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INSTIGATING MARITIME STUDIES VIA RAPID PROTOTYPING AND ROBOTICS: A CASE FROM THE SMARTBOAT INITIATIVE

Pedro Teodoro, Rosa Marat-Mendes, Mário Assunção, Nuno Alves[1], Beatriz Sanguino[2], Henrique M. Gaspar[2]

[1] Department of Marine Engineering, Escola Superior Náutica Infante D. Henrique, Portugal
Email: pedroteodoro@enautica.pt

[2] Department of Ocean Operations & Civil Engineering, Norwegian University of Science & Technology, Norway
Email: henrique.gaspar@ntnu.no

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ABSTRACT

A case on rapid prototyping is presented in this work to exemplify the use of *learn, make and share* activities to promote maritime studies. SMARTBOAT is an initiative from the Escola Superior Náutica Infante D. Henrique, in Portugal, where students are invited to interact with computer-aided design modelling, additive manufacturing and programming. Such initiative is paramount to instigate and promote higher education studies in science, technology, engineering, art, and mathematics (STEAM). The initiative is presented and discussed, with its main steps and schemes. A step forward is later discussed by the ongoing collaboration with the Norwegian University of Science and Technology (NTNU, Norway), which intend to combine the Portuguese case with recent advancements in robotics and digital twin, such as remote operation via internet of things protocols and web-based tools. The work ends with a discussion on the results and future works on autonomous shipping, as well as a call for the development and sharing of similar initiatives.

MARITIME TRANSPORTATION CHALLENGES & PROMOTING MARITIME STUDIES

Maritime transportation plays a main role in global trade, being responsible for more than 80% of all transactions worldwide. Nowadays the maritime industry faces several challenges, namely restrictions on decarbonization efforts, digitalization, automation, energy efficiency, safety, and environmental protection (UNCTAD 2022). Efficiency in energy usage is a growing concern as fuel costs increase and regulations become tight. The industry must find ways to optimize energy usage while also reducing emissions (Fan et al. 2019). Safety and environmental protection are essential considerations for the maritime industry. Accidents can have devastating effects on both human lives and the environment, and the industry must take measures to minimize these risks (Luo and Shin 2019). Digitalization and automation can help streamline operations and increase efficiency, but also requires significant investments in technology and training (Kitada et al. 2018).

To tackle these challenges, we need to improve the quality and motivation of the workforce, from undergraduate to professionals. In this context, the low number of students enrolling in European maritime schools, which is leading to a shortage of professionals in many European countries, is alarming. This shortage of professionals has several consequences, including a lack of qualified personnel to operate vessels and manage ports. It also means that there may be delays in cargo handling and transportation, which may have significant economic impacts. There is a need to raise awareness about the opportunities and benefits of careers in the maritime industry (Lau and Ng 2015). Efforts must be made to improve working conditions and ensure that the maritime industry is an attractive option for young professionals. This may include providing better pay, benefits, and opportunities for career growth and advancement. It is crucial to encourage more students to pursue education and training in this field, which can lead to fulfilling and lucrative careers (Lau et al. 2021). Addressing the shortage of professionals in the maritime industry is essential to ensure that the industry can continue to meet the growing demand for transportation and trade. Encouraging more students to pursue careers in this field and improving working conditions are critical steps in achieving this goal.

It is discussed in this paper a recent initiative developed by the authors at Escola Superior Náutica Infante D. Henrique (ENIDH), in Portugal, and currently expanded at the Norwegian University of Science and Technology (NTNU), in Norway. The initial idea for this initiative was aimed in appealing students for the engineering area, this way a brief remark to the importance of the courses at both institutions are presented in next paragraphs.

