DeepStereo: A low cost flexible system for Underwater mono and stereo imaging of marine snow.

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Abstract—Measurement of marine snow densities and flux rates is integral to the understanding of ocean ecosystems and the oceanic carbon cycle. Traditional measurements of the sinking rates of marine particles are measured through floating sediment traps or radioisotope variability measurements [1, 2]. Such measurement methods are useful when measuring average fluxes but lack the ability to sample localized particle fields or capture direct measurements of localized particle sinking rates [3, 4]. In this paper, we propose a novel design for DeepStereo, a low cost imaging system for measuring the particle densities and sinking rates of marine snow in the ocean. The DeepStereo system is designed to operate up to 500m in depth, and is based on the open source microcomputer system Raspberry Pi.The compact epoxy-potted deign of the DeepStereo system (based on the DeepPi system [5]) allows the key components of the system (camera, light controller board and battery) to be mounted radially on the outside of a cylindrical float body. Communication between the elements of the DeepStereo system is accomplished through wireless and GPIO connectivity. We describe the DeepStereo system in detail and discuss its design and usability.

Keywords— Marine snow, Remote sensing, Ocean Science, Stereo photography, Raspberry Pi, Marine imaging, Time series, Open source hardware, Rapid prototyping

I. Introduction

Marine snow is the product of the breakdown and aggregation of biological particles in the ocean. Not only does marine snow provide an important source of food material for various species throughout the ocean, but it acts as an important driving force in carbon sequestration[6, 3]. It is estimated that marine snow has absorbed roughly 40 percent of CO2 emissions since the industrial era[7]. The majority of this CO2 is sequestered as phytoplankton photosynthesize in upper ocean waters, converting CO2 to organic material. As these plankton die (or are consumed by other organisms) their biological material will eventually become particulate matter which sinks at various rates towards the seafloor[3, 7].The measuring of sinking rates and particles sizes in this process allows for better understanding of the rates of carbon sequestration; an important variable in ocean climate studies.

There are several existing strategies to measure carbon flux rates in the ocean, the primary method being the use of sediment traps to capture sinking particles over time. Sediment traps work on the basic principle of capturing sinking particles on an adhesive, upwards-facing plate which passively collects sinking particles over time[1]. Sediment traps can be moored at various depths in the ocean, or attached to probes or other devices and generally collect data over the time period of months. Particles which are captured over this time period are preserved and are available for analysis once the trap is retrieved and imaged. Sediment traps provide useful information on flux rates and particle sizes, as well as composition but are limited in their ability to measure carbon flux processes[6, 8]. Sediment traps are primarily limited by their small size (less than 1m squared surface area) and the limited amount of time they can be deployed before they capture too many particles. Furthermore, the aggregation of individual particles after being captured makes exact measurement of particles sizes difficult. Other measurement methods, such as radioisotope tracking using Thorium-234 and Polonium-210 can provide estimates on long-term fluxes in the upper ocean, but lack the ability to measure localized fluxes, or exact particle size and sinking rates[2, 1].

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To provide novel measurements of particle sinking rates, and avoid the issues discussed with Sediments traps and radioisotope matching, a Camera System is proposed to measure marine snow fluxes and densities. Camera systems are widely used in ocean science, often to capture images of underwater specimens[9]. Camera systems have several advantages when being used over other methods in regards to the measurement of marine snow characteristics. Primarily, camera systems allow for the localized measurement of particle fluxes over small time periods and allow the measurement of particle sizes and densities as the particles sink. Furthermore, camera systems are generally limited mostly by battery and memory capacity when determining the amount of time a camera system can be active. Finally, camera systems (for the purpose of visualizing marine snow) can provide a low cost, simple method of capturing images of particle fluxes. This allows camera systems to be deployed on many floats simultaneously, allowing for wide-area measurement of ocean particle fluxes.

Low cost and ease of manufacture of the camera system is required to allow for the construction of multiple units to measure particle fluxes over a wide area of ocean. To accomplish both a low cost and ease of manufacture, the use of rapid manufacturing technologies and low-cost, open-source hardware for the camera system will be used. More specifically, raspberry-pi cameras and resin printed pressure housings will allow for a low cost per camera system (less than 500 USD) and the ability to manufacture components using widely available resin printing machines, and easily available electronics components.

II. DeepStereo Design

The following section describes the design of the camera system (referred to as DeepStereo) for measuring marine particle fluxes. Subsections describe the details of particular elements of the DeepStereo system design.

a. Design Criteria

Design criteria were gathered from scientific stakeholders to constrain the specifications of the DeepStereo system. The design criteria broadly cover the operation specifications and the measurement specifications of the DeepStereo system. The design criteria are as follows:

1. The system should be capable of imaging particles with diameters of 100 to 2000 microns.

2. The system should be capable of imaging particles moving up to 0.02 meters per second.

3. The system should be able to take images such that particle sizes and velocities can be measured.

4. The system should operate up to a maximum depth of 500m.

5. The system should be able to mount flexibly on the outside of variable diameter float systems.

6. The system must be comprised of parts worth less than 500 USD.

The design criteria concerning particle sizes and velocities are derived from the most common ranged of particle sizes and fluxes found in the ocean [3, 6, 8], which show that the largest contributor to marine particle flux are the comparatively larger, faster moving particles in the 200 to 2000 micron size range (diameter), which generally move around 1 to 5 meters per day[3, 4].

