International Journal of Mechanical Engineering and Robotics Research, Vol. 14, No. 2, 2025

Applied Product Design of Autonomous Surface Vehicle-Mandakini Catra Based on Collaborated Design between Bengawan Unmanned Vehicle and Extracurricular Education Teams

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***Abstract*—This research describes a developed Autonomous Surface Vehicle (ASV) design to achieve design technology advancements in Mandakini Catra based on the assigned missions. The sample missions are based on the Roboboat Competition in Florida, United States. Bengawan Unmanned Vehicle (UV) Team, in collaboration with Madrasah Aliyah Negeri (MAN) 1 Surakarta as a partner, developed a prototype design. Furthermore, numerical simulation and on-water testing assessed the created ASV performance. Numerical assessment included stability and seakeeping analyses. Based on stability simulation results, Mandakini Catra achieved a turning degree of 30º and a Gz arm value of 0.1067 m. Seakeeping simulation results showed Mandakini Catra had a pitching value of 3.415 and a heaving value of 2.636. Furthermore, using TensorFlow Lite with the EfficientLite0 architectural model type for object detection improves the average Frames per Second to 7.6, and implementing the MAVLink communication protocol reduced the Turning Error Radius by 0.27 m. In conclusion, new object detection program algorithms, fully programmed navigation systems using MAVLink, and hull design with a modular system have been successfully implemented, optimizing the hydrodynamic performance of Mandakini Catra.**

***Keywords*—Mandakini Catra, modularity hull, autonomous surface vehicle, object detection, MAVLink**

I. INTRODUCTION

Prioritizing stability and mitigating interference from water waves amidst varying amplitudes and wavelengths, significant design enhancements could be made for the proposed design concept of a developed Autonomous Surface Vehicle (ASV) [1–8]. Consequently, adopting a symmetrical catamaran hull model was deemed optimal, allowing the vessel to return to equilibrium following external forces swiftly. Nevertheless, it is essential to note that while the symmetrical catamaran hull model offers superior stability, it also presents higher resistance than its asymmetric counterpart [9–11]. Through strategic adjustments in the ratio between the ship's demi hull (S) and length (L), the Mandakini Catra achieves a delicate balance, effectively minimizing resistance while enhancing stability to fulfill its operational objectives [12, 13].

The Mandakini Catra embraces the concept of modularity by incorporating an aluminum T-slotted profile. This profile is an essential connector between the demi hulls while functioning as a versatile deck. The primary objective is to fine-tune the ratio between the demi hull (S) and the ship prototype (L) length, thereby enhancing overall performance [14]. This modular approach facilitates the strategic positioning of components aboard the Mandakini Catra, ensuring optimal functionality during mission execution. With meticulous attention to

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Manuscript received August 29, 2024; revised October 7, 2024; accepted November 26, 2024; published March 7, 2025.

doi: 10.18178/ijmerr.14.2.103-113

detail, the Mandakini Catra is meticulously designed to meet all mission requirements in the International Roboboat Competition. The design and details of the Mandakini Catra are shown in Fig. 1 and Table I.

The Mandakini Catra operates on a thoroughly programmed system that seamlessly integrates ship navigation with optimal object detection capabilities. Utilizing a navigation system centered around a Global Positioning System (GPS) sensor, precise commands are transmitted to govern the vessel's movements throughout mission execution [15]. Then, in object detection, the central Bengawan Unmanned Vehicle (UV) team, by collaborating with the Community Partnership Program team, changed the image processing system from color detection to object detection to increase the precision of detections from obstacles sent to the navigation system to complete each mission. This upgrade significantly enhances the accuracy of obstacle detection, which is vital for informing the navigation system during each mission.

Fig. 1. Mandakini Catra design.

TABLE I. MANDAKINI CATRA PRINCIPAL DIMENSIONS

Measurement	Value	Unit
Length Overall	0.86	m
Breadth	0.62	m
Depth	0.17	m
Length Waterline	0.84	m

This study is collaborative research between the Bengawan Unmanned Vehicle (UV) Team and Madrasah Aliyah Negeri (MAN) 1 Surakarta. MAN 1 Surakarta, as a partner, hopes to develop student achievements in robotics. Bengawan UV, which has long researched and developed robots in the field of ASV, provides technology to be developed at MAN 1 Surakarta. This research uses several methods to integrate various technologies in the development of ASV. The research method uses a design approach with simulation software such as Fusion 360, Maxsurf, ANSYS, and Mission Planner. Furthermore, to test in real life, an experimental test was carried out in water to test the performance of ASV under actual conditions. In addition, to measure the influence of providing technology in robotic training to MAN 1 Surakarta, an evaluation will be conducted with a questionnaire to students.

The first test is a design test using several simulation software programs. Hydrodynamic performance testing includes stability and seakeeping using ANSYS AQWA and Maxsurf Stability software programs. The Mission Planner software assesses the ASV's maneuver performance in the navigation system test.

Experimental testing is carried out to determine the performance of an ASV in real time. The tests include a thrust test, a maneuver test, and object detection. The thrust test determines the thrust force of the thruster for the ASV to move. The maneuver test tests zig-zag and turning motion. Meanwhile, object detection testing is used to determine the level of accuracy of architectural image processing in processing images as sensors.

Finally, in implementing the robotic tutorial class at MAN 1 Surakarta, data will be collected with a questionnaire of students participating in the robotic training program. The implementation of the training program will be divided into three focus class topics: design and manufacturing, printed circuit board (PCB) design, and programming. The target of the training class is that students from MAN 1 Surakarta can understand basic knowledge about robotics so that the academic achievement of MAN 1 Surakarta students can increase yearly.

