Supplemental 1, System Engineering Detail.

1. SQUID-5 Towed Surface Vehicle (Figure 1, Table 1)

A fundamental design requirement of the SQUID-5 towed surface vehicle was a horizontal separation of approximately 0.8 m between cameras at opposite ends of the vehicle to allow SfM surface generation from discrete synchronized image collection sets. The camera separation was specified in order to create an optimal perspective change of approximately 15° (or less) between the cameras in a water depth of 3 meters (or greater), which is the expected average depth at the anticipated field sites. As built, the camera angles and separation can be slightly adjusted to accommodate other sites and a center (fifth) camera was included to ensure contemporaneous image sets with less than 15° perspective change to ensure adequate image acquisition from water as shallow as 1.5 meters.

A support vessel capable of operating in the typical nearshore shallow water environment is likely to be small, with limited deck space and minimal lifting or towing capabilities; therefore, the weight and overall size of SQUID-5 were kept to a minimum. SQUID-5 is approximately 1.5 m wide x 1.5 m long and 0.9 m tall, weighs roughly 52 kg, and is easily hand carried by two people. When towed through the water at up to 1.5 m/s, approximately 20 kg or less of drag force needs to be accommodated by the towing hardware. To ensure that the cameras remain essentially fixed relative to each other during acquisition, SQUID-5 support structure was constructed of lightweight but stiff aluminum strut channel, 2.54 cm (1 in) diameter Speed Rail, and 1.27 cm (½ in) thick by 61 cm (23 in) tall honeycomb aluminum laminate panels. The change in relative spacing between center and across track cameras due to flexure was measured to be 1 mm or less when a sideload (sheer force) of up to 15 kg (35 lbs.) was applied. For optimal SfM results camera platform stiffness is critical to minimize any geometry changes between cameras and the GNSS antenna.

A fiberglass waterproof container mounted on top of SQUID-5 protects the remote acquisition computer and provides the centrally located GNSS antenna mount point. A total buoyancy force of approximately 129 kg in seawater is provided by two inflatable pontoons (0.23 m x 1.50 m each) of urethane-coated canvas. The cameras are mounted to the lower portion of the Honeycomb panels such that their optical dome port windows are approximately 0.3 m below the water surface. This reduces the likelihood of bubbles caused by towing turbulence passing in front of the camera's viewports. Additionally, the low mounting points of the rugged and relatively heavy (~1.8 kg each) camera housings contribute to a low center of mass centered approximately 15-20 cm below the flotation pontoons providing a very stable arrangement which tows and tracks well even in 1-1.5 meters of wind driven surface chop. SQUID-5, being built primarily of off-the-shelf structural material and fasteners, is easily disassembled/re-assembled for shipping to remote field sites.

2. Cameras, lens selection, and underwater housings (Figure 2)

Camera and lens selection for SQUID-5 was based on a balance of logistics, fabrication effort, image quality, and optimal SfM requirements. The FLIR Systems Blackfly S GigE[1] machine vision camera model BFS-PGE-50S5C-C met our needs at a reasonable cost. It is a 5.0 MP

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[1] Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

(2448 x 2048) color camera based on the Sony IMX264 2/3” CMOS sensor with a 3.45-µm pixel size and uses a global shutter. It is small (an approximately 30 mm cube) and symmetric, simplifying the design and fabrication of its waterproof housing. It is controlled and powered remotely via a Power over Ethernet (PoE) connection and provides GPIO connections which can be user configured to precisely control image capture. Full color 24 bits per pixel image data can be acquired at up to seven frames per second.

A range of high-quality lenses optimized for the 5 MP sensor and minimal distortion are available for the camera. For this work we used the Fujinon HF6XA-5M, which is a 6 mm fixed focal length lens. Both focus and iris are set manually and fixed with locking knobs. The HF6XA-5M has a 74.7° horizontal field of view and 58.1° vertical. To achieve the correct image exposure, sensor gain (preferred) and length of exposure (when necessary) were adjusted prior to the start of a survey area and left fixed for the duration of that area.

