Dual-Frequency Acoustic Camera: A Candidate for an Obstacle Avoidance, Gap-Filler, and Identification Sensor for Untethered Underwater Vehicles

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Abstract- **The Dual-Frequency Identification Sonar (DIDSON) is a forward-looking sonar that can mount on an Untethered Underwater Vehicle (UUV). It performs three important tasks. In the low-frequency mode, it ensonifies the gap between the coverage of two side-scan sonars during surveys and can serve as an obstacle avoidance sonar. In the high-frequency mode, its very high resolution allows the identification of objects in turbid water where optical systems fail. The sonar is small, light, and requires only 30 watts to operate. DIDSON currently is used on three UUVs (two swimmers and one crawler) as part of the Office of Naval Research Undersea, Autonomous Operation Capabilities Program.**

DIDSON has a 29° Field of View and operates at either 1.0 MHz or 1.8 MHz. The Woods Hole REMUS vehicle, in its dual side-scan sonar configuration, has a 6-m to 8-m gap in its coverage. This gap is filled by DIDSON when looking down-range at distances greater than 16 m. The Bluefin Robotics UUV operated by the Coastal Systems Station swims in deeper water, flies higher off the bottom and has a side-scan gap up to 20 m wide. A modified DIDSON that operates at 750 kHz (DIDSON-LR) is proposed for this application. It should image at ranges in excess of 40 m.

When operating as a gap-filler, DIDSON collects data at a constant frame rate and stores that data during the duration of the mission. An analysis application is being written to sift through the gigabytes of stored data, locate objects on the seafloor and score them with respect to their mine-like characteristics. Operation efficiency will dramatically increase when UUVs can identify mines autonomously and act upon these identifications. Algorithms are being developed to perform this autonomous identification. The process starts with image processing to extract salient object features. The current approach compares these features to a knowledge base of object features, allowing for object rotation and interaction with the environment. Intelligent algorithms will be developed to associate the object under consideration to objects in the knowledge base in a statistically significant way.

I. INTRODUCTION

A number of Untethered Underwater Vehicles are now reliable platforms that can be used to efficiently probe underwater environments. One important sensor that has been difficult to obtain for small UUVs is a multi-beam, forward-looking sonar. A forward-looking sonar is useful in three ways. First, it can be used as an obstacle avoidance sonar, providing warning to the UUV that an obstacle is ahead and providing the information needed to change course and avoid collision. Second, the sonar can be used to be a gap-filler in surveys that use side-scan sonars on each side of the vehicle. Third, it could be a surrogate for a video system in turbid water. Many small submersibles are equipped with video cameras to record or transmit back images to an analyst. These images can be used for search, inspection, and identification of objects. Unfortunately, more and more work is taking place in turbid water where optical systems fail. This paper discusses a candidate multi-beam, forward-looking sonar that is small, has high resolution, and is easy on the power budget.

II. SONAR DESCRIPTION

The Acoustic Camera discussed in this paper is named "Dual-Frequency Identification Sonar" (DIDSON). DIDSON uses acoustic lenses to both transmit and receive very narrow beams of sound. The sonar operates at two frequencies. At 1.0 MHz the sonar forms 48 fan beams 0.6° horizontal by 12° vertical spaced 0.6° apart in the horizontal dimension. The sonar range is up to 40 m at 1.0 MHz. At 1.8 MHz the sonar forms 96 beams 0.3° horizontal by 12° vertical spaced 0.3° apart. The sonar range is up to 15 m at 1.8 MHz. The sonar has a field of view of 29° at either frequency.

DIDSON, shown in Fig. 1, was developed to identify underwater intruders detected by a harbor surveillance system, but its near-video quality images qualifies the sonar for many applications [1, 2, 3]. It has been mounted on the front of a submersible to detect and identify objects, on a riverbank to count fish, and on the wall of a dam to evaluate fish deflection equipment on turbine intakes. DIDSON can focus on objects that range from 1 m to 40 m from the sonar. The sonar consumes 30 watts and measures 31 cm by 21 cm by 17 cm. It has a weight in air of 7 kg (15 lbs.) and a weight in water of 0.6 kg (1.3 lbs.) negative. DIDSON updates its image between 21 frames/s

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to 5 frames/s depending on the operating frequency and the maximum range imaged. It communicates with its host using Ethernet.