II. COURSE OF ROBOTICS DEVELOPMENT ACTIVITIES

A. Profile of the Project Partner

Madrasah Aliyah Negeri (MAN) 1 Surakarta is a state high school with an Islamic religious scientific base. In 2024, 1321 MAN 1 Surakarta students will be divided into several existing majors. MAN 1 Surakarta has several programs for its students, such as those in high school. Science and social studies majors are generally included in the regular school type. In addition, excellent programs have scored many academic and non-academic achievements, such as the Religious MAPK program, Boarding School, and MA Skills. MAN 1 Surakarta is located on Jl. Sumpah Pemuda No. 25, Banjarsari, Surakarta, has three main buildings as learning locations and dormitory buildings supporting student activities, especially the boarding school program. The location and map of MAN 1 Surakarta are shown in Fig. 2.

A total of 475 students divided into three weekly classes received 3 hours of robotics course. The course taught basic robotics, introducing Arduino and small-scale sensors. However, in the existing conditions, there are obstacles experienced by teachers and students in robotics tutorial classes. The problems encountered are as follows: the design process in making robots is still fundamental, using only 2D software; Electronic design takes up much space when applied in robots; And the strategy in determining and participating in the competition is still minimal, so the non-academic achievement target of students still needs to be further developed.

At this time, MAN 1 Surakarta, under the leadership of Dr. H. Slamet Budiyono, M.Pd., has the support of 103 teachers with various scientific backgrounds who are determined to produce a superior generation for the nation's progress on a religious basis. The achievements made by MAN 1 Surakarta students in 2023 are 349 contested at the district, national, and international levels, shown in Fig. 3.

Fig. 2. Map and location of MAN 1 Surakarta.

Fig. 3. Achievements of MAN 1 Surakarta students.

The current condition of MAN 1 Surakarta students is 1321, consisting of 475 grade 1 students who receive mandatory robotics tutorial classes. From a total of 349 achievements, to optimize student achievements, especially non-academic in robotics, the partnership team from Universitas Sebelas Maret (UNS) and the MAN 1 Surakarta group innovated and applied the science learned in higher education to solve existing obstacles. UNS has a research team under the auspices and guidance of Mechanical Engineering lecturers, namely Bengawan Unmanned Vehicle (UV). Since 2017, it has independently produced robots in uncrewed vehicles, especially ships and aircraft, to achieve achievements for UNS at the national and international levels. Seeing the condition of the problems that exist in MAN 1 Surakarta partners, the experience and skills of the Bengawan UV team are solutions to be transmitted through training programs and workshops in Unmanned Vehicle robotics, as shown in Figs. 4–6.

B. Partner Issues

The obstacles experienced by MAN 1 Surakarta as a partner, especially in the implementation of robotics tutorial classes, are;

1) In the tutorial class, students only get material, especially robot design, using Coreldraw software, namely basic 2D. Meanwhile, basic 3D design is also needed to study the dimensions, essence, and manipulation process in the development of robots.
2) In making robots, students only use essential components with large dimensions compared to the robots. Partners already know electronic PCB circuit design technology but need the basics of making PCBs.
3) The achievements of robotics students in 2023 reached 13 achievements achieved at the Regency and National levels. Meanwhile, around 40 competitions were attended. The team needed help with strategizing over the created robots. The cohesiveness between team members also became a constraint coordination during the competition.

Based on the problems or obstacles at MAN 1 Surakarta, a joint discussion was held between the UNS partnership team and partners to identify the need for technology application. Some of the identification of technology needs that need to be created and implemented include:

1) 3D design training through Solidworks software in designing Robots, especially Unmanned Vehicles.
2) Training in electronic drafting and PCB circuit design for electronic efficiency in robot manufacturing.
3) Socialization and counseling of competitions in the field of Unmanned Vehicle robotics at the national and international levels. The three concrete steps are also expected to improve the basic skills of students and teachers at MAN 1 Surakarta in designing and competing in the robots made. So that non-academic achievements, especially in robotics, can be achieved at a higher international level. The implementation program is shown in Figs. 4–6.

Fig. 4. Design and manufacture lectures class.

Fig. 5. Design and PCB design lectures class.

Fig. 6. Programming lectures class.

C. Implementation of Tutorial Robotic Activities

The first stage is preparation, where a team of lecturers and student assistants prepares a plan for implementing activities, determining the location, and organizing technology. The team also held discussions and deliberations with MAN 1 Surakarta partners regarding the scheduling and implementation of each program that will be carried out. This is so that cultivators are supported in implementing the program so they can follow it properly. The flowchart implementation program is shown in Fig. 7.

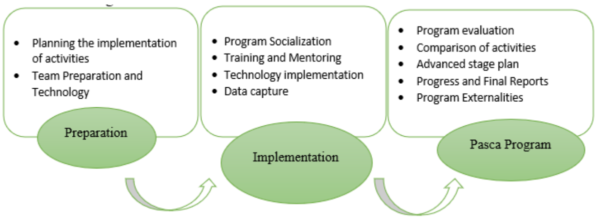


Fig. 7. Flowchart implementation program.

