Object Identification with Acoustic Lenses

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Abstract - **With increasing frequency, underwater work is situated in rivers and coastal areas where visibility is a fraction of a meter. Two acoustic lens sonars, Mine Re-acquisition and Identification Sonar (MIRIS) and Dual-Frequency Identification Sonar (DIDSON) have sufficiently high resolutions and rapid refresh rates that they can substitute for optical systems in turbid water where optical systems fail. MIRIS operates at 2 MHz and uses 64 0.3° beams to form images of objects at ranges up to 10 m. DIDSON operates at two frequencies, 1.8 MHz or 1.0 MHz, and forms 96 beams spaced 0.3° apart or 48 beams spaced 0.6° apart respectively. It images out to 12 m at 1.8 MHz and 40 m at 1.0 MHz. Both sonars have update rates between 5-27 frames/s. Identification of objects with these sonars eliminates the need to send a diver to identify them by tactile means. These sonars provide biologists with a new technology for observing marine life including counting crab and monitoring fish behavior in turbid water. In both sonars, the transmit and receive beams are formed with acoustic lenses with rectangular apertures and made of polymethylpentene plastic and FC-70 liquid. The lenses eliminate the need for beamforming electronics. DIDSON can be commanded to focus on objects from 1 m to its maximum range. The sonars are approximately 30-cm long, 20-cm high, and 17-cm wide. They consume between 20 and 30 watts, which is important to submersibles with a power budget. The paper shows images from these sonars, and discusses the basic principles of beam formation with transducers and lens elements. These sonars form images with "line focused" beams that provide good images in many but not all conditions. If objects were at the same range in the same beam but at different elevations, this type of imaging could not sort them out. An example would be to try to image an object embedded in a pile of debris on the ocean floor. True video, using "point-focused" optics could meaningfully image the object imbedded in the pile as long as it were not totally covered. Fortunately, for the great majority of imaging tasks, MIRIS and DIDSON provide unambiguous, near-photographic quality images.**

I. INTRODUCTION

In clear water and with appropriate lighting, optical systems such as cameras and the human eye can image out to 15 m. With increasing frequency, however, underwater work is situated in rivers, lakes, harbors, bays and other coastal areas where visibility is a fraction of a meter. There, optical systems have dark screens and divers resort to tactile means. This paper describes two sonars, MIRIS and DIDSON, that bridge the gap between typical sonars and optical systems. Their combination of extremely high (for a sonar) resolutions and rapid refresh rates allows them to substitute for optical systems in turbid water. They are compact and consume little power (20-30 Watts), which suit them for small submersibles with power budgets. Although these sonars were developed for specific applications discussed in a later section, they are quite suitable for a number of applications such as

Positive identification and inspection: Either sonar can be mounted on a submersible and generate images of objects in turbid water with enough detail that in most cases, a diver would not have to be sent down to identify or inspect the object by tactile means.

Navigation in close quarters: The sonars' very high resolution and rapid refresh rate may allow guidance of a vehicle in/out of docking fixtures. Either sonar mounted on a submersible allows a detailed search of a local area for geological formations, man-made objects, or marine life on the bottom or in the water column. Either sonar would allow a submersible to follow and inspect a small cable lying on the bottom.

Monitoring: Either sonar could observe fish, mammal, and crustacean mobility and interactions in turbid water. Specifically, a sonar can be mounted at a fixed location to observe fish movement near a turbine intake on a dam with the goal of improving deflectors to keep fish out of the turbines. A sonar could be used as a security video camera, but used underwater in dark and turbid conditions where optical systems fail.

II. SONAR DESCRIPTIONS

A. MIRIS (Mine Reacquisition and Identification Sonar)

MIRIS [1,2,3] shown in Fig. 1, mounts on a submersible and images objects with sufficient resolution to identify them. Lockheed Martin Perry Technologies mounts MIRIS on CETUS II, a hover-capable autonomous underwater vehicle. CETUS II has the mission to swim to a number of predetermined locations where mine-like objects have been detected. At each location, CETUS II must obtain additional information to identify the mine or determine that the object is not a mine. MIRIS and a video camera are the primary sensors. In turbid water, MIRIS is the only sensor that collects data. Figs. 2 and 3 show MIRIS images of a Rockan and Manta mine respectively. Fig. 4 is an image of a cinder block.