Design criteria numbers four and five constrain the design such that it can be used on the MINION float system. The minions float system is a low-cost isopychnal float system which is capable of gathering data various types of ocean data. The key elements of the minion system are the low cost of the system, the modularity of the system and the isopychnal nature of the float. The minion system is designed to have several partially integrated hardware systems for measuring oceanic particle densities, PH values among other scientifically relevant values. A key design criteria of the DeepStereo system is it's ability to integrate with this existing Minion platform without significant reconfiguration of existing hardware. Furthermore, a low cost of materials must be achieved to allow for the deployment of multiple minion and DeepStereo systems simultaneously. Finally, adding modularity to the DeepStereo system gives it the ability to be configured for deployments of varying length and purpose, or even removed from the minion platform altogether.

b. Camera Selection

The camera module is the most important (and costly) element of the DeepStereo system. The main goal of the camera module is to capture images of a particle field for a stereo reconstruction. Design of the camera module and selection of the optical elements is primarily driven by the sizes and speeds of the marine snow being imaged. Figure 1, reproduced from Omand et. al. [3] shows a distribution of particle sizes predicted for the North Atlantic.

As the vast majority (by number) of these particles are too small and to feasibly visualize, and also have an insignificant contribution to the mass flux of particles. Because of these factors, camera system is designed to see a range of particles between 100 and 2000 microns in size. Knowing the size of the targets, a simple image formation model can be created, which describes the vertical linear size of a target particle in pixels in relation to the actual size and distance that particle is physically from the camera. Equation 1 describes the image formation model[10, 11], where f is the camera field of view, I_h is the image height (in pixels), R_h is the real height of the particle being imaged, d is the particle distance from the camera and S_h is the sensor height (in pixels).

$$linearSize = \frac{f * I_h * R_h}{d * S_h} \tag{1}$$

Note that the image formation model assumes a spherical particle diameter, and considers the vertical linear size of the particles in the final image because the particles will be sinking (moving vertically) relative to the stationary frame of the camera, thus the resolution in the vertical axis is of great importance. Equation N denotes the relationship between the particle size (actual) and the linear size of the target particle in the final image. We can estimate the expected particle sizes by selecting an image sensor, which will define the sensor size and resolution. The selected image sensor in this case is the Sony IMX77 optical sensor. This sensor was selected for compact size (approximately 6 by 4 millimeters)

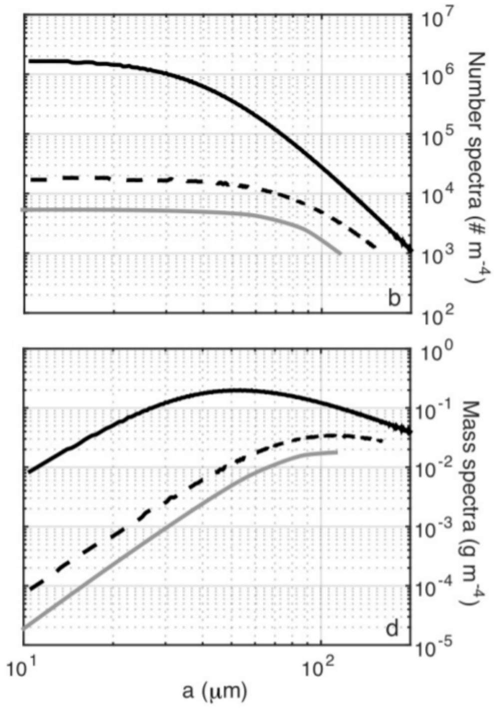

Fig. 1: Estimation of particle flux spectra in the North Atlantic. The number spectra and mass spectra are the sum total of particle numbers and masses respectively, above the diameter specified on the x axis. Reproduced from Omand et Al

and it's availability as a low-cost integrated camera module, compatible with the raspberry pi microcomputer system (the selected microprocessor). Figure 3 shows the expected vertical particle linear size versus the particle distance from the camera and the particle size (calculated for the given camera parameters). The red-dashed line on the plot shows the distance below which the movement of the float in the water would disturb particle trajectories, invalidating particle velocity measurements made at those distances.

