Development and Deployment of THEIA: A Compact Underwater Multispectral Imaging System

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Abstract

We present THEIA, a novel underwater 3D multispectral imaging system. THEIA integrates a 4MP multispectral field array camera and a high-resolution RGB stereo camera pair in a specially built underwater housing to simultaneously capture spectral and depth information. This enables detailed spectral mapping and 3D reconstructions of underwater scenes. High resolution multispectral images are obtained via a Deep Image Prior-based demosaicing algorithm that enhances the multispectral data resolution without relying on external training. Stereo imaging provides depth cues for performing radiance correction. By suitably adapting Gaussian Splat-based 3D reconstruction methods, THEIA generates high-fidelity multispectral 3D models. Successful field trials at the Kolumbo underwater volcano validate the system's reliability and potential for applications in marine science and beyond.

1. Introduction

Multispectral 3D underwater imaging is essential for advancing scientific exploration and monitoring of marine environments, especially in domains like marine geology and marine biology, where accurate visual and spectral information of the seafloor is critical. Despite recent progress in underwater photogrammetry, multispectral sensing, and robotic deployments, most existing systems either focus either on recovering geometry (e.g., stereo or Structure-from-Motion) (Burns et al., 2015, Roznere, 2024, She et al., 2024) or on spectral information (Liu et al., 2020, Song et al., 2021, Ferrera et al., 2021), but rarely on both. However, geometry and radiometry are tightly coupled in the underwater domain due to wavelength-specific attenuation factors (Akkaynak and Treibitz, 2019). Furthermore, the majority of high-quality underwater imaging pipelines require extensive post-processing comprising manual steps.

To address these limitations, we introduce THEIA, a compact, modular underwater imaging system that integrates multispectral sensing and stereo vision within a unified, 950-meter depth rated platform. THEIA was designed, developed and tested within the framework of the SANTORY project (SANTORini's Seafloor Volcanic ObservatorY) (Nomikou et al., 2022), with a focus on marine geological applications such as surveying hydrothermal vents, seafloor composition analysis, and 3D morphological documentation. The system has been tested in operational conditions at the Kolumbo submarine volcano, demonstrating both its robustness and imaging capabilities.

At the hardware level, THEIA integrates a SILIOS CMS4-C multispectral field-array (MSFA) camera, capturing eight visible bands and one panchromatic channel, alongside a synchronized stereo pair of 12MP RGB cameras, mounted on Raspberry Pi 4 camera controller. The system is enclosed in a pressure-resistant housing rated for 950 meters, and was engineered for flexible deployment, whether mounted on ROVs or operated by divers. Regarding processing of the data collected with THEIA, we exploit state-of-the-art 3D reconstruction algorithms, enabling the generation of multispectral 3D reconstructions by coupling per-frame depth maps from stereo vision, with spectral information captured from the MSFA camera. The system's imaging pipeline incorporates newly developed MSFA demosaicing and underwater image restoration methods, tailored to the constraints and requirements of submerged environments.

In this work, we present the design, integration, and field validation of the THEIA system. Section 2 reviews related work in underwater multispectral imaging, depth estimation and underwater camera systems. Section 3 outlines the foundational methods and prior developments upon which THEIA is built, including key algorithmic and architectural components. Section 4 details the hardware architecture. Section 5 outlines the core software components and the full processing framework. Section 6 outlines the field deployment at the Kolumbo underwater volcano and presents preliminary results. We conclude in Sections 7 and 8 with lessons learned and discuss future directions for extending the system's capabilities.