MIRIS operates at 2 MHz and images objects between 1 and 10 m from the sonar. CETUS II generally images objects at ranges between 3 m and 4

Fig. 1. MIRIS, acoustic lens imaging sonar. It can be mounted on a submersible right side up as shown or up side down.

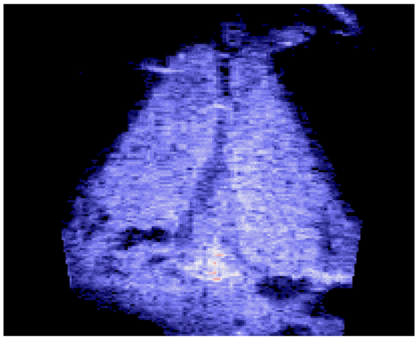

Fig. 2. An image of a Rockan mine taken approximately 3 m from MIRIS.

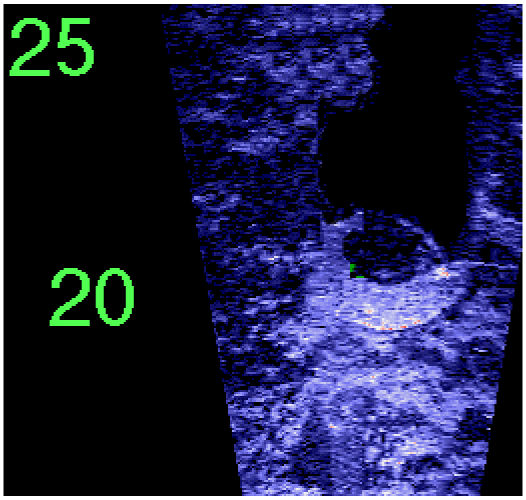

Fig. 3. An image of a Manta mine (shaped like a truncated cone) taken 6 m (20 feet) from MIRIS.

m. CETUS II communicates with MIRIS by Ethernet, and receives digital images as a series of 64 by 512 byte arrays 10 times/s. CETUS II annotates each digital image header with latitude, longitude, depth, heading and other important auxiliary data. MIRIS specifications are listed in Table 1.

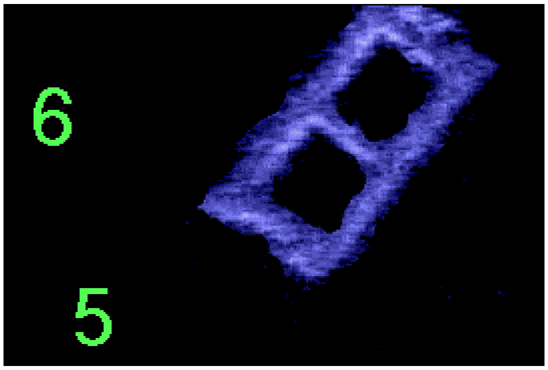

Fig. 4. An image of a cinder block taken 1.8 m (6 feet) from MIRIS.

B. DIDSON (Dual-Frequency Identification Sonar)

DIDSON, shown in Fig. 5, was developed to identify underwater intruders detected by a harbor surveillance system. It mounts on the front of a submersible or under the hull of a small surface craft sent to identify the intruder-like detection acquired from a larger coverage, low-frequency surveillance sonar. DIDSON operates at two frequencies. At 1.8 MHz it provides very high-resolution (0.3°) images similar to MIRIS and can image objects at ranges up to 12 m. At 1.0 MHz, DIDSON has lower resolution (0.6°) but can image objects out to 40 m. Fig. 6 is an image from DIDSON showing the top of a concrete foot under a bridge abutment. Note the detail in the image allows one to see the debris on the surface, a pipe at 7 m, and a tire at 12 m. The numbers on the side of the image give ranges from the sonar in meters. Fig. 7 images two fish swimming at a range of 3 m from the sonar. Fig 8 shows the stern of a fishing vessel resting in 10 m of water. In the first two figures, the DIDSON was operating at 1.8 MHz. The image of the vessel was taken with DIDSON operating at 1.0 MHz.

