Omni-Cam: An autonomous free-descent Omni-directional camera for measuring radiance in marine environments

Jules S. Jaffe, Fernando Simonet, Ben Laxton
Marine Physical Lab, Scripps Inst. of Oceanography
9500 Gilman Ave, MS 0238
La Jolla, CA 92093 USA
jules@mpl.ucsd.edu

Abstract- **To measure oceanic radiance and hence, the pelagic environment of marine cephalopods, we have built a new underwater multiple camera system that consists of a glass sphere that houses 6 machine vision cameras each capable of outputting uncompressed 2 megapixel images at 60 Hz. The cameras are arranged so that their fields of view are all orthogonal, pointing along the positive and negative directions of the principal Cartesian axes (+/- x, +/- y, and +/- z). Taking all of the camera data together, the light field incident on the Omni-directional camera system can be recorded. The system was configured for autonomous operation with batteries, computers, cameras, and ancillary electronics inside the 17" glass sphere. Preliminary data, recorded in both a pelagic and benthic environment, indicate that the data acquired by the system can provide interesting insights into spatial and temporal fluctuations in underwater animal habitats.**

I. INTRODUCTION

The daily lives of animals that live in the ocean depend on finding food and mates without being found by predators. In order to accomplish this, they employ a variety of fascinating schemes for hiding. In the case that they are subject to visual predation, they often employ a form of optical camouflage. Among these methods, some can be considered to be passive, where they simply modulate their appearance in order to take advantage of the average lighting conditions [1]. Other, more exotic techniques are active, where animals can emit light via bioluminescence that can mimic the downwelling light field, which will make them more difficult to be found [2]. Of the more exotic and interesting adaptations, cephalopods such as octopus, squid, and cuttlefish, are outstanding in that they can change their reflectance dynamically by adjusting their skin color. In the context of a larger group of investigators, we have recently created several tools to investigate cephalopod environments and display captured environmental data back to them in an aquarium setting. In this way we hope to learn more about their optical camouflage capabilities and how these responses correlate with the visual environment. The Sub Sea Holodeck is a subject of a companion article in these proceedings that describes this aquarium environment.

In these conference proceedings we describe the design, construction, and preliminary results from an omni-directional underwater camera system that we refer to as Omni-Cam. The system is intended to capture the radiance distribution [3], known as the angularly dependent light field at a 3-dimensional location, $L(r,t)$. Since our goal is to understand the visual environment of cephalopods, the system was specifically tuned to their visual abilities and hence our results can provide insight into cephalopod perception.

II. EXISTING SYSTEMS

In accessing the design requirements for the system, we initially surveyed the commercial product marketplace to see if any might be of use. Currently, there are several available portable underwater omni-directional camera systems. The Dodeca 2360 camera system [Immersive Media Co, Dallas, Tx] consists of (11) 640 x 480 resolution cameras that create omni-directional images with a resolution of 3.4 megapixels/frame. The system can acquire compressed jpeg images at 30Hz and can be used with an optional underwater housing rated to 30 feet. Another omni-directional camera is the GeoView 3000 (iMove Co., Portland, OR) that consists of (6) cameras with 1200 x 1200 pixel resolution for a total resolution of approximately 8.6 megapixels/frame. The system streams omni-directional video at 7.5 Hz into a single computer. A third omni-directional camera, the Ladybug, is offered by Point Grey (Richmond BC, Canada). It uses (6) 1600 x1200 pixel resolution cameras in a configuration that covers a hemisphere so two such system would be required to adequately cover all viewing angles. The Ladybug streams into a single computer at 7.5Hz when using uncompressed images or at 15Hz for jpeg compressed images.

Although these systems are capable of providing omni-directional data, one of our main requirements is to be able to measure the radiometric light field. This requires careful calibration and, moreover, the use of uncompressed data, as the compression process converts the images into a non-quantifiable entity. Moreover, since the flicker-fusion rate of squid is near 60 Hz [4], we require an imaging system that could capture images at, or above this rate. In addition, we required images that could easily be displayed on our Sub Sea Holodeck. Based on all of these criteria, we decided to build a, our own, new, system. As one feature, discussed in more detail in what follows, in order to accommodate the acquisition of 6 HDTV images at rates of up to 60 Hz, a computer – disk is dedicated to each camera.