2. Related Work

Underwater imaging has seen significant advancements, particularly in systems that focus on either multispectral or stereo imaging. For instance, TuLUMIS (Liu et al., 2018) employs a tunable LED-based approach for underwater multispectral imaging, synchronizing a monochrome camera with a filter wheel to capture spectral data. However, such systems often lack real-time capabilities and are not optimized for integration with depth sensing. This limitation has prompted further research into improving multispectral imaging for underwater applications. For example, (Liu et al., 2023) developed an underwater hyperspectral imaging system using liquid lenses to enable autofocus, significantly enhancing the acquisition of stable spectral data in deep-sea surveys. Similarly, (Song et al., 2021) introduced a compact underwater multispectral system based on a liquid crystal tunable filter, which achieves flexible spectral sampling suitable for marine exploration.

In the realm of stereo imaging, the explore3D system[1] offers real-time stereo vision with a global shutter sensor, suitable for deep-sea applications. While effective for depth mapping, it does not incorporate multispectral imaging, limiting its utility for applications requiring spectral analysis. Other systems, like the one proposed by (Sánchez-Ferreira et al., 2016), integrate stereo vision with image restoration techniques for underwater environments. Yet, these systems often rely on post-processing and lack the compactness and integration required for field deployment. Deep learning-based solutions are also emerging to tackle domain-specific underwater tasks,for instance the autonomous imaging system (Spanos et al., 2024a) enhances underwater bubble detection using deep learning, demonstrating how AI can refine feature extraction and detection in low-visibility settings.

THEIA distinguishes itself by combining real-time multispectral imaging with stereo vision in a compact, field-deployable system. Its integration of the MSFA camera with a synchronized RGB stereo camera, allows for simultaneous capture of spectral and depth information, facilitating detailed 3D reconstructions without the need for extensive post-processing.

3. Background

THEIA was developed and deployed as part of the SANTORY project (Nomikou et al., 2022), a large-scale interdisciplinary effort focused on the establishment of a seafloor volcanic observatory at the Kolumbo submarine volcano. The project integrates geophysical, geochemical, and biological monitoring systems to study submarine volcanic activity and its impact. Within this framework, THEIA serves as a key imaging instrument, offering the capability to acquire high-resolution, spatially and spectrally rich datasets in a compact form factor, targeting the generation of 3D multispectral photomosaics and scene classification. Importantly, THEIA is versatile, allowing for deployment on both Remotely Operated Vehicles (ROVs) and diver-operated platforms. The field deployment and testing conducted at Kolumbo provided critical validation of the system's reliability, data quality, and adaptability to complex deep-sea conditions.

The development of the THEIA system is based on a series of contributions in the areas of multispectral image processing, underwater image restoration, and real-time 3D reconstruction. These methods were suitably adapted and validated for the challenges of underwater environments before being integrated in the THEIA's processing pipeline.

In (Spanos et al., 2024b), the MD^{2}IP method was presented, based on a novel demosaicing algorithm tailored for multispectral filter array (MSFA) sensors. This method leverages the Deep Image Prior (Ulyanov et al., 2018) paradigm, which allows for the reconstruction of high-resolution multispectral images from raw, undersampled sensor data, without requiring ground-truth or pretrained models. Unlike conventional demosaicing methods that are either handcrafted or heavily data-driven, MD^{2}IP exploits the implicit regularization properties of convolutional neural networks to upscale SILIOS CMS4-C spectral bands from 682×682 pixels to the full 2048×2048 sensor resolution. This is particularly critical in underwater contexts where annotated training data is scarce or unavailable. In THEIA, MD^{2}IP forms the core of the multispectral processing stage, ensuring that the spectral fidelity and resolution required for scientific analysis are preserved without the burden of collecting domain-specific datasets.

[1] https://dwe.ai/products/explore3d-stereo-vision-camera-system-1000m-12000m

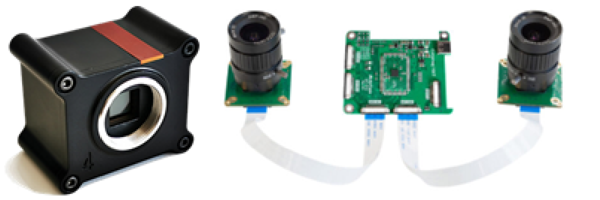

Figure 1. Multispectral camera (left) and stereo camera (right) used for building the THEIA underwater multispectral imaging system.

