Marine Particle Tracking Stereo Imaging System Build Instructions

September 2020

JunSu Jang, Allan Adams

MIT Future Ocean Lab

Contents

1 Introduction

We are interested in building a stereo imaging system to take images of particles in the shallow water at the scale of hundreds of micrometers. The purpose of this document is to share the steps that were taken to build a such system. A design work is thoroughly explained in Junsu's thesis. Assuming that we have already picked out a camera and a lens, we need to do the following things: (A) focus the lens of each imaging system; (B) make the camera waterproof; and (C) position and calibrate a stereo imaging system using a pair of imaging systems. We will explain above procedures. We assume the use of small imaging system (i.e., bare, or housed board-level cameras with M12 or CS lenses).

In each section, we share assembly instructions for hardware and relevant codes. We list the required materials in the last section (Section 5). For the parts that need to be purchased, their ID's are referred from the tables in Section 5. If a part is custom designed and laser-cut, we refer to them as "P{x}", where {x} is a reference number. The sources of deign files and codes will be shared throughout the relevant discussion.

Having the following experiences and skills would be helpful in building the system: experience using a laser cutter and its counterpart software tools (e.g., Adobe Illustrator); coding in MATLAB and rudimentary level of C++; working in Linux environment; using simple hand tools ranging from screw drivers to potting; and soldering wires. If one is to modify the system or the setups, one would have a good understanding of simple optics such as thin-lens models and how stereo cameras work.

In addition, the user should be working in a good environment to work with electronics and mechanical parts. The items that the author recommends the user to have are: soldering iron, solder, small ventilation filter for soldering, helping hands, IPA, a glue gun, screw set as well as standoff sets (both metric and imperial), and clamps.

2 Single Camera Assembly

The first step of building an imaging system for particles is to assemble the camera and the lens to the desired resolution. This involves adjusting the position of the camera as well as the focal length of the lens to ensure that a target is seen with the correct resolution. The lens also needs to be focused. This is particularly important when the depth of field is extremely narrow as it is in our case (2mm). Therefore, we have devised a setup to adjust and focus our imaging system. This setup has also been used to test various combinations of lenses and the camera to pick the high-performance imaging system. The parts are listed in Table 1 in Section 5. The setup is shown in Fig. 1 below.

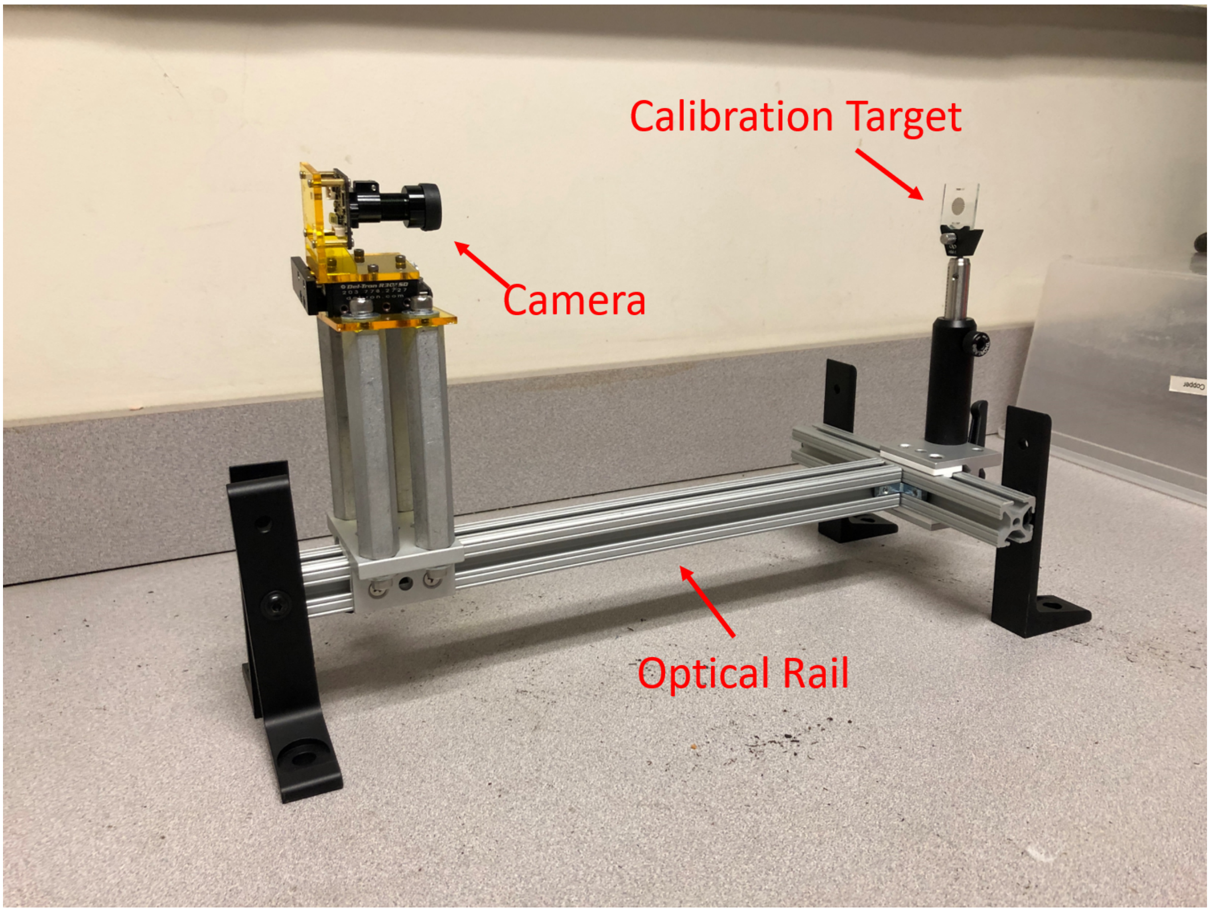


Figure 1: The setup for testing the camera performance and focusing the lens.

2.1 Assembly Steps

The fully assembled rail is composed of three parts: a camera mount, a target mount and a rail (see Fig. 1). We assemble each of these independent parts and then join them together.