Custom underwater camera housings were built for SQUID-5 in order to control optical parameters critical for the SfM process. Despite higher cost and housing complexity a 50 mm internal radius hemispherical dome port made of BK-7 optical coated glass with 5 mm thickness was selected for the pressure port window over a flat port of similar radius. The hemisphere dome is preferred to avoid variations in focal length, field of view and radial distortion all of which are known limitations of the flat port for underwater photogrammetry (Nocerino, et al., 2016). In addition, the hemispherical dome port allows for the option of a more wide-angle lens and produces a Depth of Field (DoF) increase of approximately 33% for the same aperture setting as the flat port (Menna et al., 2016). To accommodate different lenses and enable optimal placement of the lens entrance pupil at the dome radius, the camera/lens combination is mounted in an internal movable piston/cylinder which centers the lens radially and allows it to be adjusted fore and aft within the housing and then fixed in place. The camera lens entrance pupil was aligned empirically with the center of the dome radius and locked into place. Focus was set to approximately the “hyperfocal distance”, roughly 3 times the interior dome radius from the front of the dome. The aperture was fixed at approximately *f*/5.6 providing an underwater depth of field of approximately 1 m to ∞. The settings were verified by pool testing prior to the fieldwork and all five cameras were setup identically and not changed at any time during the field collection.

3. Data acquisition, system timing, and real-time quality control (Figure 3)

The accuracy and precision of time synchronization between cameras and the GNSS measured position recorded at the instant of image capture is critical for at least two reasons. First, our SfM process flow relies on the assumption that cameras have fixed physical offset vectors (lever arms) between cameras and the GNSS antenna in order to construct the surface model of the seabed. Since the entire vehicle operated in constant motion, timing errors would appear as relative motion between individual cameras, and/or the GNSS antenna location. Second, since the five cameras captured tightly synchronized image sets of the same seafloor area with different perspectives, the overall SfM results are improved by generating additional feature matches. Slowly moving objects such as eelgrass, fish, or soft corals within those five images appear fixed in time and space at that instant and can be used as if they were stationary objects within that set of five.

The time synchronization of image collection by SQUID-5 relies on the leading edge of a positive 10-volt pulse with an approximate rise time of 8 nanoseconds generated by a signal generator specifically designed for that purpose. The trigger generator output is connected directly to the event mark input of the Trimble R7 GNSS and to a general-purpose input/output (GPIO) pin on all five cameras. The event mark input to the GNSS creates a time-tag saved in the raw data stream which can be used in post processing to calculate a precise position at that instant. The GPIO pin on the cameras is configured to initiate image capture on the trigger, each camera is configured identically. The interval time between trigger pulses can be adjusted on the signal generator to account for any given water depth and survey speed.

The Blackfly S GigE FBFS-PGE-50S5C-C camera has a propagation delay of 18 µs and a variability of 13.4 µs for a maximum total of 31.4 µs when triggered by a GPIO pin. Trimble specifies that propagation delay of the time-tag and the event mark input for the Trimble R7 is typically less than 1 µs. Therefore, variability in the relative position caused by timing errors during image capture results primarily from camera propagation delay and is approximately 0.08 mm at maximum survey speed of 3 knots (~ 1.5 m/s). This position variability is small enough to be safely ignored when entering position error estimate parameters into the SfM software.

Sensor exposure time per image was fixed at 2000 µs (1/500 sec) for the duration of the fieldwork. This corresponds to a travel distance of 3 mm at our maximum survey speed and is also considerably less the best case PPK GNSS precision of 1 cm and therefore also be safely ignored when entering positional error estimates used by the SfM software.

To support a maximum image collection rate of 4 Hz simultaneously from each of the five cameras, the acquisition computer was configured to handle sustained data storage speeds of just over 300 MB/s. This is faster than the typical hard drive currently available so SQUID-5 uses four 2TB solid state hard drives configured in a RAID0 (striped) array to meet the requirement and provide a total storage capacity of just under 8 TB allowing for approximately 8 hours of continuous image collection at 4 Hz. Each GigE camera is connected to its own dedicated gigabit Ethernet port on the acquisition computer to accommodate the five-camera burst of data at each sampling instance and avoid timing inconsistencies or image loss caused by data collisions. The acquisition computer is a ruggedized industrial system with a small form factor and low power requirements. It is mounted directly on the tow vehicle in a waterproof electronics box thus reducing cable lengths to a minimum. It is remotely controlled using Microsoft's "Remote Desktop" over a local area network connection to a second "user interface" computer located on the support vessel. The acquisition computer's system time is maintained to within 30 ms using a GPS-based NTP server located on the support vessel and connected to the local network. The entire tow vehicle electronics consume less than 60 watts at 48 VDC.