In (Antoniou et al., 2024) StreamUR method was presented, a physics-informed, near real-time image restoration framework designed to address the optical degradation typical in underwater scenes. Based on a MIMO-UNet architecture, StreamUR incorporates physical models of light propagation (attenuation and scattering) with deep learning priors, allowing it to enhance image clarity in dynamic, real-time scenarios. This method is particularly well-suited for use in operational systems like THEIA, which must operate in situ and provide usable visual output even in highly turbid or low-contrast environments. In our integration, StreamUR significantly improves the radiometric quality of both RGB and multispectral data, thereby improving the accuracy of subsequent 3D reconstructions and spectral interpretations.

Finally, THEIA benefits from the application of 3D Gaussian Splatting, proposed in (Kerbl et al., 2023), for 3D reconstruction of the underwater scenes/structures. This method allows efficient real-time rendering and novel-view synthesis of radiance fields. When applied to the multispectral images captured by THEIA, Gaussian Splatting facilitates fast and photorealistic visualization of underwater structures, such as hydrothermal vents, from multiple vantage points. This technique enhances the utility of THEIA for visual analysis and interpretation in scientific workflows.

Together, these previous contributions provided the methodological and technical foundation for THEIA's successful development, and their integration into a single, compact, underwater imaging system demonstrates a novel synthesis of algorithmic research and field-ready engineering.

4. Hardware Design

The THEIA system is designed as a compact three-objective camera imaging system, comprising a stereo-camera and an MSFA camera capturing both spectral and geometric data, capable of operating in deep-sea environments. The hardware architecture consists of three main subsystems: a multispectral imaging module, a stereo vision module, and a custom underwater housing that integrates power, data transfer, and environmental protection.

4.1 Multispectral Imaging Module

At the core of the multispectral imaging subsystem is the SILIOS CMS4-C, a 4.2-megapixel multispectral field-array

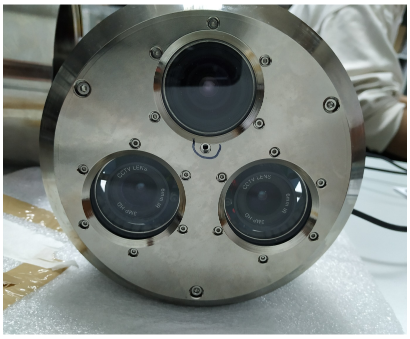

Figure 2. Front view of THEIA underwater multispectral camera system.

(MSFA) camera (Figure 1, left). This sensor captures data across eight discrete spectral bands spanning the visible range from 430 nm to 700 nm, as well as one broadband panchromatic channel. The lower end of the spectral range (blue-green wavelengths) is especially well-suited for underwater imaging, as these wavelengths experience the least attenuation and scattering in aquatic media (Shen et al., 2021). This spectral configuration enables the system to recover meaningful color and material information in underwater scenes where traditional RGB sensors often underperform. The camera interfaces with the system via a USB3 connection and is controlled directly by the embedded onboard computer.

4.2 Stereo Vision Module

For geometric reconstruction, THEIA incorporates a stereo pair of synchronized 12.3MP RGB cameras, each equipped with the Sony IMX477 sensor, as part of the Arducam Stereo Camera Kit (Figure 1, right). These cameras are managed via the Arducam Camarray HAT for Raspberry Pi, ensuring frame-synchronized acquisition. The stereo cameras were spatially calibrated in a laboratory pool, enabling accurate depth estimation through disparity computation.

4.3 Underwater Housing

Both the stereo cameras and the multispectral unit are rigidly mounted inside the underwater housing on a custom 3D-printed support structure, ensuring precise alignment and mechanical stability during operation.

