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Air-Water Communication and Sensing with Light

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***Abstract*—The ability to communicate and sense across the air-water boundary is essential for efficient exploration and monitoring of the underwater world. Existing wireless solutions for communication and sensing typically focus on a single physical medium and fall short in achieving high-bandwidth communication and accurate sensing across the air-water interface without any relays on the water surface. We study the use of laser light in this context given its ability to effectively pass the air-water boundary. We present a holistic system framework to address practical challenges such as ambient light interference and environmental dynamics. The proposed AmphiLight framework achieves 5 Mbps bi-directional throughput and zero bit error rate with ranges up to 6.1 m in strong ambient light conditions, and connection time improvements between 47.1% and 29.5% during wave dynamics. Our ongoing effort extends to realizing robust air-water sensing that enables aerial drones to track multiple underwater robots for topology planning and coordination.**

***Index Terms*—light communication, air-water communication**

I. INTRODUCTION

The underwater world is severely under-explored, profoundly limiting our ability to monitor physical, biogeochemical, and ecological phenomena in the water [4], [7], [8]. This under-exploration is in part due to the lack of effective communication and sensing technologies to transfer information from the underwater environment to stakeholders working above the water. Mainstream methods generally rely on surface relays (e.g., boats, a network of buoys) connected to both the underwater assets (via acoustic transducers) and the ground station (via tethering or Wi-Fi) [5]. However, the deployment overhead of surface buoys or vehicles constrains sensing and communication coverage, resulting in limited scalability. It is generally recognized that the use of flying drones for a bird's eye view, which communicate directly with underwater sensors/vehicles, will advance the efficiency and scalability of underwater exploration.

We seek solutions that support direct wireless communication and sensing between air and water nodes without surface relays. In this context, existing solutions mostly focus on a *single* physical medium and do not address challenges in the air-water setting. As examples, acoustic communication, the mainstream for underwater scenarios, cannot cross the air-water boundary since acoustic waves are mostly reflected by the air-water interface [10]; on the other hand, wireless technologies using radio frequencies (RF) are widely deployed in the air and yet radio signals suffer from severe attenuation in the water (3.5–5 dB/m) and result in short communication ranges [13].

In this paper we summarize our effort in exploring laser light to enable aerial drones to directly communication with and track underwater vehicles. Light is the most suitable medium in the air-water context because light effectively passes the air-water interface with less than 10% energy reflected back (when the incident angle is $\leq 50°$). Compared to acoustics, light propagates faster and entails shorter communication/sensing latency. Compared to radio frequencies, light endures much lower attenuation in the water. In particular, light in the blue/green range (420 nm – 550 nm) attenuates less than 0.5 dB/m in water [1], [9]. We specifically consider blue/green laser light because of its superior communication and sensing properties, such as: (1) nanosecond-level switching speed, (2) narrow (5–10-nm) spectral power distribution, which allows optical energy to be concentrated to the wavelength range with the smallest attenuation in the water/air, and (3) low beam divergence, which maximizes the energy efficiency and enhances communication/sensing distance.

We will first describe our AmphiLight framework that enables a bidirectional air-water communication link using laser light. We will then briefly discuss our ongoing effort in realizing direct air-water sensing.

II. PRACTICAL CHALLENGES

Despite the potential of green-blue laser light for air-water communication and sensing, we face following challenges to achieve robust communication and sensing. (1) *Ambient light*: Strong sunlight (up to 74K lx outdoors) can saturate photodiodes at the receiver, rendering them unresponsive to encoded light changes from the transmitter. It imposes non-trivial challenges for the system to maintain reasonable signal-to-noise ratios and high data rates. (2) *Path blockage*: Since light wavelengths are measured in nanometers, light-based sensing and communication requires line-of-sight propagation. Any opaque objects (e.g., suspended sediment, gelatinous zooplankton, floating algae, haze, smoke, fog) along the path can block light signals, causing the link to become unavailable. (3) *Environmental dynamics*: Dynamics of the water surface can render a laser link unstable due to the refraction at the air-water surface. For example, a rise in the water level caused