ENIDH is an academic institution within the public Portuguese polytechnic education system. The mission of ENIDH is to train qualified professionals for the maritime-port sector and related activities, with a focus

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on international officer careers such as Deck Officer, Marine Engineering Officer, and Electrotechnical Engineering Officer. The school offers Bachelor of Science degree courses (1st cycle) in navigation, management, and engineering, as well as Master of Science degree courses (2nd cycle) in navigation and engineering. Additionally, the school offers technical professional formation (short cycle) in mechanical, electrotechnical, and computer subjects. ENIDH also provides a significant selection of specialization courses and short-term professional training programs, many of which lead to maritime certification under Standards of Training, Certification, and Watchkeeping (STCW) of Seafarers regulations of the International Maritime Organization (IMO). These programs are taught through the school's Studies and Specialized Training department. ENIDH includes a research and development centre (RDC) with five investigation lines: Autonomous Vessels and Energy Efficiency; Maritime Security; Digitization Applied to Shipping; Economics and Maritime-Port Management; and Environmental Sustainability.

To turn maritime studies into a more appealing educational option, Escola Superior Náutica Infante D. Henrique (ENIDH), as a university-level institution, has developed and implemented mentorship courses for high school students. These courses enable students to experience the college environment, especially in a maritime school. This work focuses on developing a mentorship course centred around rapid prototyping of boat models which will be discussed in the following sections.

As for NTNU, the SMARTBOAT initiative is planned to be used to extend the promotion of digital twin initiatives accessible to students, exemplified previously in European Council for Modelling and Simulation (ECMS) (Fonseca and Gaspar 2020). Moreover, an extended case to use the example to the training of autonomous shipping and development of remote operating centres is also on the way. In the following sections it will be tackling the core of the initiative, via the rapid prototyping approach, as well the current digital twin case.

ASPECTS OF RAPID PROTOTYPING

Rapid prototyping is a process of quickly creating a physical model or a prototype of a product using computer-aided design (CAD) data (Kamrani and Nasr 2010). This gained a large audience in the last decade, with the development of FabLab's and Makerspace's (Wilczynski and Adrezin 2016; Marks and Chase 2019; Jensen and Steinert 2020).

Overall, the technique consists of a clear set of functional and physical specifications, which are decomposed into components, subassemblies (physical models), and functions and behaviours (logical models). CAD and 3D modelling is the core, as 3D printing became the *status quo* in the last decade (Caterina et al. 2017). Other commercially available components are included (e.g. motor, circuits, batteries), and the assembly phase is done. Programming and development of logical architectures (e.g. dashboard for controller), develops in parallel. Testing and interaction on the fulfilment of the requirements is a necessary loop. This develops the skills of planning and management of projects from a boardroom perspective. Figure 1 exemplifies the rapid prototype process cycle.

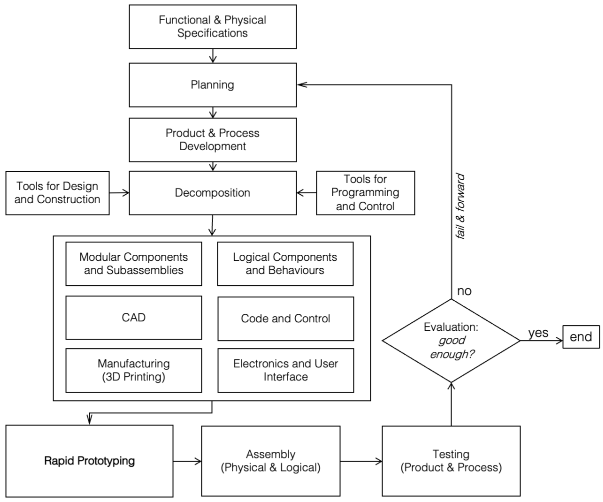

Figure 1 – Generic rapid prototyping cycle, (adapted from Kamrani and Nasr, 2010).

The technique is strongly connected to the values of *learn, make, share* (or its variations, *develop, create, do & share).* Such initiatives must be performed in a facility that includes people, tools and software in line with the Makerspace initiative, usually: 3D Printing (additive manufacturing), computer-aided design (CAD), virtual reality (VR), programming, simple robotics (e.g. Arduino, Raspberry Pi). Overall, the service-oriented architecture (SoA) in rapid prototyping is focused on using the latest technology and techniques to create faster, more accurate, and cost-effective prototypes. For the industry, these advancements significantly reduced time and required costs to bring a product ready to market, making it easier for businesses to test and refine their designs before mass production. In our case, this technique introduces in the students the principles of solving problems, such as *fail & forward* principles of trying and testing in similar iterative approaches.