The imaging modules and electronics are enclosed within a custom-made cylindrical housing machined from aluminum alloy, pressure-rated to 950 meters. The housing comprises three main components: a central cylindrical section; a front-facing cap with three flat viewing windows, one for each camera objective; and a rear cap that accommodates all external connectivity.

Each cap is sealed using dual O-rings to ensure reliable waterproofing under high-pressure conditions. The front ports are made from flat optical glass, carefully positioned to minimize refractive distortion and maintain alignment with the optical axes of the cameras.

4.4 Control Electronics

At the heart of the system is a Raspberry Pi 4 single-board computer (SBC) with 4GB of RAM. Captured data is saved to an onboard solid-state drive (SSD), while a small cooling fan maintains thermal stability for the embedded electronics.

4.5 Power and Data Interfaces

The rear cap of the housing features two main subsea connectors: a power input, which connects to an external power supply or battery pack during deployment, and an optional Ethernet interface that enables data streaming from the onboard Raspberry Pi 4 controller. When deployed on an ROV, THEIA supports real-time streaming and control over the tether via Ethernet. In stand-alone diver-operated mode, the system records data locally.

4.6 Optics Configuration

As described above, flat ports were considered for all camera objectives. For the development of the THEIA prototype, this choice was primarily to allow testing a wide range of different camera lenses. Due to the multi-port design of THEIA, the diameter of the flat ports was kept to 4cms, allowing for a reduced thickness of 8mm for the 950m depth rating. After initial tests, the final setup comprised lenses of 6mm focal length for the stereo camera (1/2.3" optical format) and a lens with 12mm focal length for the MSFA camera (1" optical format). This translates to a diagonal field of view of approximately 48° for the stereo camera and 49° for the MSFA camera in the water. The camera centers were placed on the vertices of an equilateral triangle with 60mm sides (Figure 2), striking a balance between available space inside the underwater housing and a depth resolution below 1.5cm for working distances up to 2m.

5. Software and Processing Framework

THEIA's software architecture was developed to support modular operation of its multispectral and stereo subsystems during autonomous or semi-autonomous deployments. While the focus of this work is on hardware integration and in-field deployment, the system includes a lightweight and extensible processing pipeline, centered around ROS nodes and custom drivers for each camera module.

5.1 Stereo Vision Subsystem

The stereo cameras are managed through a dedicated ROS node implemented in Python, built around GStreamer pipelines (The GStreamer Project Developers, 2025) combined with OpenCV (Bradski, 2000) for real-time image acquisition and storage. This approach enables synchronized streaming and local saving of stereo image pairs on the onboard Raspberry Pi 4 SBC. Depth maps are generated using Semi-Global Block Matching (Hirschmuller, 2007), which is robust to the underwater lighting variability encountered during field missions. These depth maps, along with the raw RGB frames, are stored per frame for downstream processing.

5.2 Multispectral Control and Band Separation

Although the SILIOS CMS4-C camera comes with a graphical user interface for interactive use, it lacks the capability for autonomous control during embedded operation. To enable full integration into THEIA, we developed a custom ROS node in C++ for camera control, triggering, and data acquisition. This node handles the capture of raw multispectral images via USB3.

The raw MSFA data, once collected, is processed offline using the MD^{2}IP algorithm (Spanos et al., 2024b), a training-free demosaicing technique based on Deep Image Priors. MD^{2}IP

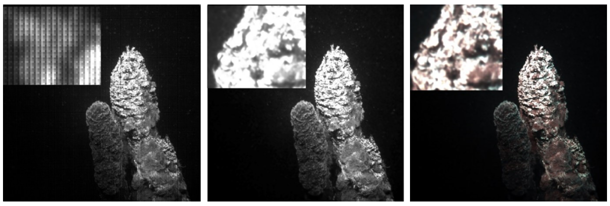

Figure 3. Example of multispectral demosaicing of underwater images using MD^{2}IP, showing the original MSFA image (left), together with the corresponding full-resolution panchromatic (middle) and RGB images (right).

upscales each low-resolution spectral band to the sensor's full resolution (2048 × 2048), as can be seen in Figure 3. This enables high-fidelity reconstruction of underwater spectral imagery without the need for ground truth datasets, a key advantage in marine environments where such data are very difficult to obtain, also due to wavelength-dependent attenuation.

