Design and Fabrication of a Towing Tank for Hydrodynamic Experiments as Ashesi University

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ABSTRACT

A two-axis towing tank for conducting hydrodynamic and biomimetic experiments at Ashesi University, Ghana, has been designed, fabricated, and validated. Motion control of the carriage along the tank is achieved through a custom-built MATLAB application controlling speed, trajectory, and data acquisition. The system is broken into four subsystems: the MATLAB-based control application, the electrical and electronic system, the mechanical system, and the data acquisition system. The MATLAB-based control application sends commands to the electrical and electronic systems, which control the mechanical and data acquisition systems. Experiments were conducted to measure the motion system's accuracy and reliability in velocity and travel distance. Sixty experiments were performed across three different velocities and travel distances, with each set of parameters tested ten times. The findings from these experiments reveal a maximum error margin of 2% for velocity and 1.82% for travel distance, indicating the system's reliability as an experimental platform. Minimal equivalent platforms have been created on the African continent; hence, this work offers significant potential to advance teaching and research in Africa's engineering programs. This design bridges theoretical learning and practical application, offering students a hands-on experience of fluid mechanics through experimental measurement and enabling technical research in areas currently limited largely to computer simulation. This system will support the development of a skilled engineering workforce equipped to tackle Africa's industrial opportunities in transportation, marine engineering, offshore technology, aerospace, sensing, and advanced technologies such as biomimetics.

Keywords: towing tank, Reynolds number, hydrodynamics, drag, lift, reliability, validation

