Low Cost Stereo System for Imaging and 3D Reconstruction of Underwater Organisms

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***Abstract*—This paper presents an autonomous low cost device for underwater stereo imaging and 3D reconstruction of marine organisms (benthos, fishes, macro and mega- zooplankton) and seabed with a high accuracy. The system is designed for deployments onboard autonomous, fixed and towed platforms. Internal hardware consists of two Raspberry Pi mini-PCs and two Raspberry camera modules. The operational pipeline is managed through a client/server paradigm. The 3D imaging acquisition system is fully programmable in acquisition scheduling and capture settings. When tested on sets of images containing objects of known size, the system returned an accuracy of metric measurements of the order of 2%. The system is intendeed as a prototype, and a collaboration with companies has been estabilished in order to realize a complete commercial product.**

I. Introduction

Underwater imaging is a very active research topic in marine sciences and technologies, as it became an actual field of interests of researchers and imaging systems are frequently requested to perform deep sea and shallow water investigations. In this context a low cost system for underwater imaging focused on stereo vision for 3D underwater reconstruction became an interesting device for several application. This paper presents a low cost system for 3D reconstruction of underwater organisms. The system is completely autonomous in terms of batteries and acquisition task. It is designed to be fully programmable in both time acquisition scheduling and camera parameters. Various tests were performed in a controlled environment and in nearshore sea, in order to validate the harware and software modules of the system.

Figure 1 shows the developed prototype of the 3D stereo underwater imaging system, without enclosure. The small size and compactness of the system make it suitable for being used with several kinds of enclosures.

Underwater 3D scene reconstruction and its applications cover several fields of marine sciences. Examples of applications concern devices equipment for autonomous vehicles or underwater robotics, mainly for seabed reconstruction [1], [2], [4], reef reconstruction [5], and object detection [3] for underwater robotics purpose. In [3] the low cost of electronic devices began a development constraint, but authors show an initial prototype limited to test disparity algorithms in an underwater environment in very shallow water. In contrast, this paper presents a low cost stereo system for autonomous underwater imaging aimed at the analysis of underwater organisms such as benthos, macro and mega zooplankton through the investigation of reconstructed 3D models of the framed targets. In order to overcome the tight constraints given by the high cost of commercial underwater stereoscopic devices and the high probability of losing these devices during deployments, the proposed system was developed as autonomous, low cost and with the smallest possible size, in order to be easily deployed both on fixed and mobile platforms (e.g. submerged stations, oceanographic moorings, floats, drifters, and AUVs). Due to its flexibility in tuning and installation, the system enables several investigation approaches, even in harsh environments. The capability of being hosted onboard many kind of platforms makes the system a promising device for fishes and macro and mega zooplankton stereo imaging in the water column, for monitoring benthos growth, and for the characterization of seabed, both in shallow waters and deep-sea.

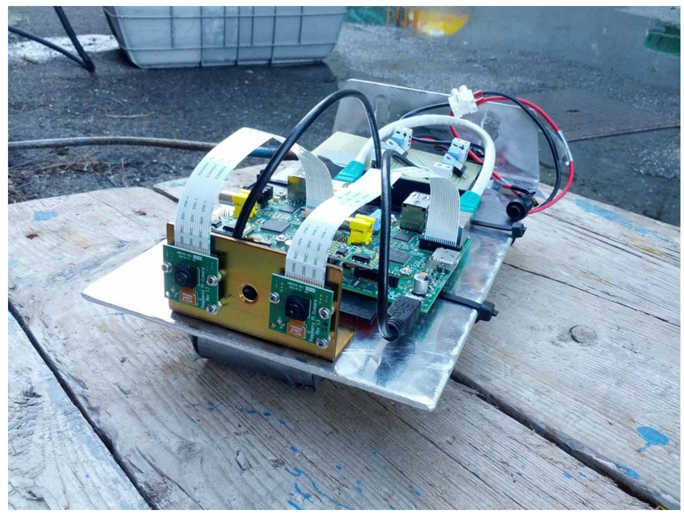

Fig. 1. The system prototype developed without enclosure.

In benthic ecology, quantitative estimation of the volume, mass, and surface of organisms is a key issue. Several measurements techniques involve invasive tasks and in some cases also distruptive methodologies. In [6] image-based 3D reconstruction faces these problems, and it is used to estimate morphometric measurements of the underwater organisms using a cube to post-calibrate size. In contrast, the system presented in this paper does not need a marker on the scene and allows to estimate morphometric measurements with the

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3D model. Due to its autonomous functionalities, it can be used without diver support in order to reach more deep depths, depends only on enclosure characteristics.

