DIGITAL TWIN OF AUTONOMOUS SURFACE VEHICLES: FROM STANDARD METHODOLOGIES TOWARDS EXTENDED DATA-BASED MODELS

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The development of Autonomous Surface Vehicles (ASVs) has significantly advanced with the integration of digital twin technology. A digital twin serves as a virtual replica of a physical ASV, providing real-time monitoring, analysis, and control capabilities. This work explores the multifaceted nature of digital twin development for autonomous surface vehicles, highlighting the incorporation of modeling and identification techniques for robotic systems, deriving from the standard procedures employed in naval systems following the ITTC guidelines. Furthermore, extended models, including environmental condition reconstruction and prediction, as well as the integration of AI-based methodologies can be developed, on the basis of standard data gathering procedures and exploiting FAIR (Findable, Accessible, Interoperable, and Reusable) data management principles.

Keywords: *ASV, identification and modeling, standard data gathering, aggregated system, evolution prediction*

1. Introduction

Autonomous Surface Vehicles (ASVs) have emerged as valuable tools for various applications, ranging from marine research to surveillance and transportation to environmental observation and climate change tracking. The integration of digital twin technology enhances ASV capabilities in handling harsh, unforeseen, and fast-changing conditions, thus revolutionizing their operational applications and procedures. This work presents an overview of the different approaches involved in developing a digital twin of an ASV, exploiting standard methodologies such as the International Towing Tank Conference (ITTC) identification maneuvers for the characterization of the vehicle performance [1]. Such modeling allows for estimating the current status of the autonomous platform, as well as predicting the behavior in the near future as a function of the operational requests. High-precision digital twin models can be reached by the integration of environmental forecasting models and Artificial Intelligence (AI) algorithms, allowing an aggregated description of the framework and extending the model representation capabilities. All these approaches are evaluated and integrated to obtain a first example of a digital twin of the SWAMP ASV (Shallow Water Autonomous Multipurpose Platform). SWAMP is an autonomous surface robotic platform (see Fig. 1) specifically designed to work in very shallow water [2]. However, thanks to its reconfigurability and modularity characteristics, it has demonstrated its ability to be used in critical environments (like polar or remote areas) and for monitoring and observing the marine environment during numerous experimental campaigns [3].

2. Digital Twin of the Robotic Platform

The basic step to obtain a digital twin of a marine surface platform is to analyze the maneuvering characteristics of the platform and to derive a suitable and reliable model. Such a model is then employed for the estimation/forecasting of the vehicle motion evolution, as well as a knowledge basis to design the guidance and control system

Figure 1: SWAMP ASV

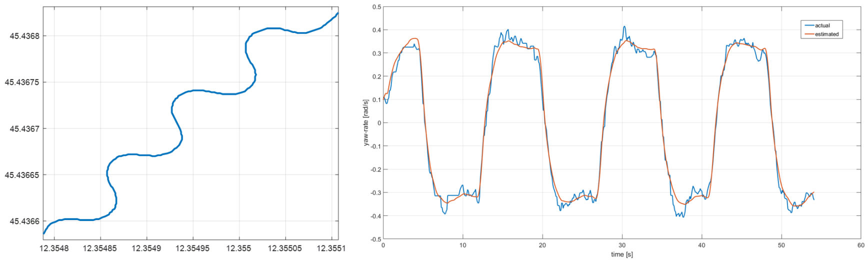

Figure 2: Yaw dynamics modeling of the SWAMP ASV. On the left, a zig-zag maneuver is executed to measure the maneuvering performance. On the right, the raw measurement is compared with the estimated signal generated by the designed mathematical model

needed to provide autonomous capabilities. With the aim of extending the digital twin development process to any general autonomous marine agent, the methodology must rely on standardized processes in such a way as to provide replicable operations. The ITTC procedures are the standard maneuvers widely employed for ship identification at sea and can be directly applied to such autonomous platforms, with appropriate adaptations related to the specificities of this class of robotic vehicles. Additionally, applying ITTC standard maneuverability procedures to groundbreaking marine technology supports the uptake of robotic sea vehicles in observational and commercial employments. These results are particularly important when a new vehicle is headed to operate in cooperation or in the proximity of commercial vessels. Moreover, the development of a digital twin for SWAMP will ensure the accurate planning and environmental mindfulness required when operating in pristine areas, whether these are located in the polar regions or simply in Marine Protected Areas (MPAs). The evaluation of the maneuvering performance is exploited to tailor-design a mathematical model able to represent such maneuvering characteristics with proper accuracy; an example of yaw dynamic modeling of the SWAMP ASV is reported in Fig. 2. The latter procedure is applied to all the measurable entities related to the vehicle motion capabilities so that the digital twin complete model embeds the global characteristics of the autonomous platform.