Figure 4 shows the distance traveled by the particles over a single frame, assuming frames are taken at the rate of one frame per second. Together, Figures 3 and 4 support the idea that the selected camera sensor should be able to take stereo images where particle sizes and velocities can be extracted. A secondary question of interest is the number of particles seen over time by the camera system. This value can be calculated knowing the particle density, particle speeds, and the shape of the viewing region in which the particles will be clearly seen the the camera. The last quantity can be calculated by determining the depth of field of the camera system in question[10]. Note that for this calculation, the acceptable circle of confusion was chosen as three pixels. This is so that the particles with the smallest apparent size (of five pixels) will still be detected in the final video. The equations used to calculate the near and far depth of field of the camera are shown below. In these equations f is the focal distance (mm), N is the F-stop of the camera, c is the circle of confusion size (in pixels) and D is the working distance (in mm).

$$DOF_{near} = \frac{D*N*c(D-f)}{f^2+N*c(D-f)} \quad (2)$$

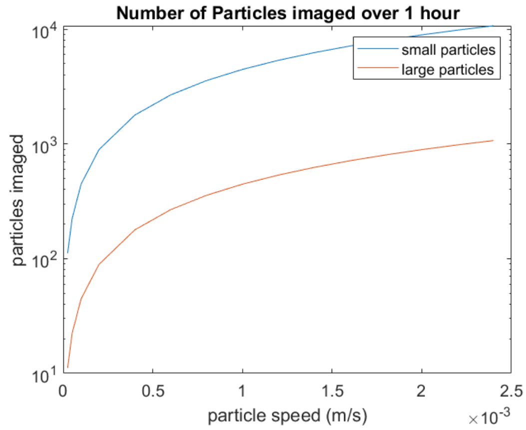

Fig. 2: The number of particles potentially imaged by the camera in one hour. This assumes the frame rate is one frame per second, and that large and small particles are divided roughly into two groups: large particles which are 200-2000 microns in size, and small particles which are far more common, and are 20-200 microns in size.

Selected Camera Parameters	
Parameter Name	Value
FOV	47 Degrees
Focal Distance	5.4mm
Resolution	4056x3040
Sensor Size	7.9mm
Frame Rate	1,10,30 fps
F-Stop	8
Shutter Speed	0.008s

TABLE 1: A TABLE OF THE FINAL CAMERA PARAMETERS SELECTED FOR THE DEEPSTEREO SYSTEM.

$$DOF_{far} = \frac{D*N*c(D-f)}{f^2-N*c(D-f)} \quad (3)$$

Using these optical characteristics, we can determine the number of particles seen over time by the camera, by determining the particle flux value (particles per square meter per second) of the particles through the top of the view field of the camera. As the camera's view field is a trapezoidal prism (with the flat faces being the near and far view-planes), the surface area is given by the area of a trapezoid, with the bases being the widths of the near and far view-planes respectively, and the height being the distance between the view planes. Computing this value gives the surface area through which the particles pass as 0.0095 meters squared. Using this value, we utilize the particle densities and speeds given for large and small particles[4, 3] to determine the number of particles seen by the camera as shown in Figure 2.

After computing these values, we determine the optimal optical characteristics for the camera system, which are shown in Table 1. The camera characteristics chosen accomplish the goal of viewing a significant number of particles of the correct size range (100-2000 microns), while also maintaining a compact size of camera and lens, which is necessary to allow integration in the existing float system.

