

Trans-Interface Optical Communication (TIOC)

Kendall L. Carder

University of South Florida, College of Marine Science

140 7th Avenue South, St. Petersburg, FL 33701

phone: 727-553-3952, FAX 727-553-3918, email: kcarder@monty.marine.usf.edu

David K. Costello

University of South Florida, College of Marine Science

140 7th Avenue South, St. Petersburg, FL 33701

phone: 727-553-3952, FAX 727-553-3918, email: dkc@monty.marine.usf.edu

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LONG-TERM GOALS

The goal of our work is to develop a system for optical communications through the sea-air interface and to provide a predictive performance model for the system for different environmental conditions, source power levels, receiver range, etc.

OBJECTIVES

The scientific objectives of the project involve understanding the spectral and temporal effects of water constituents and surface characteristics on trans-interface communication. This involves the development of a system that utilizes several, separated, redundant, sources to reduce the data drop-out rate due to wave refraction. Engineering objectives of the project are the design and development of an intelligent optical receiver that can identify the positions of redundant sources within video imagery and control a micro electro-mechanical system (MEMS) device to direct radiance from only those sources to a high-speed sensor for demodulation. This spatial filtering should reduce interference from surface reflection of skylight.

APPROACH

Wave refraction of light rays passing through the sea-air interface causes a perturbation in the path of the ray relative to its position and direction for a flat sea surface. While gravity waves range in slopes up to about 15° (e.g. Lighthill 1980), these slopes can be augmented near the crests by parasitic capillary waves (Martin 2004). According to the Cox-Munk (Cox and Munk 1954) wave-slope relationship to wind speed, a wind of 10m/s results in a mean wave slope of about 0.19. Wu (1990) suggests a more rapid increase of slope with wind speed, however. Past experience in trying to avoid sun glint when performing remote sensing operations indicates that slopes of 0.6 are not unusual for individual waves.

For capillary waves, the disruption in directionality of an optical beam or ray that results in information dropouts can be significant. This is corroborated by an experiment made in Bayboro Harbor (St. Petersburg, FL) where the continuity of signal from a single LED was contrasted against that from up to four LEDs, where four LEDs were separated by four feet at the corners of a square

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frame approximately 1 foot below the interface. Generating capillary waves with 2 air jets provides enough capillary wave activity to provide significant signal drop-outs. Redundant, spatially separated sources are used with digital signal processing (DSP) of video imagery to identify the positions of redundant sources within the imagery (areas of interest, AOIs). Radiance from these dispersed sources is then collected onto a common intensified receiver to reduce interference from surface reflection of skylight while increasing the signal for high-rate data reception.

BACKGROUND

In this concept for optical communication through the air-sea interface, multiple emitters are placed beneath the water's surface and imaged from above. These emitters appear as small points of light in a video image of the area. In a project funded by Blackbird Technologies, we have demonstrated the ability to process video in real-time and identify our emitters within the video. For this work, we designed optical emitters using LEDs that transmit data using on/off keying. Since standard video rates are used, data bandwidth is limited to 5 baud and only short messages containing emitter ID information is transmitted.

Utilizing digital signal processing (DSP) hardware, we developed a system that processes NTSC video, identifies sources within the video matching search criteria, decodes data transmitted by those sources, and outputs the input video signal with graphical overlays highlighting the detected signals and displaying received data. Fig. 1 shows the prototype electronics (left) and a screen capture from a video clip (right). The screen capture shows several sources of light imaged through a narrow band-pass filter. For the case shown, only one point of light is actually a device (ID 399) communicating data. The other points are street and car lamps with energy in the pass band of the optical filter. Without our DSP approach, these other points would not only decrease S/N but could be identified as spurious targets. We have demonstrated the ability to maintain detection of signal sources under a wide range of environmental conditions, have demonstrated tracking of moving signal sources, and proven our ability to distinguish our devices from sources that may appear similar in nature.