This paper is organized as follows. Section II details the hardware modules of the system, while section III shows the architecture overview of the software modules. The section IV shows the experimental results on the 3D organisms reconstructions, and finally in section V conclusions are given.

II. Hardware System Overview

The hardware architecture is the key core of the developed system, as it has been implemented in order to integrate state-of-the-art software reconstruction approaches, requiring adequate computational capacity and technologically complex electronics, with small size structures and low cost components. The system has been designed to integrate low cost consumer parts and custom prototypes. Two Raspberry Pi general purpose mini PCs are used for the system control, and two Raspberry Pi camera modules perform the image acquisition. Each camera module is controlled via a software module running in the associated PC.

Figure 2 illustrates the hardware architecture overview scheme. The Raspberry Pi, RPi in the scheme, is a credit card sized personal computer (85.60 mm$\times$56.5 mm) that has a broad diffusion in educational, recreational, and research fields due to its low cost and performance. It runs various linux operating system distros fitted for its ARM architecture.

The main board integrates a Broadcom BCM2835 SoC (*System on a Chip*) with a 700 MHz single-core ARM1176JZF-S, a Broadcom VideoCore IV @ 250 MHz GPU, and 512 MB (shared with GPU) SDRAM memory. On the Raspberry Pi motherboard a 15-pin MIPI camera interface CSI *Camera Serial Interface* Type 2 connector can be used with the Raspberry Pi camera modules, two models are available with visibile light and near infrared frequencies camera sensor sensibility.

A RTC, *Real Time Clock*, has been included on each mini-PC board to mantain date and time information beetween the switch on cycles. It is an external device because of the absence of it in the miniPc board. It is needed in order to acquire precise timing information that are crucial to synchronize and to couple the stereo acquired images.

The camera module used in this system has the visible light sensibility sensor. The sensor type is an OmniVision OV5647 Color CMOS QSXGA (5-megapixel) with resolution of 2592$\times$1944 pixels The sensors size is 3.67$\times$2.74 mm and each pixel has size 1.4$\times$1.4 μm The mounted lens has focal distance f=3.6 mm, with aperture $f/2.9$. The lens has a fixed focus from 1 m to infinity and a field of view fo approximately 2.0$\times$41 m at 2 m sue to its angle of view of 54$\times$41 degrees. The camera module board size is compact (25$\times$41 mm) and it aims to realize a short baseline stereo camera. The baseline of the developed stereo rig system is 4.5 cm measured from camera modules lens centers.

The two Raspberry PC are linked by a ethernet interface (ETH) for software communications and synchronization in the image acquisition task.

This low cost hardware does not have sufficient computation power to reconstruct the scene and make 3D model of organisms in real time. Due to this limitation the reconstruction using 3D state of art algorithm is performed offline on the interesting subjects.

The small dimension of the implemented system permits its deployment in several kind of enclosures. In particular the system has been tested in two different kind of enclosures. A cylindrical enclosure able to reach 40 m depth, whose diameter is 0.20 m and length is 0.30 m. This enclosure was used for shallow water test, due to its easyness of setup and deployment. A second enclosure was realized with a Vitrovex sphere capable to reach 6000 m depth, whose diameter is 0.25 m. This enclosure aims to deploy the system in deep sea, but it is more complicated to handle in deployment time. Both these enclosures are equipped with a pair of white Light Emitting Diodes (LED) providing the necessary illumination of the framed scene.

For each enclosure it is necessary to perform a specific re-calibration of the intrinsic camera parameters, in order to take into account the air-glass and glass-water interfaces. Camera parameters measurements and stereo rig calibration implemented are presented in section III.

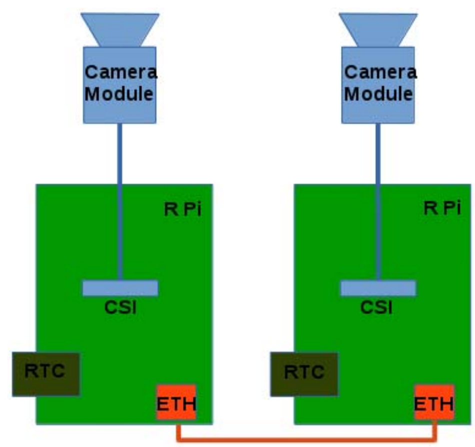

Fig. 2. Harware modules overview.