RAPID PROTOTYPING FOR PROMOTING STEAM – SHORT REVIEW

Several published works describe the use of rapid prototyping for science, technology, engineering, art, and mathematics (STEAM) learning purposes. Combining rapid prototyping and STEAM education can create a unique learning experience for students, promoting creativity, problem-solving, critical thinking, and interdisciplinary exploration.

Hamblen and van Bekkum (2013) discuss the development and implementation of a course and laboratory designed to facilitate the rapid prototyping of low-cost embedded devices, including robotics and Internet of Things (IoT) applications. The laboratory features hands-on activities that allow students to gain practical experience in using tools and techniques such as real-time operating systems, object-oriented programming, networking, and Internet connectivity. The authors describe the design and implementation of the laboratory, as well as the student learning outcomes and assessment methods used in the course.

Wickliff and Pugalee (2022) investigated the extent to which high school students apply the engineering design process (EDP) in a robotics engineering design challenge. The authors analyse data from student engineering design journals, interviews, and surveys to identify patterns of student behaviour and decision-making throughout the design process. The study found that students struggled with several aspects of the EDP, including problem definition, ideation, and testing and evaluation. The authors also suggest that targeted instructional interventions could help improve students' understanding and application of the EDP in future design challenges. The study provides insights into the challenges and opportunities of teaching engineering design to high school students.

Ota *et al.*, (2020) the authors described a short-term course that introduces high school students to the concepts and technologies of IoT through a series of hands-on exercises. The course is designed to promote STEAM education and aims to foster creativity and problem-solving skills among students. The authors also describe the structure of the course, the IoT exercises used, and the evaluation methods to assess the effectiveness of the course. The result of the study suggests that the course was successful in promoting interest and engagement in IoT technology among higher school students.

On a middle school level, Marks and Chase (2019) examined the effects of a prototyping intervention on middle school students' iterative practices and their reactions to failure in the context of an engineering design challenge. The study involved a pre-test/post-test design, with one group of students receiving a prototyping intervention and another group serving as a control. The authors found that students who received the prototyping intervention demonstrated greater engagement in iterative design practices, such as testing and redesigning their prototypes, and were more likely to view failure as a natural and necessary part of the design process. The study suggests that prototyping can be an effective pedagogical strategy for promoting iterative design practices and fostering a growth mindset among middle school students.

Jensen and Steinert (2020) discuss the importance of prototyping in both education and science, as well as the different stages of the prototyping process. The authors emphasize the benefits of hands-on learning through prototyping and describe many successful cases involving the engagement for high school and engineering students. Lastly, Kunicina *et al.,* (2020) the authors discuss the challenges of prototyping, such as time and resource constraints, and proposes strategies to overcome these challenges. Overall, the paper provides insights into the role of prototyping in promoting innovation, creativity, and practical skills development in the fields of education and science.

SMARTBOAT INITIATIVE

The idea behind SMARTBOAT is to transform the complex and multidisciplinary Unmanned Surface Vehicle (USV) project (Assunção *et al.* 2022), called USV-enautica1, into a more accessible project that can be implemented by high school students. To achieve this, the project was reduced to its basic elements, based on the principle of Figure 1, which includes the construction of a hull, the use of two propellers, a microcontroller, and a remote control. The USV-enautica1 project includes a control system which allows it to carry out several functions autonomously, the construction of a fibreglass composite catamaran with two-hulls, the propulsion command and control architectures, the navigation algorithms, and the control systems. The underlying idea presented in this work was to simplify the USV-enautica1 project and show the global vision of a maritime project.