A remote focus capability allows DIDSON to focus on objects that range from 1 m to 40 m from the sonar. When the operator selects a range span for an image, DIDSON sets the optimum focus to be in the center of that span. The operator can override the auto-focus and set optimum focus to any range in the image. As can be seen in the figures, the focus generally remains good throughout the range span in the image.

The image update rate varies from 21 frames/s to 5 frames/s depending on the operating frequency and the maximum range imaged. The 1.8 MHz mode builds an image with 96 0.3° beams spaced 0.3° apart. It builds up this image with eight transmit/receive cycles, each using a different set of 12 beams. The 1.0 MHz mode builds an image with 48 0.4° beams spaced 0.6° apart. It builds this image with four transmit/receive cycles, each using a different set of 12 beams. The 1.0 MHz mode generally is used for longer ranges (greater than 12 m) but requires half of the transmit/receive cycles so the frame rates of the two modes are similar. DIDSON specifications are listed in Table 2.

Fig. 5. The focus mechanism of DIDSON fits under the lens housing and next to the electronics housing.

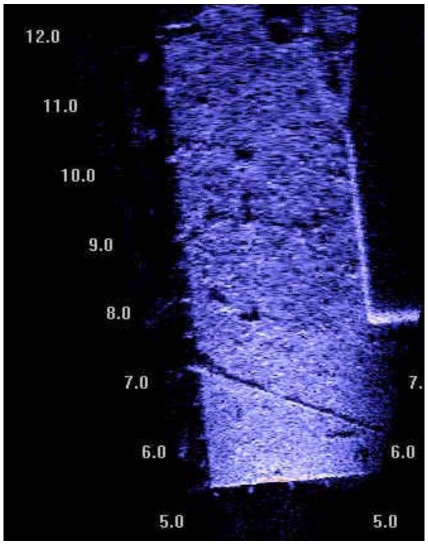

Fig. 6. The surface of a concrete foot of a bridge abutment. Range markers are in meters.

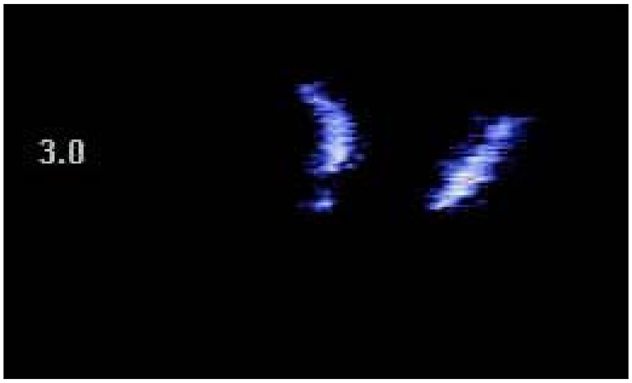

Fig. 7. Two fish swimming 3 m from DIDSON in Lake Union, Seattle.

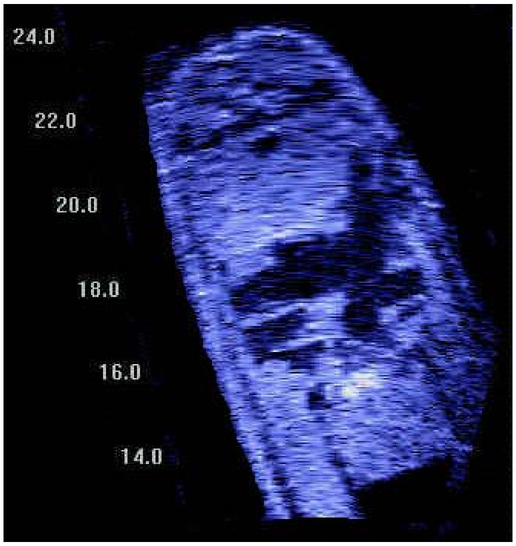

Fig. 8. The stern of a fishing vessel resting in 10 m of water. DIDSON took this image while 4.5 m under the surface and mounted on a shaft attached to a catamaran.

