A Modular Sensor Suite for Underwater Reconstruction

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***Abstract*—This paper presents the design, development, and application of a sensor suite, made with the explicit purpose of localizing and mapping in underwater environments. The design objectives of such an underwater sensor rig include simplicity of carrying, ease of operation in different modes, and data collection. The rig is equipped with stereo camera, inertial measurement unit (IMU), mechanical scanning sonar, and depth sensor. The electronics are enclosed in a water-proof PVC tube tested to sixty meters. The contribution of this paper is twofold: first, we open-source the design providing detailed instructions that are made available online; second, we discuss lessons learned as well as some successful applications where the presented sensor suite has been operated by divers.**

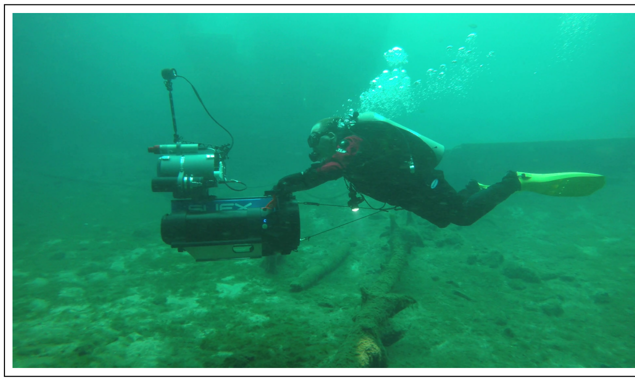

Fig. 1. Our proposed underwater sensor suite mounted on a dual Diver Propulsion Vehicle (DPV), where a stability check was performed at Blue Grotto, FL.

I. Introduction

Localization and mapping in underwater environments is an important problem, common in many fields such as marine archeology, search and rescue, resource management, hydrogeology, and speleology. Target environments include, but are not limited to wrecks (ships/boats, planes, and buses), underwater structures (bridges, docks, and dams), and underwater caves [1]–[4]. Underwater environments present a huge challenge for vision-only mapping and navigation systems, making the deployment of autonomous underwater vehicles still an open problem. Light and color attenuation, due to the presence of particulates in the water, often combined with the complete absence of natural light, present major challenges. The combination of Visual and Inertial data has gain popularity with several proposed methods for fusing the two measurements [5]–[8]. In addition, most of the state-of-the-art visual or visual-inertial odometry algorithms have been shown to fail in underwater environments [9]. However, vision still remains an accessible, easily interpretable sensor. On the other hand, the majority of underwater sensing for localization is based on acoustic sensors, such as ultrashort baseline (USBL) and Doppler Velocity Logger (DVL). Unfortunately, such sensors are usually expensive and could possibly disturb divers and/or the environment.

This paper presents the design, development, and deployment of an underwater sensor suite to be operated by human divers. The literature mainly focuses on AUVs and Autonomous Surface Vehicles (ASVs), and a body of work studies the Simultaneous Mapping and Localization (SLAM) problem and oceanographic reconstruction. Leedekerken et al. [10] presented an Autonomous Surface Craft (ASC) for concurrent mapping both above and below the water surface in large scale marine environments using a surface craft equipped with imaging sonar for subsurface perception and LIDAR, camera, and radar for perception above the surface. Folaga [11], a low cost AUV, can navigate on the sea surface and dive only at selected geographical points when measurements are needed. Roman et al. [12] proposed an AUV equipped with camera and pencil beam sonar for applications including underwater photo-mosaicking, 3D image reconstruction, mapping, and navigation. AQUA [13], a visually guided legged swimming robot uses vision to navigate underwater and the target application areas are environmental assessment [14] and longitudinal analysis of coral reef environments [15]. Our aim is to accelerate state estimation research in the underwater domain that can be eventually deployed robustly in autonomous underwater vehicles (AUV) by enabling easy data collection by human divers. In particular, a specific target application is cave mapping, where the diving community has protocols in place for exploring and mapping such dangerous environments. The primary design goal of the proposed underwater sensor suite is to reduce the cognitive load of human divers by employing robotic technologies to map underwater structures. A second design goal is to enable software interoperability between different platforms, including AUVs. In particular, the sensor suite presented in this paper contains identical sensors with an Aqua2 AUV [13], and can be deployed in different modes, hand-held by a diver, mounted on a single Diver Propulsion Vehicle (DPV), or on a dual DPV for better stability; see Fig. 1. The selected sensors include a mechanical scanning sonar, which provides robust range information about the presence of obstacles. Such a design choice improves the scale estimation by fusing acoustic range data into the visual-inertial framework [16].