This extension of the basic system involves the use of a spatial modulator to optically direct only the portions of the image containing signal sources to high-speed detectors for data reception. This concept is illustrated below in Fig. 2. Any camera outputting NTSC video is used to image the scene of interest. The video signal is processed by the DSP electronics to determine the coordinates of signal sources. These coordinates are used to control an active modulator to direct only the portions of the image containing signal sources to a high-speed detector, reducing background noise and raising the signal-to-noise ratio.

MEMS 2-D imaging arrays are commercially available and widely used in TV and data projection systems [eg. Texas Instruments Digital Mirror Device (DMD)]. The DMD is designed to tilt each of several million mirrors into 1 of 2 positions according to a video image received by the coupled electronics module. In the first (default) position the mirrors are turned off and are all coplanar. Incoming radiation is simply reflected at the same angle as the incoming beam (relative to the surface normal).



Fig. 1: Prototype electronics used to process video signals to locate and decode optical signals, and a representative screen capture showing the detection of a signal source placed near many noise sources.

In the second position, the mirrors are tilted by approximately 7 degrees. Depending on the orientation of the DMD, the reflected beam can either be at a larger or smaller angle (by 14 degrees) than the beam reflecting off the mirrors in the first position. By turning

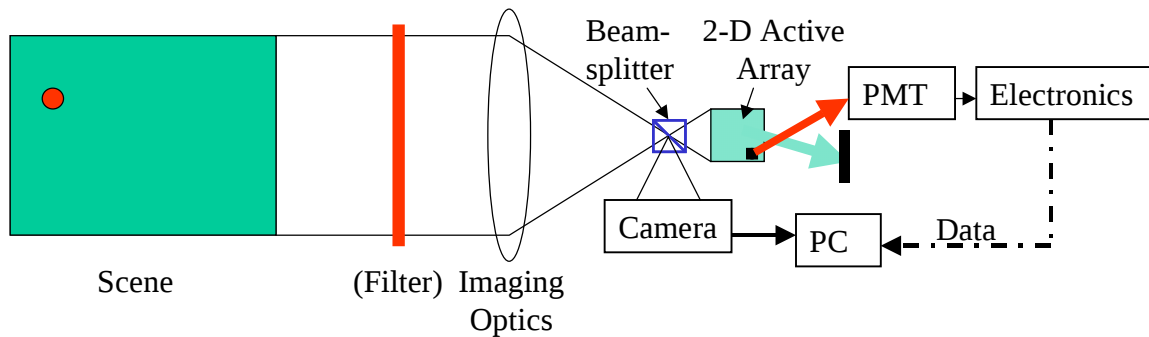


Fig. 2: Actively-steered high-speed, high sensitivity detector. 2-D Active Array (Eg. TI DLP) is used to actively project only areas of the scene of interest onto a high speed, highly-sensitive PMT detector.

the appropriate mirrors on or off, light from specific portions of the image can be separated from other regions. It is proposed that such a 2D DMD array be utilized within a custom optical system to allow simultaneous targeting of each of the individual sources that comprise the underwater transmitter. Only those mirror elements corresponding to the locations of the signals will be energized to redirect the signals to the high-speed detector. As wave action and other factors interfere with the reception of

an individual source, the corresponding mirror elements will be turned off and only light from the other valid sources will continue to the high-speed detector. In the best case, all individual sources will be present and their combined energy will be directed to the detector for maximum signal to noise. Note that by rejecting residual background image noise due to reflected skylight or sun glint, the gain on the high-speed detector can be increased.

WORK COMPLETED

Scientific A single-wavelength (525 nm), 4-source, LED array was constructed and deployed in both day and night field tests. Analysis of the data acquired during these deployments indicates that the basic hypothesis is correct and that our envisioned approach is viable (Carder et al. 2007). Redundant sources increased transmission efficiency in both daytime and nocturnal field tests. We utilized only narrow-band-pass and polarization filters on the camera. Compared to losses with one LED, data drop-outs for the redundant sources were reduced by factors of 6-14 (see Fig. 3).