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by precipitation or a tide can elevate the light's incident point on the surface of the water. The resulting refracted light would then be translated and hence permanently miss the original underwater target. We also note that periodic waves caused by wind or moving objects can swing the refracted light in the water and the resulting oscillation can lead to link unavailability of up to 70%. (4) *Laser hardware limitation*: Off-the-shelf lasers experience a temperature rise when they are constantly on. This increase in temperature can shift the emission wavelength up to a few nanometers, which is undesirable for communication and sensing. Better heat dissipation demands dedicated temperature controller and active heat sinks, which are bulky (9lbs), expensive (≥$1000), and power hungry (up to 60W [2]). Furthermore, commercial lasers are typically powered with bench-top power supplies with current and voltage limits or mobile drivers that do not support fast modulation bandwidths (e.g., <2MHz [3]).

III. AIR-WATER COMMUNICATION

To solve these above challenges, we have designed the AmphiLight framework to realize robust air-water communication. The framework consists of a portable laser communication link with full-hemisphere beam steering, and a proactive wave sensing and beam adaptation mechanism to maintain link connection in the presence of water wave dynamics. Next, we first overview key elements in AmphiLight and then present the implementation and main experimental results.

A. Design Overview

Basic Laser Communication Link. To support Mbps-level throughput and low energy consumption, we apply the DarkLight concept in [11]. Specifically, DarkLight applies overlapping pulse position modulation, where data is encoded into the position of the rising edge of a light pulse within a symbol. We extend DarkLight to the context of laser light, leveraging laser diodes' fast switching speeds to increase the data rate while still maintaining a low duty cycle. Reducing the duty cycle removes the need for a dedicated temperature controller and reduces the power consumption issues typically associated with laser communication. Finally, to address strong ambient light interference, we exploit the sparsity of laser's spectrum emission profile. Considering that the energy of ambient light spreads the whole visible light spectrum while laser light energy is confined in a few nanometers, we add a narrow optical bandpass filter that allows only the wavelength range of the laser light to pass, and filter out the majority of ambient light. We pair it with an ultra-sensitive silicon photomultiplier (SiPM) light sensor to ensure the robust detection of low-power laser light at meter-level distances.

Full-Hemisphere Beam Steering. We adapt the fine-grained steering mechanism from free-space optics by expanding its limited steering range with a judiciously designed optical circuit. Specifically, we combine a small-angle microelectromechanical-systems (MEMS) mirror with a miniature fisheye lens to enlarge the small-angle steering to ±90° in two dimensions. Traditionally, fisheye lenses concentrate light rays coming from a full hemisphere to a small image plane (Figure 1). Given the path symmetry of light propagation, we consider the inverse direction of the light path by sending light rays through the image plane instead. This leads to an outgoing light ray steered to a larger irradiance angle, thus expanding the small input steering range to an entire hemisphere.

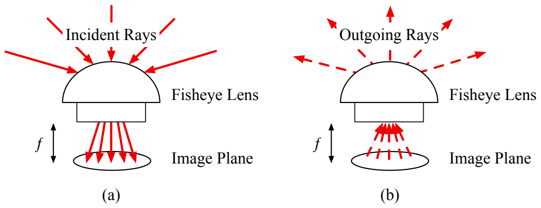

Fig. 1. (a) Light enters the fisheye lens and is projected onto a small image plane, compressing the wide incoming light directions into a smaller range. (b) We consider the inverse of the propagation path to enlarge a narrow steering range to full hemisphere.

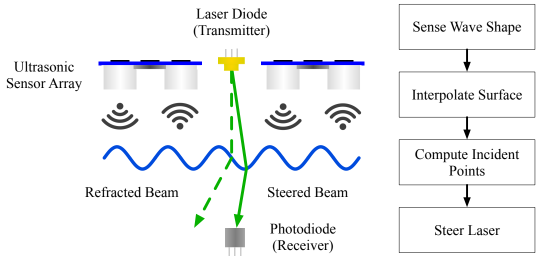

Fig. 2. Addressing water dynamics by continuously sensing the water with an array of ultrasonic sensors, interpolating the surface, computing the optimal path to the receiver, and steering the laser.

