Istanbul Technical University Autobee Team VesselBee**03** RoboBoat'24 Technical Design Report

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***Abstract*—This report presents the comprehensive design and development of VesselBee03, a competitive vessel crafted by Istanbul Technical University's Autobee Team for the RoboBoat 2024 competition. It outlines the innovative approaches in mechanical and hydrodynamic design, advanced navigation and control systems, and sophisticated electrical architecture. Emphasizing the integration of autonomous technologies, the report details the vessel's capabilities in task efficiency, maneuverability, and adaptive strategies in dynamic marine environments. This document serves as a testament to the team's engineering expertise and strategic vision in maritime robotics.**

I. Introduction

THIS document briefly describes the technical specifications of **VesselBee03** (hereby referenced as "the vessel") designed, manufactured and developed by ITU Autobee Team.

II. Competition Goals

Team Autobee has been designing and executing vessel projects with Vesselbee series since 2022. After completion of Vesselbee 02 and its success in Norway, Team has decided to attend Roboboat 2024. After inspected, both competitions showed same level of complication and sophistication about autonomy. So for 2024 Roboboat Team heas decided to perfect what they have done best which are tasks 1,2,3,4,5 and 8. Team has already executed these movements and have won an international competition. Team's primary goals are for Roboboat 2024 for are to complete tasks 1, 2, 3, 4, 5 and 8 in most efficient and fastest way possible.

III. Design Strategy

A. Mechanical

1) Thruster Design: The propellers were created using MATLAB's OpenProp code, employing a design tailored to our vehicle's specific parameters. To ensure the hydrodynamic integrity of our propeller, we employed CFD programs such as ANSYS and OpenFOAM for verification. The portable propeller we manufactured underwent rigorous testing at the Ata Nutku Experiment Laboratory's circulation pool, situated within our esteemed institution. The revisions made to the propellers resulted in enhanced acceleration capabilities for the boat. The propellers and thruster body were intricately designed to accommodate the DXW2838 300 KV motor, which operates within a voltage range of 3-6s (11.1V-22.2V). The decision to utilize these specific motors was primarily based on their waterproof nature and impressive power output of 350 Watts. The total thrust generated by the thruster was measured at 2.89 kg force, achieved at 4250 RPM using a 4S 14.8 Volt battery. For a visual representation of the designed thruster, please refer to Figure 1.

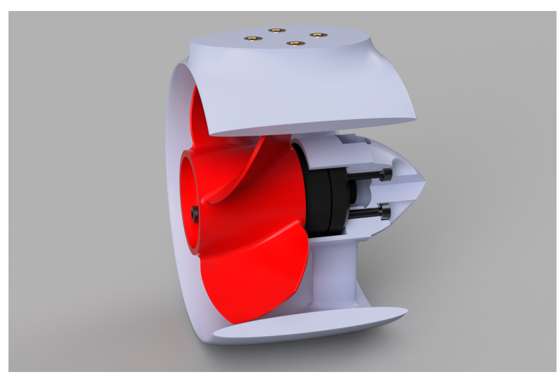

Fig. 1: Thruster design

2) Hull Manufacturing: We have determined that opting for a high Froude trimaran design would be most advantageous due to the required platform size and stability considerations. The selection process, despite its complexity, will not present any challenges as we have decided to utilize the FDM 3D Printing technique for production. Given the abundance of FDM printers available in various sizes, we have chosen to manufacture the hull using PLA and implement post-processing techniques to ensure a waterproof and rigid structure. The body will be fabricated in blocks and subsequently assembled as depicted in Figure **??**. The finalized design of the boat can be observed in Figure 3.