III. BASIC PRINCIPLES

MIRIS and DIDSON use acoustic lenses to form very narrow beams during transmission of pulses and reception of their echoes. Conventional sonars use delay lines or digital beamforming techniques on reception and generally transmit one wide beam on transmission that covers the entire field of view. Acoustic lenses have the advantage of using no power for beamforming, resulting in a sonar that requires only 30 watts to operate. A second advantage is the ease to transmit and receive from the same beam. The selective dispersal of sound and two-way beampatterns make the images cleaner due to reduced acoustic cross talk and sharper due to higher resolution.

A. Lenses

Fig. 9 shows a photograph of DIDSON with the lens housing removed. The acoustic lenses and transducer array are shown above the electronics housing. The small cylinder under the side of the lens housing contains the focus motor and mechanism that moves the second lens forward and aft. This movement focuses the sonar on objects at ranges from 1 m to 40 m. The front lens is actually a triplet made with two plastic (Polymethylpentene) and one liquid (3M FC-70) component. The plastic lenses as well as the transducer array are separated by ambient water when the lens system is submerged. Optical lens design programs [4,5] determined the lens curvatures. The designs were analyzed by custom software [6,7] to evaluate the beampatterns over the field of view of interest.

B. Transducer array

The DIDSON and MIRIS transducer arrays are linear arrays. DIDSON has 96 elements with a pitch of 1.6 mm and a height of 46 mm. The elements are made with PZT 3-1 composite material constructed by the dice-and-fill method.

Table 1. MIRIS Specifications

Resolution	2 cm at 4 m range
Beamwidth (two-way)	0.25° horizontal by 10.8° vertical
Number of beams	64
Field of view	19.2°
Start range	0.384 m to 11.9 m in 0.384-m increments
Window length	1.5, 3, 6, 12 m
Range-bin separation	3, 6, 12, 24 mm respective to window length
Sample rate	250, 125, 62.5, 31.24 kHz respective to window length
Pulse length	4, 8, 16, 32 µs respective to window length
Frame rate	4 to 27 frames/s depending on range
Source level (average)	207 dB re 1 µPa at 1 m
Operating frequency	2 MHz
Power consumption	24 watts (1.62 amps at 15 volts)
Weight	4.95 kg (10.9 lbs.) in air, 0.77 kg (1.7 lbs.) positive in freshwater
Dimensions	20.5 cm (8.09 in.) high, 16.8 cm (6.63 in.) wide, 29.4 cm (11.58 in.) long
Output format	Ethernet or NTSC video
Control	Ethernet, RS232, or switches
Depth rating	30.3 m (100 feet)