Microsoft Visual Studio and the Software application Development Kit (SDK) provided by the camera manufacturer were used to develop custom camera control and image acquisition software for SQUID-5 in the C# programming language. Both control and acquisition programs were written as simple command line executables to maintain simplicity and minimize network and computer resource requirements. The control program cycles through each of the cameras to set the exposure time and sensor gain value entered by the user. The acquisition program is written as a client to an individual camera and simply waits for a network message from the host camera indicating an image has been acquired. At that instant the program reads the computer system time (kept accurate by the NTP server mentioned above), collects the image data from the camera, and then stores it locally to the disk array using a file name created from the system time, camera serial number, and a running total number of images. An instance of the acquisition program must be associated with each camera on SQUID-5. The total time between the initiation of image collection and the file being written to disk is less than 0.125 seconds. Since the acquisition computer uses a multi-tasking operating system, there is some variability in the time stamp used for the file name and the timestamp saved by the GNSS in the position data stream. Therefore, some post-collection reconciliation of the images to ensure the correct five image set is associated with the correct GNSS time stamped location must be done before SfM processing. This was usually just a matter of rounding the time to a lower precision than the three decimal places stored on the GNSS since the acquisition rate was every 0.5 seconds. In rare instances, discrepancies which required more attention were encountered. This is an area of opportunity for improving the data acquisition software.

Software was written in Python to view and monitor image quality during collection. Python was chosen because it offered a range of tools to rapidly analyze and display image files while maintaining low system-usage, crucial for allowing the acquisition software to operate smoothly and continuously. The program is run on the acquisition computer (tow vehicle) and displays a Tkinter-based graphical user interface (GUI) on the remote desktop visible on the (shipboard) control computer. The GUI displays images from any one of the five cameras selected by the user, refreshes the images at an adjustable time interval, and can optionally generate image histograms useful for real time quality control.

Image files are displayed based on an algorithm which uses the system time and inferring filenames utilizing the naming convention described above. When the user changes the camera selection on the GUI, that camera's serial number is used in the filename string generation. If the program can't find images using the inferred filenames, a warning is shown on the GUI to alert the operator that there may be a collection error.

Occasionally during collection, a small number of images were missed by the acquisition software, the cause of which yet to be determined and area of opportunity to improve the system. Identifying missing images is important for reconstructing individual moments so that the correct images are used for a given instant. Because of the large number of images (as many as 1200 images/min), finding one or two missed images over the time required to collect an entire survey line was achieved using a Python script that analyzed the directory of files. Because each filename contained the camera number and time the computer captured that image, the five images for each collection instant could be matched. The output is a spreadsheet showing the timestamps, the files from each camera corresponding to that time, and any missing images.

Table 1. Physical characteristics of the SQUID-5 towed surface vehicle.

Characteristic	**Description**
Fin Construction	Honeycomb Aluminum laminate
Lateral strength members	Aluminum strut channel and speed-rail
Rigidity	Less than 1mm flex with 15kg lateral or longitudinal sheer force
Waterline width	1.0 m
Overall width including lifting handles	1.5 m
Waterline (overall) length	1.25 m
Overall height including GNSS antenna	0.9 m
Draft	0.3 m
Operational weight	52 kg (in air)

Buoyancy from pontoons	129 kg (in seawater)
Center of mass (approximate)	0.15 m below waterline (centered)