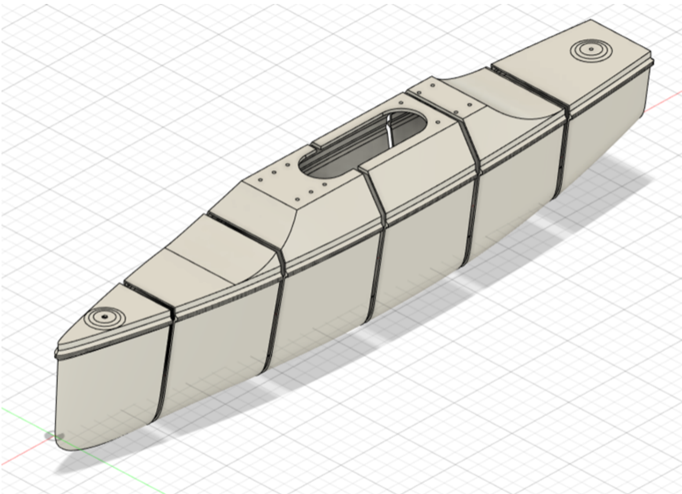

Fig. 2: Sections of a single hull

3) Final Design and Assembly: The final design culminates in processed body parts being affixed, assembled, primed, and painted. Once the hull has been mechanically completed, the cables will be routed throughout its entirety. Following the completion of cabling, the electronics and remaining sensors will be attached to their designated locations. Figure 3 showcases the final form of the catamaran.

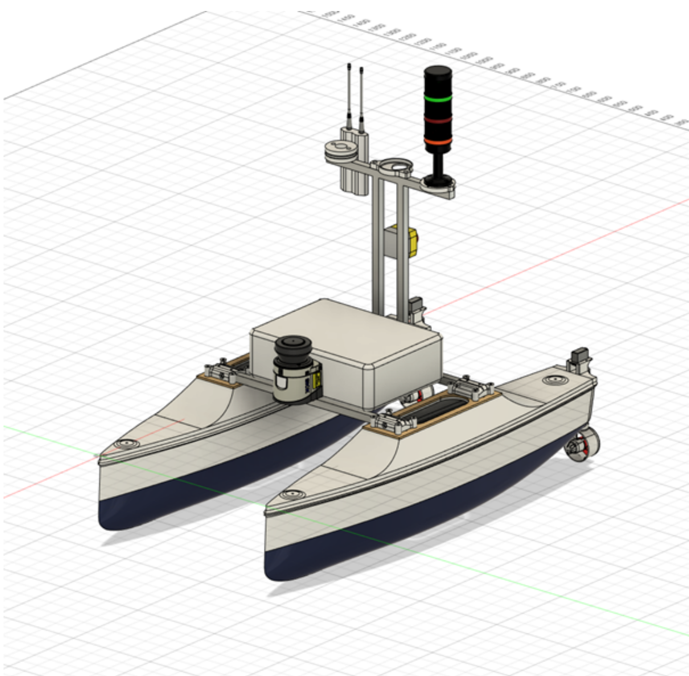

Fig. 3: Wave distruption of the hulls

B. Hydrodynamic Analysis

To ensure that the design choices are correct and will be suitable for open sea conditions and competition environment, the design has to be analyzed & tested under certain conditions. Next step is to decide desired speeds. Desired speeds are the main factor in ship design. When electronic inventory and image processing considered our team has decided that cruise speed should be around 0.6-1.0m per second. Yet due to some task's scenarios catamaran should be moving between 1.2-3.2 meters per second to be able to finish the task faster. The resistance values it is exposed to at these speeds are also important in shaping the design.The resistance values of the Autonomous Surface Vehicle are as follows: the vehicle weighs $26,6kg$, has a volume of $74Liters$ draft amidship of $140mm$, an immersed depth of $139,6mm$, a waterline length of $1211mm$, a maximum beam extent on the waterline of $329,3mm$, a wetted area of $343286mm^2$ a maximum sectional area of $17880mm^2$ a waterplane area of $137943mm^2$ a prismatic coefficient (C_p) of 0.598, and a block coefficient (C_b) of 0.483. The lengths of the LCB and LCF are $646,1mm$ and $594mm$, respectively. The L/B ratio is $5,95$ and the B/T ratio is $1,5$. The hydrostatic calculations of the boat were performed using ANSYS CFD. The resistance values obtained from the calculations are presented in Figure-x, and wave disturption of the hulls is shown in reffigurefigure6. Figure 4 displays the resistance results, while Figure 5 presents the wave disturption of the hulls.