The implementation team carries out the preparation stage, coordinating the implementing lecturers and the student team. The division of job desks and class schedules ensures the suitability of the topic to be taught, both theoretical and practical. Classes will be divided into five weekly meetings, one on the Wednesday after the formal class. However, there are obstacles to determining a schedule before getting a definite schedule, such as student activities in the dormitory. The mentors in each class consist of two assistant implementers who provide material in the first 30 min for theoretical and the next 60 min for practical.

The training and workshop began with designing to determine the robot's dimensions, designing the placement of mechanical components, and simulating motion. Continuing with the application of design into body materials or manufacturing stages, the design and manufacturing stages are very related because the dimensions in the design must be appropriate when in the manufacturing process. The focus expected to be implemented in this proposal seeks to provide technological innovation to improve the non-academic achievement of MAN 1 Surakarta students, especially in robotics.

Improving design skills and designing PCB design electronics is a solution previously discussed with partners regarding how to apply it in schools. The implementation of the introductory robotics class was delivered in five meetings. In each meeting, the students were given practical tasks on different materials with assistance while working. From data taken from five meetings in class, 83% of students quickly understood the introductory material provided. The students' performances indicated that the material was easy to understand because there was immediate practice for the results of the change in the basic pre-class of robotics, with the post-class divided into three data taken from each class, as shown in the graph in Figs. 8–10. The technical aspects of the hull-system design, one of the community partnership program's outputs, are presented in the following sections, including design performance simulation and manufactured prototype testing.

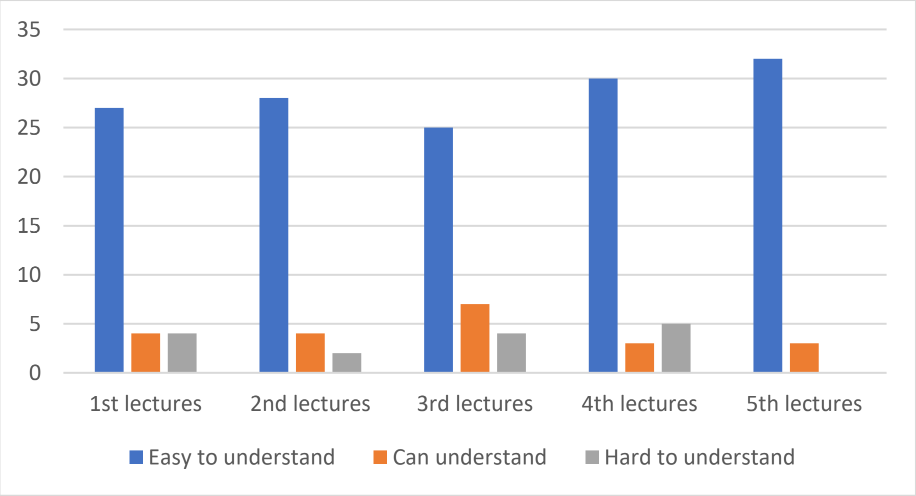


Fig. 8. Result program of Design and Manufacture lectures class.

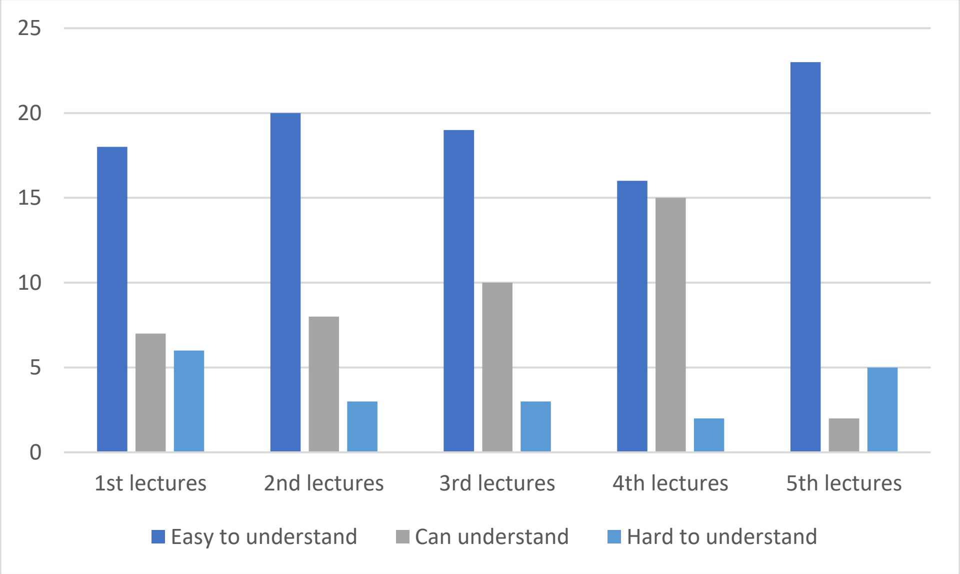


Fig. 9. Result program of Design and PCB Design lectures class.

