Multistatic optical imaging system compatible with AUV platforms

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***Abstract* - Conventional optical imaging systems have limited performance in Degraded Visual Environments (DVE) such as dust, fog, sand, and turbid water due to multiple scattering of the light on the path from the source to the target. Their large platform size also makes them unfavorable for compact, autonomous systems. In recent years, researchers at NAVAIR in Patuxent River, MD have developed a compact submersible laser imaging system based on a multistatic system architecture, allowing the source and multiple receivers to reside on separate, smaller, independent platforms. The system geometry can be better optimized for the environment, allowing it to obtain high quality imagery through much higher attenuation lengths (between the target and receiver) when compared to conventional imaging systems. The smaller source also lends itself to integration into an autonomous underwater vehicle (AUV). A compact, multistatic imaging system designed for integration into a REMUS 600 AUV has been developed and is currently being tested in a laboratory environment. System design and laboratory test plans will be presented.**

Keywords – underwater, optical, imaging, communications, AUV, autonomous

I. INTRODUCTION

High resolution imagery is an important capability for underwater platforms in defense and commercial sectors. When compared to acoustics, optical imaging has the advantage of higher resolution and is capable of true optical identification, a requirement in some missions. One type of conventional optical imaging system, shown on the left side of figure 1, employs a pseudo-monostatic architecture where the source and the receiver are on the same platform and are synchronously scanned. This type of sensor has limited performance in Degraded Visual Environments (DVE) such as dust, fog, sand, and turbid water due to multiple scattering of the light on the path from the source to the target. Increasing the separation between the source and receiver (d_{sr}) is one of several ways to reduce the effects of scattering, but this leads to an increase in platform size, making it incompatible with a compact autonomous infrastructure. The utility of conventional systems is also limited in airborne operations when imaging through the air-sea interface. Upon propagation through the water surface, random wave slopes steer the light away from the intended position on the target causing distortions in the collected imagery.

In recent years, researchers at NAVAIR in Patuxent River, MD have developed a compact submersible laser imaging system based on a bistatic system architecture, shown on the right side of figure 1 [1]. This architecture alleviates the need for a single platform, enabling the source and receiver to reside on separate, smaller, independent platforms. The system geometry can now be better optimized for the environment and mission. Specifically, the source can be placed much closer to the target, increasing image quality by reducing the amount of light that is forward and back-scattered between the source and target. To create an image, the source sequentially illuminates small portions of the object. This creates a time-varying intensity signal corresponding to reflectivity changes of the object, which is detected by the distant receiver. By sequentially illuminating the object, the source spaces the image out over time so that each pixel of the image does not spatially interfere with the others, even when multiply scattered on its way to the receiver. All of the light from each pixel, even multiply scattered or refracted light, carries useable information. This fact is what allows the bistatic system to image through the air-sea interface and can also be leveraged to form a non-line-of-sight imaging system [2,3]. In order to synchronize the source and receiver, a wireless optical communications link is formed via the object reflected light by intensity modulating the source. Information concerning the scan, such as the location of a new image line, is encoded on the modulated source using frequency shift keying (FSK). The receiver demodulates and decodes this information and uses it to help reconstruct the received imagery. Modulating the intensity of the laser also has the advantage of using an AC-coupled receiver, which is less sensitive to solar ambient fluctuations. In addition to the

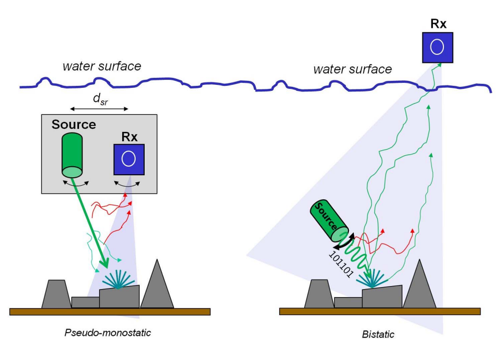

Fig. 1. Comparison of pseudo-monostatic (left) and bistatic (right) architectures

benefits listed above, the smaller source also lends itself to integration into an autonomous underwater vehicle. Multiple vehicles and receivers can then be networked via the wireless optical communications, forming the foundation of a distributed sensing system.

Field testing of the bistatic system performed in the Chesapeake Bay and Patuxent River in previous years has verified the system's ability to collect high resolution imagery not only in turbid environments, but also through the air-sea interface without distortions (source below water, receiver above water). These previous demonstrations used a fixed source/target geometry to simplify operation by eliminating any relative motion between the source and object during the imaging process. While this serves to simplify operation, allowing us to isolate the effects of the environmental parameters on sensor performance, it does not reflect the desired application where a source would be placed on a mobile autonomous vehicle (AUV) moving about a scene. To this end, we report on a modified system where the source is mobile relative to the scene. Additionally, we implement a multistatic extension of the bistatic approach by using multiple receivers to increase the effective receiver field of view. Together, these modifications result in a necessary step to the implementation on mobile autonomous vehicles. Figure 2 depicts the intended application: the source is on a moving platform, illuminating a stationary object, while multiple receivers located above the air-sea interface collect the object-reflected light. The signals from multiple receivers are processed and imagery is displayed via a custom data fusion program. In the following paper, system components and their interactions will be discussed along with plans for laboratory tank testing and plans to integrate the system into a REMUS 600 AUV.

