µ-NAUTILUS, AN AUTONOMOUS LIGHTWEIGHT PROFILER WITH DEPTH CONTROL AND CONFIGURABLE SAMPLING TIME

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Abstract: Coastal lagoons, such as Mar Menor, hold significant ecological importance but are vulnerable to environmental disruptions from resource exploitation. Continuous monitoring is crucial for understanding critical situations and assessing recovery efforts. Manual sampling, as used in Mar Menor, is costly and yields limited results. Therefore, demand exists for automatic methods to enhance data collection and reduce operational tasks. This paper presents the design of a compact autonomous submersible profiler, µ-Nautilus, building upon the previous s-Nautilus model. It weighs 11 kg, which is half the weight of its predecessor. µ-Nautilus aims to stop at a configurable depth with less than 20 cm depth error using a single 750 cm^3 ballast tank for control. Cascade control is employed, and satisfactory depth control (±15 cm error) is obtained during tests at sea. µ-Nautilus is powered by batteries with a capacity of 12.8 Ah and 11.1 V to run the ballast tank and 16.75 Ah and 3.6 V for the rest of the electronics. It can operate autonomously for 48 days performing cycles every 6 hours, suitable for the cleaning frequency needed due to fouling in Mar Menor.

Keywords: profiler, sensor platform, WSN, depth control, Mar Menor

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Introduction

The monitoring of marine environments is currently experiencing a period of significant growth, driven by the need to better understand the behavior of these ecosystems and address the environmental challenges they face. A prominent case is the Mar Menor, the largest hypersaline coastal lagoon in Europe where various agricultural, economic, and touristic activities converge.

The Mar Menor provides numerous ecosystem services to society, including significant fisheries, extensive tourist and recreational activities on its beaches, and a variety of nautical activities supported by numerous marinas and extensive urban developments. However, the basin that feeds into the Mar Menor hosts one of most technologically advanced agricultural sectors of Europe, characterized by intensive cultivation and high economic yields. Over the years, this intensive agriculture has resulted in an excess of nitrogen in the aquifer. Consequently, during the rainiest seasons, such as in recent years, there has been an increase in the discharge of groundwater laden with nitrates, leading to severe eutrophication episodes like the one in 2016 and subsequent events such as the mass fish mortality incidents in 2019 [8] and 2021, each resulting in over five tons of dead organisms, significantly impacting the biodiversity of the lagoon. These environmental crises have led to declines in fisheries [10] and considerable depreciation in housing prices in the area [4], [5]. However, spurred by citizen mobilization, the Mar Menor has achieved a significant milestone in Europe by being granted rights of personhood, recognizing the lagoon's right to exist as an ecosystem and evolve naturally, as well as its rights to protection, conservation, maintenance, and restoration [9].

To address the challenges of protection and restoration the importance of continuous and detailed monitoring of the Mar Menor lagoon has been recognized. In the Mar Menor monitoring programs, data collection has been carried out manually at different points in the lagoon on a weekly basis [1]. However, this approach has limitations in terms of human and economic resources. In addition, the low sampling frequency makes it difficult to draw clear conclusions and to develop predictive models for the hydrodynamic behavior of the lagoon.

In response to these limitations, the s-Nautilus profiler was developed [6]. It is an autonomous device designed to continuously monitor a variety of environmental parameters along the water column. This profiler uses a ballast system to change its depth, allowing it to take measurements along the water column, from the bottom to the surface. However, this s-Nautilus profiler is not capable of stopping at a specific depth. In addition, the size and weight of this profiler (21 kg) requires at least two operators to transport and install it.

The stratification of the marine water column [3] requires instruments capable of stopping at specific depths to obtain precise and stable measurements of environmental parameters. This capability is crucial for a better understanding of oceanographic processes and interactions between different components of the marine ecosystem.