Fig. 1. Side view of DIDSON. The lenses are in the upper rectangular compartment. The electronics are in the cylindrical housing. A focus motor moves the center lens element fore and aft to focus on objects from 1 m to max range.

III. A SENSOR FOR A UUV

Untethered Underwater Vehicles are capable and reliable platforms that are finding a number of uses in the scientific, commercial and military communities. DIDSON promises to be a useful forward-looking sonar for these vehicles. UUVs are typically small and are very sensitive to power consumption. Reducing power consumption increases mission time for a given weight and volume of batteries. DIDSON consumes only 30 watts and generates an image frame (48 or 96 beams wide by 512 range bins long) to store on the sonar's optional disk drive or transmit for storage on the UUV. Also, DIDSON's size and weight have been kept as small as possible to accommodate UUVs. A forward-looking sonar can fulfill three tasks on an UUV: serve as a side-scan gap-filler during surveys, provide information for obstacle avoidance, and collect images for object identification in turbid water where optical systems fail.

A. Gap-Filler

When UUVs survey the bottom for objects, they typically have two side-scan sonars. Each side-scan covers a swath on one side of the UUV from some minimum range to some maximum range. The terrain under the UUV and between the two minimum ranges is called the "gap." A gap-filler is a forward-looking sonar with a field-of-view sufficiently wide to fill the gap.

Forward-looking sonars typically have a field-of-view between 90° and 120°. DIDSON has a field-of-view of only 29°. A few lines of trigonometry indicate that DIDSON's cross-range (CR) (gap filling capability) at a given down-range (DR) is approximately one-half of the down-range as illustrated in Fig. 2.

The Woods Hole Oceanographic Institution's REMUS UUV has a side-scan gap between 6-m and 8-m wide when flying between 3 m and 4 m above the bottom. To fill that gap, DIDSON has to look down range greater than 16 m. DIDSON can barely do that in high-frequency mode but easily can do that in low-frequency mode. The Bluefin UUV flies higher (10 m) and forms a gap of 20 m between side-scan coverages. A DIDSON would need to detect the objects of interest at ranges that exceed 40 m. That range is difficult for the DIDSON that operates at either 1.8 MHz or 1.0 MHz. We are currently developing a DIDSON-LR that will operate at either 750 kHz or 1.25 MHz. We expect it will have a maximum range beyond 50 m. Figs. 3 and 4 show examples of gap-filling images when operating DIDSON at 1.0 MHz. The bright returns from the objects as well as their shadows allow the operator to detect the objects at 17 m and 42 m respectively.

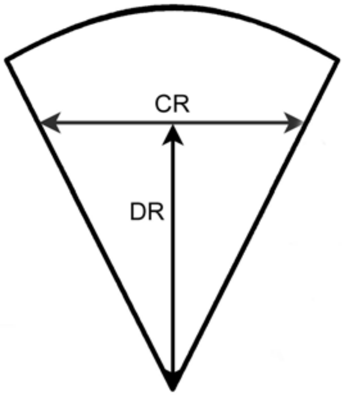

Fig. 2. The cross range (CR) ensonified by DIDSON is one-half the down range (DR). For example, DIDSON can image an 8-m wide swath when looking down range 16 m.

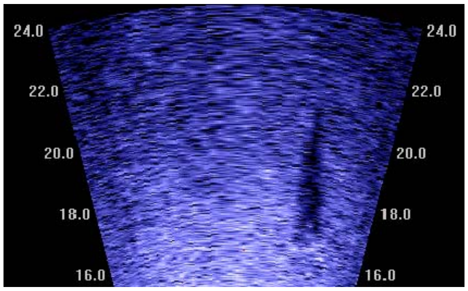

Fig. 3. DIDSON detects an object and its shadow 17-21 m in front of the sonar.