The Navigation Instrumentation Laboratory is a program offered by ENIDH that provides mentorship to high school students in the regional education network of the municipality of Oeiras. The goal of the program is to teach students how to create a 3D-printed boat that can be controlled by a smartphone, known as the SMARTBOAT, using rapid prototyping and open-source software to make the project easily reproducible. The program is composed by five sessions, each lasting two and a half hours, divided in: 3D modelling, 3D printing, parts assembling, programming, and testing/validation. Students are separated into groups of 2-3 students to create their own SMARTBOAT prototype, with guidance and problem-solving strategies provided throughout the sessions. The instructor leading the class gives guidelines for students to learn and use the open-source software used in the initiative. At the end of the program, students test their own prototypes in the ENIDH swimming pool.

The SMARTBOAT initiative is taught in 6 main steps as shown in Figure 2. In the first step (a), the students were asked to create a model of the boat's hull using a free CAD software (www.onshape.com/ - Figure 3). The 3D model consists of two parts. The first part, the vessel's cover, was the same for all groups and was previously modelled. The second part is the hull, which the students had to design. They needed to consider that the upper part of the hull had to attach to the cover while also having the freedom design the bottom geometry.

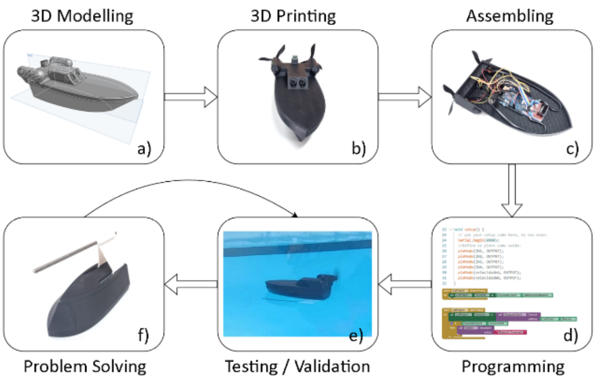

Figure 2 – SMARTBOAT prototype development steps

The weight of the various used components was given to the students, which is about 400g, and were asked to determine the height of the boat's hull to achieve a freeboard of 3 centimetres. In step (b), a 3D slicer free software (CURA) was used to slice the hull mesh (Figure 4). To prevent water leakage through the 3D printed hull, the students considered several settings to maintain a compact and waterproof hull, including the overlapping shell's outer walls percentage, flow's percentage, and line thickness. Once, the hulls and covers were printed, a kit containing all the required physical components was given to each group and the students were asked to assemble them in the back of the vessel's covers (step (c) - Figure 5).

The electronic components used in SMARTBOAT, consists of an Arduino microcontroller, 2 DC-motors, a h-bridge, a small breadboard, a distance sensor, and a Bluetooth module to communicate with a smartphone. In step (d), the students needed to program the Arduino and to create a smartphone app to control the boat (Figure 6). This step was split in 3 tasks: in the first one, the students were focused in finding a solution to control the vessel manoeuvrability by using 2 propellers; in the second, the students were asked to program the Arduino; in the final, the students created an app to control the boat through the open-source software MIT APP Inventor. After completed, the boats were tested in the swimming pool (Figure 7). In the first trial, the boats did not maintain the stability due to the high centre of gravity. Therefore, a solution to solve this situation was discussed and encouraged to be found. The solution was to take advantage of the fins slits to print a special kind of keel with a stainless-steel rod to counterbalance the boat in water. This solution was a success, and the students could prove the effectiveness of the found solution.

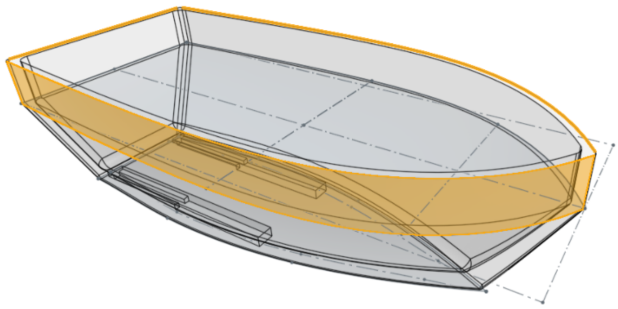
Figure 3 – SMARTBOAT 3D design model step