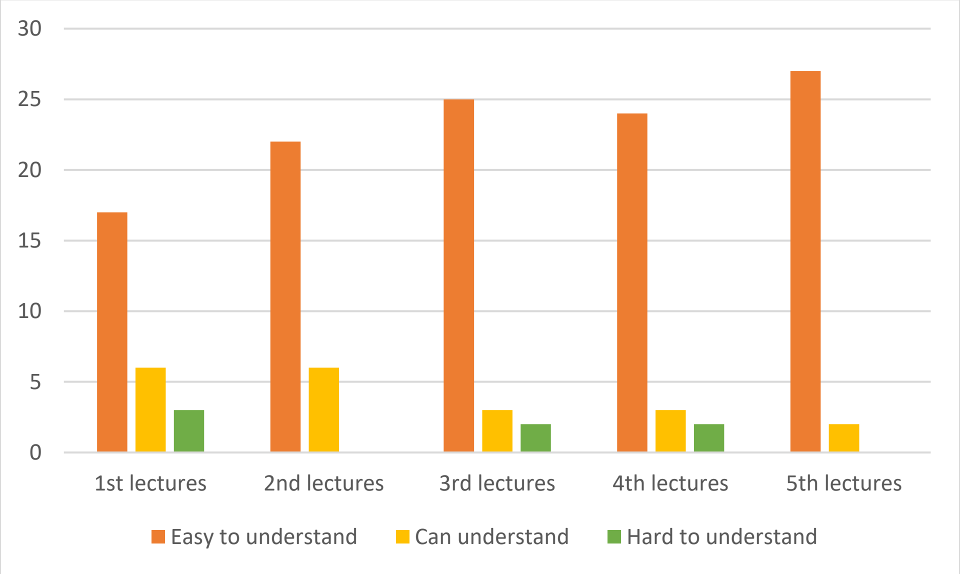


Fig. 10. Result program of Programming lectures class.

III. EXPERIMENTAL METHODS

A. *Hull, Frame Design, and Propulsion System*

The Mandakini Catra's hull features an increased thickness of both fiberglass and gelcoat layers compared to the Mandakini EVO (2022 prototype). This augmentation results in enhanced rigidity, eliminating the necessity for additional structural support within the Mandakini Catra's body [16]. Furthermore, the integration of the Blue Robotics thruster T200 markedly improves the vessel's performance relative to the Mandakini EVO, which relied on an unbranded thruster. Consequently, the Mandakini Catra exhibits superior mission success rates. The propulsion system remains consistent with the previous year's model, employing two azimuth thruster propulsion systems [17–19]. This choice is predicated on the system's proven ability to offer superior maneuverability at low speeds and more excellent stability during maneuvers compared to contemporary rudder systems [20–23].

Advancements in the Mandakini Catra encompass various hydrodynamic performance metrics, including resistance, seakeeping, maneuverability, stability, propulsion, and construction costs. Ship stability is defined as the vessel's ability to return to its initial position after being subjected to external forces. Stability is influenced by critical factors such as buoyancy, gravity, and the metacentric point [24]. When external forces are applied, the ship experiences a shift in its center of buoyancy, altering the angle of inclination and affecting the righting lever curve (Gz) [25]. According to the International Stability Code (IS Code) 2008, the maximum righting lever (Gz) should occur at a heel angle of no less than 25 degrees. The formula for stability is given in Eq. (1).

$$\frac{dGz}{d\varphi}(\varphi \geq 25°) = 0 \tag{1}$$

where Gz is the righting arm, and $\emptyset$ is the heel angle. The Response Amplitude Operator (RAO) is a vital parameter for analyzing a ship's response to ocean wave movements or other disturbances. RAO measures the amplitude of a ship's motion in response to external forces, predicting various motion components such as surge, sway, heave, roll, pitch, and yaw. The RAO formula is provided in Eq. (2).

$$RAO = \left(\frac{\emptyset_a}{\zeta_a}\right)^2 \tag{2}$$

where $\emptyset_a$ is the ship motion response amplitude, and ζ_a is the incident wave amplitude (deg). Heaving refers to the vertical movement along the z-axis, typically caused by waves impacting the ship from the front (head sea conditions). The magnitude of heaving can be calculated using Eq. (3), which accounts for the dynamics of wave interaction with the ship.

$$a\ddot{z} + b\dot{z} + cz = F_0 cos\omega_\theta t \tag{3}$$

where $a\ddot{z}$ is the inertial force, $b\dot{z}$ is the damping force, cz is the restoring force and $F_0 cos\omega_\theta t$ is the exciting force. Pitching is the rotating movement occurring in the transverse axis. This motion can occur because of waves that cause a height difference between the front and back of the hull [26]. Eq. (4) is used to determine the pitch motion of the ship.

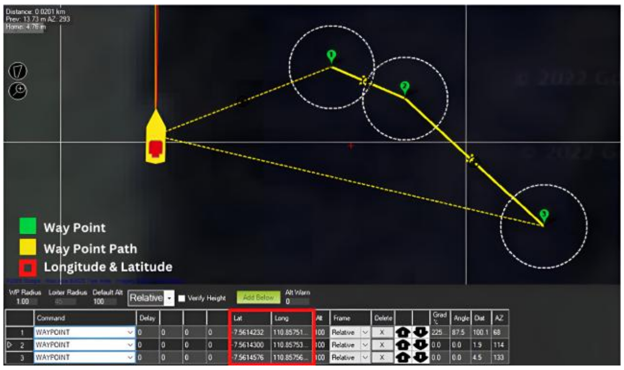
$$d\ddot{\emptyset} + e\emptyset + h\emptyset = M_0 cos\omega_e t \tag{4}$$

where $d\ddot{\emptyset}$ is the inertial force, $e\emptyset$ is the damping force, $h\emptyset$ is the restoring force, and $M_0 \cos \omega_e t$ is the exciting force. This research utilizes Maxsurf and ANSYS AQWA software to simulate ship stability and seakeeping. Stability simulations are performed using Maxsurf Stability, while seakeeping simulations are conducted with ANSYS AQWA. The Mandakini Catra was tested through simulation software and on-water testing at the lake facilities of Universitas Sebelas Maret.