Therefore, the aim of this work is to design an improved and miniaturized version of the profiler, called μ-Nautilus. This new device will retain the basic capabilities of the previous model but will focus on improving its size and weight to facilitate its transport and deployment in the field by a single operator. In addition, the μ-Nautilus will be designed to stop precisely and stably at specific depths for a configurable period of time, using ballast tanks as the only control action. This approach will enable more precise and detailed measurements of environmental parameters along the water column, improving our understanding of the marine ecosystem and our ability to manage it effectively.

This paper presents the methodology used to design the profiler and control its depth. In addition, the resulting profiler and its characteristics are presented, as well as the results obtained in terms of control. Finally, a detailed discussion is given, and the conclusions drawn from the results obtained are presented.

Materials and Methods

Profiler design

The profiler discussed in this paper has been designed to meet specific monitoring needs in the marine environment. It builds on the fundamental capabilities of its predecessor, the s-Nautilus profiler.

On the one hand, it requires adaptable specifications to be able to measure various physical parameters and accommodate different sensors, such as dissolved oxygen, temperature, and electrical conductivity, among others. Additionally, it must support a data transmission protocol and have a communication design that ensures knowledge of the lagoon status in near real time. Firstly, Wi-Fi communication will serve as the conduit for operator-profiler interaction, allowing for the adjustment of operational parameters. Secondly, Sigfox communication will facilitate the transmission of recorded measurements to a server.

To address logistical concerns regarding the maintenance of the lagoons, it is necessary to set a minimum autonomy of three weeks. This will ensure minimal human intervention, while allowing for the necessary maintenance to be carried out on the sensors, which are prone to fouling in the Mar Menor. Consequently, the mechanical, electronic and software design are emphasized by energy autonomy specifications.

In terms of mechanics, the design must ensure isolation, withstand pressures of up to two bar, and use readily available components to ensure replicability and cost-effectiveness.

Finally, the entire design has been based on the objective of achieving a lightweight, compact profiler for the purpose of facilitating transport and installation by a single operator. Consequently, the design of the s-Nautilus predecessor has been reduced to half the weight.

On the other hand, the operational mode of this profiler is based on a sequence of states. State 0 represents the initial deployment phase, during which the profiler should be situated on the surface with the ballast tank empty and Wi-Fi communication activated to allow the user to initiate the operational cycle. Upon activation, the date and time are updated via Sigfox, Wi-Fi is deactivated, and State 1 is initiated. At this state, the profiler initiates the immersion process by filling the ballast tank. Upon reaching the bottom, the power sources are deactivated, and the microcontroller enters a deep-sleep mode, transitioning to State 2. During State 2, the profiler remains stationary on the seabed for a predetermined period, with all functions deactivated to minimize energy consumption. Upon the expiration of this period, the profiler transitions to State 3. In State 3, the power sources are activated to preheating the sensors for measurement, and the profiler initiates the control cycle. The device measures a series of parameters at various locations: at the seabed, rising to each set depth, and finally at the surface. Subsequently, in State 4, the tank remains empty, and Wi-Fi communication is reactivated to allow the user to adjust control parameters if necessary. The sensor measurements are transmitted via Sigfox. Subsequently, the cycle commences once more in State 1.

Control design

To design a depth control system, it was determined that it would be inadvisable to use actuators that must be installed externally on the profiler structure, such as thrusters [7]. This is because this type of actuator requires frequent maintenance as a result of the prevalence of fouling in the Mar Menor. Therefore, depth control will be achieved using Variable Ballast Systems (VBS).

The μ-Nautilus profiler is equipped with a single ballast tank, specifically the Kolbentank XP750-12V 540 from Alexander Engel KG (Richard-Wolf-Str. 2, D-75438 Knittlingen, Germany), with a capacity of 750 cm^3. The time required for the piston to complete a full stroke is 18 seconds [2].

The system modelling considers the different principles that influence the process: Archimedes' principle, hydrodynamic forces, and the weight of the profiler together with the ballast in the tank.