	Measurement	Value	Units
1	Displacement	13,29	kg
2	Volume (displaced)	12962385,2	mm^3
3	Draft Amidships	140,0	mm
4	Immersed depth	139,6	mm
5	WL Length	1211,5	mm
6	Beam max extents o	329,3	mm
7	Wetted Area	343286,2	mm^2
8	Max sect. area	17880,4	mm^2
9	Waterpl. Area	137943,2	mm^2
10	Prismatic coeff. (Cp)	0,598	
11	Block coeff. (Cb)	0,483	
12	Max Sect. area coeff	0,830	
13	Waterpl. area coeff.	0,718	
14	LCB length	646,1	from zero pt. (+ve fwd) m
15	LCF length	594,0	from zero pt. (+ve fwd) m
16	LCB %	53,330	from zero pt. (+ve fwd) %
17	LCF %	49,026	from zero pt. (+ve fwd) %
18	KB	84,2	mm

Fig. 4: Hydrostatics

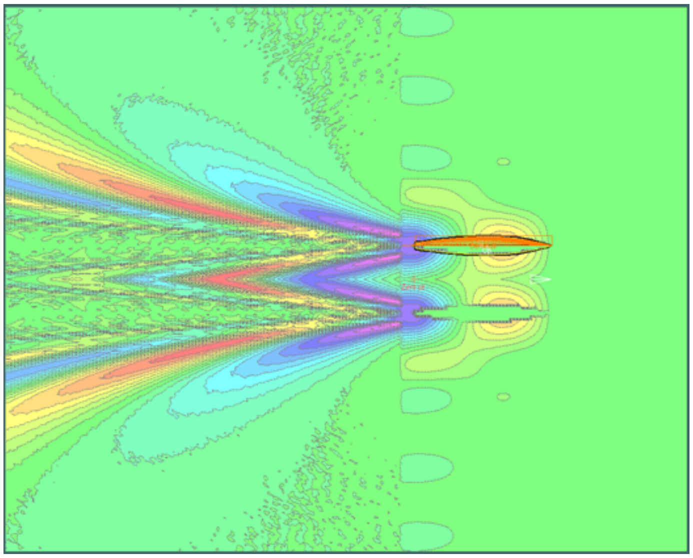

Fig. 5: Wave distruption of the hulls

C. Guidance, Navigation and Control

The software for the vessel can be divided into two sections, higher and lower level software. The lower level primarily consists of all control related software, focusing on the motion control of the vessel. For this, a mathematical model of the vessel dynamics is formed with the help of the parameters obtained from hydrodynamic analysis.

1) Mathematical Modelling: The body dynamics can expressed as below considering the vessel follow the assumptions made in [1] *Assumption 3.1*

$$\begin{aligned} M(v)\dot{v}(t) + C(v)v(t) + D(v)v(t) + g(\eta) &= \tau + \tau_E \\ \dot{\eta} &= J(\eta)v \end{aligned} \quad (1)$$

where M is the sum of rigid body M_{RB} and added mass M_A matricies, C is the coriolis matrix, D is the damping matrix, η is the position vector in the world frame, v is the velocity vector in body frame, τ is the control forces exerted on the body, τ_E is the vector of external disturbances such as wind or currents.

$$\begin{aligned} M(v) &= M_{RB} + M_A(v) \\ C(v) &= C_{RB}(v) + C_A(v) \\ D(v) &= D_l + D_q(v) \\ v(t) &= [v_x, v_y, w_z]^T \\ \tau &= [F_x, 0, T_z]^T \\ \eta &= [p_x, p_y, \psi] \end{aligned} \quad (2)$$

Also,

$$M_{RB} = \begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & I_{zz} \end{bmatrix}, M_A = -\begin{bmatrix} X_{\dot{v}_x} & 0 & 0 \\ 0 & Y_{\dot{v}_y} & 0 \\ 0 & 0 & Z_{\dot{w}_z} \end{bmatrix}$$

$$\text{C} = \begin{bmatrix} 0 & 0 & C_{xz} \\ 0 & 0 & C_{yz} \\ -C_{xz} & -C_{yz} & 0 \end{bmatrix}, \text{D}_l = -\begin{bmatrix} X_x & 0 & 0 \\ 0 & Y_y & Y_\psi \\ 0 & N_y & N_\psi \end{bmatrix}$$

$$\text{D}_q = -\begin{bmatrix} X_{|x|x}|v_x| & 0 & 0 \\ 0 & Y_{|y|y}|v_y| & Y_{|y|w_z}|v_y| \\ 0 & N_{|y|y}|w_z| & N_{|y|w_z}|v_y| + N_{|w_z|w_z}|w_z| \end{bmatrix}$$
$$C_{xz} = -m(x_g w_z + v) + Y_{\dot{v}_y} v_y + Y_{\dot{w}_z} w_z$$
$$C_{yz} = m v_x - X_{\dot{v}_x} v_x$$
(3)