III. Technical Details

The overall goal of the Omni-Cam system is to capture high-resolution images that cover the entire viewing sphere at fast frame-rates (> 60 Hz). Furthermore, the images need to be uncompressed and have as much dynamic range as possible to be quantifiably related to the underwater light environment. An additional, special design consideration, is necessary to measure the light environment as perceived by most cephalopods. The system, as designed, is able of to capture and store to disk up to 180 million pixels per second of 14-bit uncompressed data. In addition, since the system is housed in a deep diving glass sphere, it was configured for autonomous deployment at depths of 6000 meters. Here, we describe the engineering details of the system that consists of the electronics, housing, and optics in addition to the software to control the system and stream the data to disk.

A. Hardware

A CAD model of the Omni-Cam system is shown in Fig. 1a and the assembled system without the external frame for deployment is shown in Fig. 1b. As seen, the electronics and optics are encapsulated in a glass sphere. For deployment and retrieval, and to hold ancillary instruments, the glass sphere is anchored inside two hemispherical hard hats (not shown) with external legs and titanium framing. The Vitrovex glass sphere (Nautilus Marine GmbH, Bremen, Germany), depth rated to 6000 m, is primarily used for deep-sea floatation. However, after application of a special polishing procedure, the sphere can provide optical clarity suitable for underwater deployment. When fully assembled the Omni-Cam system is slightly positively buoyant, however, the external framing has attachment points for weights to allow for the system to be negatively ballasted. As shown in Fib 1b, the glass sphere housing has 10 connectors protruding through it. The top 6 connectors provide high-speed USB (Universal Serial Bus) links to readout the collected data. The bottom 4 connectors provide charging capability; Ethernet connectivity, 2 serial communication ports and a conduit for DC power. Inside the glass sphere is a 3-piece anodized aluminum frame to which all of the electronics and optics are mounted. Finally, the design has the hemispherical interface of the glass sphere sitting at an angle relative to the principal axes of the camera pointing angles. While this makes for a more complicated assembly process, it was necessary to ensure that each of the six cameras have an unobstructed field of view.

Inside the sphere, mounted to the aluminum armature, are 6 cameras with lenses, 7 embedded PCs, several types of sensors, electronics for synchronized triggering, batteries. and a power management module. The cameras are positioned along the positive and negative directions of the principal Cartesian axes (+/- x, +/- y, and +/- z) so that, when combined they cover the complete view over 4 pi steradians of solid angle. The fields of view intersect at ½ meter in the horizontal plane and at 1 meter in the vertical plane. The Allied Vision Technologies GX1910 GigE (Ahrensburg, Germany) cameras are used, due to their compact size, high sensitivity sensor and high bandwidth capabilities. The GX1910 can achieve streaming rates up to 1920 x 1080 pixels at 60 fps. Each GX1920 camera is outfitted with a Fujinon (FujiFilm, North America, NJ) FE185C086HA-1 fisheye lens.