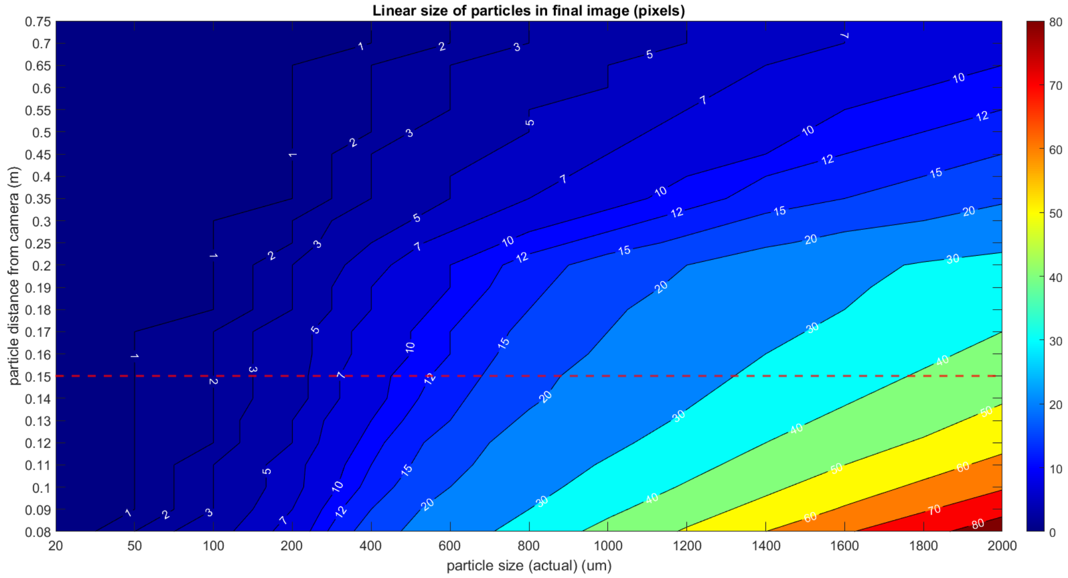

Fig. 3: Particle linear size estimates taken from the model in Equation 1. The color-bar and contour labels represent the apparent linear size of particles in the final image. The x-axis is the actual size of a particle, whereas the y-axis is the distance a particle is from the camera.The red dashed line represents the minimal distance from the camera which particles can be imaged. Particles below this threshold will be effected by the movement of the float.

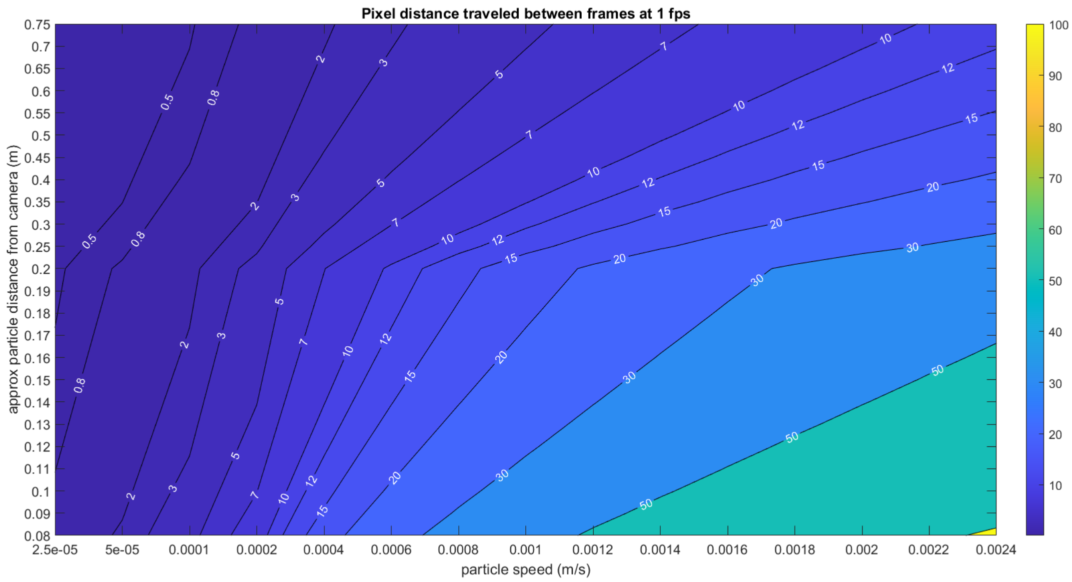

Fig. 4: Particle pixel distance traveled estimates taken from the model in Equation 1. The color bar and contour labels represent the apparent pixel distance traveled of particles in the final image. the x-axis is the particle speed, whereas the y-axis is the distance of the particle from the camera. The majority of particles will travel only a few pixels per frame when frames are taken at one frame per second, so an even slower frame rate could be used, however a longer time between frames would reduce stereo synchronization accuracy.

c. Light Design

To operate in the darkness of deep ocean, the DeepStereo system requires a light subsystem to illuminate particles in the view field of the camera. The key factor of the light system is that it have enough power to illuminate all particles within the field of view of the camera, but also not be an excessive source of energy drain to the system's batteries. To calculate the light power required, candidate LED components were picked and their important characteristics were used in a simple lighting model[10, 9]. The LEDs chosen for this purpose are the CREE XPLAMP LEDS. These LEDs provide a high output light power, while maintainign a small factor. Furthermore, the LEDs are available in the wavelengths of 625-645 (near infrared) which is important for avoiding the attraction of marine animals. The lighting calculation takes into account the wavelength and the power irradiated by the light source, as it travels through the water and bounces off a particle and into the camera which allows us to compute the signal-to-noise ratio (SNR) of the camera. In this case, the schematic in Figure 5 shows the path of a virtual light ray from the light to a particle and back to the camera sensor, and denotes the power or the light ray as it travels through the scene.

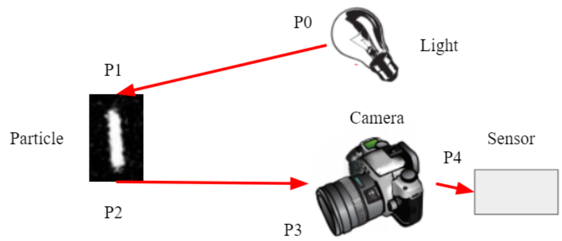

Fig. 5: A simple schematic showing the light power values as they pass from the light, through the water, off the particle, and eventually into the camera lens.