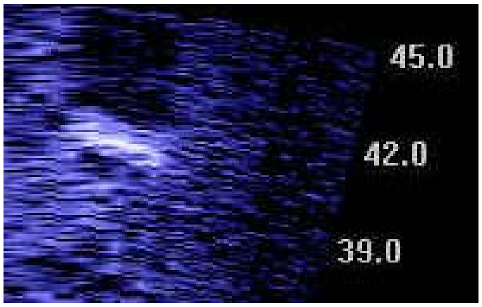

Fig.4. Another detected object 42 m in front of DIDSON.

B. Obstacle Avoidance

In the April 2002 ONR Review on Autonomous Vehicles, some UUV operators ranked Obstacle Avoidance as more important than Gap Filling. A UUV can fill the gaps left by the side-scans by overlapping the swaths such that a side-scan swath on a current pass covers the gap left in the previous pass. All agreed this was less efficient, but some noted that the redundancy (in the non-gap regions) gave two looks at the same object. Two looks at different aspects increase the probability of detection and correct classification. Thus surveys can occur without a gap-filler.

The substitute for obstacle avoidance is to fly high enough over the bottom to be sure that the UUV is above hazards. Flying high reduces the resolution in both the side-scan and forward-looking sonars. The UUV height should be governed by the required resolution in the sonars, not the height of potential hazards.

Fig. 5 shows an object detected by DIDSON. The sonar height (SH) was 3.3 m above the bottom, the object's shadow length (SL) was measured to be 4.6 m, and the slant range (SR) to the far tip of the shadow is 12.8 m. These quantities give the object height (OH) by the simple ratio OH/SH = SL/SR. In the case of Fig. 5, the object measures to be 1.2 m off the bottom. A simple algorithm for an obstacle avoidance sonar would be to calculate the lengths of shadows of objects in front of the vehicle. If the shadow length exceeds a calculated value, then the object is too high and needs to be avoided.

If the UUV is approaching a wall or ridge, the image will show a bright return from the wall or ridge with darkness beyond as illustrated in Fig. 6, an image of a bridge abutment. The concrete foot of the abutment is imaged and the two near vertical sides of the abutment are shown as bright lines with a shadow beyond. The distance to the bright lines gives the range to the abutment. Data from DIDSON allows the calculation of height and cross-extent of objects in front of the UUV. The 29° field-of-view updates 3-10 times/sec. This allows real-time navigation around obstacles.

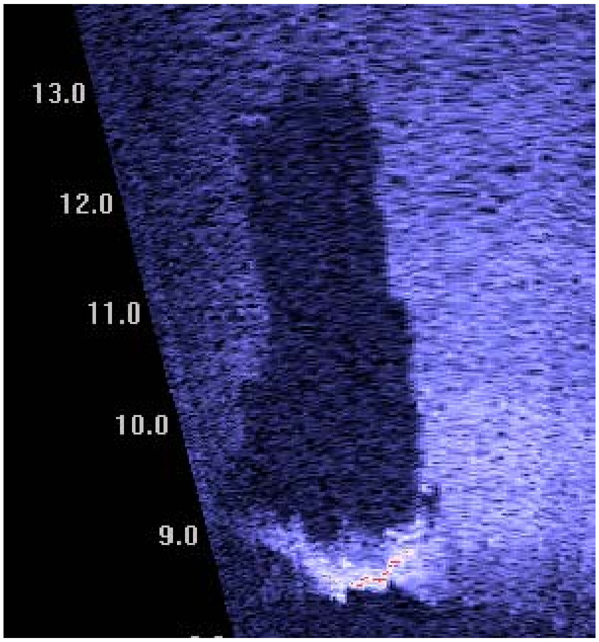

Fig. 5. Obstacle height can be determined by the length of its acoustic shadow, the obstacle distance from the sonar, and the sonar height above the bottom.