The paper is structured as follows. The next section outlines the design layout of hardware and software, deployment strategies, and the two versions of the sensor suite. Section III presents some experimental results on datasets we collected

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in different underwater structures. The paper concludes with a discussion on lessons learned and directions of future work.

II. Sensor Suite Design

The sensor suite hardware has been designed with underwater cave mapping [1] as the target application to be used by divers during cave exploration operations. In general, it can be used for mapping a variety of underwater structures and objects. In the following, the main requirements, hardware, and software components, are presented. Note that the full documentation for building and maintaining the hardware, as well as the necessary software can be found on our lab wiki page [17].

A. Requirements

Given that the sensor suite will be primarily used by divers who are not necessarily engineers or computer scientists, the following requirements drive the hardware and software design of the proposed sensor suite:

- Portable.
- Neutrally buoyant.
- Hand-held or DPV deployment.
- Simple to operate.
- Waterproof to technical-diver operational depths.

Furthermore, the following desiderata are considered to make research in state estimation applied to the proposed sensor suite easily portable to other platforms, such as AUVs and ASVs:

- Standardization of hardware and software.
- Easy data storing.
- Low cost.

B. Hardware Design

In this section, the electronics selected and the designed enclosure are discussed, together with lessons learned during the construction of the proposed sensor suite.

1) Electronics: To assist vision-based state estimation, we employ an Inertial Measurement Unit (IMU), a depth, and an acoustic sensor for accurate state estimation in underwater environments. The specific sensors and electronics of the sensor suite were selected for compatibility with the Aqua2 Autonomous Underwater Vehicles (AUVs) [13]. Figure 2 shows the computer and internal sensors on a Plexiglas plate, where the different electronic boards were placed optimizing the space to reduce the size of the sensor suite. In particular, the electronics consists of:

- two IDS UI-3251LE cameras in a stereo configuration,
- Microstrain 3DM-GX4-15 IMU,
- Bluerobotics Bar30 pressure sensor,
- Intel NUC as the computing unit,
- IMAGENEX 831L Sonar.

The two cameras are synchronized via a TinyLily, an Arduino-compatible board, and are capable of capturing images of 1600×1200 resolution at $20\,\mathrm{Hz}$. The sonar provides range measurement with maximum range of $6\,\mathrm{m}$ distance, scanning in a plane over $360°$, with angular resolution of $0.9°$. A complete scan at $6\,\mathrm{m}$ takes $4\,\mathrm{s}$. Note that the sonar provides for each measurement (point) 255 intensity values, that is $6/255\,\mathrm{m}$ is the distance between each returned intensity value. Clearly, higher response means a more likely presence of an obstacle. Sediment on the floor, porous material, and multiple reflections result in a multi-modal distribution of intensities. The IMU produces linear accelerations and angular velocities in three axis at a frequency of $100\,\mathrm{Hz}$. Finally, the depth sensor produces depth measurements at $1\,\mathrm{Hz}$. To enable the easy processing of data, the Robot Operating System (ROS) framework [18] has been utilized for the sensor drivers and for recording timestamped data.