5.3 Post-Processing and Restoration

In post-processing, the system applies several restoration and enhancement techniques to address the unique challenges of underwater imagery. A core component developed by our group is StreamUR (Antoniou et al., 2024), a near real-time, physics-informed restoration framework based on a MIMO-UNet architecture (Cho et al., 2021). This method corrects for underwater-specific distortions such as color attenuation and backscatter. In addition, we implement channel-specific denoising and normalization during MSFA post-processing, a standard practice in spectral imaging, to improve signal-to-noise ratios prior to 3D reconstruction or classification. These methods are applied offline, allowing computationally intensive algorithms to be executed on more powerful systems after deployment. They serve as a critical preprocessing step before visualization or modeling, particularly when generating composite multispectral 3D reconstructions.

6. Testing and Field Deployment

The THEIA system underwent its first field deployment as part of the SANTORY project, focusing on the active Kolumbo submarine volcano, located approximately 8 km northeast of Santorini Island. Kolumbo is a significant geological structure within the South Aegean Volcanic Arc, characterized by a 3 km wide crater and active hydrothermal vents at depths around 500 meters.

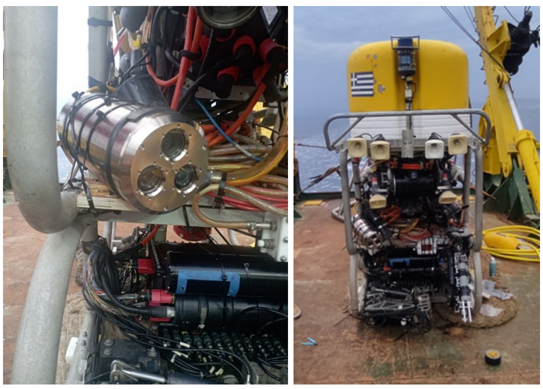

Figure 4. THEIA camera system, mounted on the Max Rover ROV of HCMR, during the field operations at Kolumbo.

6.1 Lab Testing and Preparation

The THEIA camera system prototype was tested and calibrated in an underwater tank. Color fidelity with respect to object distance in the waters was assessed using a 4 × 6 colorchecker board. Calibration was performed in the underwater tank environment regarding camera configuration and internal parameters using a planar chessboard pattern. Regarding the stereo camera specifically, stereo calibration was performed, enabling accurate rectification and disparity estimation. Using the same calibration sequence, the internal parameters of the MSFA camera and its pose with respect to the stereo camera, are recovered. The calibration is considered fixed per deployment and ensures that depth information remains consistent and reliable throughout the mission.

As part of the laboratory evaluation, we also conducted long-duration submersion tests to assess the watertight integrity of the housing. The system was submerged for extended periods to simulate real deployment durations. During these tests, issues were revealed with the housing's waterproof integrity, specifically micro-leaks at the glass interfaces. These were resolved through mechanical refinements to the sealing design prior to the Kolumbo dive, ensuring the system's reliability under operational conditions.

6.2 Deployment Platform and Integration

THEIA was deployed using the ROV Max Rover (see Figure 4), operated by the Hellenic Center for Marine Research (HCMR). This work-class ROV is rated for depths up to 2000 meters and is equipped with advanced navigation systems, including USBL positioning, providing precise georeferencing for each frame captured during the mission. THEIA was mounted on the ROV's frame, facing towards the region between the ROV manipulators. This configuration allowed operators to adjust the captured scene easily as this region is also covered from the ROV's main navigation camera, facilitating targeted data collection of specific seafloor features, such as hydrothermal vents and other geological formations.