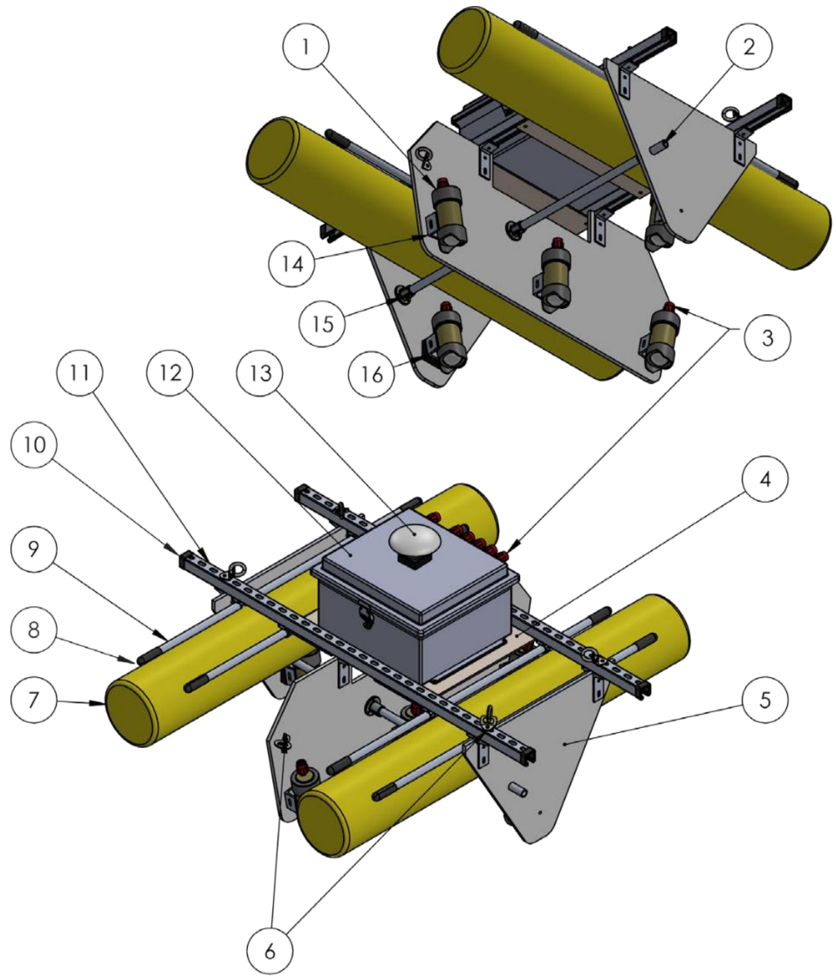

Figure 1. SQUID-5 Towed Surface Vehicle Major Components

1. Camera assembly, one of five.
2. 1-inch diameter aluminum pipe provides lateral stiffness to fin assembly.
3. Watertight connectors for marine ethernet and multiconductor cables (not shown in diagram). Enable communication and power transmission between each camera and the onboard data acquisition computer and between the tow vehicle and support vessel.
4. All panels including camera mounting fins are fabricated from lightweight but extremely stiff aluminum honeycomb laminate.
5. Camera Mounting fins. Enable cameras to be mounted below the air-surface interface and provide vehicle stability.
6. Stainless steel swivel rings used for towing and lifting of the vehicle.
7. Inflatable pontoons made of polyurethane coated re-enforced fabric provide buoyancy and deflate for transport.
8. Soft vinyl push-on round caps to protect inflatable pontoons from sharp edges.
9. 1-inch diameter schedule 40 PVC pipe to provide stability and support for inflatable pontoons.
10. Soft vinyl push-on strut channel end cap to protect support vessel and operators during launch and recovery.
11. Aluminum strut channel used as primary strength and alignment vehicle components
12. Submersible enclosure with a raised hinged cover houses the on-board data acquisition computer, signal and power connection busses.

13. Onboard survey GNSS antenna used to precisely measure camera vehicle location at the instant images are acquired.
14. Camera mount which enables the camera to be fixed into a desired yaw and pitch relative to the tow vehicle.
15. Aluminum slip-on rail fitting which fixes the AL support pipe (#2) rigidly to the camera support fins (#5).
16. Reversible Delrin block which fixes the side camera angle to point either inward or outward 10° from vertical.