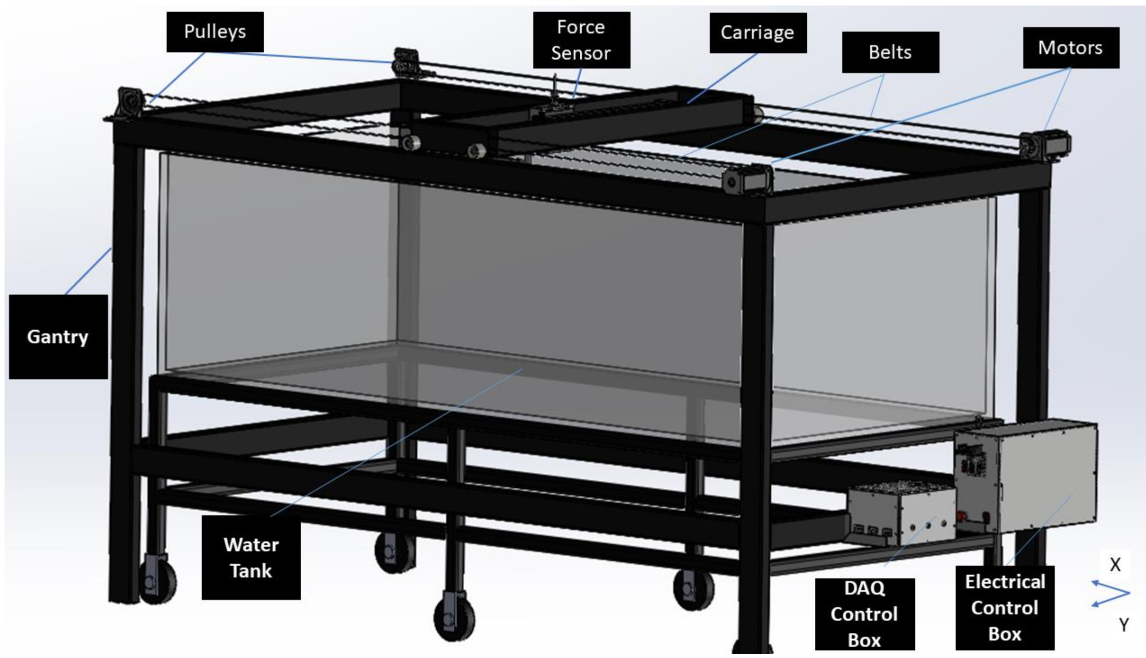
1.0. INTRODUCTION

Experimental hydrodynamic measurements are essential for studying the design of marine vehicles, offshore structures, underwater robotics, and aerodynamic systems. Measuring these vehicles' hydrodynamic coefficients and structures is necessary for designing and optimizing their performance. Reliance on computer simulations can limit accurate prediction of real-world performance, and fabrication of full-scale prototypes is expensive. Hence, researchers have sought to leverage experimental approaches to testing scaled models scaled models over the last several decades. Some examples of experiments carried out in experimental hydrodynamic measurement include testing designs of ship models and turbines (Toncel Zuleta and Cabrera T. 2014), finding means of reducing drag on ships in seawater conditions (Khomyakov and Elyukhina 2019), and improving the efficiency of horizontal-axis tidal turbines (Alamian et al. 2020).

Another emerging area that benefits from hydrodynamic measurements is the design of experimental platforms, such as biomimetic vehicles, which leverage natural phenomena to inform technology design. Researchers used a towing tank at MIT to test the performance of a flexible body robot designed for biomimetic locomotion in high Reynolds number flow (Valdivia Y Alvarado and Youcef-Toumi 2005). A similar system was used to test the propulsion performance of a pectoral fin in sinusoidal motion (Cai, Bi, and Zhang 2010). A propulsive performance analysis of a waterjet-propelled amphibious vehicle was carried out to determine parameters such as the net thrust coefficient, torque coefficient, and net efficiency of the waterjet-propelled amphibious vehicle at the Seoul National University (Seo et al. 2022).

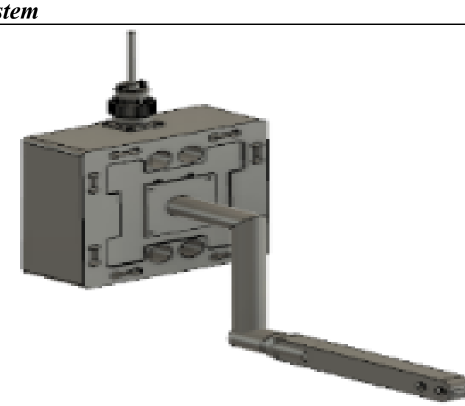
Multiple platforms to conduct measurements on various hydrodynamic parameters exist. Key among these are water tunnels and towing tanks. Water tunnels operate by recirculating water through a closed loop. These tend to be large systems that require complex piping systems to successfully recirculate the water and ensure uniform flow as it re-enters the test section (Shao et al. 2017). As a result, the systems require a significant physical footprint and several components, such as one developed at NASA (Neuhart 1988). Because of the motion of the water, water tunnels can also face leakage problems (Saeed et al., 2018). Towing tanks, on the other hand, operate by traversing the test object (mounted on a carriage) through a water tank. Both systems achieve the same purpose based on the equivalent relative velocity experienced by the test object. In terms of the design, however, the towing tank offers an advantage in its relatively fewer number of components involved and the generally smaller physical footprint required. Towing tanks can also incorporate wave generators, providing an expanded range of test conditions.

Existing towing tank systems have been developed in different contexts and with varying specifications regarding tank size, motion control approach, and data acquisition type. One of the towing tank systems at MIT is a $2.4m \times 0.6m \times 0.6m$ acrylic tank with carriage motion supported by vacuum preloaded air bearings, a linear encoder on the carriage to measure velocity, and forces on the test object measured using a load cell (Valdivia Y Alvarado and Youcef-Toumi 2005). A significantly larger system is that at the Seoul National University (SNU) – a $110m \times 8m \times 3.5m$ with a maximum carriage speed of *5.0m/s*-wave generation capabilities with wave height in the 0 to $0.3m$ range. This tank can conduct propulsion tests, seakeeping and maneuvering tests, motion measurements, and loads on moored floating bodies (Shinrim-Dong n.d.). There is a need for towing tank facilities in Africa to support teaching and research;



(a) Towing Tank Full System

(b) CAD Model of the Carriage



(c) Three Axis Load Cell and Test Object Mount

(d) Motor Control Box

(e) Load Cell Control Box

however, minimal evidence of their presence exists. One such facility (92*m* long, 4.2*m* wide, and 2.7*m* deep) has been documented in South Africa (Stellenbosch University, 2022). Construction of such platforms in other parts of the continent would enable students to carry out hands-on learning and open up a myriad of hydrodynamic research, enhancing existing local marine structures and informing novel designs.