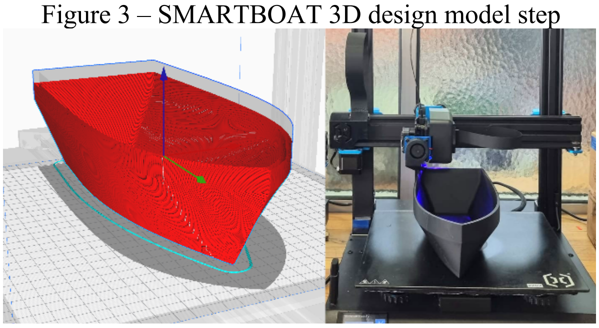
Figure 4 – SMARTBOAT 3D model (left) and 3D printing of the hull (right)

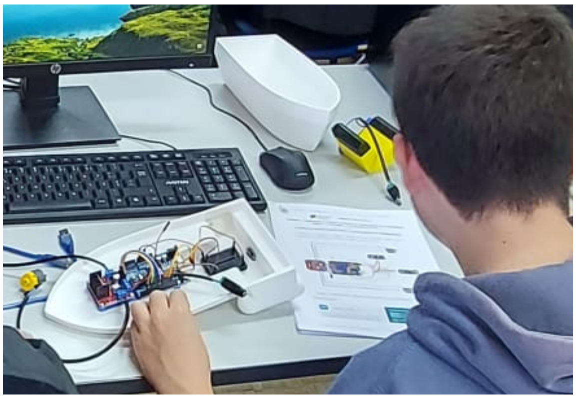
Figure 5 – SMARTBOAT Assembling step, microcontroller, and electric part schematics.

