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Research Article

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Development And Validation of an Automated Marine Sampler for Environmental Monitoring in Shallow Coastal Ecosystems

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ABSTRACT

This study presents the design, development, and experimental validation of a compact automated water sampler intended for marine environmental monitoring, representing the continuation and expansion of previous work presented at the Marine Technology Workshop (Martech 2025) [1]. The project focuses on fragile coastal ecosystems such as the Mar Menor (Murcia, Spain), a Mediterranean lagoon that has suffered severe eutrophication and biodiversity loss due to decades of nutrient accumulation from agricultural and urban runoff [2].

The progressive and continuous degradation of this ecosystem highlights the urgent need for autonomous, affordable, and high-frequency monitoring technologies. Such systems must be robust enough to operate in shallow, highly dynamic, and vulnerable marine areas.

The proposed device addresses these environmental and technical challenges by integrating mechanical, electronic, and software subsystems into a single, modular structure optimized for precision, autonomy, and reproducibility. The developed system allows the automated and sequential collection of discrete water samples at predefined depths without the need for human intervention during field operations.

The sampler is designed as a complementary subsystem to the µ-Nautilus profiler previously developed at the Polytechnic University of Cartagena (UPCT) [3]. Its integration enables simultaneous measurement and physical sampling, thereby improving spatial and temporal resolution of monitoring campaigns. This synergy provides a more comprehensive understanding of water-column dynamics and nutrient distribution environmental management.

From both a technical and environmental perspective, this sampler represents a significant advancement in the development of effective solutions for the ecological challenges facing the Mar Menor. By enabling the acquisition of high-resolution, depth-specific data, the system ensures precise, real-time monitoring of the lagoon's water column dynamics.

Keywords: Marine Monitoring, Automated Sampling, Mar Menor, Coastal Ecosystems

Introduction

The environmental degradation of the Mar Menor constitutes one of the most significant ecological problems along the European Mediterranean coast. This ecosystem, of great ecological, economic, and social importance, has experienced episodes of severe eutrophication over recent decades due to intensive agriculture and urban practices s in the surrounding area.

This persistent accumulation of nitrates and organic matter has catalysed advanced eutrophication processes, leading to critical hypoxia events and massive mortality episodes among marine fauna [4]. Furthermore, this precarious state is periodically exacerbated by extreme meteorological events, such as severe

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isolated depression at high altitude storms (known as DANAs), which abruptly increase surface runoff and accelerate the catastrophic transport of land-based pollutants directly into the lagoon [5].

In order to improve the environmental conditions of the Mar Menor, the Polytechnic University of Cartagena (UPCT) has developed lightweight, self-contained, submersible profilers' systems that forms a marine measurement network for monitoring parameters in the Mar Menor [3].

However, while *in situ* sensors enable high-frequency temporal monitoring, the precise quantification of specific chemical compounds still requires laboratory analysis. This is particularly evident in the case of dissolved nutrients, such as nitrates, where measurement via in situ sensors is constrained by significant technical or economic limitations.

Under these critical scenarios, or upon the real-time detection of atypical parameter concentrations, acquiring physical water samples becomes essential to conduct detailed chemical characterizations and precisely evaluate the true state of the ecosystem.

Materials and Methods

The proposed device addresses these challenges by integrating mechanical, electronic, and software subsystems into a single, modular structure optimized for precision, autonomy, and reproducibility.

Mechanically, the system consists of four 60 mL syringes arranged radially and actuated by a lead-screw transmission system coupled to a cam–follower selector. This configuration allows the sequential collection of discrete water samples at predefined depths without the need for human intervention. The motion is generated by two stepper motors, one for actuation and another for sample selection, providing fine control and mechanical reliability.

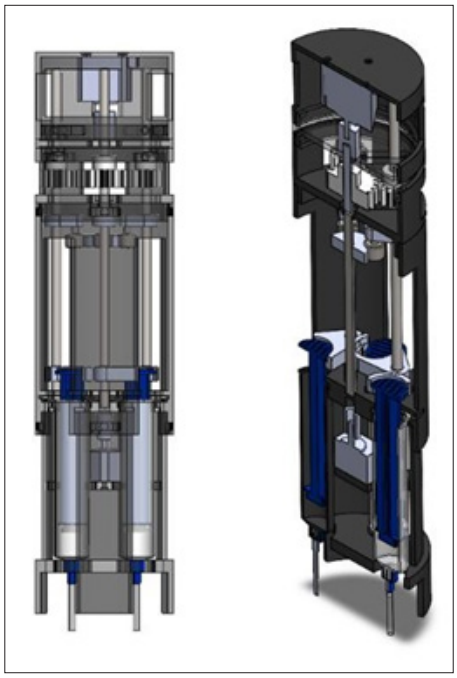

Figure 1: Sectional view of the sampler

The control architecture is based on open-source electronics centred on an ESP32 microcontroller, integrated with temperature, humidity, and pressure sensors. These sensors operate in combination to provide an accurate assessment of the system's operating conditions. Pressure measurements are used to estimate the system depth throughout operation, while temperature and humidity data provide complementary environmental information.