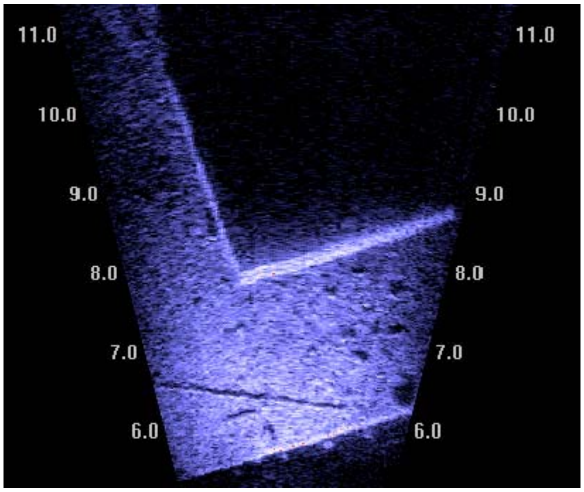

Fig. 6. The bridge abutment totally blocks the sound after bright returns at 8 m. This indicates a wall that extends above the height of the sonar. Obstacle avoidance software should indicate to the UUV how to plan a path that avoids the shadowed area.

C. Object Identification with UUVs

Identification of objects underwater requires a lot of detail. Accepted methods are optical (eyes, photographs, video, or laser) in water with sufficient visibility, and touch by divers in turbid water where optical systems fail. Side scan sonars can provide very good images in clear or turbid water (although not usually good enough for object identification), but give only one look per pass. Object identification with DIDSON would occur in the second phase of a UUV survey. In the first phase, the UUV uses side scan sonars and possibly a gap-filler to cover a lot of surface area. At the end of this phase the operator will have a list of targets of interest along with their latitudes and longitudes. During the second phase the operator directs the UUV to take DIDSON to these locations and get a number of images at close range and at different aspects. Figs. 7 and 8 are examples of such images. The details provided by DIDSON will allow identification of objects in turbid water without having to send down a diver.

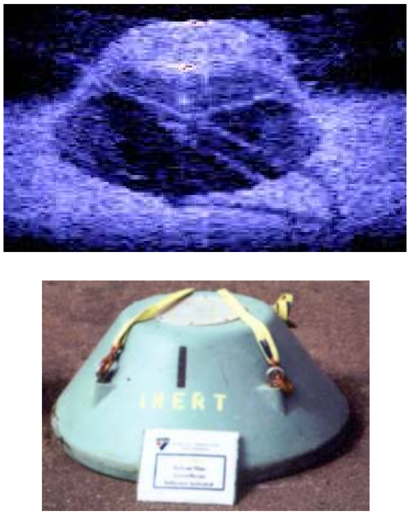

Fig. 7. A DIDSON image and a photograph of a MANTA mine.

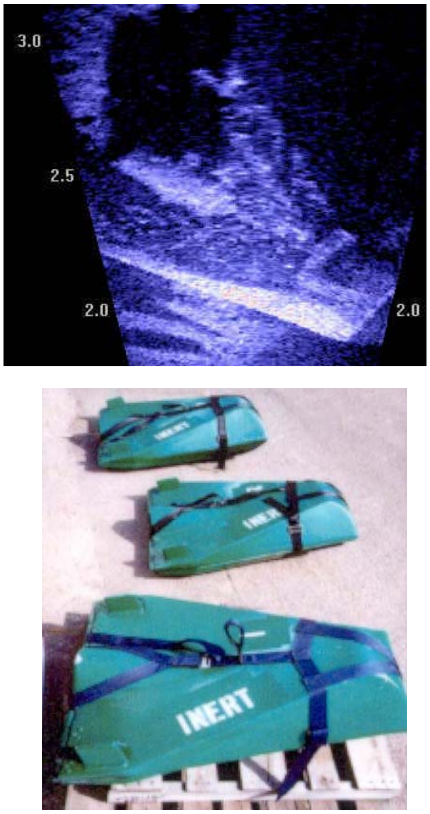

Fig. 8. A DIDSON image and a photograph of a ROCKAN mine.