Table 2. DIDSON Specifications

Low frequency mode	
Operating Frequency	1.0 MHz
Beamwidth (two-way)	0.4° horizontal by 10.8° vertical
Number of beams	48
Source Level (average)	205 dB re 1 µPa at 1 m
Range settings Start range Window length	 0.75 m to 23.25 m in 0.75 m intervals 4.5, 9, 18, 36 m
Range-bin separation	8, 17, 35, 70 mm respective to window length
High frequency mode	
Operating frequency	1.8 MHz
Beamwidth (two-way)	0.3° horizontal by 10.8° vertical
Number of beams	96
Source level (average)	205 dB re 1 µPa at 1 m
Range settings Start range Window length	 0.4 m to 11.63 m in 0.4 m increments 1.1, 2.2, 4.5, 9 m
Range-bin separation	2.2, 4.4, 9, 18 mm respective to window length
Both Modes	
Frame rate	4-21 frames/s
Field of view	29°
Remote focus	1 m to maximum range
Power consumption	30 watts (using 115VAC or 14-18VDC)
Depth rating	152 m (500 ft) or 2400 m (8000 ft)
Control	Ethernet, RS232 or switches
Output format	Ethernet and NTSC video
Cable length	152 m (500 ft)
Dimensions	30.7 cm long by 20.6 cm high by 17.1 cm wide (500-ft depth option)
Weight in air	7.0 kgs (15.4 lbs.) (500-ft depth option)
Weight in water	0.6 kgs (1.3 lbs) negative (500-ft depth option)
Topside requirements	Computer running Windows, Ethernet card, and video monitor (optional)

Fig. 9. DIDSON with the lens housing removed. The middle plastic lens moves fore and aft to change focus. The transducer array at the back of the lens both transmits and receives sound through the lenses. When the sonar is submerged, ambient water surrounds the lenses and transducer array.

The 3-1 composite provides a wide bandwidth allowing DIDSON to operate at 1.8 MHz or 1.0 MHz, the upper and lower ends of the transducer passband. The composite also allows the transducers to be curved in the height direction to aid in the formation of the elevation beampattern. All 96 elements are used when operating at 1.8 MHz. Only the "even" 48 elements are used when operating at 1.0 MHz.

C. Beam Formation

Fig. 10 shows a ray diagram of the MIRIS system. A plane wave entering the left side through the front triplet L1 and single lenses L2 and L3 is focused to a line perpendicular to the page at the transducer T. If the normal to the plane wave is perpendicular to the front lens surface at the center, the acoustic line is formed at 0° in the diagram. If the normal is 9° off from perpendicular, the line is formed at 9° in the diagram. When a focused line of sound coincides with a long, thin transducer element, the acoustic energy is transformed into electrical energy and processed. Fig. 11 shows 3 of the 96 beampatterns formed with a DIDSON lens set. The 3-dB one-way beamwidth is approximately 0.35° and the sidelobes are down 15 dB. The sonar both transmits and receives with these beams such that the two-way pattern has a 3-dB beamwidth of approximately 0.25° and side lobes are down 30 dB. The DIDSON beamformer loses approximately 10-dB in sensitivity each way with beams 15° off-axis. Even with this reduction, DIDSON images fill the 29° field of view as shown in Figs. 6-8. The average beamwidth in the vertical direction for both MIRIS and DIDSON is 14° (one-way). The lenses form the horizontal beamwidth and the curved transducer element forms the vertical beamwidth. Fig. 11 shows the spacing of beams during a transmit/receive ping cycle for DIDSON. Sound is transmitted only in these beam directions, and the sonar is sensitive to only these directions during a single transmit/receive cycle. This makes the image sharper and less noisy than those produced in sonars with one broad transmit beam and receive beams separated by their 3-dB beamwidths.