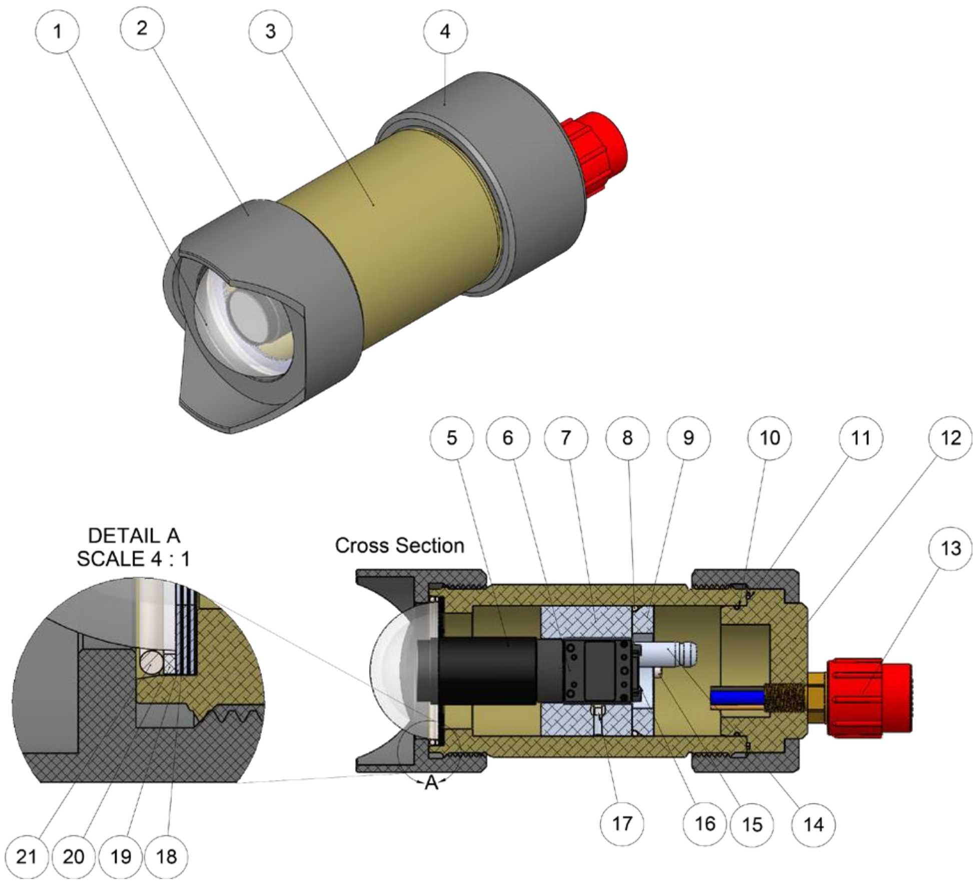

Figure 2. SQUID-5 Camera Major Components

1. Hemispherical dome window BK7 optical glass 60mm OD, 5mm thickness.
2. Threaded Delrin lens hood and dome window containment collar.
3. Camera housing body 6061-T6 Aluminum, hard anodized 7.24mm minimum wall thickness.
4. Threaded Delrin endcap containment collar.
5. C-Mount lens, fixed focus and aperture. Model HF8XA-5M shown.
6. FLIR Blackfly S 5.0-megapixel POE machine vision GigE camera. Model BFS-PGE-50S5C.
7. Piston Camera Mount. Centers camera radially, accommodates various lens sizes and facilitates dome window and lens entrance pupil alignment.
8. Butyl O-ring used to fix fore and aft position of Piston Camera Mount when compressed by Piston Camera Mount Lock Ring, size AS568-137.
9. Piston Camera Mount Locking Ring.
10. Camera Housing End Plug radial seal Butyl O-Ring, size AS568-034.
11. Camera Housing End Plug face seal Butyl O-Ring, size AS568-037.

12. Camera Housing End Plug 6061-T6 Aluminum, hard anodized 11.4mm minimum end thickness.
13. Subconn Circular Ethernet Series connector 13 Male Pin with Locking Sleeve.
14. LEMO connection used for “trigger” signal to initiate image capture.
15. Socket cap screws used to tighten Piston Camera Mount Lock Ring and compress O-Ring which locks the piston mount in place.
16. POE Ethernet connector used for image data transfer, camera configuration, and to supply power to camera.
17. Set screw to fix camera into Piston Camera Mount.
18. One of three circular disks of Kapton interspaced with three circular disks of Titanium (#19) to form a set of slip planes which prevents point stress buildup if the housing is subjected to high pressure. The slip plane stack also forms the high-pressure watertight seal.
19. Titanium circular disk (1 of 3), see #18 description.
20. Teflon backup ring which prevents O-ring #21 from extruding between glass dome and slip plane stack under repeat high-pressure exposure.
21. Low pressure seal for glass dome, also radially centers and captures the BK7 glass dome behind #2.