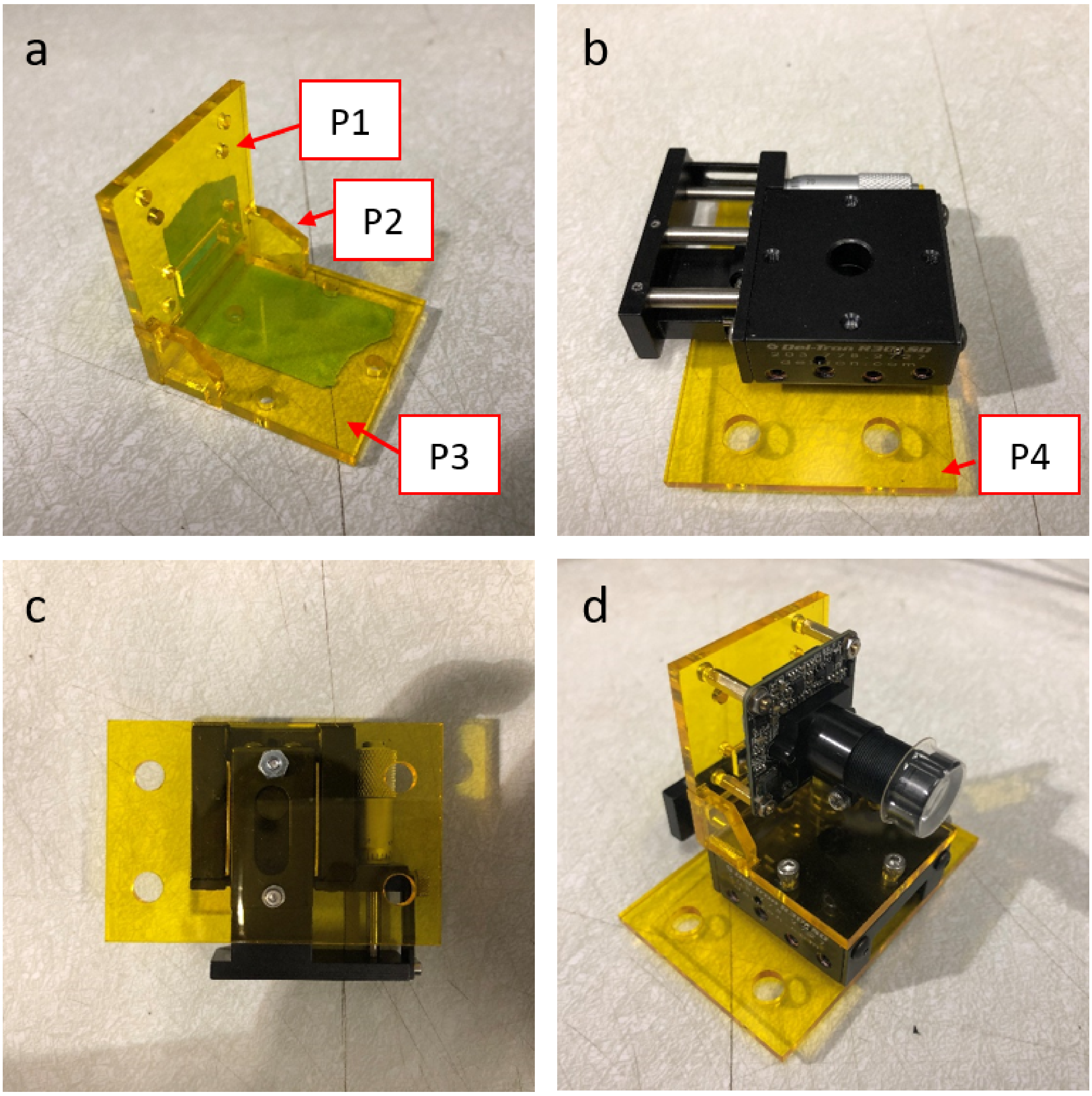


Figure 2: Close up images of the camera holder and X-axis stage. (a) P1, P2 and P3 welded together (b) top view of the stage mounted on P4 (c) Bottom view of the mounted stage on P4. (d) Assembled camera holder along with the camera.

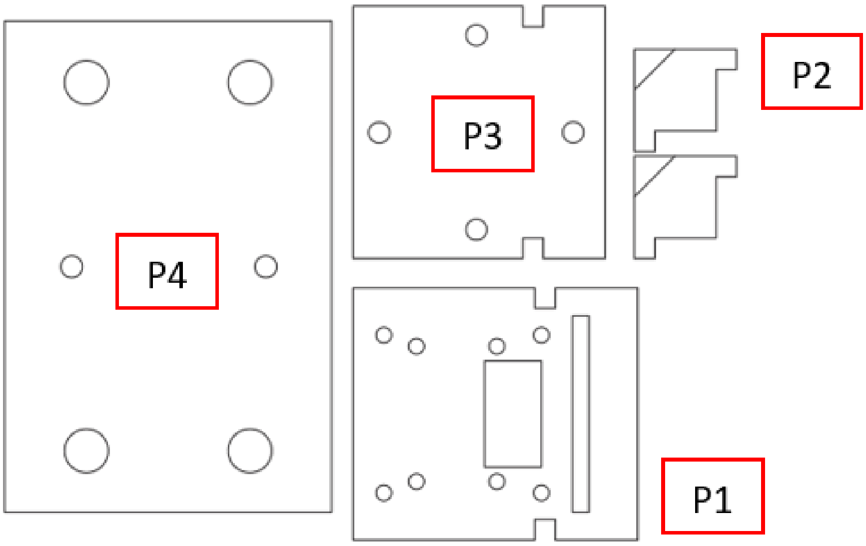


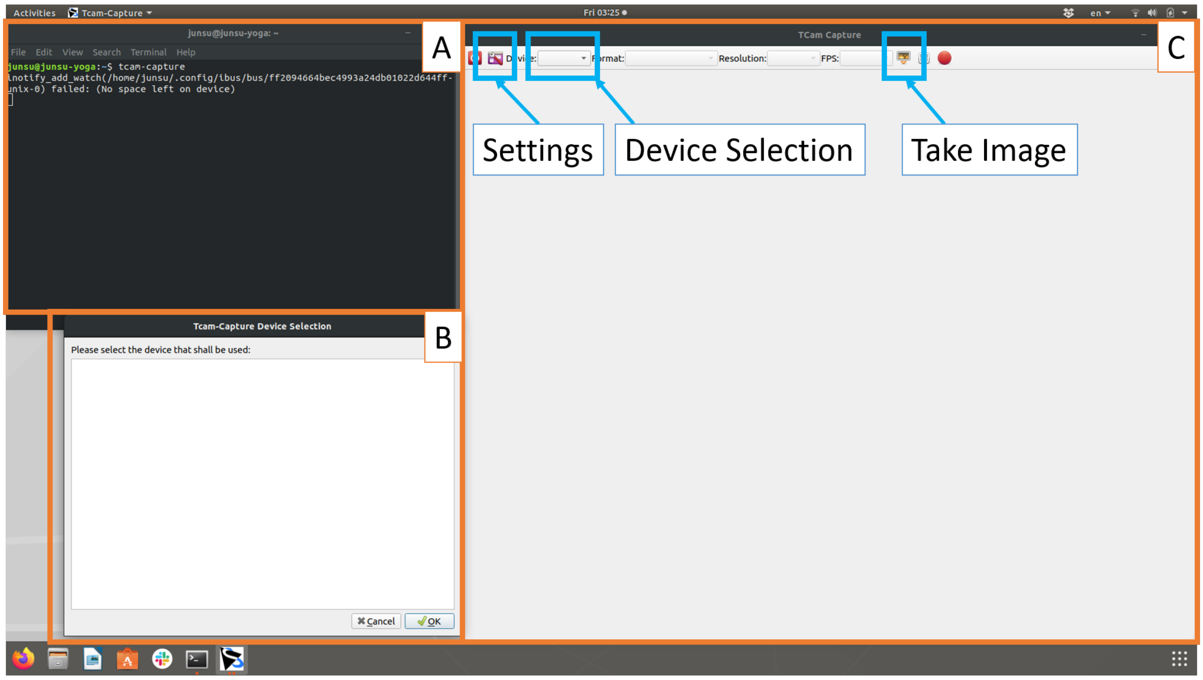
Figure 3: Laser-cut parts for building the camera mount in Fig. 2.

