with arrays in the vertical orientation displays a strong linear feature corresponding to the ocean floor. The transform starts from a reference point and searches through the image for strong evidence of lines.

The result of the transform is a series of candidate solutions. Selection of the best candidate line is determined by three factors: First a four-state Kalman Filter was used where the measurement model includes: vehicle pitch, pitch rate and the two rotation angles determined by the transforms (one for each image).

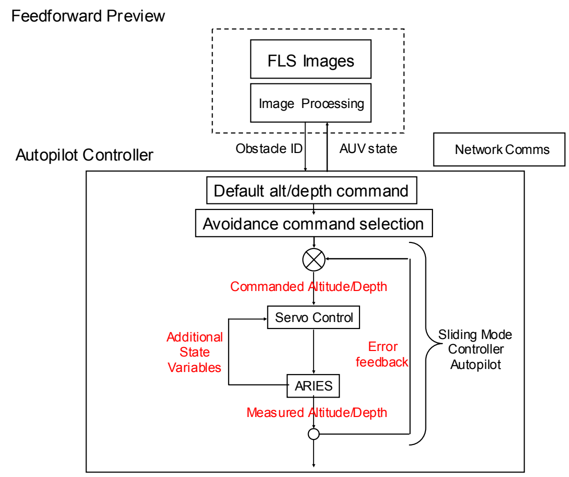

Fig. 6. Feed Forward Control Diagram

The filter produces an estimate for the rotation angle necessary to produce a flat ocean floor slope. This estimate together with an added margin of error is used to deselect candidate lines. Second, the line segment length is used as a criterion for selection where longer lines are considered stronger candidates. The final criterion is the location of the line segment in the image. Stronger candidate lines are located close to the predictive near and far boundaries of the sonar projection on the ocean floor given a vehicle altitude. The combined effect of the selection process is to serve as a spike rejecter for erroneous transform results.

After the proper slope of the ocean floor has been selected a Region of Interest (ROI) was identified. Position of the ROI is dependent on the altitude of the AUV. Using (2), one can project the ROI search space based on the current altitude; this defined the near and far ROI boundaries. The lower ROI boundary is determined by the vehicle altitude and the upper ROI boundary is defined by the upper image boundary. This ROI is well-suited for vertical avoidance and obstacle searches proud of the ocean floor; different ROIs are required for volume and horizontal searches.

The ROI search space is where obstacles are detected and tracked. Detection is accomplished by searching for contours in the binary image and calculating the interior area. If the object is large enough it is registered as an obstacle. Obstacles are tracked using a second Kalman Filter where if the relative speed of the obstacle matches closely to ARIES forward velocity, the trajectory is on a collision path and the obstacle has been identified greater than a threshold, a network message is sent to the autopilot controller.

While the two arrays are mounted in a vertical configuration, there is an approximately 12 degree horizontal component to the images. The arrays are mounted so that the horizontal components have a small degree of overlap. This can be helpful in determining when ARIES is on a collision course. If the obstacle appears equally strong in each image and the vehicle is traveling in a straight path, the AUV is on a collision course. Conversely, the appearance of an obstacle in one image and not in the other indicates that the vehicle can make small horizontal corrections to the opposite side. This information can also be used for tracking vehicle navigation by applying Optical flow techniques to image analysis.

VIII. EXPERIMENTAL RESULTS

Initial experiments and demonstrations were accomplished during the Office of Naval Research (ONR) AUV FEST 2005 at Naval Undersea Warfare Center, Keyport, WA, June 06-16, 2005. The objective was to demonstrate avoidance in the vertical plane by navigating over the top of a designated obstacle proud of the ocean floor. The obstacle was a sunken barge, which at its peak is 6 meters off the ocean floor and approximately 15 meters wide.

Fig. 7 shows the results of an ARIES avoidance run. From the top moving downward, the graph includes the total water depth, vehicle altitude, depth and pitch and the results of the image processing to determine the image rotation necessary to project a flat ocean floor. The abscissa image number taken at each sonar ping and the ordinate is in degrees or meters as appropriate. The difference between the vehicle pitch and image rotations

is the mounting angle of the sonar staves (approximately -6 degrees). The avoidance behavior is highlighted in the box area of Fig. 7 between images 250 and 300. The additive (and subtractive) altitude command is the result of sonar image processing identifying and passing the

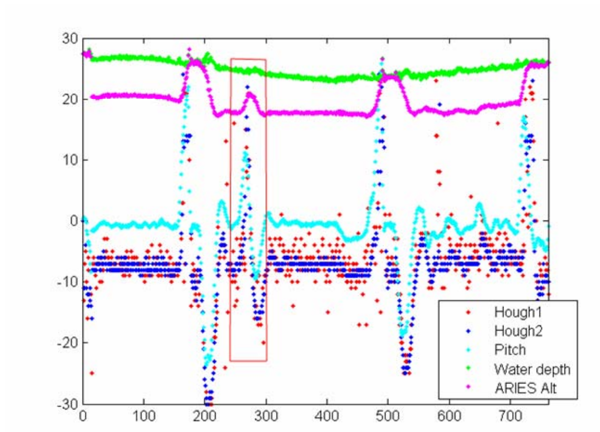

Fig. 7. ARIES OA Results

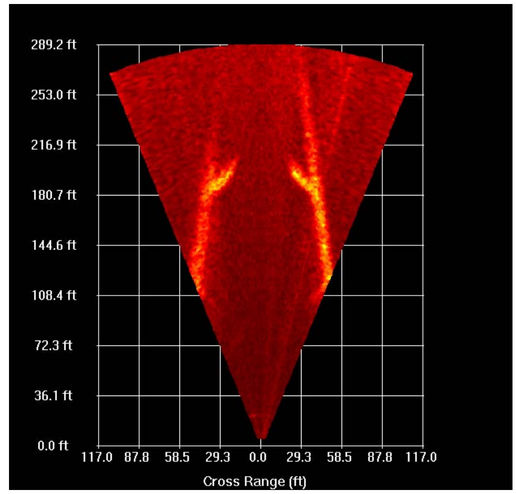

Fig. 8. Blazed Array FLS Images of Underwater Barge

position and height of the obstacle to the vehicle controller. The autopilot controller avoids the obstacle using the Gaussian additive function to the original fixed altitude navigation run. The remaining altitude adjustments are the results of GPS navigation updates and mission completion. Fig. 8 shows a sonar image from both staves of the underwater barge.

IX. CONCLUSIONS

In a variety of circumstances, AUVs can benefit from an OA FLS. The sensor provides greater understanding of the ocean environment and with software to support obstacle detection it can improve vehicle survivability and permit greater vehicle autonomy. The Blueview Blazed Array is a small, quality sonar that has proved to be capable of providing accurate sonar images for OA. This represents a significant improvement for small to mid-sized AUVs since the cost, size and energy budget of the FLS make it reasonable as a sensory system. The challenge is developing the software to accurately and robustly detect and avoid navigational hazards. This includes use of computer vision techniques for detecting and measuring obstacles and the design of autopilot controllers for efficient avoidance behaviors. The NPGS Center for AUV Research has demonstrated an initial vertical OA capability with the ARIES AUV. Remaining tasks include making the vertical OA more robust to reduce false contacts, development of a horizontal OA behavior and development of a path planning module.

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