The thrust generated by the external geometry of the profiler and its weight are known. The force exerted by the ballast at each moment is determined by the piston position measured by a Hall Sensor for Compact Tank Switch CTS2.2 from Alexander Engel KG (Richard-Wolf-Str. 2, D-75438 Knittlingen, Germany).

With a total of 388 pulses in a complete stroke and a piston length of 0.2 m with a cross-sectional area of 0.00375 m^2, the force exerted by the tank can be modelled in Formula 1.

$$F(t) = \rho_w \cdot \frac{p(t) \cdot V_{max}}{p_{max}} \cdot g \qquad 1$$

where ρ_w is the density of water, V_{max} is the maximum volume of the tank calculated over the piston length and cross-sectional area, p_{max} is the maximum number of pulses per stroke, $p(t)$ is the number of pulses in each time interval t, and g is the gravitational constant.

The control method exhibits a slow response due to the sluggish action of the piston when introducing or expelling ballast (approximately 18 seconds per stroke). It is crucial to limit the piston travel around the neutral buoyancy point to minimize overshoots.

Given the inherent inertia of ballast control, a cascade control scheme has been designed, comprising three control loops from the innermost to the outermost: piston position, speed of the vertical component of the profiler and depth, respectively. The piston position controller operates in three states: fill, empty, or stop. The velocity and depth controllers of the profiler are PID controllers with saturation limitation, which prevents outputs from exceeding system limits.

The Figure 1 represents the cascade control described.

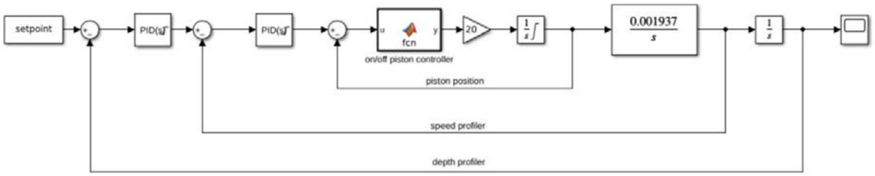

Figure 1 – Cascade control implemented in the µ-Nautilus profiler for depth control.

Energy consumption tests

The application of this profiler will focus on the performance of complete cycles (see “Profiler design” in this section) every six hours. These will comprise measurements of the seabed at four intermediate depths and at the surface.

The ballast tank is powered directly by four 3S Lipo batteries with a capacity of 3200 mAh and a voltage of 11.1 V 80C from Zee Power CO., Limited (Lucky Centre, Wan Chai, Hong Kong).

The electronic board is powered by five 1S Li-Ion batteries with a capacity of 3350 mAh and a voltage of 3.6 V from LG CHEM (Yeongdeungpo-gu, Seoul, South Korea).

To determine the autonomy of the profiler, it was decided to perform complete cycles continuously while controlling at four intermediate depths. By determining the number of completed cycles, it is possible to establish the autonomy of the profiler in real conditions, which include the performance of cycles every six hours.

Testing methodology

The design of the controllers is achieved using MATLAB simulation software. Furthermore, to ascertain the efficacy of the µ-Nautilus profiler and the depth control response in a real-world setting, a test tank was installed at the Polytechnic University of Cartagena facilities to perform preliminary testing. The diameter of the tank is 0.5 meters, with a maximum depth of 2 meters. Subsequently, the dynamic behavior of the profiler was validated in the sea at the Real Club de Regatas de Cartagena (Spain) facilities.

Results

Structural results

The resulting profiler exhibits a set of key physical attributes, including a weight of 11 kg, a minimum diameter of 50 mm, and a maximum diameter of 250 mm for the main body. Additionally, the profiler has a maximum height of approximately 819 mm, which includes a lower structure functioning as a landing platform, elevating the bottom of the profiler by 88.6 mm. This design element serves to prevent equipment damage and minimizes impact with underwater flora.