1. **Camera Mount** (see Fig. 2)
   (a) Laser cut the camera holder parts (P1, P2 and P3) and the micrometer stage platform (P4) out of an 1/8" acrylic plate (A16) using the illustrator file from the Github repository. They are also labelled in Fig. 3.
   (b) Weld P1, P2 and P3 together as shown in Fig. 2(a) using the acrylic adhesive (A15). We managed to hold them together with a tape. Please wear a glove!
   (c) Mount the microstage (A14) onto P4 with 2x4-40 screws that go through the bottom. One screw is inserted from the bottom and another from the top, and they are held by nuts.
   (d) Screw on the camera holder onto A14 with 4x4-40 screws.
   (e) Attach 4 standoffs (4xA9) with P4 using 1/4"-20 screws by screwing through the holes on each corners of P4.
   (f) Similarly, attach the camera mount on the horizontal mount flanged bearing (A6) by screwing with 4x1/4"-20 screws onto the bottom of the same A9's. The holes on A6 should be aligned with the position of A9's.
2. Assemble the handle (A8) with A6
3. **Target Mount**
   (a) Assemble the optical post holder (A10) and the post (A11).
   (b) Screw the bottom of target holder (A12) onto the tip of A11.
   (c) Mount A10 onto the side mount flanged bearing (A7) through one of the available holes using a M6 screw.
   (d) Assemble A8 with A7.
4. **Rail Body Frame**: Join the two T-slotted frames, A1 and A2 using two corner brackets (A5). The long one (A1) should join A2 in the middle and form a T-shape
5. **Final Assembly**
   (a) Slide A6 onto A1, and slide A7 onto A2.
   (b) Slide a foot (A3) whose second hole is loosely screwed with A4 onto each corner of the T-shape body frame as shown in Fig. 1.
   (c) Mount the camera system onto P1 using eight M2 screws and four M2 female standoffs.

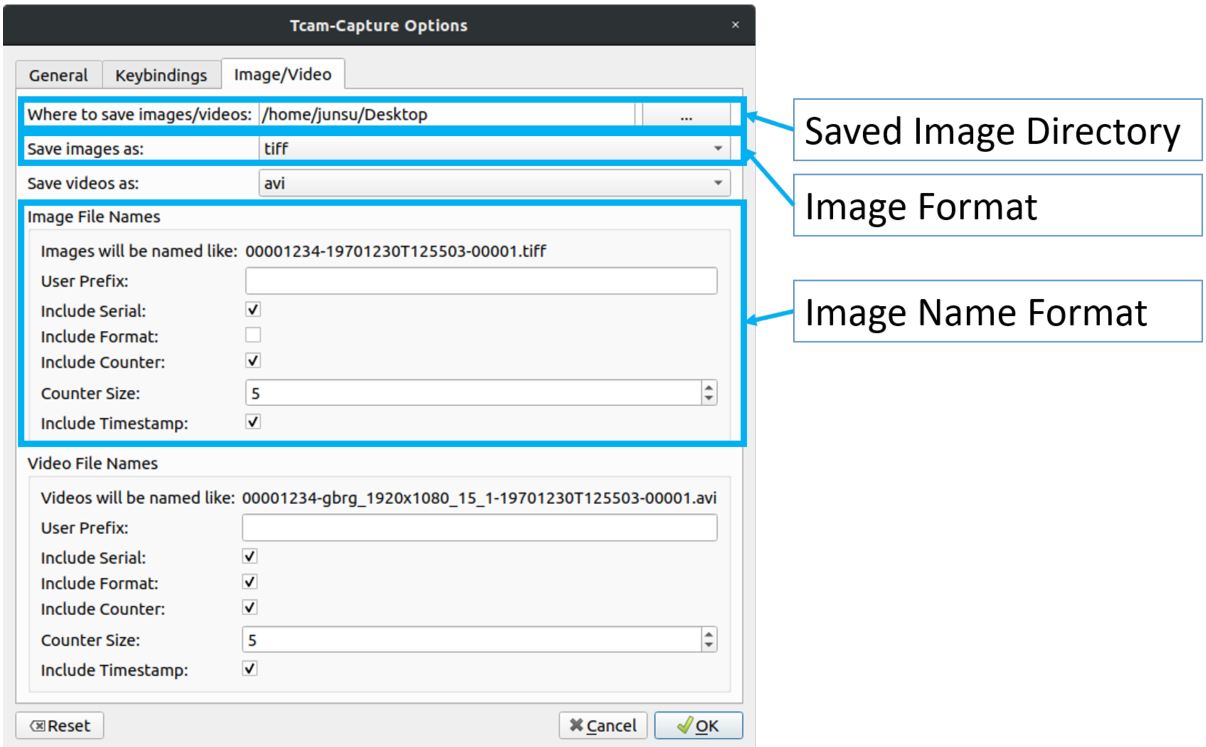
2.2 Focusing the Lens

2.2.1 Software

This section describes how to interact with the camera via software provided by the camera manufacturer. For both software, Ubuntu16.04+ is recommended (the author uses 18.04). Please install tiscamera library, OpenCV, and a custom image contrast evaluation tool. Provided by the camera manufacturor, the tiscamera library provides code to manipulate the camera and a GUI that lets users interact with the camera. A tutorial for the tiscamera library is also available here.



(a) A screenshot with labels with the panes that get opened when you run “tcam-capture” on the terminal. No camera was connected in this incident, so there is no option for choosing the camera on pane B, but it will be obvious. Similarly, on pane C, the currently viewed image will be displayed on the right and the configuration options on the left.



(b) The window that is opened when you click the settings button. You can change the directory to which the images are saved as well as the image format in this window.

Figure 4: GUI’s provided by the camera manufacturer and relevant panes to interact with the cameras.

1. GUI (Fig. 4)

   (a) On terminal, run “tcam-capture” as shown in pane A in Fig. 4a.