Figure 6 – SMARTBOAT smartphone app step

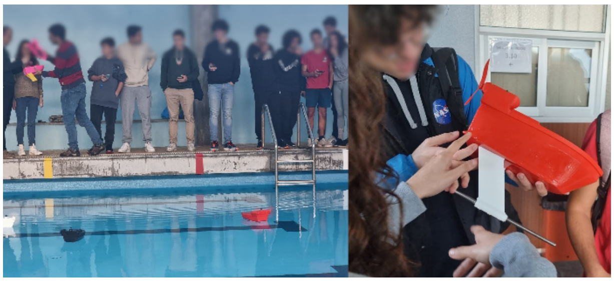

Figure 7 – SMARTBOAT testing and validation step

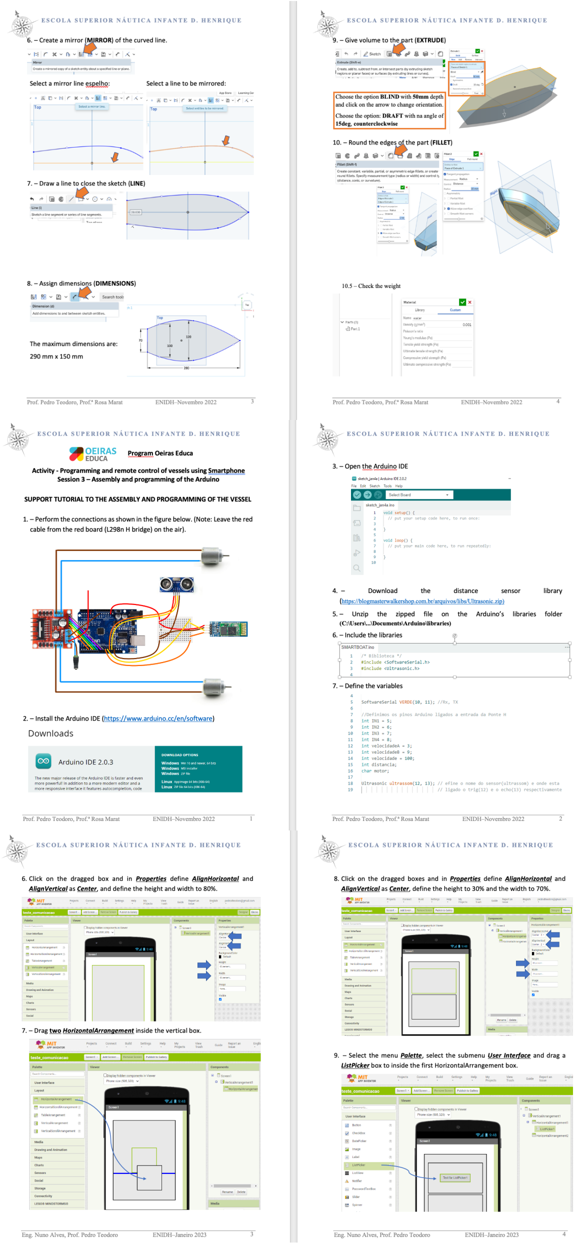

Figure 8 – Tutorial for the three main tasks of the initiative: CAD (top), electronics (middle) and programming of user interface (down) in the SMARTBOAT development.

The SMARTBOAT mentorship course program was conducted from November 2022 to January 2023. The course was attended by high school students who were potential candidates for science university studies. The students voluntarily chose to participate in the program, which raised expectations, and their interest and motivation were key factors in achieving successful outcomes. During each session of the program, the rapid prototype steps were followed step-by-step. This approach enabled the students to learn about various technologies and open-source software, with the goal of creating and performing rapid prototypes. Additionally, the SMARTBOAT case study was used to introduce the students to maritime studies and professional careers in the field.

Guidance was given to the students prior to the design of the hull's vessel, the assembly of the electric components and the implementation of the SMARTBOAT smartphone app. This guidance was delineated via tutorials with basic explanations so that students can learn the basic concepts and develop through the given tools the proposed SMARTBOAT.

Figure 8 presents an extraction from each tutorial, namely: CAD modelling of the boat; assembly and programming of electronics; and programming of the smartphone app (user interface). The tutorials are available online at the projects page (http://sea2future.pt/).

A CASE FOR REMOTELY OPERATED VESSELS AND DIGITAL TWIN

The SMARTBOAT initiative contain all the key elements to close the loop of rapid prototyping and instigate the concept of learn, make, and share currently advocated in the Makerspace philosophy. In so, it contains the basic digital and physical assets to step forward the initiative into trend research and industry topics, such as remotely operated vessels and digital twins (Fonseca and Gaspar, 2019; 2020).

The example is currently being expanded by NTNU as the initial example in remotely operated vessels, to exemplify large projects to a wider audience. Take the remote operation case presented at ECMS 2021 (Major *et al.,* 2021). The digital twin and remote control mentioned for a research vessel follows the same principles of the smart boat, as we need the physical asset (real vessel), electronics (sensors and control) and user interface (dashboard). The real case, however, requires a larger laboratory and researchers on both ends of the line: at the remote-control centre and in the boat. Aside, the boat needs crew, fuel, maintenance. To repeat and re-use similar experiment in for students is not possible, as the real boat is limited and expensive to operate.

Fonseca and Gaspar presented one year early (2020) how fundamentals of digital twins that can be applied to examples ranging in different degrees of complexity, from a toy boat to a larger experiment. This is the mindset currently. Therefore, the currently development includes the successful implementation of the remote operation of the boat, via Message Queuing Telemetry Transport (MQQT) protocol and a planned digital twin dashboard. The remote operation is achieved by substituting the Bluetooth by a wireless connection (either internal network or 4G). This gives unlimited range to the boat, as it only requires a mobile network signal to be operational.