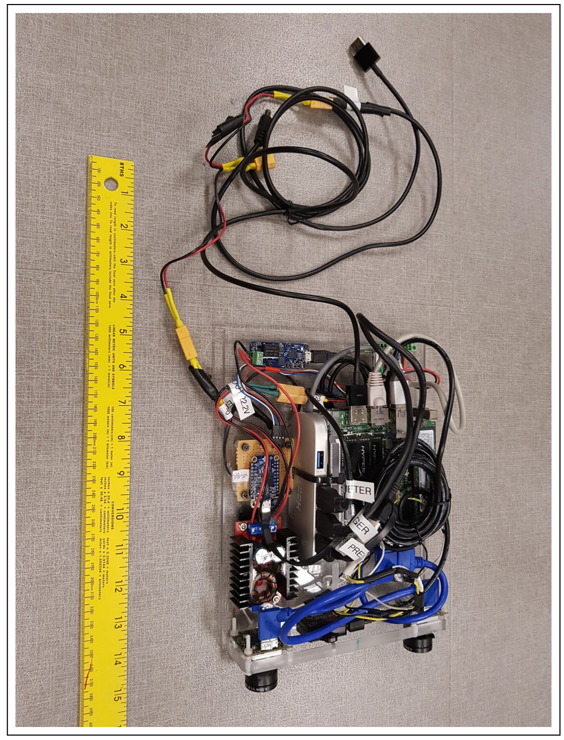
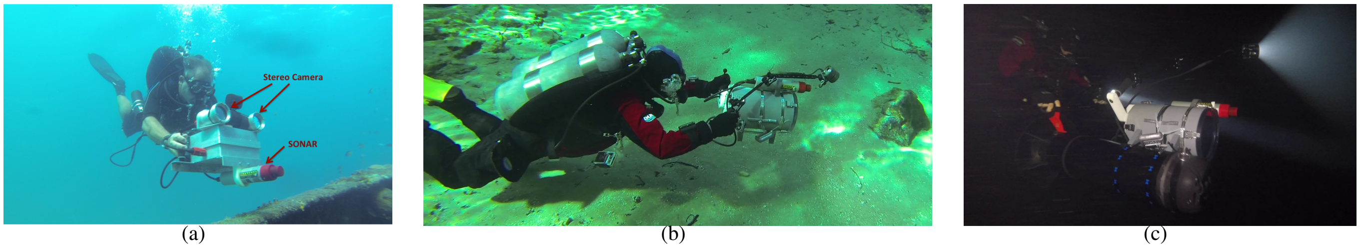


Fig. 2. The Main Unit containing stereo camera, IMU, Intel NUC, and Pressure sensor.

A 5 inch LED display has been added to provide visual feedback to the diver together with a system based on AR tags is used for changing parameters and to start/stop the recording underwater [19] (see Section II-C).

2) Enclosure: The enclosure for the electronics has been designed to ensure ease of operations by divers and waterproofness up to $100\,\mathrm{m}$. In particular, two different designs were tested. Both of them are characterized by the presence of handles for hand-held operations. The handles have been chosen so that a dive light can be easily added using a set of articulated arms. Note that all enclosures are sealed with proper o-rings/gaskets (details are reported in the linked documentation).

In the first design (see Fig. 3(a)) the main unit, a square shaped aluminum box – composed of two parts tighten together by screws – contained the computer, sensors, and other related electronics. The two cameras were sealed in aluminum tubes with tempered glass in front of the camera lenses. The



(a) (b) (c)

Fig. 3. (a) First version of the stereo vision setup, where the two cameras are mounted externally to the main unit. (b) Second version of the sensor suite, where the stereo camera is inside the main unit. (c) Second version where the sensor suite is mounted on a DPV.

stereo camera and display were mounted on the top of the main unit whereas the sonar was on the bottom of it. Both the cameras and sonar were connected to the main unit by underwater cables. The rationale behind such a design was to allow for an adjustable stereo baseline. Unfortunately, the USB 3.0 interfacing standard used by the cameras is not compatible with the underwater cables available in the market, resulting in highly degraded performance for the cameras with multiple dropped frames. In addition, the aluminum body made the sensor suite relatively heavy and negative buoyant. Furthermore, the position of the screen was not optimal for seeing it during regular diver deployment.

In the second design (see Fig. 3(b)), we took into account the lessons learned from the first design. In particular, a PVC tube was used instead of the aluminum box. This made the enclosure lighter and positive buoyant. Some rails at the bottom allows for additional weights for ballasting. Furthermore, the main enclosure hosted the two cameras as well. In this way, the cameras can be directly connected to the computer with standard USB 3.0 cables, to avoid unnecessary transmission of data over underwater cables as it was in the first design. The front panel is made of transparent Plexiglas, $33\,\mathrm{mm}$ thickness, while the back panel is made of aluminum, where a waterproof switch, a display, pressure sensor, and underwater connector for the sonar are mounted. Stainless steel Latches are used to close the panels with the PVC tube, so that it can be easily open and maintained. The sonar was mounted on the top with the scanning plane parallel to the image plane and connected to the main unit by a standard SubConn underwater cable. Such a design and choice of material reduced the size and weight, and made it easier to carry and maintain. In addition, the second design of the sensor suite allows for modularity in terms of electronics used: a Plexiglas plate inside the enclosure was used to mount all the electronics and can be easily removed for troubleshooting or changed with a different computer, cameras, and IMU.