B. Navigation System

The Pixhawk 2.4.8 serves as the primary navigation controller for the Mandakini Catra, vitally processing commands from ground control and translating Pulse Width Modulation (PWM) signals to drive the propulsion system. The GPS integrated within the Pixhawk is essential for determining the vessel's location and orienting its direction along a designated trajectory [27]. A significant enhancement has been implemented through MAVLink communication, enabling the transmission of ship movement commands via a Python program [28].

These commands are categorized into global maneuvering and local maneuvering directives. Global maneuvering commands are utilized for navigation between mission waypoints, while local maneuvering commands are applied when the vessel is actively engaged in a mission. The global command uses the longitude and latitude references of the Earth, as shown in Fig. 11. Conversely, local commands use velocity vectors on the *x* and *y* axes relative to the ship's heading, with positive *x* indicating forward motion and positive y indicating a left turn, as shown in Fig. 12. This dual-command structure ensures precise and adaptable control of the Mandakini Catra's movements across various operational scenarios.



WP Radius 1.00
Loiter Radius 45
Default Alt 100
Relative
☐ Verify Height
Alt Warn 0

	Command	Delay				Lat	Long	Alt	Frame	Delete			Grad %	Angle	Dist	AZ
1	WAYPOINT	0	0	0	0	-7.5614232	110.85751...	100	Relative	X			225...	87.5	100.1	68
▷ 2	WAYPOINT	0	0	0	0	-7.5614300	110.85753...	100	Relative	X			0.0	0.0	1.9	114
3	WAYPOINT	0	0	0	0	-7.5614576	110.85756...	100	Relative	X			0.0	0.0	4.5	133

Fig. 11. Global command illustration with latitude and longitude references in the red square area.

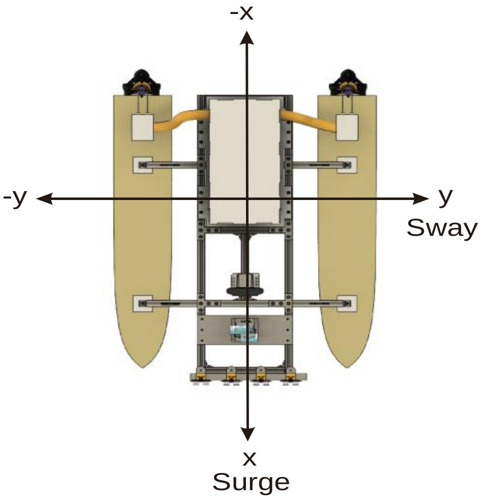


Fig. 12. Local command illustration of the Mandakini Catra.

Global motion commands are transmitted from a ground control device at the home base using radio telemetry to the Pixhawk navigation controller. Upon receipt, Pixhawk forwards these commands to the Raspberry Pi, the primary computing device during missions. The Raspberry Pi, in turn, processes the commands and sends them back to Pixhawk for execution. When the Raspberry Pi detects the need for camera-based navigation, it switches from sending global commands to issuing local motion commands to Pixhawk. These local commands are transmitted using the Python MAVLink protocol (pyMAVLink), enabling precise control of the vessel's movements via digital signal inputs. The process flow chart for the Mandakini Catra motion commands is shown in Fig. 13.

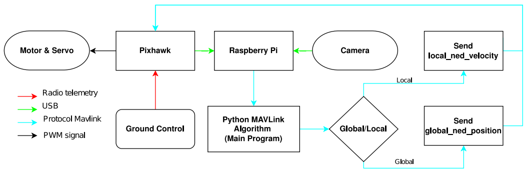


Fig. 13. Flowchart of the motion process on the Mandakini Catra.

The navigation system of the Mandakini Catra employs Proportional Integral Derivative (PID) control to enhance its operational effectiveness and precision under various conditions. PID control optimizes several critical parameters, including the steering rate and speed throttle. This optimization improves maneuverability, ensuring precise control during acceleration and complex maneuvers, as demonstrated in Fig. 14. When the PID control variable is activated, its impact is readily observable in the Mission Planner software. This software provides real-time feedback on the ship's performance, highlighting the increased maneuver precision and responsiveness facilitated by the PID control system. The implementation of PID control thus represents a substantial advancement in the Mandakini Catra's navigation capabilities, ensuring reliable and accurate mission execution.

(a) (b)

Fig. 14. Turning tests: (a) before PID control and (b) after PID control.

C. Object Detection

The primary Bengawan UV research team, by collaborating with the Community Partnership Program team, has integrated an advanced object detection system into the Mandakini Catra, utilizing an object detection algorithm powered by TensorFlow Lite [29]. The algorithm is selected by adjusting the team's component device. The team decided to use an object detection algorithm because, from the detection results using the color detection method, the detection program could not distinguish different obstacles with the same color. For example, the detection could have been more accurate in Navigating the Panama Canal and Magellan's Route, as shown in Fig. 15. The object detection algorithm addresses this issue by leveraging a broader range of parameters, enhancing detection accuracy. This method can accurately identify more specific objects, significantly improving the system's reliability [30]. The enhanced object detection capability ensures that the Mandakini Catra can more effectively complete its missions, demonstrating optimal and accurate obstacle recognition and avoidance. This technological advancement is critical to the vessel's operational efficiency and mission success.