The MQTT is a widely used protocol in the field of IoT due to its lightweight nature and ability to handle the communication needs of devices with limited resources. IoT devices often have limited processing power, memory, and battery life, and require a communication protocol that can minimize the amount of data transmitted while ensuring reliable delivery. It operates on a publish-subscribe messaging pattern, in which publishers send messages, or *publish* messages, to a central broker, which then distributes the messages to subscribers who have expressed interest in receiving messages on a particular topic. The main elements of this protocol are:

- *Clients*: There are two types of clients in MQTT: publishers and subscribers. Publishers are devices that send messages to the broker, while subscribers are devices that receive messages from the broker.
- *Topics*: Messages in MQTT are organized by topics, which are strings that describe the content of the message. Topics are arranged in a hierarchy, with each level separated by a forward slash (/).
- *Broker*: a central hub that receives messages from publishers and distributes them to subscribers. It acts as an intermediary between publishers and subscribers, ensuring that messages are delivered to the correct recipient.
- *Connection*: To establish a connection with the broker, clients must send a *connect* message that includes their client ID, username, and password (if required). Once connected, clients can subscribe to topics of interest or publish messages to the broker. Connections can also be open (public) or encrypted (private).
- *Publishing*: When a publisher sends a message to the broker, it includes the topic to which the message should be published, the message payload, and the quality of service (QoS) level for the message. The broker then distributes the message to all subscribers that have subscribed to the topic.
- *Subscribing*: When a subscriber connects to the broker, it can subscribe to one or more topics of interest. The subscriber then receives all messages that are published to those topics.

The physical asset (boat) can be observed as a machine that can be controlled remotely. It must *subscribe* to receive orders and *publish* its status. An overview of the approach is presented in Figure 9. The MQTT protocol represents here two clients (a boat and a dashboard), connected to a broker. The boat is equipped with three programs that run simultaneously on its Raspberry Pi - one to control the motors, one to obtain distance measurements using an ultrasonic sensor, and one to determine the boat's GPS position. The boat publishes data from the distance and GPS programs in two different topics (*distance_sensor* and *GPS_position*) on the broker. The dashboard, a webpage with an MQTT protocol implemented in JavaScript, subscribes to these topics, and displays any new data whenever they are published in the broker.

The joystick on the dashboard (Figure 10) controls the speed and direction of the boat, by controlling the two motors on it. The further the joystick handle is pushed, the faster the motors will run, and if the handle is pulled to the side, one of the motors will slow down, causing the boat to turn slowly. The dashboard converts the position of the joystick handle into motor speeds, which are published on the broker in the topic *motor_action*. The boat subscribes to this topic and receives the motor requested speeds whenever they are published. The boat then uses this information to control the motors.

A future version of the boat can be designed to move autonomously, by incorporating additional sensors and control systems, while still having the remote control available at any time. This way, the MQTT protocol can serve as a tool for both monitoring the boat's status and controlling it as necessary. As this is web-based, it allows unlimited access, following the principles discussed in (Fonseca and Gaspar 2019). Physical and Digital (3D) representations of the boat is observed in Figure 11.

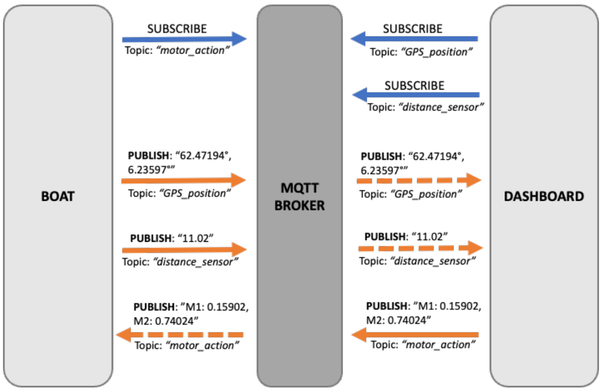

Figure 9 – Remote operation of the boat via MQTT protocol, with the robot (boat), broker and dashboard (remote-control centre)

Additionally, by including more sensors and improving the dashboard, the initiative can be a great example for digital twin. The basic exchange of information is the same presented in Figure 9, with the addition of many more visualization tools in the dashboard. The full extent of this technology is greatly discussed by (Zhang et al. 2022) and (Fonseca and Gaspar 2020).