   (b) Pane B in Fig. 4a will show up. Select the camera that is connected, and a live frame will be displayed on pane C. You can change the image directory by clicking settings, which pops up a new window with "Image/Video" tab shown in Fig. 4b.

   (c) Uncheck the box "auto-gain" and "auto-exposure" on the left side of pane C in Fig. 4a so that the computation of contrast is valid throughout the process.

2. Contrast Tool

   (a) On another terminal, clone the a contrast measurement tool from this Github repository.

   (b) Follow the instruction in README.md to build and compile the code.

   (c) Run the code by providing the appropriate input arguments (i.e., serial number, frame dimension and region of interest). A scalar value of contrast in the region of interest will be streamed on the terminal that runs the code.

2.2.2 Initial Setup

If the target is transparent, we recommend placing a white backdrop behind the test target to maximize contrast. In our case, a box whose surface was covered in white paper was placed behind the target. We also placed a desk lamp above the target to saturate the background with light. The setup without lighting and backdrop would look like the one shown in Fig. 1.

2.2.3 Procedure

The goal is to maximize the contrast at the desired working distance (i.e., camera resolution). One can compute the expected working distance between the lens aperture and the target by using a ratio of similar triangle.

1. Connect the camera to the computer and run two software as instructed above.

2. Adjust the camera location to the expected distance by sliding the mount on the rail and locking it with its handle.

3. Due to imperfection of the lens, the image is unlikely to be focused. Screw the lens appropriately so that the contrast measured by Software B is at its maximum.

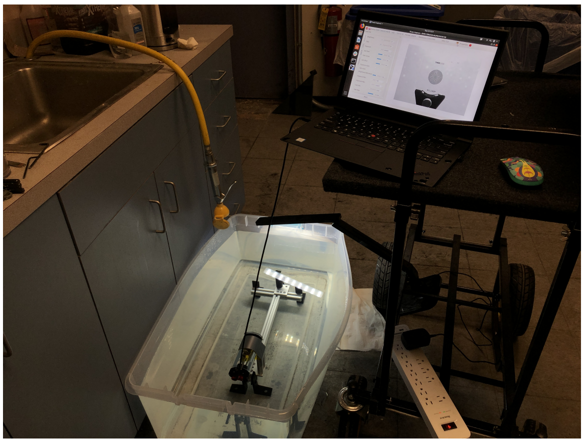
4. For our case, the diameter of the test target (A13) is 1cm. The Software B displays a 500×500px box. It should be filled with the target circle if the resolution of the imaging system is indeed 20µm/px. If the circle does not fit the box, adjust the distance by using the microstage until it does. The target will becomes less focused, so re-focus it following the step B.

5. Once the lens is focused at a desired resolution, lock the lens onto the camera by screwing the side locking screw (see Fig. 2d) tightly. The final focal length will be computed along with the stereo calibration.

3 Underwater Camera Mount

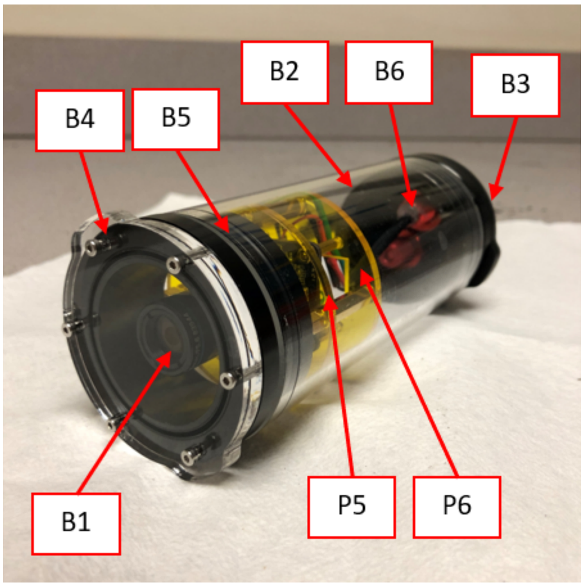
To test and calibrate the cameras underwater, we need to house the camera in a waterproof housing (see Fig. 6a). This can be accomplished easily by using off-the-shelf housing from BlueRotobics and some laser-cut parts. To mount the camera onto a rail and to adjust the angle of the camera for a stereo setup, we devised some more mechanical structure as demonstrated in Fig. 6b. The parts are listed in Table 2 in Section 5

(a) A setup where we used a spotlight and a white backdrop (cutting board in this particular setup)

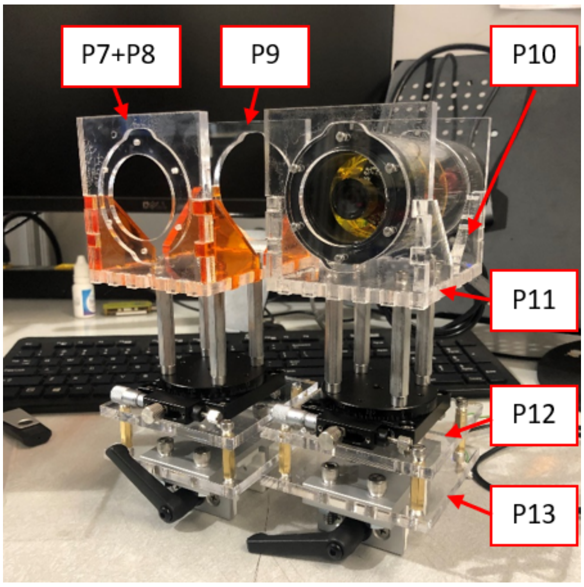


(b) A setup where we used a broad light source, which reduced the overall contrast of the image

Figure 5: Demonstration of testing the cameras underwater from the previous setup. For testing the performance of the lens, we found out that light scattering in the water affects the result significantly. The setup on the right did not yield a great result. The GUI mentioned in previous section is also visible on the computer screen.