The external structure has been fabricated using commercial PVC pressure components. Additionally, other components have been created using PLA through a 3D printer. These include mounts for external sensors mounted on the outside of the profiler, as well as an internal structure housing various electromechanical component, such as the power supply, the ballast tank for depth adjustment, a control electronic board, and a communication antenna.

Figure 2 depicts the external and internal design of the µ-Nautilus profiler.

Figure 2 – External and internal architecture of the µ-Nautilus profiler.

Depth control results

The tests were conducted in both a test tank and in the sea at the Real Club de Regatas de Cartagena. However, for the sake of brevity, only the results obtained are presented for the latter scenario with more challenging conditions.

Figures 3-5 present the control results obtained at the Real Club de Regatas.

Figure 3 illustrates the depth evolution when control was applied at 4.5, 3.5, 2.5, and 1.5 meters, with each setpoint established for 120 seconds.

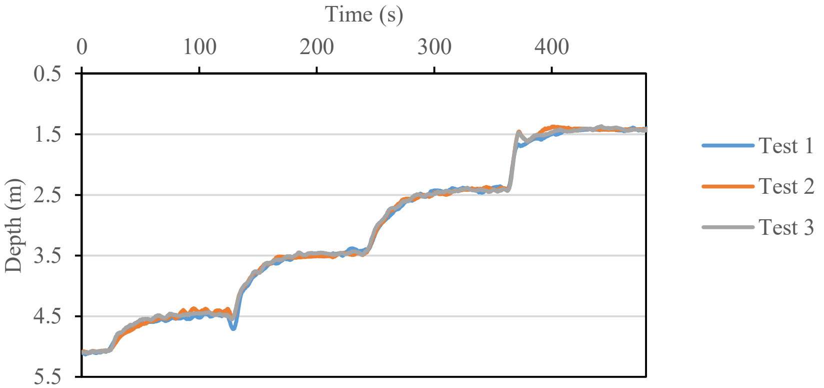

Figure 3 – Depth evolution for 4.5, 3.5, 2.5, and 1.5 meters, setting each setpoint for 120 seconds.

The user is afforded the option of configuring the dwell time at each depth. To reduce energy consumption, it was determined that once the profiler reached the setpoint within the established error range, it would remain at that depth for 20 seconds. This configuration allows a reduction of time for the actuator operation if the prevailing environmental conditions are optimal. The outcomes of this type of control are presented in Figure 4.

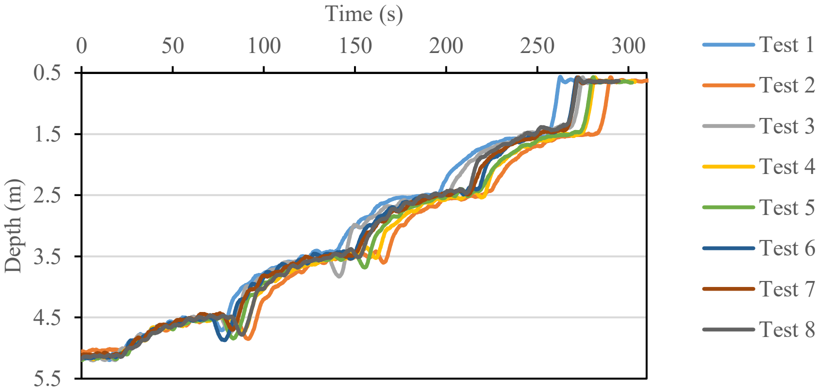

Figure 4 – Depth evolution for 4.5, 3.5, 2.5, and 1.5 meters, remaining at each setpoint within the error range for 20 seconds.

Figure 5 illustrates the absolute depth error in relation to the established setpoint over the past 20 seconds of control at each depth level.