We can use a lighting model[10, 12] to calculate the power of the light ray at each step to determine the pixel SNR. First we determine the initial power $P0$ emanating from the light by calculating the number of watts irradiated per square centimeter of the LED. Assuming a drive current of 350 milliamps at 2.1 volts, we determine the watts per square centimeter as 0.31 ($P0$, as per the lighting-power curve provided by the manufacturer. We can then calculate $P1$, the power incident on the particle. This is calculated from Equations 4 and 5, where I is the Irradiance (power), $P0$ is the calculated watts per square centimeter, S is the particle surface area and r is the distance to the particle (taken here as 15 centimeters).

$$P0' = P0 * \frac{S}{r^2} \tag{4}$$

We also reduce the power incident on the by the amount absorbed by the ocean water using Equation 5. In this case, we assume the water is clear, and the effect of particle scattering will be minimal, as the viewing distance is relatively low (15 centimeters) and the size of scattering particles is in the range of particles we seek to image. In Equation 5, r is the distance to the particle, a is the absorption coefficient of clear ocean water[12], $P0'$ is the modified irradiance from Equation 4 and Al is the reflectance (albedo) of the particle. In this case, we estimate the albedo of the particle to be 0.8, according to measurements of particles of similar size in literature[1, 6, 4], however the exact reflectively, surface roughness and other optical characteristics of the particles vary widely in practice. We estimate $P1$ to be $4.5e-9$.

$$P1 = Al * P0' * e^{ra} \tag{5}$$

$P2$ is calculated similarly to $P1$, as we assume that the particle radiates the received light in a hemisphere back towards the camera. In reality, particle roughness causes scattering, and an angular shaped particle could cause light to be reflected away from the lens. We calculate $P2$ by repeating the same calculations as shown in Equations 4 and 5, simply on the reverse path. We calculate an output value of $1.45e-9$ watts per square centimeter into the camera lens $P3$. To determine the power $P4$ onto a pixel, we multiply by the lens efficiency of the lens, which is approximately 0.8. Finally, we convert the incoming luminous power into photons using Equation 6, which relates the energy of a light source to the number of photons. In this case, n is the number of photons, h is Planck's constant, c is the speed of light, t is the shutter speed and λ is the wavelength of light of the light source[10].

$$n = \frac{P4 * t * \lambda}{h * c} \tag{6}$$

Finally, we use Equation 7 to convert from the number of photons to the pixel SNR. In this equation, v is the sensor efficiency (taken from the sensor datasheet) and n is the number of photons calculated from Equation 6.In our case, we assume the camera is not dark noise limited, and therefore any noise caused by dark-current and read-out error is assumed to have zero contribution to the overall noise, which is formulated as simply statistical noise. In our case, we determine a SNR of 41.6, which is within the acceptable range of most imaging systems $(20-100)$[10, 9].

$$SNR = \sqrt{v * n} \tag{7}$$

d. Power System

The power system is composed of two components, the PiSugar board and the LED driver. A simple schematic of the power system is presented as part of Figure 14 (Appendix). The PiSugar board is responsible for the power control of the main battery, a standard 1200mah lithium-polymer-ion battery, which will supply power to both the raspberry-pi zero board and the led driver. The PiSugar board has an on-board clock and timing feature, which allows it to intermittently supply power to the raspberry-pi board and battery. The timing feature allows the power to be completely turned off when the system is not in use, reducing the idling power of the electronics and increasing the deployment time. The power system is deliberately kept simple and modular. Both raspberry-pi board and battery simply require a constant DC 5 volt input, supplied by a live and ground wire. This allows the battery to be exchanged by any battery pack which can provide a minimum of 5 volts, which enables reconfiguration for longer deployments.

e. Housing and Mounting Design

In accordance with design criteria number four, the camera system should be able to operate up to 500m in depth. To ensure operations up to these depths, a resin-printed housing was designed to house the camera, lights and all other electronic components. A resin printed design was chosen due to the high strength of epoxy-filled resin prints, as well as the ease of manufacture of resin printed parts. The epoxy filled design is based on the DeepPi[5] design, which used similar resin printed parts. Figure 6 shows the internals of a resin printed housing, which houses the camera. An acrylic disk acts as the viewing window and front of the housing. The disk is kept in place by a metal retaining ring, and supported by a rubber o-ring, which creates the pressure seal. Directly underneath the acrylic disk is an air cavity, which allows for the camera optics to function. Below the lens, the remaining cavity which houses the camera electronics is filled with an epoxy that hardens to encase the electronics permanently. The added epoxy layer serves to distribute the pressure forces on the acrylic plate to the walls of the resin housing and theoretically allow for greater pressure resistance than air filled resin housings would alone. Figure 7 shows an exploded view of the camera housing.