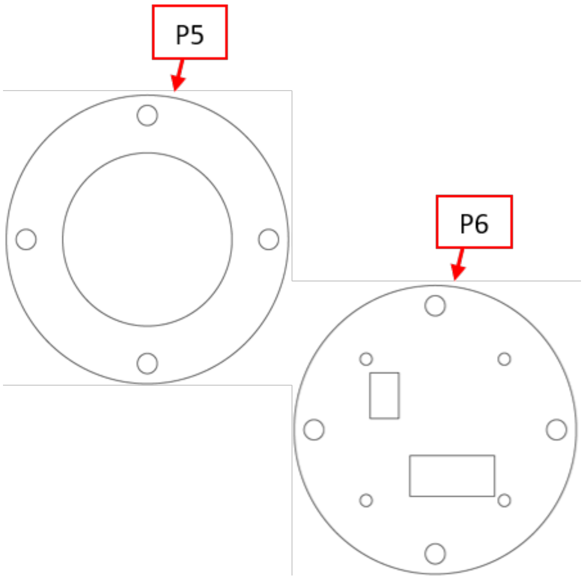


(a) A close up image of the camera housed inside an acrylic tube

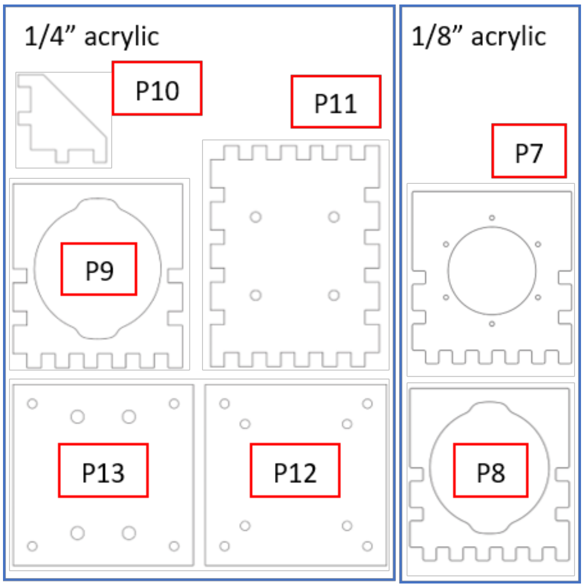


(b) The underwater camera mounts with labelled individual laser-cut parts

Figure 6: A close-up image of the housed camera (left) and the underwater camera mount (right)



(a) Chassis for mounting the camera in the underwater housing in Fig. 6a.



(b) Parts for underwater camera mount with rotational platform shown in Fig. 6b.

Figure 7: Laser cut parts with labels for reference. They are are not to scale.

3.1 Assembly Steps

1. Pot penetrators: to connect to the camera, we need to put a wire through the penetrator and make it watertight. Please wear gloves while potting.
   (a) If needed, replace a USB cable port with a connector that mates with the camera's port. This may involve splicing the cable, crimping connectors, and soldering wires together.
   (b) Mark the point on the cable such that the length beyond the penetrator (B6) once inserted is 1.5 times the length of the housing tube.
   (c) If needed, sand the part of the cable that will be potted and clean it with IPA.
   (d) Insert the wire into the penetrator to the intended length.
   (e) Seal off the bottom of the penetrator using a hot glue. Wait until the glue is hardened.
   (f) Assemble the epoxy cartridge (B7) with the nozzle (B8) and the dispensing gun (B9).
   (g) Dispense the epoxy until little air bubbles are visible.
   (h) Fill the penetrator from the top
   (i) Affix the penetrator facing up using a clamp. Wait for a day.
   (j) Repeat st ep 1 for as many as the penetrators and the wires need.
2. Housing Assembly[1]
   (a) Download and laser cut the chassis from this repository to hold the camera in place inside the housing.
   (b) Mount P5 onto the flange. There are four M3 threaded holes accessible in the inner surface of the o-ring flange (B5). We use four 5mm long male-female M3 standoffs to mount P5 onto the flange.
   (c) Mount the camera (B1) onto P6 using four M2 female standoffs and eight M2 screws.
   (d) Mount P6 with the camera onto P5. We use four 20mm male-female M3 standoffs to mount P6 onto P5 by screwing their male ends to the female end of the 5mm long standoffs[2].

[1] At the timing of the writing, the version of housings and related components from BlueRobotics have retired. They are currently selling an improved version of the housing that should have a similar if not the same mechanical parameters that are relevant to our assembly.

[2] We designed the chassis as well as the camera holding platforms such that the axis of rotation of the staging is aligned with the center of the imaging sensor.

(e) Make sure that the camera is oriented correctly (e.g., the image is not vertically flipped or rotated when mounted for testing) depending on the way in which the camera will be mounted.
(f) Screw on the potted penetrators onto the flange cap (B3).
(g) Mount B3 with penetrators onto one end of the tube (B2).
(h) Connect the cables with the cameras
(i) Mount the flange (B5) with the camera onto another end of B2.
(j) If you only need to assemble the housing, mount the acrylic endcap (B4) onto B5. If you intend to mount the housing onto a rotating platform, follow step 3 below.

3. Rotational Platform on Rail Assembly

   (a) Download and laser cut the platform parts from this repository. There are parts for 1/8" thick acrylic and 1/4" thick acrylic plates. Parts for 1/4" thick plates may require multiple rounds of cutting or very slow laser motion speed to fully cut through.
   (b) Welding the housing holder requires caution and patience.
      i. Weld P10s onto P11 first. Wait at least one hour. It is recommended to simply fit P10 onto P11 and let it stand on top.
      ii. Weld P9 onto P10 and P11. Wait until fully welded
      iii. Let the welded piece stand on P9. Stack P7 onto P8 and weld them onto P10 and P11 on the other side of P9. If there is a clamp, simply clamp between P7 and P9.
      iv. Weld P7 and P8 together.
   (c) Using four M4 screws and nuts, mount B10 onto P12.
   (d) Screw four B9 onto four holes on B10.
   (e) Mount the housing holder onto B9 by screwing four M4 screws through the holes on P11.
   (f) Assemble B7 and B8.
   (g) Mount P13 onto B7 using four 1/4"-20 screws and nuts.
   (h) Mount P12 onto P13 with M4 screws and female standoffs[3]. The length of these standoffs will depend on the vertical height of the camera. We used 20mm long standoffs.

[3]The rotational platform's handle was blocking one hole on P12. We recommend threading the holes and using male-female standoffs.

4 Stereo Imaging Pair

We are now ready to assemble the rig for the stereo setup. We need to build two housed cameras and assemble another frame. Depending on the user's setup, the height may be shorter or taller than what we have built. For us, one of the goals to build this frame was to mount a XYZ-axis stage onto the 2" wide rail to take images of manually moved potted particles. This is described in the thesis. However, one can easily replace the 2" wide rail with a 1" wide one. We also encountered some problems with brackets to join the rails together, so we have listed out better alternatives to hold the frames more steadily. The parts are listed in Table 3 in Section 5.