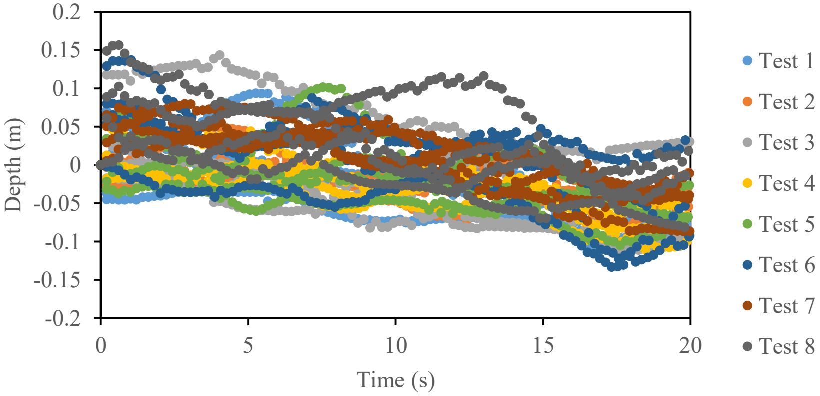

Figure 5 – Depth error obtained during the last 20 seconds of control.

Discussion

The utilization of commercial PVC pressure components for the external structure of the μ-Nautilus profiler confers flexibility upon future design modifications, while simultaneously reducing the associated costs. Furthermore, this design allows for the simultaneous disassembly of all components, thereby simplifying maintenance procedures.

The dimensions and weight of the μ-Nautilus profiler permit its transportation and installation by a single operator, thereby facilitating its deployment and enabling the rapid replacement of profilers when necessary for maintenance.

Furthermore, the more compact profiler with a single ballast tank is less costly in terms of materials than the s-Nautilus profiler.

Regarding control, Figures 3 and 4 illustrate the satisfactory and configurable depth control of the profiler. It was determined that once the profiler reaches the setpoint within the specified error range, it should remain at that depth for 20 seconds to minimize energy consumption, as illustrated in Figure 4.

This dwell time was selected as it is considered sufficient to allow for the precise capture of the marine parameters of interest, although it can be adjusted according to the specific requirements of the application.

Figure 5 illustrates that the depth error remains within the range of ±15 cm. Both the dwell time at the setpoint and the error range are configurable. However, prolonging periods at a specific depth or reducing the error margin will entail longer actuator activity, thereby increasing energy consumption and decreasing the autonomy of the profiler.

Further research has determined that a control for four intermediate depths and provided with four batteries of 3200 mAh and 11.1 V to run the ballast tank and five batteries of 3350Ah and 3.6 V for the rest of the electronics, the profiler can complete 192 cycles. Given that these devices will be deployed in the Mar Menor for sampling every six hours, the 192 cycles represent an autonomy of 48 days. This time is more than enough considering that it is recommended to clean the sensors every three weeks due to the predominant fouling in the Mar Menor. It is important to note that, while the tests were conducted in a real environment, it was protected and experienced fewer disturbances than those encountered in the Mar Menor. Consequently, further study is required to elucidate the control dynamics in the actual application environment.

Conclusion

This study is concerned with the development of the autonomous profiler μ-Nautilus, which has been designed to operate in shallow environments such as the saltwater lagoon Mar Menor. The reduction in weight and size of this profiler facilitates its transportation and installation, both for laboratory testing and field implementation. Furthermore, the capacity of the profiler to maintain a specific depth enables precise monitoring of marine parameters.

The profiler offers configurable control parameters, including dwell time, depth error, and depth setpoint, as well as operational parameters such as the interval between cycles. This versatility renders it an attractive proposition for the continuous observation of shallow marine environments, which are of crucial importance for the modelling of the hydrodynamics of Mar Menor and the implementation of preventative measures against unfavorable events such as anoxia episodes.

It is important to note that while the results are presented in a real environment, further study of its performance in Mar Menor, the actual application scenario, is still required. This would assist in the determination of its operational dynamics in the real application environment.

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