III. Software

The software module of the system, installed on both Raspberry PC, is responsible for the image acquisition and 3D model reconstruction. For these reasons the sotware onboard the system is composed by two separate modules. Figure 3 shows the entire operational pipeline governed by the two software modules and highlights the strong connection beetween the software modules, both modules can be represented in the same pipeline even if are well separated. However, due to power consumption and hardware constraints, only the image acquisition is performed in real time. The 3D reconstructions are performed offline using information and meta-data collected in the image acquisition step.

The first software module is responsible for the image acquisition. Image acquisition is operated by a specific software framegrabber based on a client/server paradigm. Each Raspberry runs a server program that aims to activate the camera acquisition with pre-programmed parameters. The scene acquisition is triggered by a specific client program that run on one Raspberry PC. The client multithread program that allows for changing camera acquisition parameters (as exposure time, iris aperture, ISO speed, etc.) and shooting schedule. It fires acquisition signals according to the user specifications. The signals encapsulate camera acquisition information that are decoded by each server program in order to acquire images with the same parameters. Concerning the camera acquisition synchronization, assessment tests returned average delays between the two cameras of the order of the nanoseconds.

The second software module handles the 3D reconstruction of the framed scene. This module involves some different steps, that are all inserted on a on a typical dense stereo vision pipeline as shown by Figure 3. The preprocessing module involves some tasks; image dedistorsion, compensation for light refraction in water, and a Contrast Limited Adaptive Histogram Equalization, CLAHE [7], are performed in order to prepare images to the next processing steps. Contrast enhancement step is limited to the case of low turbidity acquired images to avoid noise increase that can have a disruptive effect on 3D reconstruction quality. Moreover, the image dedistorsion task in this module is performed with the intrinsic parameters obtained by a separate calibration task. The intrinsics and extrinsics camera calibration was performed in a controlled condition environment with a checkerboard calibration pattern [9]. Camera intrinsic parameters calibration was performed using the MatLab Calibration Toolbox [11]. A rectification step is crucial to obtain a stereo images pair useful for the disparity computing. In this step the epipolar lines of the pair are aligned to allow the correspondences searching for the dense stereo disparity algorithms tasks [12]. DSI computing step allows to compute the disparity from a rectified image pair. The output of this step is a DSI, a *Disparity Space Image*, in which each pixel represent the distance beetween two corresponding points of the image pair. The DSI is obtained with a dense stereo Semi-Global Block Matching (SGBM) [8]. This algorithm is selected because of its easyness to use, relative low number of parameters, and for its fast computing time. The Middlebury site shows a state-of-art updated list of stereo algorithm [10], in the future release of the system other algorithms will tested in order to investigate the performance for the 3D reconstruction of underwater image. Finally a point cloud is extracted with a triangulation transformation from DSI to real coordinates, in order to obtain data for the 3D model reconstruction stage. The disparity evaluation function obtained by the stereo system is very dense and enables the complete capability of taking accurate metric measurements within the obtained 3D models. The point cloud and 3D model reconstructed are manipulated with the point cloud library [13], to compute some specific filters and precise measurements on the reconstructed models.

IV. Experimental Results

The system has been tested in both controlled environment and real sea conditions.

Initially, tests on 3D reconstruction have been performed in a controlled environment, into a tank with no direct sunlight illumination, facing underwater organisms and objects with a known size. The tank has size of $1.0\times1.0\times0.9$ m, and it is filled by fresh water. These initial tests are done to calibrate

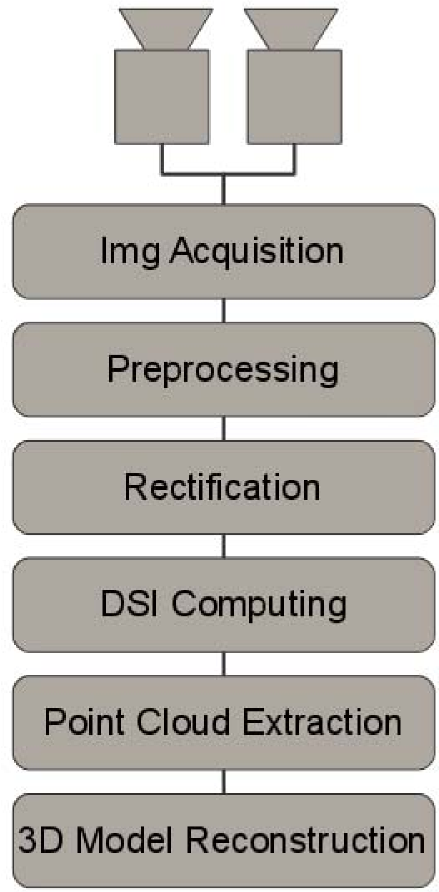

Fig. 3. Software modules architecture overview.

the cameras in a controlled underwater environment, to test the acquisition system, to perform acquisition without backscattering and turbidity problems, and to investigate measurements capabilities of the system using well known size artifacts.