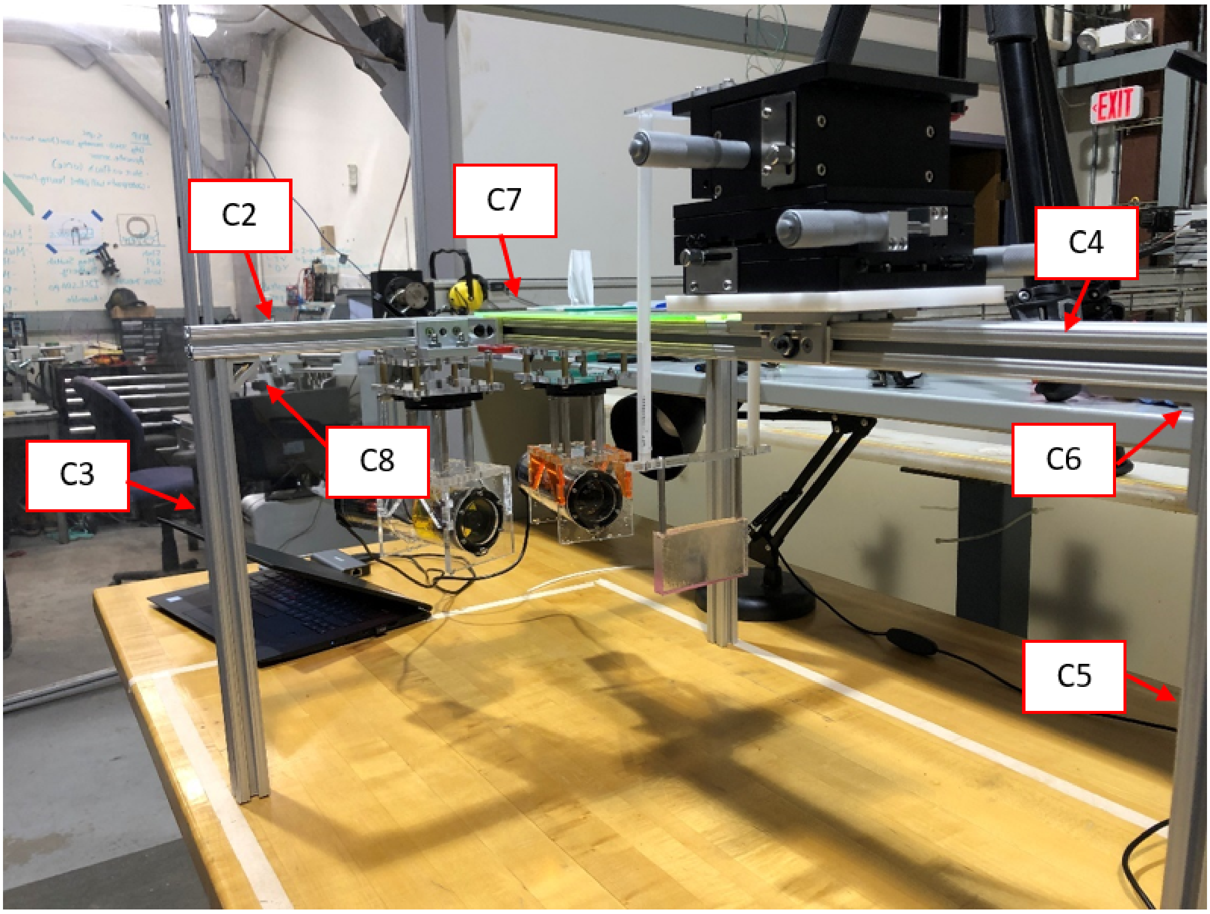


Figure 8: A front view of the stereo camera rig. In this setup, we were trying to take image of potted microspheres. The parts that were used to build the frames are labelled here.

An important note about the setup is the location of the rotation axis of the camera. The lens aperture varies camera by camera due to manufacturing imperfection. Hence, we cannot expect the location of the lens aperture. However, we know the precise location of the imaging sensor, and thus, the axis of rotation is aligned with the center of the imaging sensor. This complicates the calibration procedure a little bit. The MATLAB calibration outputs an extrinsic value in a 3D coordinate space whose origin is the aperture of the left lens. Hence, upon calibration, we need to readjust the baseline and the angle based on similar triangle to actually build and test the intended stereo design.

4.1 Assembly Steps

1. Build two sets of mountable underwater cameras (C1) following sections A and B.
2. Frame Assembly
   (a) Assemble C2 and C4 to form a T-shape by applying two C7's at the top with provided fasteners.

(b) Assemble C4 and C5 to be right angle (C5 is the leg) using C6 with the provided fasteners. C4 should be on top of the surface of C5.
(c) Slide in C1 on each side of C2. The handles should be on the opposite side of C4.
(d) Assemble C3 and C2 to be right angle (C3's are the legs) using C8 with the provided fasteners. C2 should be on top of C3.

4.2 Calibration

Calibration can take place either in the air or in the water. If in the water, fill up a tank/basket with water to a height at which both the camera and the calibration target are fully submerged. This will depend on the length of B9.