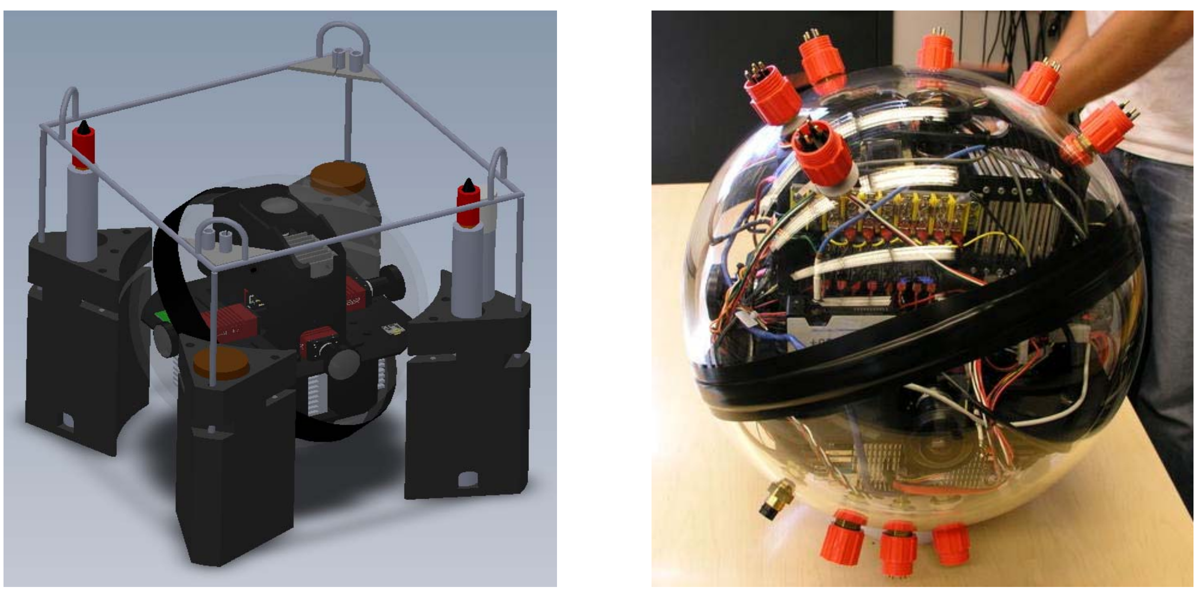
In order to "mimic" the visual system of the animal, we choose to adjust the camera's spectral sensitivity and frame rate so that the animals' single visual receptor light sensitivity and speed could be accommodated. As such, the monochrome GX1920 cameras were equipped with a filter response so that the aggregate sensitivity of the system (camera + filters) would mimic that of the animals'. A second biologically driven design consideration relates to the animals' flicker fusion frequency, which is less than 60 Hz [4]. The GX1910 cameras were chosen because they are capable of recording the visual light fields at those, or even greater, rates.

Each of the 6 GX1920 cameras is connected to a VIA (Taipei, Taiwan) EPIA-P720 embedded PC. The EPIA-P720 is a full-featured PC in a very compact form factor. The 6 EPIA-P720 PCs were each outfitted with 2GB of RAM, a 256GB solid-state drive for storage, and gigabit Ethernet for camera connectivity. As each camera is connected to a dedicated PC uncompressed images can be streamed at a resolution to support our requirements. This was necessarily higher resolution and higher frame rates than the commercially available systems, discussed above. A seventh EPIA-P720 PC is used to coordinate the 6 camera PCs, read from the auxiliary onboard sensors, monitor the system status and execute programmed deployment strategies. In addition to the 6 cameras and PCs there are several other sensors including an Ocean-Server (Fall River, MA) OS5000 orientation sensor, an Ocean Optics (Dunedin, FL) USB2000+ spectrometer, an exterior mounted sea temperature and depth meter, and a National Instruments (Austin, TX) DAQ board. The seventh EPIA-P720 simultaneously controls, monitors and archives the data from all of these sensors. The system is designed to run on battery power with a life of four hours. The battery voltages are monitored and controlled by an Ocean Server power management board. Since the system runs on battery power alone it is capable of autonomous untethered deployments. Upon retrieval the data is read out in a parallel fashion via the set of six USB connectors, one for each camera/microprocessor combination. At that time, the system's lithium ion batteries can re-charged though an connector throughput. An innovative feature, is that each of the 7 PCs have wireless connectivity and run a local adhoc-network.

In this way the system can be completely accessed, controlled and updated using an exterior laptop computer without opening the housing.

B. Software

The entire system is controlled by a set of in-house developed programs that operate in parallel to synchronize all of the cameras, store the collected data from each camera and all auxiliary instruments, and carry out programmed deployment scenarios. The control software can logically be broken into two components; 1) the camera streaming program and 2) the system synchronization and control program. The camera-streaming program was developed in C++ using the Allied Vision Technologies SDK and standard C++ multithreading libraries. This program was designed to allow for full configuration of camera parameters and for image data to be streamed to disk as fast as possible. The system is capable of writing image data to disk at a 60 MB/s sustained rate for each camera giving a total system throughput of 240MB/s. This allows uncompressed 1920 x 1080 images with 14-bit depth from each camera to be collected at an uninterrupted rate of 15fps or 3x3 binned images to be collected at rates up to 100 frames per second. Each of the 6 PCs runs this same program. The seventh PC runs the control software that synchronizes all of the cameras and auxiliary instruments and stores time-series light-meter, temperature, depth, and diagnostic data for each experiment. The control program synchronizes the 6 cameras through a National Instruments DAQ board that is capable of outputting a programmable pulse train, which is used as a hardware trigger for the cameras. In tandem with the synchronizing pulse train, the control program collects the light spectrum from the USB2000+ spectrometer, pitch-roll-yaw orientation from the OS5000 and sea temperature and depth from an exterior Seabird (Bellevue, WA) SBE39. In addition to the synchronization and collection of data the control program facilitate the autonomous operation of the Omni-Cam system. Autonomous deployments are achieved through user configurable triggers that control when data acquisition should start, end, and under what conditions the system should ascend to the surface. Currently, experiments can be configured to collect data based on depth, elapsed time or external temperature. When a stopping condition is met the control program sends a signal through the NI DAQ board to burn a wire, which causes Omni-Cam to drop weights and float to the surface. The design of the ballast system is identical to that developed for the "deep sounder" vehicle that was configured to record ambient ocean noise to great depths [5]. In addition to carrying out pre-programmed deployment scenarios the control software contains several fail-safe mechanisms that monitor internal temperature, elapsed time, depth and battery life to ensure the system's return in case of some malfunction.