The second version of the sensor suite has been designed considering two different deployment strategies: hand-held and on different diver propulsion vehicles (DPV). Such deployment strategies depend on the structure of the environment and the distance to cover. The hand-held approach is more appropriate for covering a smaller area for a short period of time, whereas the sensor suite can be mounted on a single or double DPV in order to collect data over longer distances while being under water. Mounting the rig on a DPV is specifically useful in cave diving, at larger depths, to make better use of limited underwater time. Hand-held operations are possible through the handles on the side of the PVC tube, as shown in Fig. 3(b). DPV operations can be performed in two ways. First, mounted on a single DPV unit; see Fig. 3(c). Second, mounted on a dual DPV unit; see Fig. 1.

Fig. 4. Front top view of the assembled sensor suite.

Fig. 4 shows a front view of the sensor suite fully assembled. The two side-ring holders are used to mount a canister battery for the video light; usually, a 13.5Ah NiMH standard battery.

3) Mounting Options: Mounting the sensor suite on single or dual DPVs uses different attachment methods. For single DPV attachment hose-clamps are used through the two metal bars to secure the sensor; see Fig. 5(a). Please note, the bottom of the sensor suite has a round hollow that fits on a SUEX[1] DPV; either XJ37 or XK1 models. For mounting on a dual DPV, an attachment system is used; see Fig. 5(b). The PVC components are hooked through the supporting metal poles at the bottom; see Fig. 5(c) where the plate is half mounted.

[1] https://www.suex.it/

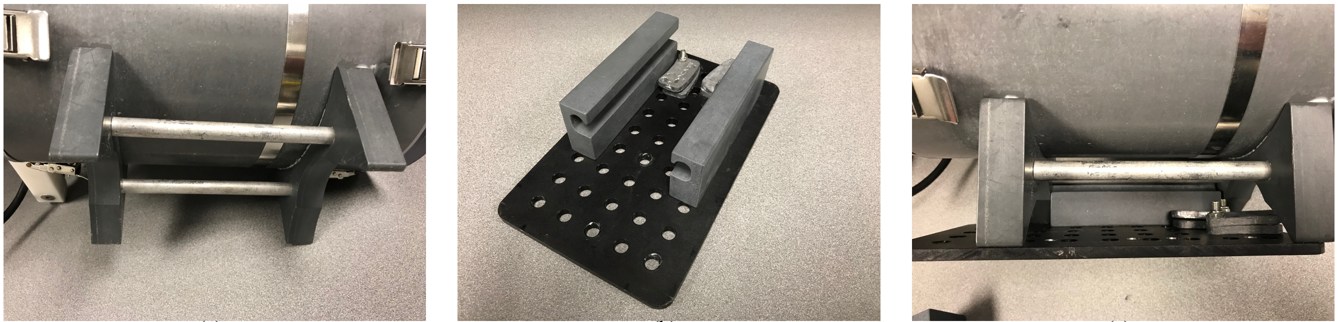


Fig. 5. (a) The mounting system for single DPV deployment. (b) Mounting attachment for use with a dual DPV. (c) The dual DPV attachment partially mount on the bottom of the sensor suite.

When the plate is attached to the bottom of the sensor suite, then it locks on the railing system of the dual DPV unit. The mounting on the DPV can be carried out while in water, allowing divers to easily carry modular parts to the entry point for the dive. It is worth noting that the cheese-board and rail design allow for changing the location of the sensor on the dual DPV.

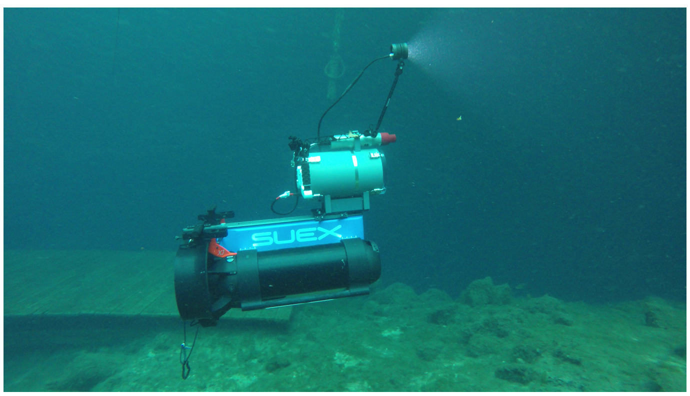


Fig. 6. Sensor suite on a dual DPV free floating, neutrally buoyant.