IV. MISSION DATA ANALYSIS AIDS

When DIDSON returns from a mission as a gap-filler or as an ID sensor, it will have collected many megabytes, possibly gigabytes of data. In this section we discuss our goals for analysis aids that allow an operator to efficiently sift through these data and detect as well as identify objects of interest. The development of this software has two phases. The first phase allows the operator to view all the data and mark targets of interest. The software for the second phase will automatically detect targets of interest and form a list of these targets for later review by an analyst.

A. Phase I: Operator Detection

The DIDSON playback software allows the operator to view the data at up to 30 frames/s. If data were taken at 3 frames/s on a platform, the operator could review data at up to 10 times real time. Target-free data can look like a blank sheet (featureless sand) or contain features that include mounds, ripples, and areas of plant growth and rock outcroppings. Proud mines typically return a bright cluster of highlight pixels with distinct shape and size as well as a distinct acoustic shadow. The contrast of the bright return connected to a shadow is easy to recognize. When such a combination occurs, the operator freezes the “movie” and clicks on the object in question. The frame header contains platform location (latitude, longitude), altitude, heading, velocity, heading rate, and a number of other parameters. Thus when the operator clicks on a target, the target’s latitude and longitude is determined from the platform position, range to target, and bearing to target.

As the operator selects targets of interest, a file is generated with target locations, an operator ranking, and any notes the operator cares to write about the target. At the end of the selection process, the operator can run an application that plots icons of all the selected targets on a map of the survey. When she clicks on an icon, appropriate data files are opened and frames that contain that object are screened for review. Also any operator notes are displayed and can be edited. If additional data are needed to identify the object, a UUV can be sent to that location to collect additional data.

B. Phase II: Autonomous Detection

In the second phase, we will develop algorithms that automatically scan the frames and mark targets of interest. These algorithms will consider the area, shape, and brightness of clusters of pixels and an associated shape and size of an acoustic shadow. Rather than make a “yes or no” decision, the algorithms will grade mine-like features. Assume there are five grades for “mine-likeness” with 5 being the most likely. The algorithms will scan a set of selected data files and return a list of targets with their locations and grades. The analyst can select a geographical area of interest and a grade range of interest and then obtain a sub-list of targets to examine. As in Phase I the analyst will be presented with all images/movies in the data sets of the selected targets. Phase I is a necessary first step to ground truth and refine the selection process in Phase II.

V. AUTONOMOUS IDENTIFICATION OF OBJECTS

When a UUV can identify an object and act upon that identification, operation efficiency will dramatically increase. Algorithms are currently being developed to perform these autonomous identifications. Instead of a UUV being redirected to minelike objects by an operator after a detection/classification pass through an area, the autonomous identification algorithms will build on information obtained in the classification stage in a decision tree approach. Part of the autonomous identification algorithms will be a detailed target database containing features of a set of mines that can be identified. This implies that positive identification can not be achieved for objects not in this database.

Classification algorithms typically use target highlights and acoustic shadow regions to estimate gross object dimensions (length, width, and height). A UUV equipped with a DIDSON will gather data at classification ranges from multiple aspects to further solidify the classification decision, and narrow the list of potential mine types. At a certain threshold of information about the object under consideration, the UUV will be directed to close on the object and gather close range (high resolution) multiple aspect image data. Particular features of potential mine types (bolt patterns, fins, etc.) will be searched for in the images and correlated with the features in the database, with consistent spatial distribution of the features in the multiple aspect data compared to the database being an important identification clue.

Note that this concept of operations requires a feedback loop from the classification/identification algorithms to the vehicle navigation system. The vehicle will have a high-resolution sensing system, and will be directed by information provided by what is sensed, forming a highly autonomous overall system.

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