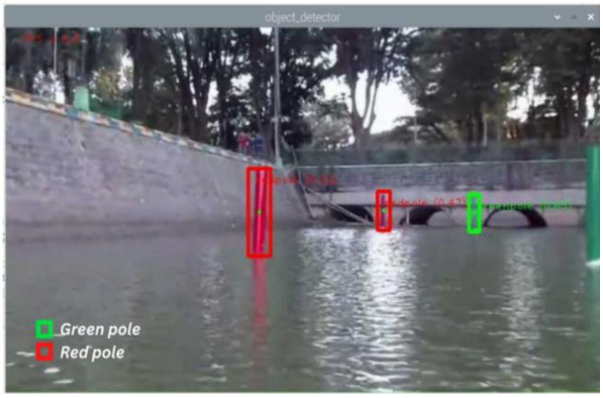


Fig. 15. Object detection on Magellan's route task.

D. Water Blaster System

The Mandakini Catra employs a sophisticated mechanism involving a 2-axis robotic arm to enhance its operational capabilities. The robotic arm's linkage is driven by a servo motor, which the Raspberry Pi meticulously controls. This setup ensures precise movement and positioning of the arm. The water blaster was placed on the front of the hull with a nozzle height of 0.18 m. The water pump is installed below the water level to ensure a continuous and reliable supply. This placement is critical for maintaining an uninterrupted flow, essential for the blaster's effective operation. Fig. 16 shows the prototype of the water blaster. This innovative design enables the Mandakini Catra to perform tasks requiring precise water jet application, expanding its functional versatility and enhancing its mission performance.

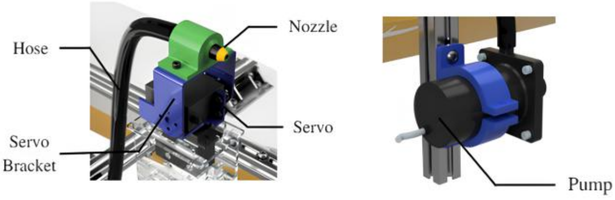


Fig. 16. Mandakini Catra water blaster system.

IV. RESULTS AND DISCUSSION

A. Water Blaster System

The Mandakini Catra's performance was analyzed by combining several software programs and live testing on the water in the Universitas Sebelas Maret (UNS) lake facilities. Mandakini Catra hull testing was performed using ANSYS AQWA and Maxsurf Stability software. The Mandakini Catra's hull testing prioritizes stability and the Response Amplitude Operator (RAO), which aims to analyze the ship's ability to return to its equilibrium point and its motion response to the dynamic water waves. The Mandakini Catra stability simulation is shown in Fig. 17.

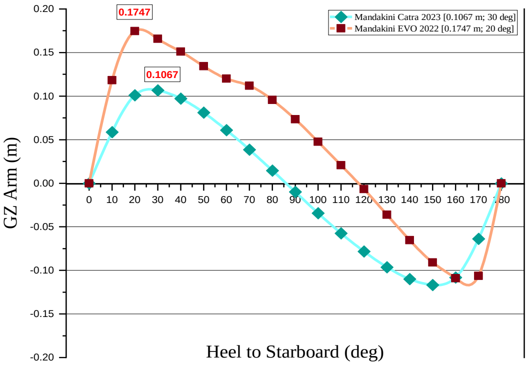


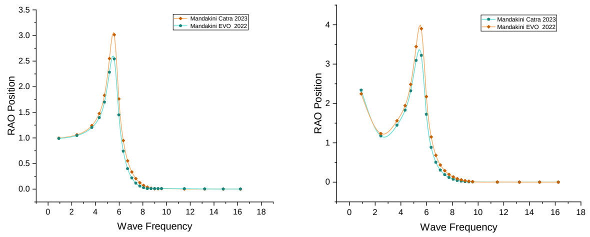
Fig. 17. Stability simulation results.

Based on the results of the stability analysis, it can be concluded that the Mandakini Catra has better stability, with a turning degree of 30° and a maximum Gz value of 0.1067 m, compared to the Mandakini EVO, with a turning degree value of 20° and a maximum Gz value of 0.1747 m under the same simulation conditions [31]. Analyzing the Response Amplitude Operation (RAO) determines the value of the effect of the amplitude of water waves on the ship's movement [32]. The data from the RAO simulation on the Mandakini Catra are shown in Table II.

TABLE II. RAO SIMULATION RESULTS

Name	Parameter	Frequency (Hz)	RAO Position
Mandakini Catra (2023)	Pitching	5.491	3.415
	Heaving	5.491	2.636
Mandakini EVO (2022)	Pitching	5.491	4.052
	Heaving	5.491	3.091

Based on the simulation data, the Mandakini Catra has a lower RAO position value, with a value of 3.415 in pitching conditions and 2.636 in heave conditions, compared to the Mandakini EVO, with a value of 4.052 in pitching conditions and 3.091 in heave conditions with the same frequency conditions; the RAO heave and pitch graphs are displayed in Fig. 18. This explains the nature of the Mandakini Catra's motion movement better in dealing with the amplitude of water waves. It can optimize the program reading on the ship by the camera vision.



(a) (b)

Fig. 18. RAO graph results: (a) heave motion and (b) pitch motion.

A static stress simulation of the Mandakini Catra's frame was also conducted using Autodesk Fusion 360 software. The Mandakini Catra's frames are designed to fulfill the safety factor value or construction safety requirement. In the simulation, frames were given a load of 11.9 kg. The safety factor value obtained must be greater than 4.0 to guarantee safety [33]. The static stress simulation results obtained a minimum safety factor value of 4.77, indicating that the Mandakini Catra's frame is within safe operational limits and satisfies all construction safety requirements, as shown in Fig. 19.