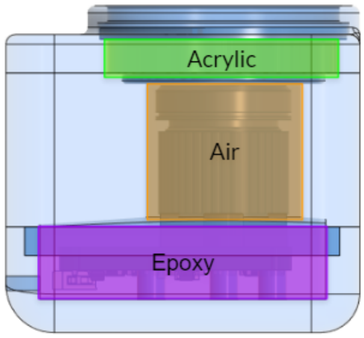

Fig. 6: A side view of the internals of the camera housing. The colored sections show the internal material contained in that section.

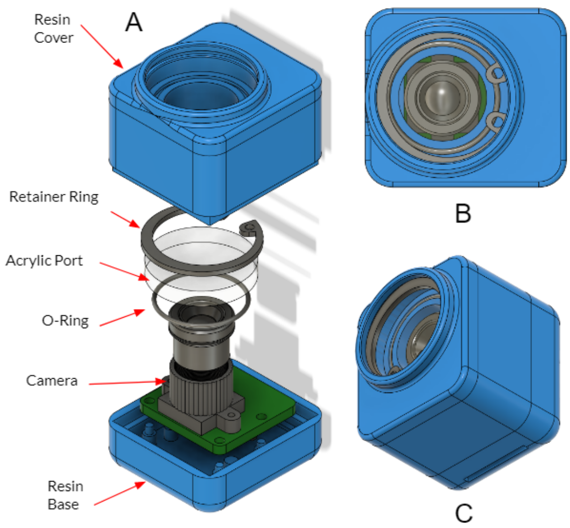

Fig. 7: An exploded view of the camera housing. The light housing has a similar pressure seal and port design, whereas the controller and battery hosuing

To increase the modularity and the reconfigurability the DeepStereo system, the outside of the pressure housings are designed with screw-mounts that allow the housings to swivel around one axis. Furthermore, the housings are attached to the outside of the float by a simple 3D-printed mounting system that uses plastic ties to clamp the housings and mounts to the external cylindrical surface of the float. Such an attachment system allows for movement of the mounts along the circumference of the exterior of the float as well as vertical movement.

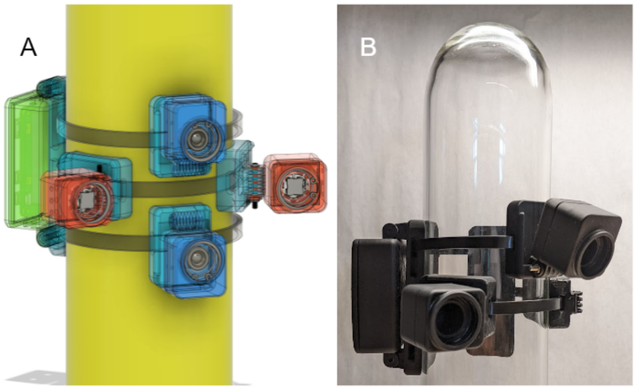

Fig. 8: A side by side comparison of the 3D model for the DeepStereo housings mounted on the outside of the MINION cylinder.

f. Software Overview

Figure 14 (Appendix) displays a simplistic overview of the system connectivity. The system is mirrored such that the right and left halves are physically identical. The software, however, is set up in such a way that there is a leader and a follower raspberry pi controller. The leader and follower exchange signals through a GPIO (General Purpose Input-Output) interface in order to synchronize the capture of images. This synchronization is important to creating stereo images of the particles in which velocities can be extracted. Only synchronization to the tenth of a second is required, as the particles move at a slow enough speed that they will appear nearly stationary in images taken less than a tenth of a second apart. The software of the system is described by the following sequence of behaviors:

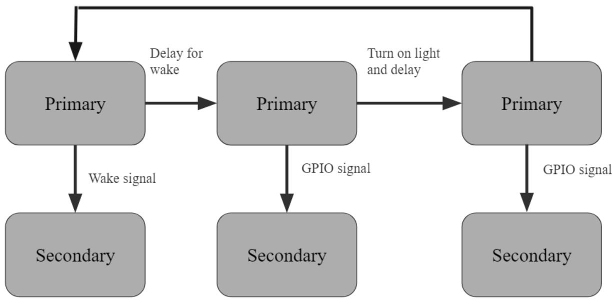

Fig. 9: A simple schematic of the communication between the primary and secondary controller boards.

- The primary raspberry-pi controller will send a signal over the GPIO cable to wake the secondary raspberry-pi. The primary will be cycled on using the PiSugar's built in timer module.
- After a delay for the secondary to initialize, a GPIO signal will be sent to tell the secondary to begin recording video at a frame rate of ten frames per second.
- After a one to two second delay to ensure both cameras are recording, the lights will be turned on by the primary. This is how the cameras will be synchronized. In the final output video, the timestamps of the frames of the cameras may not be identical, due to each camera having a different warm-up and picture adjustment time. The light provides a synchronization point, where

the frame at which the light was turned on can be found in both output videos and used as a way to synchronize the output videos during post-processing.