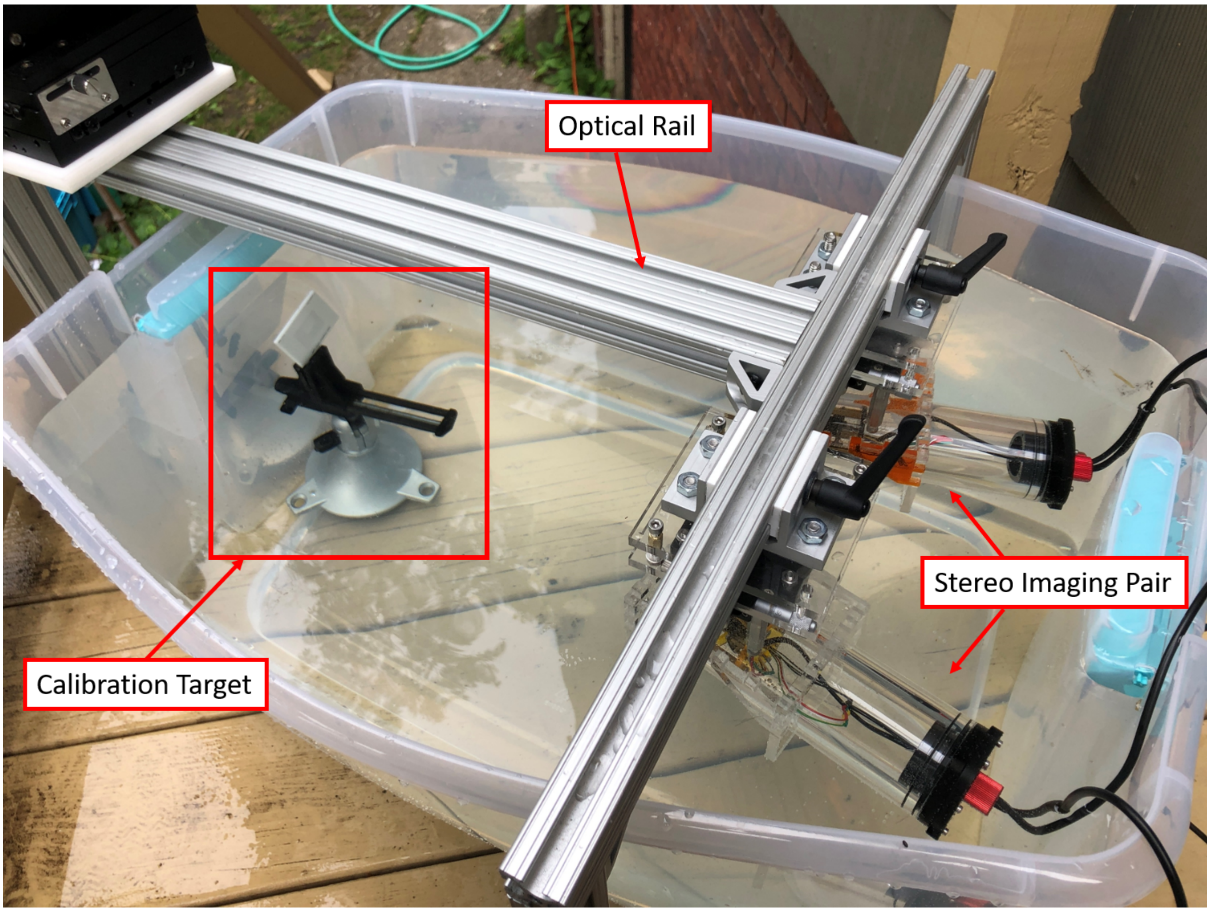


Figure 9: An underwater stereo calibration setup.

1. Place the calibration target at a distance that is mostly focused by both cameras. All 26x26 circular grids should appear on both frames.
2. Manually take a photo from each camera using the GUI described in "Software" in section B.
3. Alter the orientation of the calibration target. Note that the rotational alteration is more effective than the translation in terms of calibration.
4. In the Minions github repository, go to code/optical-analysis/stereo-calibration and follow the instructions provided in README.md. Take the images and run C++ code, then MATLAB, code to get the final extrinsic calibration result.
5. The resultant can be saved as a file file with ".mat" extension, and more explanations for using the resultant parameter is more explained here. An example of running the "showExtrinsics" and "showReprojectionErrors" from the example images are shown in Fig. 10 and 11, respectively

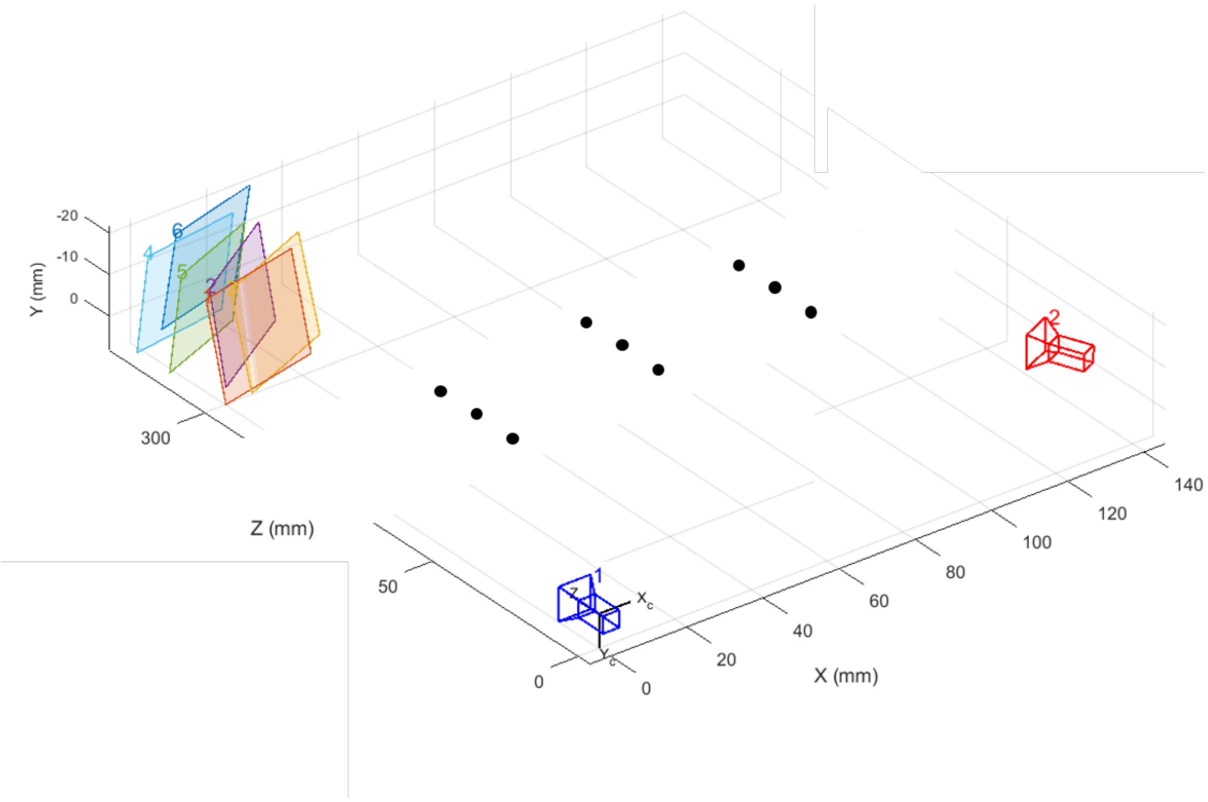


Figure 10: Extrinsics parameter visualized in a 3D coordinate space using the function “showExtrinsics” in MATLAB. The orientation of the targets are visualized in the left corner.

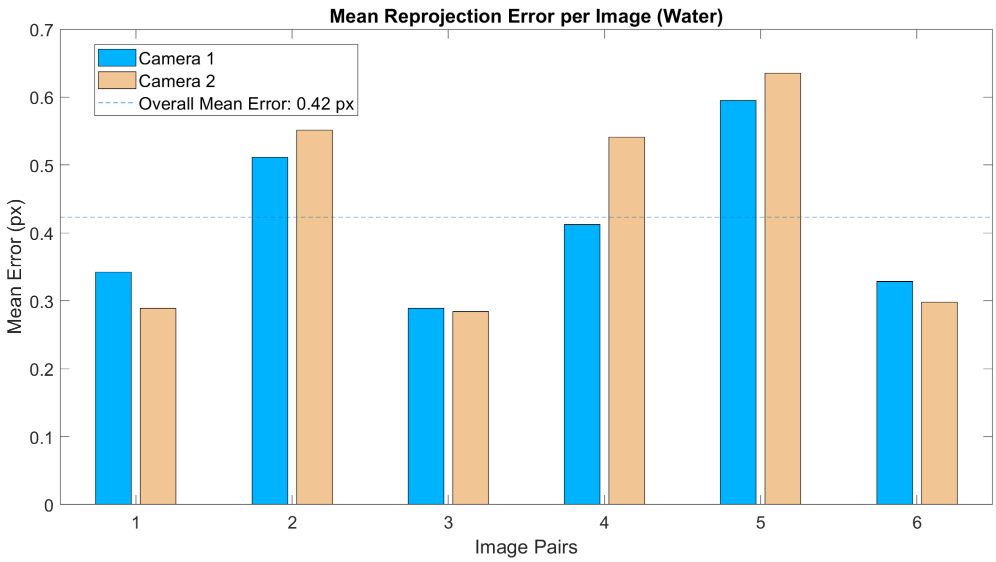


Figure 11: The reprojection error of the target points upon calibration based on the setup in Fig. 9. This can be reproduced by running “showReproejctionErrors” in MATALB. The blue graph is the left camera and the orange the right camera.