The field testing deployment has been conducted on a coastal seabed in the Ligurian Sea The test performed in the real sea condition highlighted the critical issues to be addressed in order to optimize and tune the system. In particular, shallow water light reflections caused by the surface, the water turbidity, real backscattering, and the configuration of the LEDs pair came out as the major criticalities, acting as main causes of the metric measurements errors. Tests on seashore have been conducted in shallow water (maximum 5 m depth), in different daily hours to achieve information about sunlight underwater reflection and associate image artifacts, and in different day in order to investigate different turbidity influence in image acquisition that cause 3D reconstruction problems.

Figure 4 shows a benthic organism acquired during experiments performed into a controlled environment inside a tank (top), its 3D reconstruction with system algorithms (center) and an elaboration with measurements on Z-axis in color code from blue to red (bottom). Model measurements on the 3D virtual reconstructions highlight precision of the order of the centimeter. The error on reconstruction amount of 2% of the organisms size.

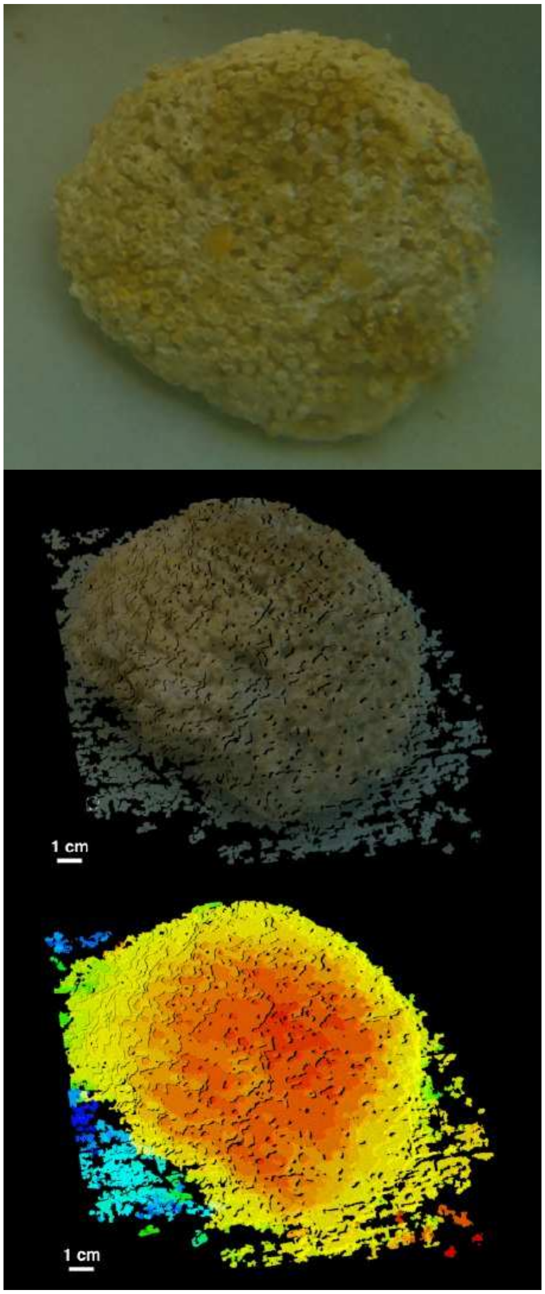

Fig. 4. 3D reconstruction of a benthos organism.

V. CONCLUSIONS

In this paper a low cost system for underwater stereo imaging and 3D reconstruction of underwater organisms has been presented. Due to its flexibility in tuning and installation, the system enables several investigation approaches, even in harsh environments. The capability of being hosted onboard several kind of platforms makes the system a promising device for fishes and zooplankton stereo imaging in the water column, for monitoring benthos growth, and characterization of seabed, both in shallow and deep-sea. The developed system is suitable to be used as underwater imaging device in a stand alone mode in a fixed station to monitor the benthos growth for long period. Due to its reduced size and flexibility, it can be also installed on autonomous vehicles to monitor a large underwater areas or towed to reconstruct the seabed. The system is capable to reconstruct objects with complex 3D shapes with sizes in the order of the centimeter. Errors on measurements appear mainly due to turbidity, reflections or lack in lighting, and they amount to 2% of the subject size. A collaboration with industrial companies has been estabilished, considering this system as a prototype, in order to expand its capabilities, to find new application fields, and to realize a commercial product.

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