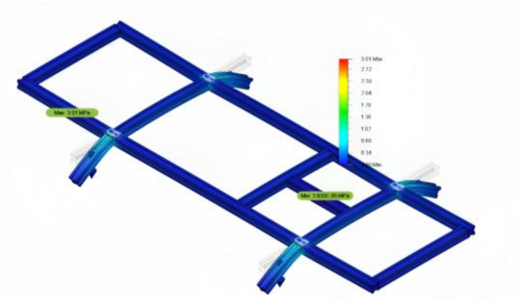


Fig. 19. Safety Factor for the frame of Mandakini Catra.

Thrust tests were carried out directly in the water by hooking the frame of the Mandakini Catra with a digital scale. Then, the thruster was given a maximum speed on the motor in five attempts. Based on these tests, the maximum thrust value on the ship was obtained at 10.46 kg. The lowest thrust value was received at 7.55 kg. Thrust test results are shown in Fig. 20 and Table III.

(a) (b)

Fig. 20. Mandakini Catra to the thrust test: (a) digital scale view and (b) Mandakini camera view.

TABLE III. MANDAKINI CATRA THRUST TEST

Test	Result (kg)
1	7.55
2	7.55
3	8.17
4	9.94
5	10.86
Maximum	10.86

The next test was a maneuver test on the ship. This test was carried out by performing a turn on the buoy and providing 100% throttle at 30% maximum thruster speed. After conducting five experiments, the leading research team of Bengawan UV, collaborating with the Community Partnership Program team, obtained data with an average turning radius of 0.39 m clockwise and an average radius of 0.37 m counterclockwise. Maneuver testing and test result data can be seen in Fig. 21 and Table IV. This is followed by the International Maritime Organization (IMO) standard—Maritime Safety Committee (MSC).173(76) Resolution from the year 2002 [34].

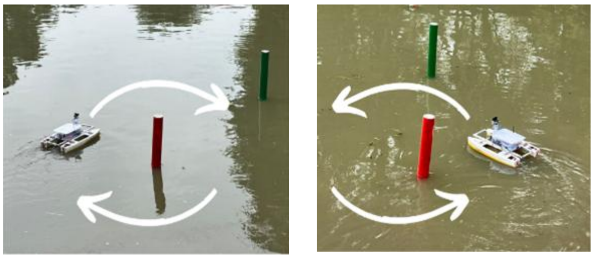

(a) (b)

Fig. 21. Mandakini Catra maneuver tests: (a) clockwise and (b) counterclockwise.

TABLE IV. MANDAKINI CATRA MANEUVER TESTING RESULT

Test	Clockwise Result (m)	Counter Clockwise Result (m)
1	0.35	0.36
2	0.44	0.35
3	0.40	0.41
4	0.37	0.40
5	0.42	0.36
Maximum	0.39	0.37

B. *Navigation System*

Navigation testing of the Mandakini Catra was conducted on the water by setting five waypoints and varying the vessel's speed. This testing method, also employed in IRC 2022, incorporated PID control to enhance the vessel's navigational precision. The PID control values were adjusted for each test to account for different speed variables, as varying speeds affect acceleration and maneuvering outcomes. The tests were performed five times at three distinct speeds: 0.5 m/s, 1.0 m/s, and 1.5 m/s. Fig. 14 presents the average test results for each waypoint, comparing the performance before and after adding PID control in the Mandakini Catra and against the Mandakini EVO. Based on the test results, a speed of 1 m/s was chosen with a PID value (P =1.7, I = 0.5, D = 0.3) as the standard speed of the Mandakini Catra to carry out the mission because it had the lowest radius error value. Fig. 22 shows the average testing results at each waypoint before and after adding a PID control to the Mandakini Catra compared to the Mandakini EVO.

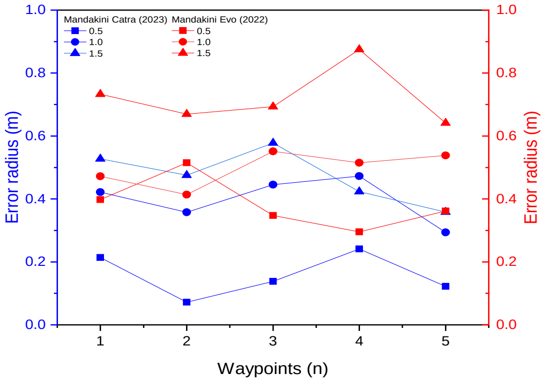


Fig. 22. The accuracy of the navigation system during water testing.

C. *Object Detection*

In the Tensorflow Lite framework, five architectural models can be used to train custom models. Before conducting training, it is necessary to collect a sample of objects divided into 2, i.e., 85% for training models and 15% for data validation [35]. The architecture model was tested using the Raspberry Pi 4. The results obtained on the sample data and the number of step trains tested were average frames per second (FPS) and mean average precision (mAP), as presented in Fig. 23. From the test data obtained by the team, it was decided to use the EfficientDet-Lite0 architecture model because it had an average FPS result of 7.6 and 25.69% mAP so that the Raspberry Pi 4 device could perform optimal object detection when carrying out missions.