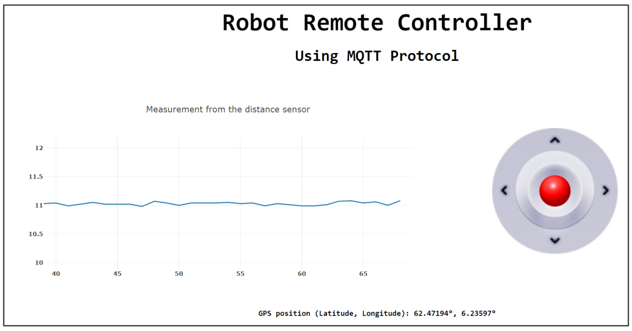

Figure 10 – Web-based Dashboard for the Sensoring and Remote-control centre for the boat.

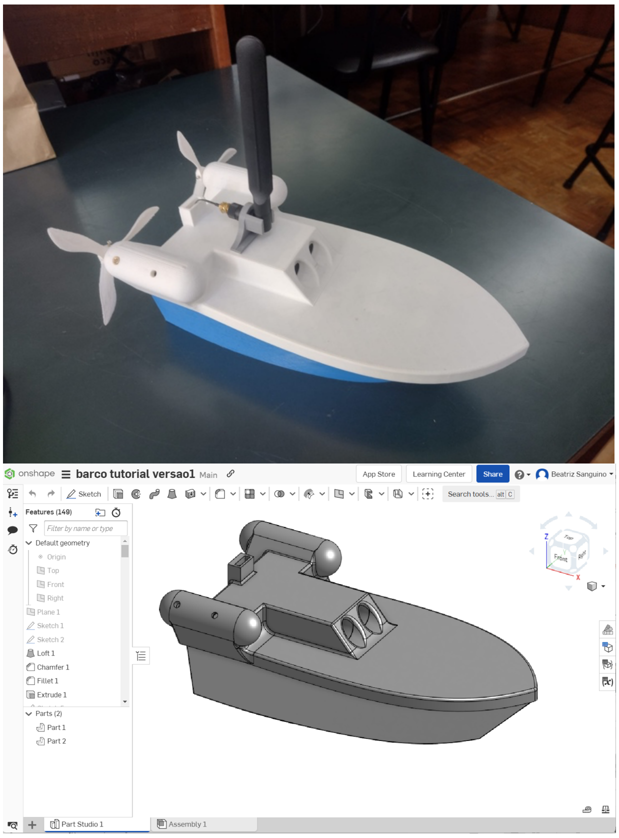

Figure 11 – Physical and Digital Images for the SMARTBOAT

CONCLUDING REMARKS – CALL FOR FUTURE INITIATIVES

This paper presented an initiative to promote STEAM studies via rapid prototyping and digital tools. The SMARTBOAT aggregates the full loop of modern maker projects, with CAD, 3D printing, electronics and user interface. The case promoted by ENIDH is tailored to high school students, following the *learn, make, share* principles. An extension of the case is currently done, focusing on the remote control and web-based technologies at NTNU. Both institutions intend to continue and extend the project towards other examples that can accommodate industry topics, such as robotics, autonomous shipping, and digital twins (Leng *et al.* 2021).

The research makes use open standards to create the robotic boat, which can be easily reproduced, modified, and executed at various educational levels. For example, at the BSc level, students can develop more advanced instrumental navigational sensors, acquire, and validate data from sensors, explore new design solutions, and test the performance of different hulls. Moving on to the MSc level, students can implement a control design system, an energy monitoring system, and an autonomous navigation system that uses sensor data fusion. At the PhD level, researchers can take things to the next level by developing a synchronized network of SMARTBOAT's, incorporating AI implementation, and creating a digital twin, as well as extending it to real cases with remote operated vessels and autonomous shipping. Furthermore, the SMARTBOAT has potential for industrial purposes, as it can be used by hobbyists or educational robotics groups without modification.

SOURCE CODE AND TUTORIALS

The source code for the first example is available on http://sea2future.pt/ (ENIDH). The source code for the NTNU case is found in http://vesseljs.org/ .

ACKNOWLEDGEMENTS

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