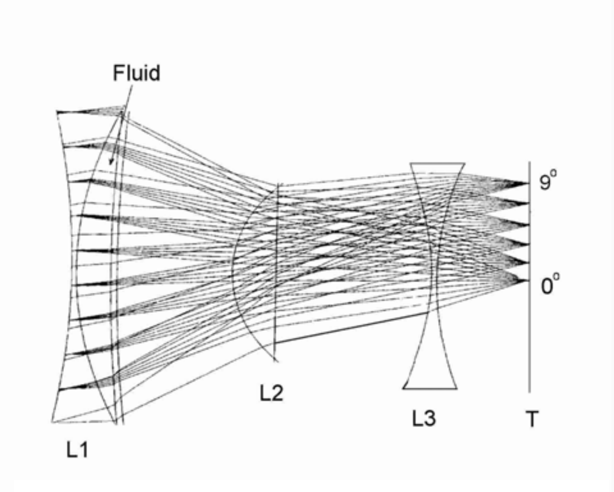

Fig. 10. A diagram of the MIRIS lens system. L1 is a lens triplet consisting of a biconcave plastic lens, a fluid, and a second thin plastic lens. L2 is a convex-planar plastic lens that moves closer and farther from L1 to change focus. L3 is the third and last lens before the transducer array, T. Ray traces show rays from six plane waves with azimuth angles ranging from 0° to 9°. A plane wave perpendicular to the center of lens L1 focuses on the array at "0°." A plane wave 9° off from perpendicular focuses on the array at position "9°." Each element in the array transmits to and receives from a single beam.

D. Image Formation

Fig. 12a shows one transducer element and a lens together forming a "line-focused" beam. When the sonar is tilted down, each beam ensonifies a stripe along the bottom as shown in Fig. 12b. The sonar transmits a short pulse and then receives its echo as it sweeps along the stripe. The echo amplitude varies in time as the reflectance varies with range along the ensonified surface. Echoes from 96 adjacent lines, which together map the reflectance of the ensonified sector-shaped area, are used to form a DIDSON image.

The difference between optical video and images from these sonars is more than the usage of light or sound. The sonar must be oriented to project beams with a small grazing angle to the surface of interest as shown in Fig. 12b. The resulting image appears to be viewed from a direction perpendicular to the surface and the shadows indicate a source off to the side. Optical video could image a surface with the camera view perpendicular to the surface. If the sonar beams were perpendicular to the surface, the resulting image would show a single line perpendicular to the center beam axis. The line would be located at the range the

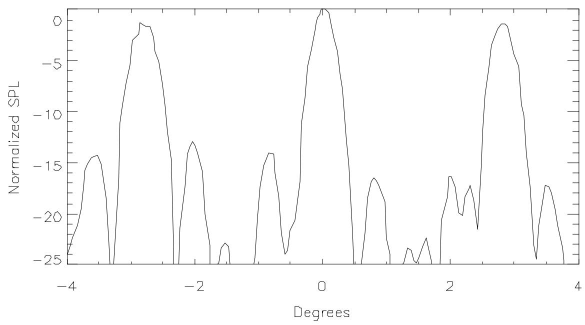

Fig. 11. Three center beams from a set of 12 from DIDSON. Note the separation between maxima give a large degree of isolation between beams transmitted in parallel. This allows sharper, less noisy images.

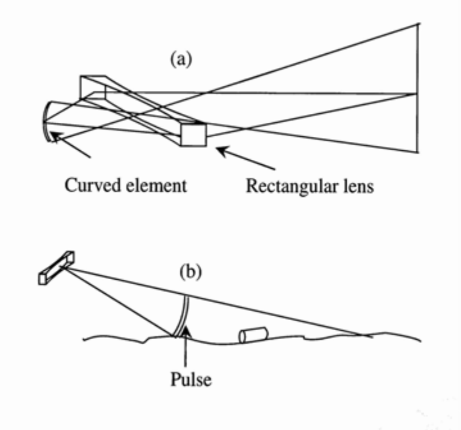

Fig. 12(a). A line-focus lens system uses a lens with a rectangular aperture and curved element to form a focused line of sound. (b). When the line of sound is directed to a slanted object plane, it interrogates a line segment on the object plane as a function of time.

surface is from the sonar. The sonar images are formed with "line-focused" beams that provide good images in many conditions but not in all conditions. If objects were at the same range in the same beam but at different elevations, this type of imaging could not sort them out. An example would be trying to image an object in a pile of debris on the ocean floor. If the object were imbedded in the pile, the acoustic images from MIRIS and DIDSON would be confusing. Video using "point-focused" optics could meaningfully image the object imbedded in the pile as long as it was not totally covered. Fortunately, the great majority of imaging tasks does not have multiple objects in the same beam, at the same range, but at different elevations. In most cases, MIRIS and DIDSON provide unambiguous, near-photographic quality images as shown in the examples above.

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