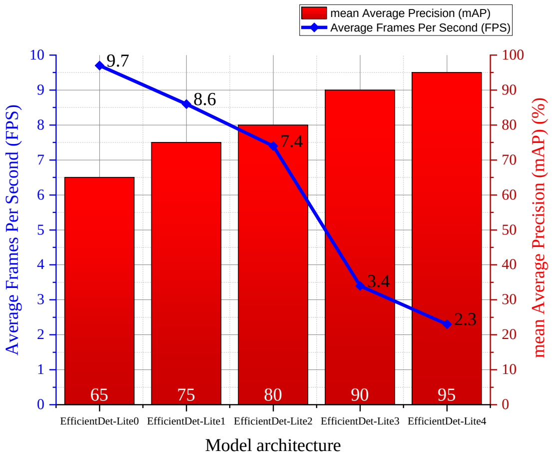


Fig. 23. Result test of the five TensorFlow Lite architecture models.

D. *Water Blaster*

A comprehensive evaluation of the Mandakini Catra's water blaster system was conducted through direct land-based testing. Positioned 1 meter from the target, the water blaster nozzle demonstrated its capability to project water up to a distance of 3.2 m at a 38° angle from the water surface. Water was consistently directed at a designated target hole during the test to assess accuracy and performance. The evaluation also included measuring the efficiency of the water refill process. The average time required to fill the water blast tank was 20.93 s. These results highlight the water blaster's effective range and operational efficiency, ensuring its readiness for various practical applications and mission scenarios. This testing underscores the reliability and functionality of the water blaster system of the Mandakini Catra.

V. CONCLUSIONS

Based on the results of the Mandakini Catra test using both software simulation and on-water testing conducted in the Universitas Sebelas Maret lake facilities, it can be concluded that:

1) The results of the stability simulation indicate that the Mandakini Catra exhibits superior stability compared to the Mandakini EVO. Specifically, the Mandakini Catra achieves a turning angle of 300°

and a maximum GZ (righting arm) value of 0.1067 m. In contrast, the Mandakini EVO only reaches a turning angle of 200° and a maximum Gz value of 0.1747 m under identical simulation conditions. This higher stability performance makes the Mandakini Catra a safer vessel.

2) Regarding seakeeping performance, the Mandakini Catra also demonstrates advantageous characteristics over the Mandakini EVO. The Mandakini Catra records lower values in pitching and heaving motions, with respective values of 3.415 and 2.636. These lower motion values indicate that the Mandakini Catra offers improved motion responses and better handles the amplitude of water waves, thereby enhancing its seakeeping capabilities.
3) The Mandakini Catra, equipped with an aluminum T-slotted frame, demonstrated exceptional structural integrity, supporting a load of 11.9 kg without bending during water testing. Additionally, the vessel met the required thrust performance, achieving a thrust of 1.46 kg. Maneuverability tests further confirmed the vessel's capabilities, with an average turning radius of 0.39 m clockwise and 0.37 m counterclockwise. These results collectively indicate that the Mandakini Catra meets the stringent requirements for participation in the 2023 International Roboboat Competition, showcasing robustness and precision in its design and performance.
4) The Proportional-Integral-Derivative (PID) settings control the ship's acceleration and maneuverability. After extensive testing, a PID configuration with P = 1.7, I = 0.5, and D = 0.3 was selected due to its minimal radius error. The GPS signal's accuracy significantly enhances the precision of the PID settings. High-precision GPS signals contribute to reduced speed variation and extended range, thereby minimizing the error radius of the ship's trajectory. The optimal PID settings identified in these tests were subsequently applied to operational missions, ensuring improved control and performance.
5) TensorFlow Lite EfficientDet-Lite0 was selected for object detection tests due to its performance metrics, achieving an average frame rate of 7.6 FPS and a mean Average Precision (mAP) of 25.69%. These results indicate that the Raspberry Pi 4 can perform optimal object detection during mission execution. Furthermore, water testing revealed that varying sunlight conditions significantly impact the precision of object detection, highlighting the importance of accounting for environmental factors in deploying object detection systems.
6) The Mandakini Catra's water blaster system demonstrated optimal performance, capable of shooting water up to 3.2 m at an angle of 38° as tested on the land. The testing revealed that the average time required to fill the water blast tank was 20.93 s. These findings confirm that the Mandakini Catra meets the requirements for the Ponce de Leon task in the 2023 International Roboboat Competition, highlighting its efficiency and suitability for the challenge.
7) Finally, further research is needed to develop autonomous surface vehicles, including object detection, sensors, control systems, manufacturing hulls, and mechanical design. Operations under extreme conditions, such as storms or high waves, are considered in the design process.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

MZM: Writing—Original Draft, Writing—Review & Editing; NNS: Formal analysis, Writing—Original Draft; FSU: Methodology, Project administration; IY: Investigation, Supervision, Funding acquisition; ARP: Writing—Original Draft, Writing—Review & Editing, Supervision, Funding acquisition; RA: Conceptualization, Software, Resources; QTD: Conceptualization, Methodology; SDP: Writing—Review & Editing, Visualization; DDDPT: Investigation, Funding acquisition; NM: Data Curation, Visualization; EPB: Investigation, Resources. All authors had approved the final version.

FUNDING

This research was supported by the 2024 RKAT PTNBH Universitas Sebelas Maret under the Community Partnership Program / "Program Kemitraan Masyarakat" (PKM-UNS) with grant no. 195.1/UN27.22/PT.01.03/2024. The support is gratefully acknowledged.

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