6.3 Lighting and Visibility Conditions

Illumination during the dive was provided by the ROV's onboard lighting system. The Max Rover is equipped with multiple high-intensity lights, including two 100-watt HID lights and four 150-watt quartz lights, delivering sufficient illumination for imaging tasks at depth. These lighting conditions ensured adequate visibility for both the stereo and multispectral cameras, allowing the capture of high-quality imagery despite the challenging underwater environment.

6.4 Operational Depth and Environment

The deployment reached depths of up to 500 meters, insider the crater floor of Kolumbo. The area is known for its high hydrothermal activity (Kilias et al., 2013), including the venting of metal-rich fluids and the presence of polymetallic sulfide hydrothermal vents. The ROV's lighting system effectively mitigated the low-light conditions at these depths, allowing for clear imaging of the seafloor and hydrothermal structures.

6.5 Data Acquisition and Streaming

As previously described, the system was deployed on the Max Rover ROV during the dives at the Kolumbo underwater volcano and operated in autonomous mode. THEIA was connected to the ROV communications hub, allowing to monitor its

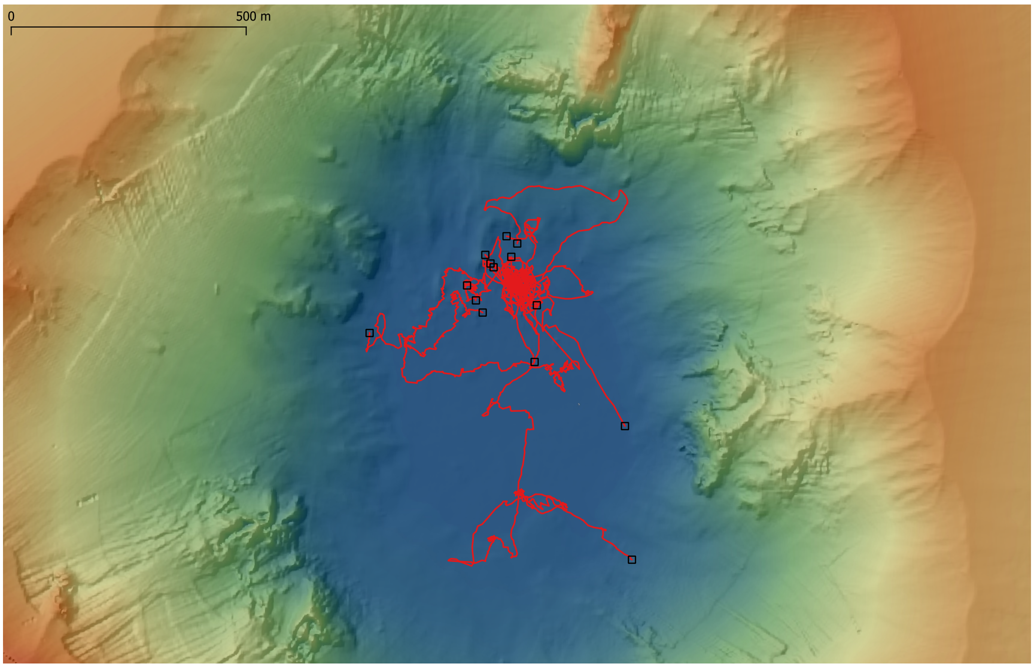

Figure 5. Trajectories of ROV inside the Kolumbo crater, along which data from THEIA were captured.