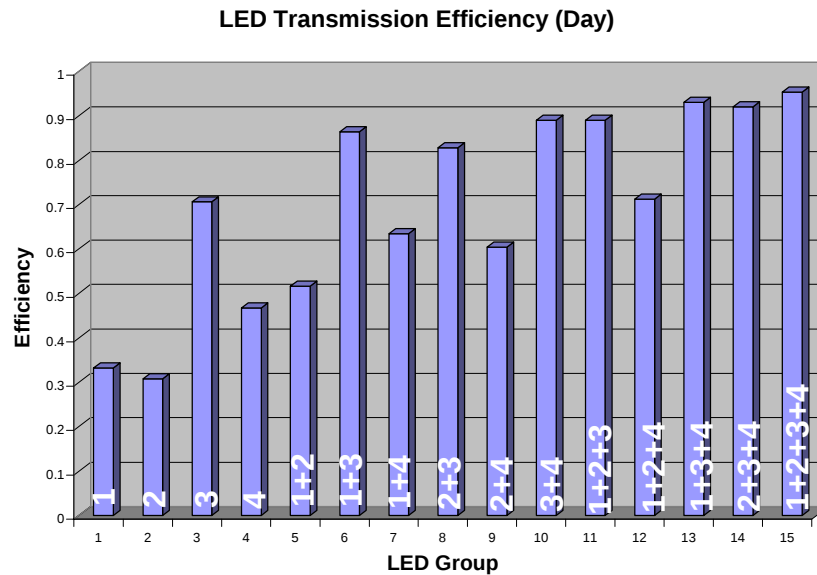


Fig. 3: Statistical analysis of the various permutations of the four, redundant, LED sources. Transmission efficiency increased to 95% utilizing all four sources versus 30% utilizing a single LED.

When completed, spatial filtering is expected to increase the signal-to-noise, and thus range and/or data rate, by a factor equivalent to the ratio of the total image area divided by the sum of the LED-neighborhood areas of the images (e.g. > 20X).

Engineering Engineering activities have focused on construction and testing of prototype hardware to demonstrate proof-of-concept. We have completed the initial design of this hardware, but have experienced significant delays in construction and testing. Both purchasing and equipment malfunctions have delayed the project by about four months. Work is progressing well now and we expect to complete this project within budget. A summary of work completed is provided below.

We completed construction of the prototype receiving hardware as shown below in Fig. 4. The main lens views the target and produces an image on a beam splitter. One path from this beam splitter is directed towards a video camera for image display and processing. In the second path, an enlarging lens relays the primary image onto the spatial modulator (DMD). To compensate for the different sizes of the camera sensor and the spatial modulator, the relayed image is magnified by a factor of 1.6. Light reflecting off the spatial modulator is collected and focused onto the data detector for subsequent analysis.

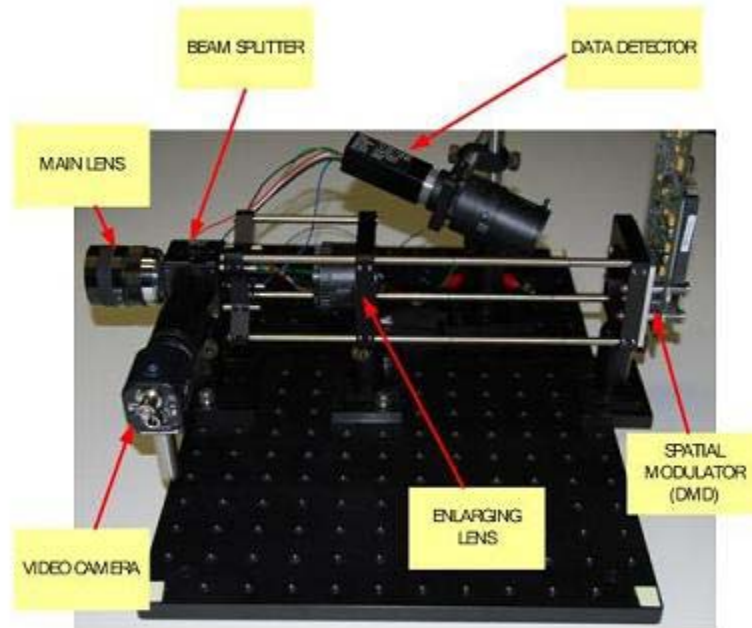


Fig. 4: A photo of the prototype optical receiving hardware.