5 Materials

5.1 Single Camera

ID	Description	Part #	Vendor	Qty	Unit Price ($)	Total Price ($)
A1	T-Slotted Framing, Single Four Slot Rail, 1”x 1” (4ft)	47065T101	McMaster-Carr	1	12.31	12.31
A2	T-Slotted Framing, Single Four Slot Rail, 1”x 1” (2ft)	47065T101	McMaster-Carr	1	7.79	7.79
A3	Fixed Height Mounting Foot	47065T711	McMaster-Carr	4	11.85	47.4
A4	End-Feed Nut with Flanged-Button Head	47065T142	McMaster-Carr	1	2.30	2.3
A5	Silver Corner Bracket, 2” Long	47065T239	McMaster-Carr	2	5.25	10.5
A6	Horizontal Mount Flanged Bearing	47065T959	McMaster-Carr	1	46.16	46.16
A7	Side Mount Flanged Bearing	47065T953	McMaster-Carr	1	43.51	43.51
A8	Hand Brake	60585K31	McMaster-Carr	2	10.77	21.54
A9	Female Threaded Hex Standoff, 4” Long, 1/4”-20 Thread	91780A365	McMaster-Carr	4	5.79	23.16
A10	Post Holder 75mm long	PH75/M	Thorlabs	1	8.52	8.52
A11	Graduated Optical Post	TR75E/M	Thorlabs	1	15.48	15.48
A12	Optical Filter Mount, Edge Grip, 1.0 in. Optics, 8-32	HM-1	Newport	1	72	72
A13	Positive Sector Star Test Target, 36 bars	R1L1S2P	Thorlabs	1	165.56	165.56
A14[4]	Microstage	R301SD-X	Deltron	1	310.00	310
A15	Acrylic Adhesive	CECOMINO-D039446	Weld-On	1	11.18	11.18
A16	Acrylic plate (1/8” thickness)	8560K239	McMaster-Carr	1	9.15	9.15
A17	USB 2.0 cable – Mini B	Example	Amazon	1	5.70	5.70
A18	USB 2.0 monochrome board camera	DMM 72BUC02-ML	The Imaging Source	1	119.00	119.00
A19[5]	M12 lens adapter	TLH 10-2	The Imaging Source	1	13.40	13.40
A20	25mm FL f/8, Blue Series M12 Imaging Lens	83-955	Edmund Optics	1	95.00	95.00

Table 1: Parts for building an optical rail for a camera resolution test and focusing the lens

.

[4]This could be replaced with a cheaper alternative from Optical Focus such as this one

[5]There is no item page for this product. Instead, it requires quotes from the manufacturer.

5.2 Underwater Camera Mount

ID	Description	Part #	Vendor	Qty	Unit Price ($)	Total Price ($)
B1	Assembled Camera from Section A.	-	-	1	-	
B2	Acrylic tube housing (2")	WTE2-P-LOCKING-TUBE-150-R1-RP	McMaster-Carr	2	26.00	
B3	Flange Cap – Aluminum 2 Holes (2")	WTE2-M-LOCKING-FLANGE-CAP-2-HOLE-R1-RP	McMaster-Carr	2	29.00	
B4	End Cap – Acrylic (2")	WTE2-P-END-CAP-R2-RP	McMaster-Carr	2	12.00	
B5	O-Ring Flange (2")	WTE2-M-LOCKING-FLANGE-SEAL-R1-RP	McMaster-Carr	2	27.00	
B6	M10 Cable Penetrator for 4-5mm Cable	PENETRATOR-M-BOLT-5MM-10-25-R2-RP	McMaster-Carr	4	4.00	
B7	Toughened Epoxy, Loctite® E-90FL, 1.69 oz.	6430A18	McMaster-Carr	1	16.76	
B8	5.9" Long Taper Tip Nozzle	74695A12	McMaster-Carr	4	1.30	
B9	Dispensing Gun for Two-Part Cartridge	74695A71	McMaster-Carr	1	23.76	
B7	Horizontal Mount Flanged Bearing	47065T959	McMaster-Carr	2	46.16	
B8	Hand Brake	60585K31	McMaster-Carr	2	10.77	
B9	Male-Female Threaded Hex Standoff (M4, 51mm long)	98952A450	McMaster-Carr	8	3.34	
B10	Manual Rotation Stage	MAR-60R	Optics Focus	2	94.00	
B11	24"x24" 1/8" acrylic plate	8560K259	McMaster-Carr	1	24.61	
B12	24"x24" 1/4" acrylic plate	8560K357	McMaster-Carr	1	54.68	
B13	Acrylic Adhesive	CECOMINO-D039446	Weld-On	1	11.18	
B14	USB Cables (1m long)	Example	Amazon	4	5.70	22.80

Table 2: Parts for building the underwater camera mount

5.3 Stereo Setup

ID	Description	Part #	Vendor	Qty	Unit Price ($)	Total Price ($)
C1	Camera Mount from Section B	-	-	2	-	
C2	T-Slotted Framing, Single Four Slot Rail, 1"x 1" (4ft)	47065T101	McMaster-Carr	1	12.31	
C3	T-Slotted Framing, Single Four Slot Rail, 1"x 1" (3ft)	47065T101	McMaster-Carr	2	10.57	
C4	T-Slotted Framing, Double Six Slot Rail, 2"x1" (6ft)	47065T107	McMaster-Carr	1	30.39	
C5	T-Slotted Framing, Double Six Slot Rail, 2"x1" (3ft)	47065T107	McMaster-Carr	1	16.53	
C6	T-Slotted Framing, Corner Bracket, Double/Quad Rail	47065T253	McMaster-Carr	1	7.91	
C7	Silver Flush 90 Degree Angle Bracket	3136N157	McMaster-Carr	2	11.22	
C8	Silver Gusset Bracket, 2" Long	47065T736	McMaster-Carr	2	9.99	
C9	Dot Array, .25mm Dots on 1.0mm Centers, White Ivory	FA145	II-VI Aerospace&Defense	1	308.70	
C10	Helping hands with rotational degree of freedom	Example	-	-	-	

Table 3: Parts for building the stereo rig and calibration