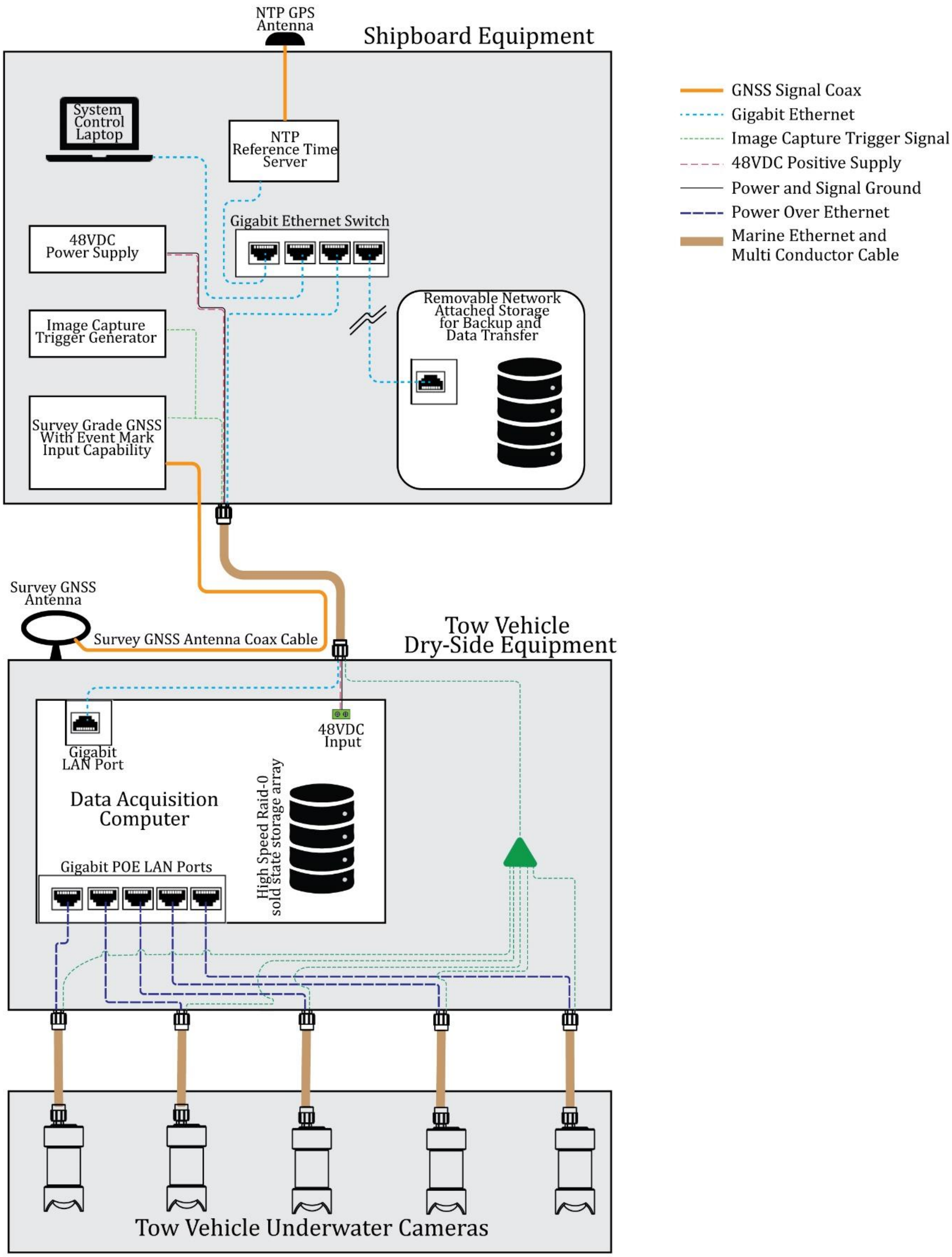

Figure 3. SQUID5 System Diagram.

References

Menna, F., Nocerino, E., Fassi, F., and Remondino, F. (2016). Geometric and Optic Characterization of a Hemispherical Dome Port for Underwater Photogrammetry. *Sensors (Basel)* 16. doi:10.3390/s16010048.

Nocerino, E., Menna, F., Fassi, F., and Remondino, F. (2016). Underwater Calibration of Dome Port Pressure Housings. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 34, 127–134. doi:10.5194/isprs-archives-XL-3-W4-127-2016.