Not shown in the figure are the electronics used to process images and control the spatial modulator (refer to Fig. 1). In our concept, optical transmitters will appear as small dots in the images. These transmitters will modulate data at a high rate ($> 100 \text{ KHz}$) within a much slower modulating envelope ($< 10 \text{ Hz}$) that can be detected with a standard video camera. Image processing will detect the slow modulation and activate only those elements of the spatial modulator upon which the modulating signal is incident. The active elements reflect the incident light to the data (high-speed) detector for analysis. The goal of this approach is to increase the system's signal-to-noise ratio by filtering out ambient scene light and ultimately detecting only that light received from the transmitter(s).

To increase gain, we replaced the photodiode initially chosen for the data detector with a photomultiplier tube (PMT). These detectors offer excellent sensitivity and frequency response at the cost of complexity. There was an unanticipated delay of 90 days waiting for the manufacturer to ship this detector. While software development could somewhat continue during this time, hardware development essentially was on hold. We have received this detector and are currently integrating it into the system.

We have completed initial programming and evaluation of the software required to operate the receiving system. In our approach, the software contains nine fundamental modules:

1. Camera capture thread
2. Frame bank switching
3. Optical communication interface
4. Bitmap stream creation
5. Display thread
6. DMD activeX control
7. DMD communication
8. System timing/control
9. Graphical user interface (GUI)

Each of the nine modules have been programmed and passed initial testing. Two challenges in this project have been the integration of the all modules under the Windows operating system and a longer-than-expected communication time to the DMD device. The module integration issues have been addressed by investigating their operation separately and the full application is currently being reassembled. The communication delays appear to be caused by a slow universal serial bus (USB) implementation on the DMD commercial hardware. While this means we will not be able to update the DMD at full video rates (30 Hz), it should not adversely affect the overall system's performance. Since our initial demonstrations will utilize stationary emitters, we do not require rapid adjustment of the DMD.

Work over the remainder of the project will include:

- Complete integration of the PMT
- Laboratory testing and characterization of the receiving hardware/software
- Out-door demonstration of the system.

RESULTS

- Use of four redundant LED light sources separated by ~ 1 m decreased the data drop-outs from as much as $\sim 70\%$ to $\sim 5\%$ for a daylight test across a capillary-wave interface
- We have completed initial programming and evaluation of the software required to operate the receiving system: nine fundamental modules:
 - o Camera capture thread
 - o Frame bank switching
 - o Optical communication interface
 - o Bitmap stream creation
 - o Display thread
 - o DMD activeX control
 - o DMD communication
 - o System timing/control
 - o Graphical user interface (GUI)
- All components are available for integration and testing

IMPACT/APPLICATIONS

There are many scenarios where communication between a submerged asset and an airborne asset would be very desirable. However, communication through the air/sea interface is, at best, problematic and any high-bandwidth communication strategy remains elusive. Field tests of our basic approach (not yet with spatial filtering) have shown that our hypothesis is sound, and data dropouts were reduced by factors from 6X to 14X. Additional, brighter LED sources will further reduce drop-outs. With the addition of the DSP and MEMS DMD technology, we expect further rejection of ambient noise and an increase in S/N ($\sim 20X$) and data rate. This technology should not only make optical communication through the air/sea interface feasible but also allow for high-bandwidth communication.

RELATED PROJECTS

- USF College of Marine Science Center for Underwater Observability and Optical Communication – Utilization of the ROSEBUD ROV and the TOPO-13 air platform
- Eric Kaltenbacher, SRI International – Optical tagging and 3D underwater imaging.

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