2) Thruster Modelling: In order to exert the forces and torques on the body as described in Equation 1, the thrusters needs to be modelled. Since the dynamics of the thrusters are very fast compared to the body dynamics, the transient characteristics of the thrusters can be neglected.

Therefore the thrust force generated by the thrusters can be expressed as

$$F(\rho, V_{batt}) = (a_1 * V_{batt} + a_0) \cdot (b_2 * \rho * |\rho| + b_1 * \rho + b_0) \quad (4)$$

where the V_{batt} is the voltage supplied to the thruster, ρ is the duty cycle (%) of the applied signal.

3) Thruster Allocation Matrix: The forces exerted on the body can be expressed as

$$\begin{aligned} \tau &= \begin{bmatrix} F_x \\ 0 \\ T_z \end{bmatrix} \\ T(\lambda)\lambda = \tau, \quad & \lambda = \begin{bmatrix} \lambda_F \\ \lambda_\phi \end{bmatrix} \\ \lambda_F = \begin{bmatrix} F_{t1} \\ F_{t2} \end{bmatrix}, \quad & \lambda_\phi = \begin{bmatrix} \phi_{t1} \\ \phi_{t2} \end{bmatrix} \end{aligned} \quad (5)$$

In order to construct a QP the following minimization problem can be used

$$\begin{aligned} min \quad & \frac{1}{2} x^T Q x \\ s.t \quad & Ax = b \end{aligned} \quad (6)$$

where,

$$x = \begin{bmatrix} F_{t1x} \\ F_{t1y} \\ F_{t2x} \\ F_{t2y} \end{bmatrix}, b = \begin{bmatrix} F_x \\ F_y \\ T_z \end{bmatrix} \quad (7)$$

A is the linear constraints and

$$\begin{aligned} F_{t1x} &= F_{t1} * cos(\phi_{t1}) \\ F_{t1y} &= F_{t1} * sin(\phi_{t1}) \\ F_{t2x} &= F_{t2} * cos(\phi_{t2}) \\ F_{t2y} &= F_{t2} * sin(\phi_{t2}) \end{aligned} \quad (8)$$