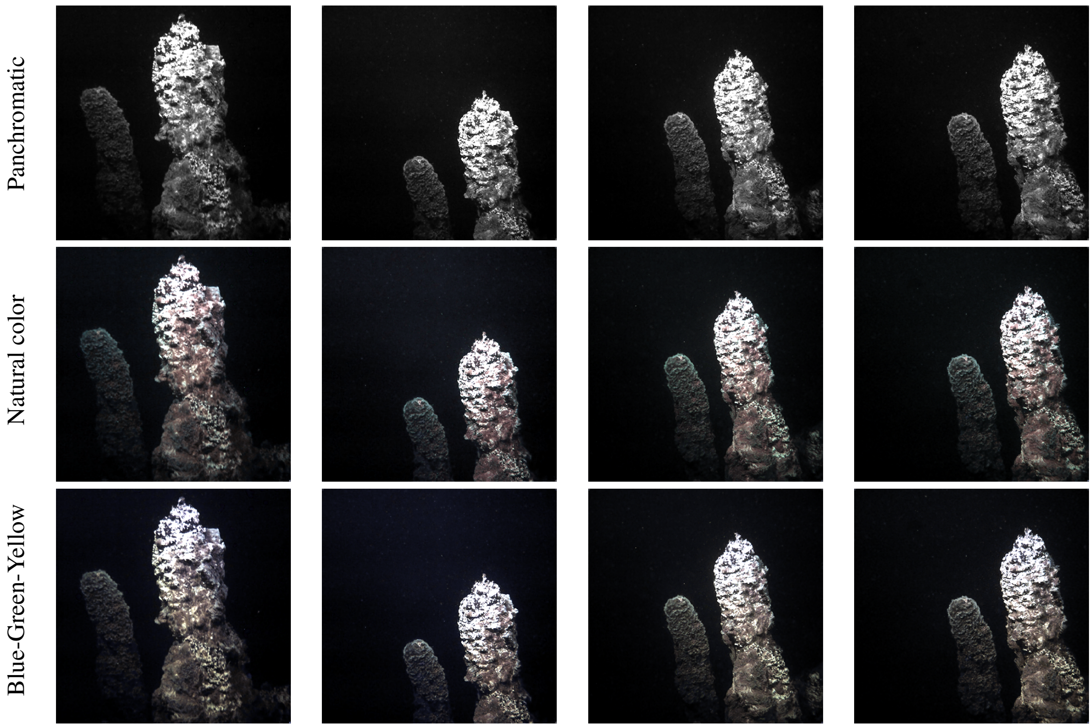

Figure 6. Panchromatic (top row), natural color composite (middle row), and false color composite (bottom row) images of a hydrothermal vent in the active area of Kolumbo volcano.

operation and stream the captured images to the surface vehicle during operation, demonstrating its capability for autonomous field deployment in deep-sea environments.

6.6 Duration and Date

Data acquisition took place over two days, specifically on the 13rd and 14th of June 2023, during which a total of nine dives were conducted. The ROV remained underwater for approximately 8.5 hours on the first day and 6.5 hours on the second, totaling 15 hours approximately of underwater operation. The trajectories followed by the ROV during these missions are illustrated in Figure 5.

6.7 Data Volume

The total volume of data collected during the mission was approximately 4TB, with the majority generated by the stereo cameras due to their higher capture rate and resolution. However, a substantial portion of this data corresponds to transit periods, such as navigation from the surface to the seafloor and vice versa, limiting the volume of mission-relevant data to a smaller, usable subset.

6.8 Preliminary Results

Figure 6 presents panchromatic and color composite images generated from the captured multispectral data,selected to support downstream analysis and visualization, tailored to highlight specific features relevant to hydrothermal vent environments and to address the unique imaging challenges encountered in deep-sea conditions.

The panchromatic image, captures reflectance across the visible spectrum, offers high spatial resolution and is particularly valuable for structural feature extraction and for feeding into 3D reconstruction where spectral fidelity is less critical than geometric accuracy.

The natural color composite, built based on the *Red-Green-Blue* spectral bands, replicates the visual appearance of scenes as perceived by the human eye, making it an intuitive reference point, aiding both expert interpretation and communication with broader audiences.

Additionally, the *Blue-Green-Yellow* composite exploits the Blue and Green spectral bands, as the ones that exhibit the least amount of absorption, hence enhancing visual clarity and allowing clearer imaging at depth. At the same time, this combination aims to enhance the visibility of mineral deposits and bacterial mats associated with hydrothermal vent activity, with the yellow band improving the differentiation of surface textures and chemical deposits commonly found near vent structures.