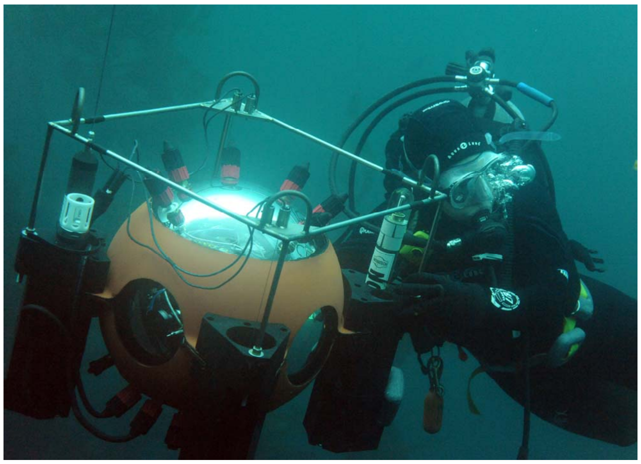


(a) (b)

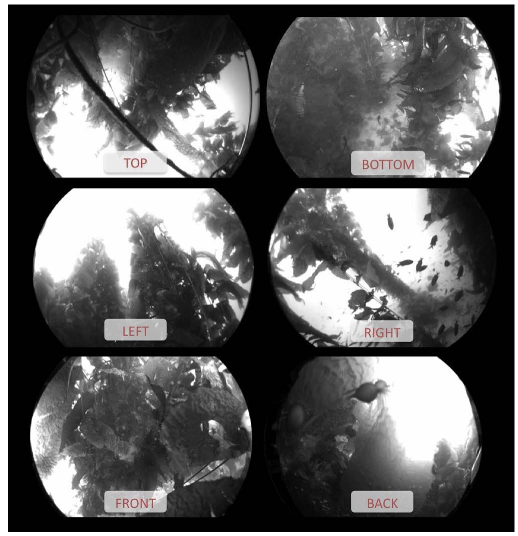
Fig. 1 (a) The mechanical armature of the Omni-cam system with several of the cameras shown as well. For convenience of viewing, the enclosing hard hats and the glass sphere were remove. (b) The glass sphere and enclosed electronics for the system. Note the orange connectors that permit parallel read-out of the data, communication with the system, charging and interfacing with various external devices such as depth sensors and lights.

IV. Field Data

The system has been used in several field programs starting with an initial deployment in June of 2010. A deployment in the Gulf of California consisted of measuring water column radiance over a 10 day period at various times of day and dusk to depths of 300 meters. The system was either hand deployed from a boat or deployed by divers swimming with it. Figure 2a shows the divers, underwater, with the system. A second deployment, designed for a benthic habitat, took place on Catalina Island during the Fall of 2010. Here, the system was placed close to the sea floor to record the ambient light environment that would be encountered by animals living in that habitat. Over the course of 6 days, the system was positioned in various environments ranging from rocky/sandy to inside a kelp forest. Changes in the light patterns, incident on the sea floor, were clearly visible over the 6 cameras recording data, as shown in Figure 2b.



(a)



(b)

Fig. 2 (a) Diver led deployment strategy for omnicam. (b) A sample of the data recorded by the six synchronized cameras clockwise from upperleft shows the top,bottom,right, back, front, and left views.

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