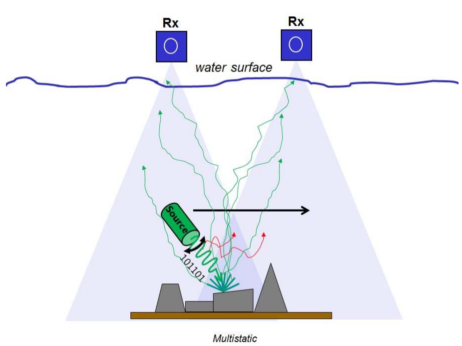

Fig. 2. Envisioned operation of the multistatic system. The source is on a mobile autonomous platform while receivers observe from afar.

II. MULTISTATIC IMAGER COMPONENTS

A. Modulated Laser Illuminator

The modulated laser illuminator (shown in figures 3 and 4) utilizes a 2 watt green (532nm) diode pumped solid state (DPSS) laser as the illumination source. This laser source is over 30 times more powerful than the laser source used in our older bistatic imaging system [2]. This change was made to increase the useful range of the multistatic system in absorption limited scenarios, despite the increase in laser size and power consumption. The laser output is externally intensity modulated via a resonant electro-optic amplitude modulator (EO-AM) system. The material used in the modulator is rubidium titanyl phosphate (RTP) which is designed to handle the high power density of our laser source. A resonant system was chosen to lower the required drive power for the modulator. The resonant cavity is tuned to 70 MHz nominally.

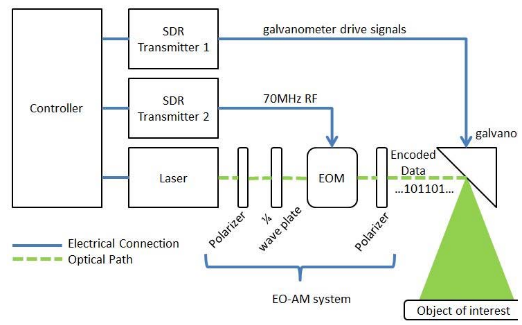

Fig. 3. Block diagram of modulated laser illuminator.

The output of the EO-AM system is deflected by a small galvanometer to form a line scan on the object to be imaged. The modulation drive signal for the EO-AM and the drive signals for the galvanometer are generated by two software defined radios (SDR). SDRs are very flexible devices programmed via software allowing quick and easy changes to modulation techniques and laser scan shape, swath, and speed. They are truly multi-mission devices supporting easy field programming based on real time environmental factors, optimizing its performance for the specific scenario in which it will be operating. The radios used are USRP-N210s from Ettus research and are interfaced with the GNU Radio Companion (GRC) development environment. A nominal modulation frequency of 70 MHz was chosen to match the resonance of the EO-AM cavity. Frequency shift keying (FSK), at data rates up to 250kbps, is used to encode the laser with synchronization information to assist the distant receiver in reconstructing the image from the collected light. A pseudo-random sequence is currently used for synchronization. Appropriately named the "start of line code", it is transmitted at the beginning of each scan line. The receiver uses this as a flag to parse the incoming samples into image lines. Details of the reconstruction process are discussed later in the section labeled Signal Processing.

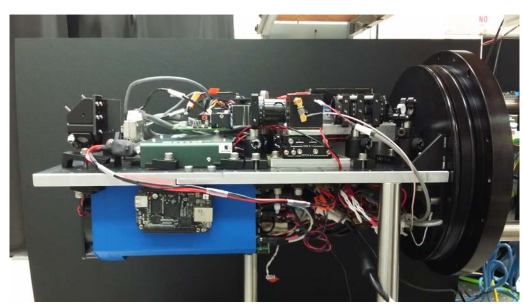

Fig. 4. Modulated illuminator packaged in a footprint compatible with REMUS 600 AUV.

B. *Optical Receivers*

Two identical optical receivers are used to collect the object reflected light. Because the receivers are not adversely affected by scattered light, their objective is to collect as many photons as possible to maximize the signal to noise ratio (SNR). A Galilean telescope composed of 152mm diameter Fresnel lenses is used to increase the collection aperture of the receiver. The collected light is passed through a 50mm optical interference filter tuned to the wavelength of the illumination source (532 nm). This filter rejects ambient light, allowing the sensor to operate in daylight conditions. A 50mm photomultiplier tube (PMT) converts the filtered light to an electrical signal for signal processing and image reconstruction. The full angle field of view of each receiver is 14 degrees. The electrical bandwidth of the PMT is 200 MHz, enough to resolve the proposed 70 MHz modulation envelope. It is important to note that the multistatic architecture is not limited to two receivers, but can be expanded to however many suits the application. More receivers allow for a larger system field of view, but would put more demand on the data acquisition system and signal processing on the host computer.