Regarding 3D reconstruction of the hydrothermal vent scene, Figure 7 presents synthetic views corresponding to different vantage points around the vent, generated by using the 3D model of the hydrothermal vent constructed using 3D Gaussian Splats.

7. Discussion

The field deployment of THEIA during the SANTORY mission offered valuable insights into both the capabilities and limitations of the system, particularly in relation to long-term underwater operation and environmental robustness.

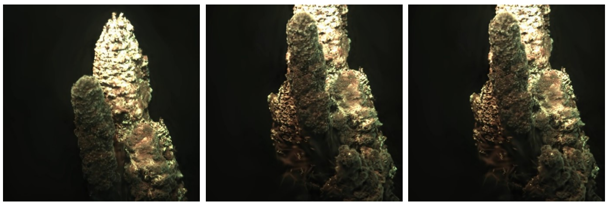

Figure 7. 3D reconstruction of a hydrothermal vent in Kolumbo. Each image is reconstructed from a different vantage point.

7.1 Imaging and Processing Pipeline

Both the multispectral and stereo imaging systems performed stably under operational pressures and temperatures. The depth maps produced by the stereo subsystem were consistent and multispectral images captured spectral bands with adequate signal quality. The post-processing pipeline, worked reliably with the collected data, confirming its robustness on real-world, noisy underwater inputs. Storage and data transfer systems also functioned as expected, with no observed data loss or bottlenecks during continuous acquisition.

7.2 Mechanical and Material Performance

During the initial missions, no leakage, pressure-related failures, or major mechanical issues were observed. However, an important concern arose post-recovery as visible material degradation was detected on parts of the housing, even though the system had been submerged for no more than 15 hours in total. The likely cause of this degradation is a chemical interaction between hydrothermal vent emissions and the aluminum alloy components. Similar forms of corrosion and material wear have been reported in other deep-sea deployments conducted near active hydrothermal vents, suggesting this is a known risk in such chemically aggressive environments.

7.3 Future Directions

Moving forward, our goal is to develop THEIA into a fully autonomous underwater imaging system capable of real-time or near-real-time integration of spectral and depth information. Central to this advancement is the on-line spatial and temporal alignment of multispectral outputs with stereo-derived depth maps, allowing for the real-time generation of dense, radiometrically accurate 3D models of submerged environments. To achieve this, the processing pipeline will be expanded with advanced modules for spectral upscaling, real-time image restoration, and high-fidelity 3D rendering.

Integration efforts will also focus on the use of dedicated calibrated and possibly adaptive lighting modules (Vasilescu et al., 2010), ensuring radiometric consistency and improved fidelity across reconstructed surfaces, which is essential for applications involving material classification and quantitative analysis.

In parallel, we are exploring improved mechanical designs and materials for the system housing, with a focus on resistance to corrosion and degradation during long-term deployments near hydrothermal vents. These upgrades aim to allow for long-term deployments in challenging underwater environments, such as the one of Kolumbo underwater volcano, enabling broader scientific exploration with minimal human intervention.

8. Conclusions

This paper presented THEIA, a compact underwater imaging system designed to collect both multispectral and stereo visual data in deep-sea environments. Developed within the SANTORY project, the system was deployed at the Kolumbo submarine volcano, where it operated successfully and captured high-quality spectral and depth information under real field conditions.

THEIA combines a robust mechanical design with custom acquisition software, allowing flexible deployment on ROVs. The system performed reliably during the mission, and the collected data support a range of applications in underwater mapping and analysis. Field experience revealed specific areas for improvement, including material durability and future integration of spectral and geometric outputs. Ongoing work focuses on advancing THEIA toward a more autonomous platform for dense, multispectral 3D reconstruction of complex underwater environments.

Acknowledgements

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