3. Data Management for Extended Digital Twin

Since the digital twin of an ASV relies on a vast amount of data collected from various sensors and systems, in order to provide data integrity, accessibility, and interoperability, a consistent data management approach must be employed. For such a reason, the data management guiding principles known as FAIR (Findable, Accessible, Interoperable, and Reusable) [4] are exploited. The principles emphasize machine-actionability (i.e., the capacity of computational systems to find, access, interoperate, and reuse data with no or minimal human intervention), so that, if data are consistently gathered and tagged, computer-based systems can automatically aggregate the information, providing extended digital models. To this end, work is underway [5] to extend the SWAMP management architecture for data acquisition, both robotic and environmental, producing "FAIR by default" data. With this ambitious definition, we refer to the practice of developing procedures for data acquisition, management, and sharing integrated from the beginning into the design and operation of the robot. A first example of an automated procedure, allowing to transform raw data into standard data format, characterized by a high level of fairness, already containing the necessary metadata to understand and reuse them, with a few simple steps was implemented and tested for SWAMP. FAIR data management facilitates a seamless integration of data coming from different sources, enhances simulation capabilities, and enables more effective decision-making for optimizing the performance and operational adaptation of the SWAMP, including the development of an extended digital twin of the robotic platform, relying on data-based models. Thanks to data standardization, the digital twin can be validated against real-world scenarios, utilizing historical data, sensor observations, and environmental forecasts. This validation process ensures that the digital twin accurately represents the ASV's behavior, accounting for both internal and external factors. Furthermore, it supports collaboration and data sharing, driving innovation and advancements in autonomous surface robotic platforms thanks to the reliability of the corresponding digital twins.

The further outcome of FAIR-based data acquisition is the availability of a number of compatible data sets that can be integrated to enhance the modeling of both the autonomous platform and its sensors and the operational environment in an aggregated way. With this approach in mind, it would be possible to predict the evolution of the system as a whole, virtualizing the presence of the operators while at the same time increasing the promptness of the interventions. For instance, imagining the periodic observation of a coast of sandy beaches subject to strong storm surges, the development of an extended digital twin will allow the design of proper patrolling and data gathering schedules, focusing on the most sensitive spots in the area of interest (on the basis of the environmental evolution prediction) and the subsequent autonomous execution of monitoring of bathymetry evolution and sediment displacement by means of the ASV.

As a final step, beyond the current state of the art, the integration of AI-based methodologies for data analysis and performance improvement is under investigation. AI-based decision support systems are currently advancing at a hectic pace, revolutionizing the way humans interact with computer-based systems. A preliminary experiment focused on learning-by-imitation control of SWAMP ASV was carried out and provided encouraging results as reported in [6]. Finally, a high-level decision system can be developed in order to schedule and control the employment of one or more ASV, collecting environmental data and, in real-time, re-planning the operations on the basis of the online predicted evolution of the overall systems based on both the information gathered as well as on the forecast obtained from the extended digital twin. The ASV can leverage its digital twin to perform a task replanning. This consists of modifying the original mission in case of changes in the initial conditions. For example, if the battery is draining faster than expected due to currents, winds, or obstacles, the digital twin can estimate the remaining consumption and decide how to complete the mission. The AI-based decision support system together with a digital twin can replan in an efficient and effective way, that is, minimizing the energy costs and the navigation times and maximizing the satisfaction of the mission criteria. In this way, the vehicle can evaluate different alternatives and choose the best one based on predefined criteria.

ACKNOWLEDGMENTS

This work is developed within the framework of the National Recovery and Resilience Plan (PNRR), RAISE-Robotics and AI for Socioeconomic Empowerment, and the Horizon Europe Twinning Project MONUSEN - Montenegrin Centre for Underwater Sensor Networks.

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