- After five minutes of recording, the primary will send a GPIO signal to the secondary to stop recording, save the video data, and turn off. The primary will then sleep, until the PiSugar's timer wakes it after a ten minute time period. The process then repeats from the initial step, until the battery on the primary is drained.

In order to retrieve images from the DeepStereo system, a wireless communication between the receiver and the system can be established using the wireless SSH capabilities of the raspberry-pi boards. In the future, wireless triggering of the cameras and lights could also be incorporated to allow integration into existing float hardware.

III. System Construction

The following images show the system construction, based on the system design.

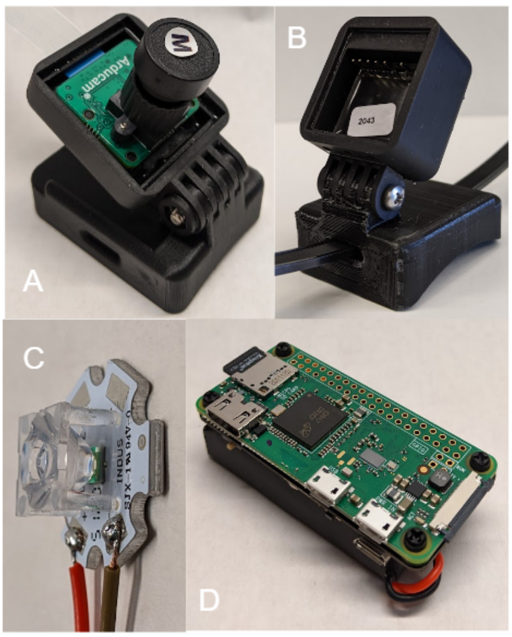

Fig. 10: Images of the partially constructed (A) camera inside the camera housing, (B) LED driver in the light housing, (C) assembled LED and LED lens and (D) raspberry-pi board and attached PiSugar.

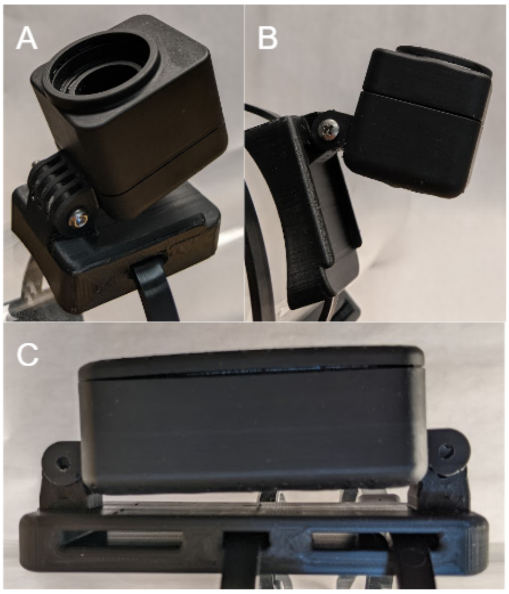

Fig. 11: Views of the (A) camera housing, (B) light housing and the (C) raspberry-pi housing.

IV. System Testing

V. Initial Deployment Results

VI. Conclusion

The DeepStereo system provides an inexpensive and modular system for underwater photography. While the current system has been optimized for specific stereo-particle measurements, the design of the system allows it to be easily modified for other types of measurements. The camera lenses, for example, can be removed and replaced in the current design. The raspberry-pi module is easily reprogrammable over a remote wireless SSH connection, so that the type of images, frame rates and other parameters can be changed. Future studies can be conducted to incorporate additional battery housings for increased deployment time, or separate light housings which independently trigger. As long as future designs utilize the same standardized mounting system, the camera and light housings should be replaceable. The simple and standardized connections between housings ensures a wide compatibility and ease of integration with many types of open-source hardware. The ability of resin printing to be used in the manufacture of housings further decreases the cost, and makes manufacturing simple. With the release of open-source designs for the DeepStereo project, it is the hope that many researchers will modify and improve the core design for their underwater photography research.

VII. Acknowledgment

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A. Appendices

a. Additional Figures

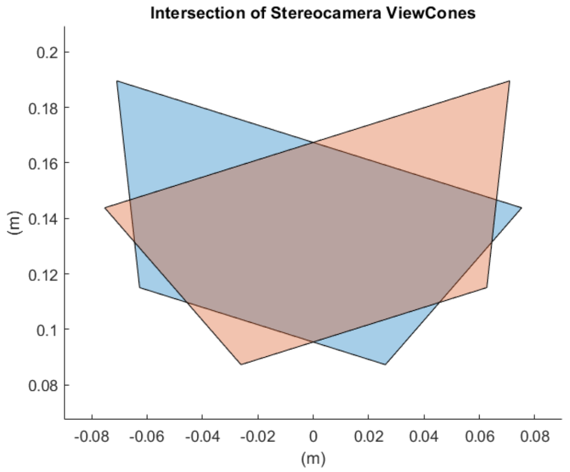

Fig. 12: A computed intersection of the camera view cones using the given camera parameters and depth of field. The y-axis show the distance from the camera, whereas the x-axis shows the horizontal distance from the center of the float platform.