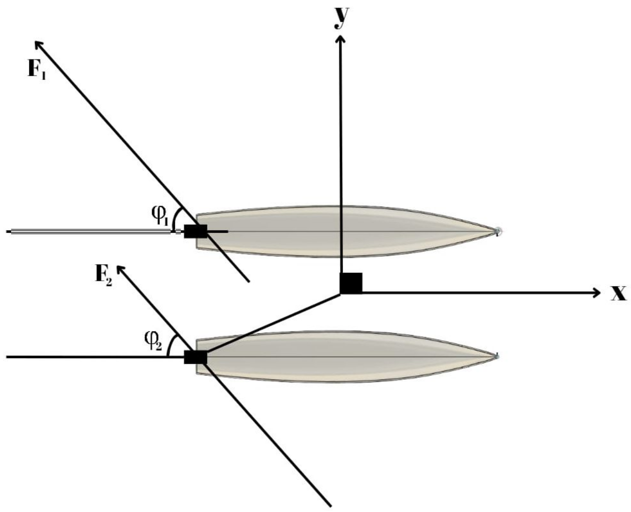

Fig. 6: Thruster azimuth angles

An example solution to the optimization problem above can be seen in Figure 7

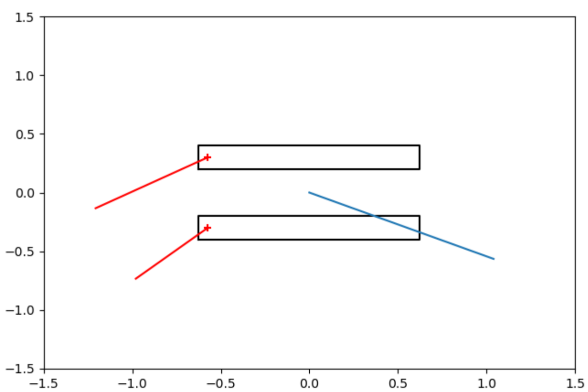

Fig. 7: Thruster Forces required to produce total force & torque

4) Controller Design: In order to develop a controller, it's essential to analyze the mathematical model of the system. The presence of quadratic terms in this model indicates that the system is nonlinear. Consequently, controllers typically used for linear systems won't perform uniformly across various regions of the workspace. A potential solution is to linearize the model around certain operating points. This approach simplifies the problem, making it feasible to apply linear control techniques. However, this simplification may lead to reduced performance when the system's conditions deviate from these specified operating points.

D. Electrical Design

All of the electrical components are placed in an $0.4 \times 0.5 \times 0.24$ electrical box, except the 2 × 6S 20000mAh Lithium-Polymer batteries, which are placed in each hull to lower the center of mass.

1) Power Distribution: MATEK FCHUB-6S is employed to manage power distribution. This particular device is designed to accommodate a maximum of 6S (22.2V) and 184 amps. The decision to utilize a high-voltage, high-current PDB was made to ensure that the components do not generate excessive heat within the hull and to provide regulated 5V, 9V, and 12V power lines throughout the boat.

2) STM32: The embedded software also establishes an interface layer for the high-level software, allowing for vehicle control and sensor data collection through the use of Rosserial1. This functionality enables all motherboard features to be accessible on the ROS network. Through this real-time operating system (RTOS) based embedded software, these features can be prioritized and scheduled within the task scheduler, resulting in enhanced efficiency and a modular system.

E. Higher level algorithm design

In order to incorporate high level algorithms into the vessel's software smoothly, *ROS* is used. This brings the flexibility of asynchronous task execution and inter-process communication with minimal effort.

Acknowledgment

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References

[1] D. Do and J. Pan, *Control of Ships and Underwater Vehicles*, English. Netherlands: Springer, 2009, ISBN: 9781848827295.

TABLE I: Component Specifications

Component	Vendor	Model/Type	Specs	Cost(if new)	Year of Purchase
ASV Hull Form/Platform	3D Printed PLA Hull	VesselBee Catamaran	LOA = 1.24 m, D = 0.25 m, T = 0.12 m, B = 0.75 m	108 USD	2022
Waterproof Connectors	-	-	-	-$	-
Propulsion	3D Printed PLA Prop and Shroud	Thruster Body	80mmx65mm	-$	2022
Thruster Motors	DXW	Motor	2838 300 KV 3-6S	54 USD	2021
Power System	Tattu	LiPo	4S 5200 Mah 35C	126 USD	2022
Motor Controls	HobbyWing	ESC	40A V4 Brushless	165 USD	-
CPU	NVIDIA	Jetson AGX Xavier	512-core NVIDIA Volta architecture GPU with 64 Tensor Cores 8-core NVIDIA Carmel Arm®v8.2 64-bit CPU	2000USD	2019
Teleoperation	RFDESIGN	RFD686x	Long range ¿40km,1 Watt (+30dBm) transmit power	373 USD	2019
Compass	HERE	HEREPRO Multi-RTK	Nav. Update Rate: Up to 20 Hz for RTK Position Accuracy: RTK 0.01 m + 1 ppm CEP Heading Accuracy: 0.4 degrees	935 USD	2022
Intertial Measurement Unit (IMU)	HEX	Orange Cube	32bit ARM® STM32H753 Cortex®-M7with DP-FPU 400 Mhz/1 MB RAM/2 MB Flash	454 USD	2018
Doppler Velocity Logger (DVL)	-	-	-	-$	-
Camera(s)	WaveShare	USB Camera	5 MP, CCD=1/4 inch, F:2.8	14 USD	2019
Hydrophones	-	-	-	-	-
Algorithms	GPS + Compas Navigation System, Object Avoidance	-		-$	-
Vision	Image Processing OpenCV Library and ML	-	-	-	-
Localization and Mapping	Sick	LMS151	30 meters	4200 USD	2022
Autonomy	-	-	-	-	-
Open-Source Software	-	-	-	-$	-