Wave Sensing and Beam Adaptation. To sense the water surface condition, we utilize ultrasonic distance sensors (Figure 2). To sense the shape of the water surface, we employ an array of M sensors that are uniformly distributed on the transmitter plane. Because all sensors operate at the same ultrasonic frequency, we instruct the sensors to sample the distance sequentially. To reduce the reconstruction latency, we exploit the fact that water waves are periodic and forecast the height samples of the water surface, i.e., instead of waiting for the readings from all sensors to be ready, we can forecast the distances based on historical data. Forecasting reduces the sensing latency of each frame (i.e., time period between adjacent frames) to $1/M$ of the non-forecast method, approximately 3 ms in our implementation.

To reconstruct a continuous wave surface for every frame, we need to interpolate between the discrete distance samples output by the array. We adopt a bicubic surface model [6] to fit the distance outputs given its shape flexibility and computational simplicity. We fit the model using linear regression, which is computationally inexpensive and suitable for real-time reconstruction. Once the shape of the surface wave is estimated, we next seek an incident point on the surface such that the refracted light can reach the receiver.

(a) (b)

Fig. 3. (a) Experimental setup in the pool, with transmitter in the air and receiver underwater. (b) Transmitter and receiver, respectively, in waterproof containers.

Although the incident light and refracted light are subject to Snell's law, this equation is intractable because of the trigonometric functions. Consequently, we model the problem as an optimization problem and solve it with gradient ascent.

B. Implementation and Results

We have fabricated a proof-of-concept prototype of AmphiLight. The prototype includes: (1) a transmitter, which encompasses the optical circuit, electronic circuit, and modulation scheme, (2) an ultrasonic sensor array, and (3) a receiver that includes optical filtering and demodulation hardware. To transmit data pulses accurately using OPPM, we utilize an Arduino Due, Basys3 FPGA, and TI laser driver. Our optical circuit consists of a 140 mW green laser diode, 3.6 mm MEMS mirror, and miniature fisheye lens. We implement our ultrasonic sensor array with 16 low-cost ultrasonic sensors, and perform demodulation offline using MATLAB and a high-speed oscilloscope.

Real-World Performance. We start by examining the link performance under calm water and measure the average throughput and bit error rates (BERs) for each distance configuration (Figure 3) Throughout our experiments, the mean throughput was constantly above 5.03 Mbps and the BER below 0.01. We are able to achieve a zero-BER range in the air up to 6.5 m and a zero-BER range in the water up to 2.5 m.

We next examine the link performance under water dynamics. We augment the transmitter with our ultrasonic sensor array and conduct experiments in a water tank setting. To generate waves, we stir the water by hand for ten seconds, creating roughly uniform waves with amplitudes between 10 – 12 cm and wave frequency of approximately 1 Hz. We compare our method to two baselines: (1) no steering, where the direction of the light is fixed without any wave sensing; (2) wave sensing without our forecasting method.

Both methods using wave sensing improved the link throughput, achieving 29.5% and 47.1% increases compared to no steering (Figure 4). Without steering, the link is disconnected 48.1% of the time because of the periodic surface changes, whereas active sensing and laser steering improves the connection percentage to 82.8%. Compared to prior work [12] which only supports throughput up to 400 bps, our system maintains a throughput of 4.2 Mbps with OPPM during wave dynamics – a 10,500 times improvement.

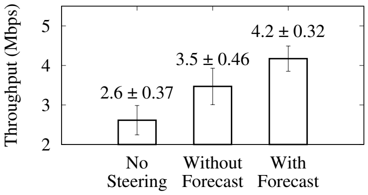

Fig. 4. Average throughput results under different water conditions. Error bars are standard deviation.