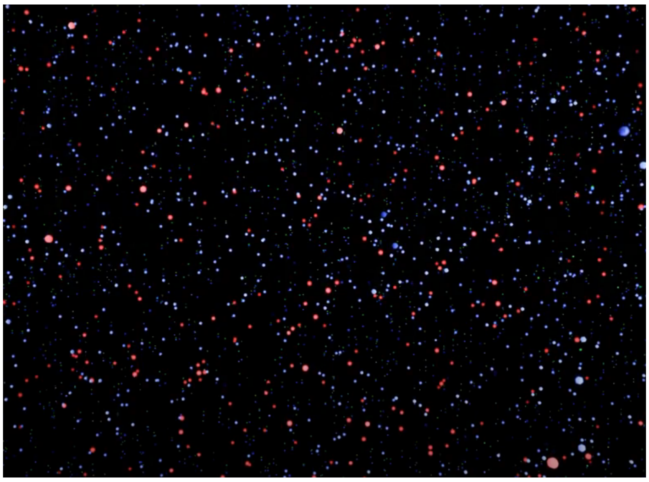

Fig. 13: A simulated particle field in using the given camera parameters and the blender rendering software. Particles are colored by size, red representing particles between 500 and 2000 microns, blue particles represent particles of size between 100 and 500 microns and green particles represent particles between 20 and 100 microns. Particles are rendered as spheres, and their numbers are determined by their estimated densities per cubic meter.

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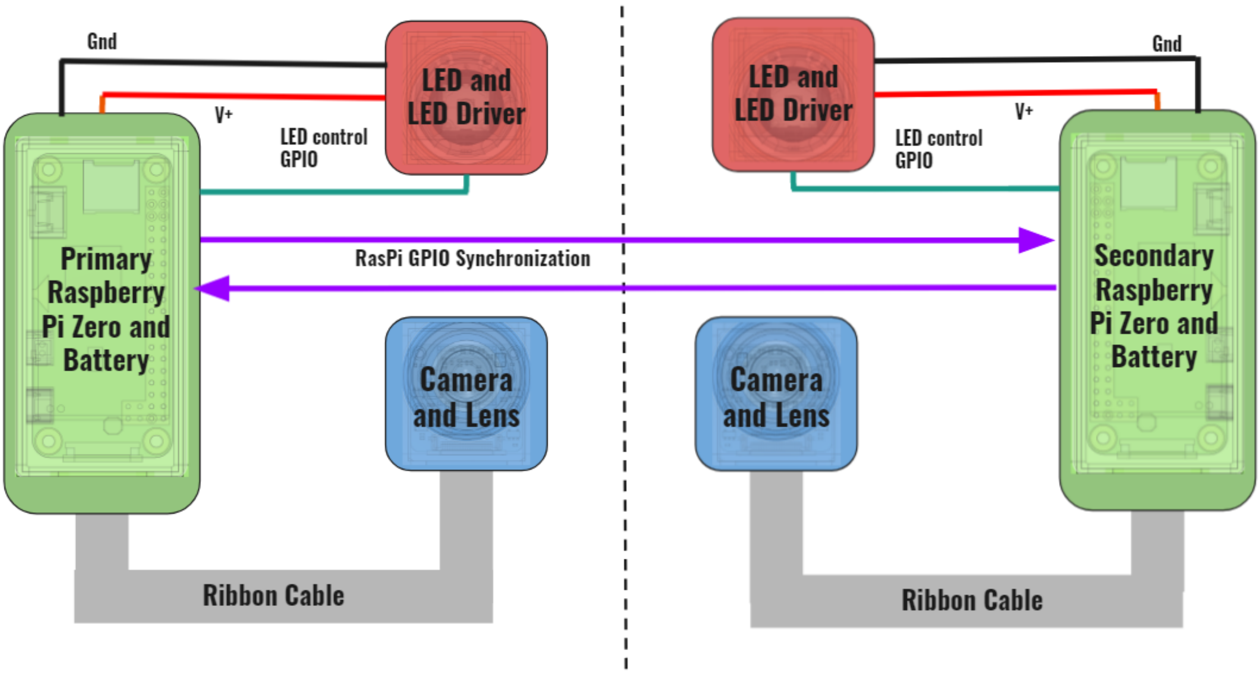

Fig. 14: A diagram of the component connections. The primary and secondary raspberry-pi boards work together to take stereo images, and are synchronized by a GPIO signal. The LED is controlled by a single signal cable and requires only a ground and voltage in wire to connect it to the controller, whereas the camera only requires a ribbon cable for power and information transmission.