C. *Signal Processing*

Figure 5 shows the optical and signal processing system of the receivers. The output from each PMT is split into their respective DC and AC (modulation) components. The DC-coupled outputs are monitored to ensure that the PMTs operate within the linear portion of their dynamic range. The AC-coupled signal is down converted and digitized by a software defined radio (SDR) receiver and the resulting baseband data is sent to a computer for further signal processing. As with the illuminator, SDRs were chosen for their flexibility. Parameters of the electrical portion of the receiver such as center frequency, bandwidth, gain, and even the signal processing algorithm can be changed via software, allowing the same sensor to be used for multiple missions without any expensive hardware changes. The SDRs used in this system are the same type as in the illuminator: the Ettus Research USRP-N210.

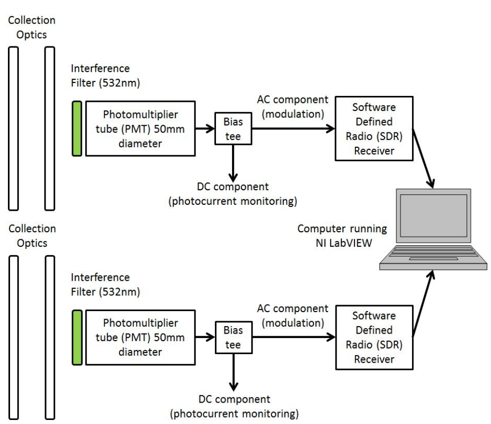

Fig. 5. Block diagram of optical and signal processing system of the receivers.

National Instruments LabVIEW is used for signal processing and image reconstruction. The signal from each PMT is digitized at 1MS/s, however the SDRs have the flexibility to operate at slower or faster rates if necessary. The digitized data is examined in real time for the synchronization information transmitted by the illuminator, which is extracted from the data via cross correlation. If the synchronization information is found, the receiver will begin parsing the data into image lines. Each time a synchronization sequence is found; a new image line is saved and displayed. The magnitude of each sample, which is directly related to object reflectivity, is calculated and displayed in a waterfall fashion one line at a time. The image reconstruction program assumes that the horizontal image information comes from the galvanometer motion, whereas the vertical image information comes from the illuminator's forward movement. The data from each receiver can be inspected individually, or combined into a single image. This combined image, called the "Super Aperture" fuses the data from both receivers, increasing the field of view of the system.

III. Lab Exeriments

Initial laboratory tests, depicted in figure 6, will be conducted in a 7.2m diameter water tank. The illuminator will be packaged in a Prevco™ subsea housing, shown in figure 7, and mounted to a translation stage that will hold it approximately 1 meter from the bottom of the tank. A resolution target used to test the spatial resolution of optical systems will be placed at the bottom of the tank in the path of the illuminator. The translation stage will allow us to simulate the movement of an AUV albeit in a very predictable fashion.

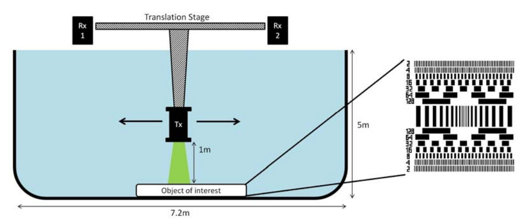

Fig. 6. Proposed test setup (left) and target (right).

Fig. 7. Subsea housing from PREVCO™ that will be used to house the illuminator for tank testing. Its size was chosen to be compatible with the REMUS 600 AUV. Internal dimensions: 25 cm diameter x 45 cm long

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Two receivers, one of which is shown in figure 8, will be mounted above the water looking down, but not necessarily directly at, the target. The LabVIEW program will collect imagery as the illuminator is moved over the target. The speed of movement will be controlled so that the illuminator is moving at speeds representative of a REMUS 600. Maalox antacid, or a similar product, will be incrementally added to the water to simulate multiple water conditions, ranging from open ocean to turbid harbor.

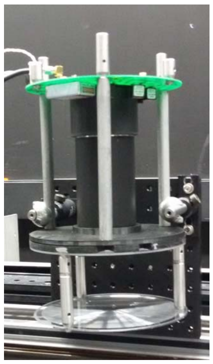

Fig. 8. Assembled receiver, showing the collection optics and PMT.

IV. SUMMARY

The work presented in this paper is a necessary step toward mobilizing laser imaging and communication systems for use in the undersea environment. The bistatic architecture has been proven to obtain high quality images in turbid media and the small sensor footprint afforded by this architecture lends itself to small, autonomous platforms. A mobile, multistaic extension of the bistatic architecture is proposed. This is the first step towards using this imaging and communication method for distributed sensing of the subsea environment. Laboratory tank test will be performed to examine the effectiveness of the new modulated illuminator and custom data fusion program. Future work will involve maturing the technology to be integrated into a REMUS 600 AUV.

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