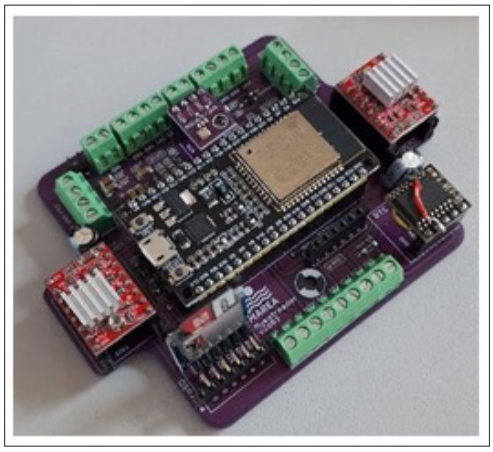

Figure 2: Sampler's Electronics

Additive manufacturing was employed to fabricate the mechanical housing and structural components, reducing both production costs and assembly time.

The developed water sampler has been designed to operate in two different modes depending on the monitoring requirements. In standalone mode, it can be deployed independently to collect physical water samples from defined locations within the marine environment, making it suitable for routine monitoring campaigns or targeted sampling missions.

Figure 3: Inner and outer view of the sampler

Alternatively, the sampler can operate in conjunction with the profiler previously developed by the UPCT. In this configuration,

physical water samples are collected simultaneously with the in situ measurements acquired by the profiler. This enables the direct association of laboratory analyses performed on the collected samples with the environmental parameters recorded at the same location and depth, facilitating a more comprehensive characterization of the Mar Menor.

Figure 4: Profiler and sampler

Results

The developed water sampler was successfully validated under controlled operating conditions, demonstrating reliable autonomous performance throughout the sampling process. As shown in the Figure 5- Graphic of validation process depth-time, the system consistently executed the predefined sampling sequence, reaching the programmed depths and collecting water samples without operator intervention. The pressure sensor provided continuous depth estimation, allowing the activation of the sampling mechanism at the desired locations within the water column.

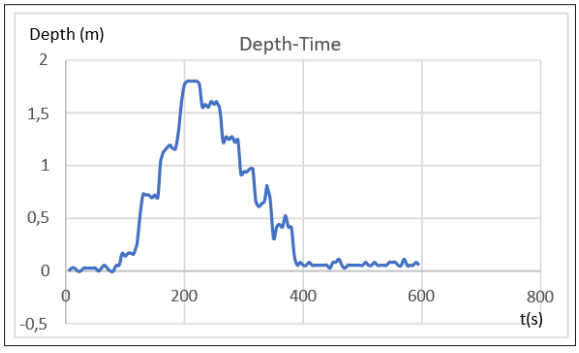

Figure 5: Graphic of validation process depth-time

From a mechanical perspective, the modular architecture proved to simplify both assembly and maintenance. The use of additively manufactured components enabled rapid fabrication and straightforward replacement of individual parts without requiring modifications to the remaining structure. In addition, the lightweight construction facilitated system handling during deployment and retrieval, making the platform suitable for field operations.

Finally, the proposed system represents a reproducible and cost-effective solution for marine water sampling. The use of open-source electronics together with additively manufactured components significantly reduces manufacturing costs compared with conventional commercial systems, while maintaining the flexibility required to adapt the platform to different monitoring scenarios. Furthermore, the dual operating mode allows the sampler to be deployed either as a standalone platform or integrated with the profiler, enabling the correlation of in situ environmental measurements with laboratory analyses of physical water samples collected at the same location and depth.

Discussion

The experimental validation demonstrates that the proposed automated sampler provides a practical solution for collecting discrete water samples in shallow coastal environments while maintaining a compact and modular design. The reliable operation observed during the tests confirms the suitability of the proposed mechanical and electronic architecture for autonomous underwater sampling applications.

One of the main contributions of the developed system is its ability to complement continuous environmental monitoring platforms. While in situ sensors provide high-frequency measurements of physical parameters, they are often unable to directly determine specific chemical compounds that require laboratory analysis. By enabling synchronized water sampling at predefined depths, the proposed device allows laboratory results to be directly associated with the environmental conditions recorded at the same location and time. This capability is particularly relevant for monitoring eutrophication processes and nutrient dynamics in vulnerable ecosystems such as the Mar Menor.

Conclusion

The developed automated water sampler represents a valuable contribution to marine environmental monitoring by enabling the autonomous collection of discrete water samples at predefined depths. Its reliable operation under submerged conditions demonstrates the feasibility of combining a compact mechanical architecture to provide an effective sampling platform for shallow coastal environments.

The proposed system offers a lightweight, modular, and cost-effective solution that can be easily adapted to different monitoring scenarios. Moreover, its capability to operate either as a standalone device or in combination with the profiler allows laboratory analyses to be directly correlated with in situ environmental measurements. This integrated approach provides a more complete characterization of water-column dynamics and supports more informed assessment of ecosystem health.

Overall, the proposed sampler constitutes a practical tool for monitoring fragile ecosystems such as the Mar Menor and establishes a flexible platform for future developments in autonomous marine observation systems.

Acknowledgements

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