Fig. 6 demonstrates the stability of the sensor suite on a dual DPV. The unit floats in the water neutrally buoyant, with the video light on top illuminating forward.

C. *Software Design*

The main software components of the sensor suite consist of:

- drivers for each hardware unit,
- a ROS interface for communication between sensors and data processing,
- an interface for user and sensor suite interaction.

1) Drivers: The aim for the software design is to have a modular system that ensures re-usability for both the system as a whole and also for each component. Each driver provides consistent interface for communication with the Robot Operating System (ROS) framework [18]. The main ROS drivers are:

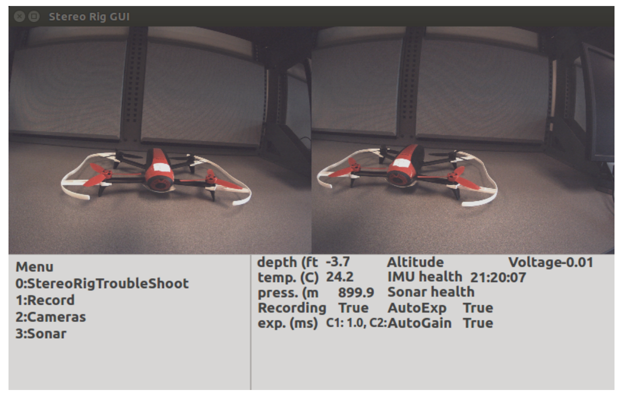


Fig. 7. The default view of the menu.

- UEye driver for each camera, together with the Arduino code for the trigger to synchronize the cameras – available open-source [20].
- IMU driver – available open-source [21].
- Sonar driver – developed in our lab, released open-source [17].
- Depth sensor driver - developed in our lab, released open-source [17].

2) ROS platform: For easy data collection, each sensor node publishes the related data. All the operations are performed on the computer that runs a Linux-based operating system. In particular, the Software was tested both on Ubuntu 14.04 and 16.04. After the operating system boot, a startup script runs all sensor nodes and at the same time starts the recording of sensor data through ROS bag file[2] that allows for easy play-back.

3) Interface: The interface consists of two components: Graphical User Interface (GUI) for online data monitoring; and AR tags [22] that supports user and sensor suite interaction, similarly to the proposed system by Sattar et al. [23]. The GUI – based on Qt[3] for modularity – shows the current video stream of each camera and outputs the overall health of the system. Fig. 7 shows the sensor data from the GUI. Depth in feet

[2]http://wiki.ros.org/rosbag
[3]https://www.qt.io/

and altitude represent the distance from the surface and from the bottom respectively; measured by the depth and the Sonar sensors. The temperature of the CPU is also reported in case there is overheating, especially if operations are started above water. In addition, the GUI shows a menu with a list of options that a user can select; left side of the screen. Each option has a corresponding AR tag associated with its number. Through the menu a user can perform basic operations on the computer – such as reboot or shutdown – start or stop recording data, get access to both camera or sonar settings. When a camera is selected, a user can change its gain and exposure and perform camera calibration. In addition, sonar data can be visualized through rviz[4] by selecting the corresponding option. Note that such a menu is modular and straightforward to add, remove, or modify the menu entries. Fig. 7 shows how the GUI looks like.

III. Applications and Results

The proposed sensor suite has been used to collect Sonar, visual, inertial and depth data, in a variety of environments. More specifically, shipwreck and coral reef data were collected during field trials in Barbados. More data were collected at Fantasy Lake, NC, and at different locales near High Springs, FL, using both the first and the second version of the sensor. The collected data were post-processed and used for structure modeling; see Fig. 8 and 9, which shows the reconstruction by the Sonar Visual Inertial Odometry algorithm developed by the authors [16]. We are currently exploring the deployment of the same software on the Aqua 2 AUV. Furthermore, a dual DPV platform has been acquired for the deployment of the sensor in different cave systems.