Ambient-Light Interference. Given that our ultimate application scenario is outdoors, we evaluate the impact of strong sunlight on our link. We compare two extremes: a low-light condition indoors (illuminance between 5 and 7 lx) and a strong-light condition outdoors (73,900 lx), typical for direct sunlight at noon. We measured a zero-BER distance at 6.1 m outdoors, compared to 6.5 m indoors with low ambient light. This demonstrates that our receiver design is robust to strong sunlight, benefiting from the narrow emission bandwidth of laser light and spectral filtering.

IV. ONGOING: AIR-WATER SENSING

Our ongoing effort aims to realize robust air-water sensing with laser light. Specifically, we aim to enable an aerial drone to locate and track multiple underwater robots directly. The sensing capability will sustain air-water communication with moving drones and robots. It will also allow the system to identify path blockage in real time and actively search for alternative paths to re-establish broken links. Existing methods to locate and track underwater robots are based on underwater acoustic positioning (e.g., Ultra-Short BaseLine). These methods are expensive and require either a buoy or a surface vehicle with nontrivial logistical and deployment overhead. We will utilize laser light to remove the need for surface vehicles/buoys.

The air-water sensing system consists of a laser steering and sensing component on the aerial drone, and an angle-of-arrival (AoA) sensing component and a retroreflective tag on the underwater robot. The aerial drone actively steers a laser beam in the full hemisphere and senses light retroreflected by the underwater robot to identify the robot direction. Once the drone's laser beam hits the robot, the robot senses the incident angle of the laser beam and sends the angle and its depth (sensed by the built-in depth sensor) back to the drone. The drone then combines the information with its own GPS location and height (sensed by the drone's built-in acoustic depth sensor) and compute the precise location of the robot in real time.

The major technical challenge of the above design is to deal with the extremely weak retroreflected light traveling across the air-water boundary. While the choice of retroreflectors can help reduce the energy loss during retroreflection, the options with the highest energy efficiency (e.g., cornercube retroreflectors) are large and rigid, making it difficult to colocate the AoA sensing component. Flexible retroreflectors (e.g., retroreflective tapes), on the other hand, can be seamlessly molded around the robot surface, yet cause a large amount of specular and diffusive reflection, retroreflecting less than 40% of light. This is extremely unfavorable when coupled with the attenuation caused by the air-water boundary. Additionally, as for the AoA sensing, existing techniques all require a photodiode array, which is undesirable for a laser beam with a narrow beamwidth that is unable to cover the whole sensor array. Commercially available laser AoA sensors are very costly ($\geq$5K) and are less sensitive in the blue/green spectrum range, which is the most effective spectrum for the air-water setting.

We are exploring following design elements to address above challenges. *First*, to sense weak retroreflected light traveling through the air-water boundary, we are studying a novel hardware design that utilizes an optical fiber ring to maximizes the amount of retroreflected light to be sensed. Given the flexibility and thinness of the optical fiber, the ring is collocated as close as possible to the laser source. The ends of the optical fiber bundles is diverted away from the transmitter's lens, passed through an optical bandpass filter tailored to the transmission wavelength (to filter out ambient light interference), and captured by an ultra-sensitive photodiode (SiPM). The use of the fiber bundles expands the sensing area, resulting into aggregated light with higher energy density being projected to the small sensing area of a high-gain photodiode. *Second*, to realize AoA sensing at the robot, we design a pinhole sensing mechanism using a low-cost image sensor. As an incoming laser beam passes the pinhole, its incident angle is translated into different coordinates of the light spot sensed by the image sensor. *Third*, we design a backscatter communication channel for the robot to reuse incoming laser light to send back its AoA results and depth value once the laser beam hits the the robot. We exploit the polarity nature of laser light to avoid the energy loss during the creation of linearly-polarized light used by existing light-based backscatter systems. We also seek novel optical designs to make the system robust against various orientation of the drone and robot.

V. CONCLUSION

We summarized our efforts in enabling direct air-water communication and sensing with laser light. The proposed technologies are built upon off-the-shelf, low-cost hardware. Validated by initial experimental results, they are promising to be deployed on flying drones and underwater robots to advance the exploration of the underwater world.

ACKNOWLEDGMENT

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