IV. Conclusion

In this paper, we presented the design and development of a sensor suite for underwater reconstruction, together with some lessons learned during its construction. Our proposed sensor suite has been used by divers in coral reefs, shipwrecks, and cave systems to collect visual, inertial, and sonar data, and different algorithms have been studied to improve state estimation in caves.

Immediate future work on the proposed sensor suite includes a comprehensive study on the quality of cameras for underwater operations, as well as a more user-friendly electronics placement and wiring. More broadly, such a sensor suite will be mounted on a platform that can operate autonomously, to allow for easy swap of sensors on a robot.

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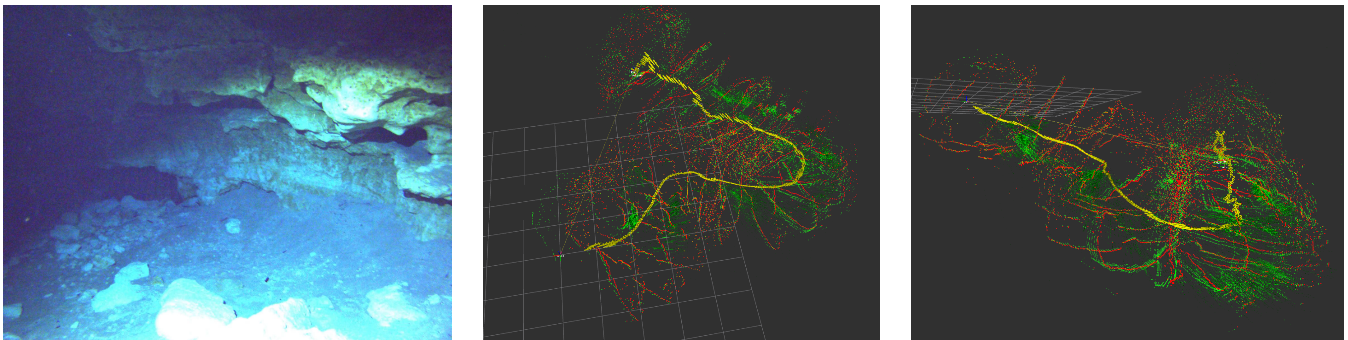
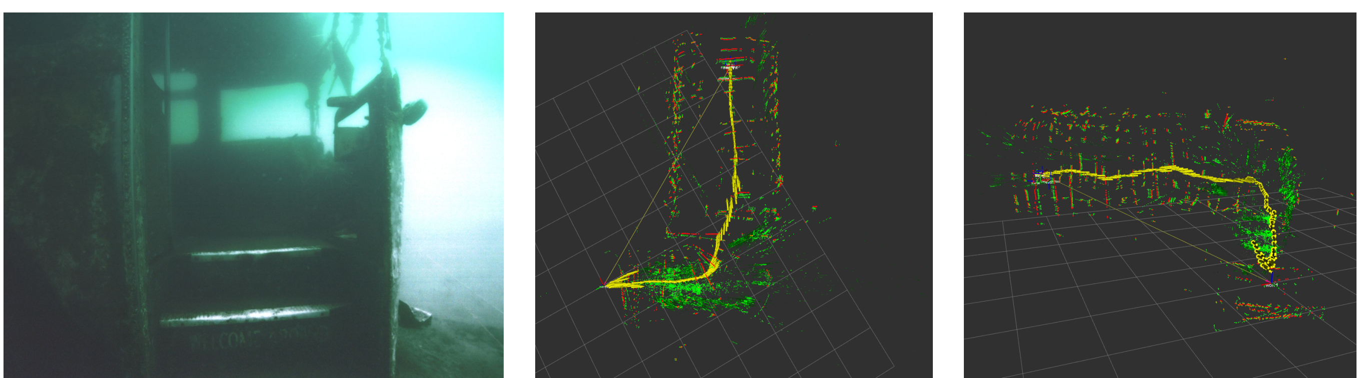


(a) (b) (c)

Fig. 8. Underwater cave, Ballroom Ginnie cavern at High Springs, FL, USA. (a) Sample image of the data collected inside the cavern. (b) Top view of the reconstruction. (c) Side view of the reconstruction.



(a) (b) (c)

Fig. 9. Sunken bus, Fantasy Lake Scuba Park, NC, USA. (a) Sample image of the data collected from inside the bus. (b) Top view of the reconstruction. (c) Side view of the reconstruction, note the stairs detected by visual features at the right side of the image.