This paper outlines the in-house design and fabrication of a towing tank system at Ashesi University, Ghana. The intention is to prove the concept and inspire other African engineering institutions to implement or modify it. The high-level design criteria were for the system to take up a reasonably small physical footprint, be simple enough to fabricate in-house and produce reliable enough motion trajectories to conduct repeated experiments. Figure 1(a) depicts a CAD model of the entire towing tank system, with major parts labeled, such as the gantry where the carriage sits, motors, belts, pulley system, and tank. Figure 1(b) highlights the carriage, which is the component that traverses the length of the tank (x-axis of motion), towing a mounted test object. It also includes a linear stage used to translate the test object across the width of the tank (y-axis of motion. Figure 1(c) shows the three-axis load cell and the test object mount, connecting the test object to the carriage. Figure 1(d) depicts the control box of the motor containing the motor drivers, power supply, and microcontroller. Figure 1(e) shows the load cell control box, which houses the weighing transmitters, power supply, and microcontroller.

2.0 METHODOLOGY

The methodology began with the design of the system and its subsystems. There are four main subsystems- mechanical system, electrical and electronic system, data acquisition system, and the MATLAB-based control application. The control application sends commands (Gcode) for speed and trajectory to the drive system, which moves the carriage and the towing mechanism while recording data from the three-axis load cell to the application. The system commands two axes of motion and can, therefore, be programmed to move the test object in different trajectories. For example, a sinusoidal or a linear equation can create a motion trajectory for the object. Forces experienced by the object during these motions are recorded onto the application. The design of each subsystem is considered next.

2.1. Mechanical Design and Fabrication

The mechanical system consists of the gantry, the carriage, and the drive mechanisms. The gantry is the frame around the tank. The carriage sits in the gantry, carrying the towing mechanism consisting of a RATTMMOTOR EBX160 400mm leadscrew driven by a NEMA 17 motor. The carriage system is moved on the gantry by a 2GT Synchronous Wheel 2M 20T pulley and 6 *mm* belt mechanism connected to two NEMA 34 motors. The dimensions of the gantry are 3.1 *m* x 1.43 *m* x 1.59 *m,* and the carriage is 1.325 *m* x 0.353 *m* x 0.0508 *m*. The drive mechanism consists of a belt and pulley system and the lead screw system. The belt and pulley system moves the carriage across the gantry , and the leadscrew mechanism moves the test object from side to side. The gantry and carriage were fabricated by drilling, cutting, and welding 4" by 2" galvanized steel tubes.

2.2. Electrical & Electronic System

The electrical system consists of motors (NEMA 17 and NEMA 32), motor drivers, power supply, emergency stop, proximity sensors, and an Arduino Uno microcontroller. The power supply provides the DC voltages required for the motor drivers to control the motors. The motor drivers receive Gcode commands from the microcontroller, which runs the grbl software, controlling the proximity sensors and emergency stops. The electrical and electronic system is housed in the control box, which was fabricated by assembling 20*mm* by 20*mm* aluminum extrudes and laser-cut plexiglass. The dimensions of the control box are 0.335*m* x 0.21*m* x 0.505*m*. The control box's CAD image is depicted in **Error! Reference source not found.Error! Reference source not found.**). Figure 2 shows the connection between the electrical and electronic systems that power the motors. As described above, an Arduino Uno sends a control signal to the motor drivers to run the motors. When the limit switches, which are connected to the microcontroller, are activated, they stop the movement of the motors. The diagram also shows the switches that connect the system to power.

2.3. Data Acquisition

The data acquisition system consists of a three-axis load cell (GPB160 multi-axis load cell three-axis, 50*N* force sensor), power supply (12 Volts, 10 Amps), the weighing transmitter (GT202 Single Channel Weighing Transmitter), and an Arduino Uno microcontroller. The load cell measures force data (y-direction: lift and x-direction: drag) experienced by the test object, and the weighing transmitter amplifies the data. The weighing transmitter and power supply

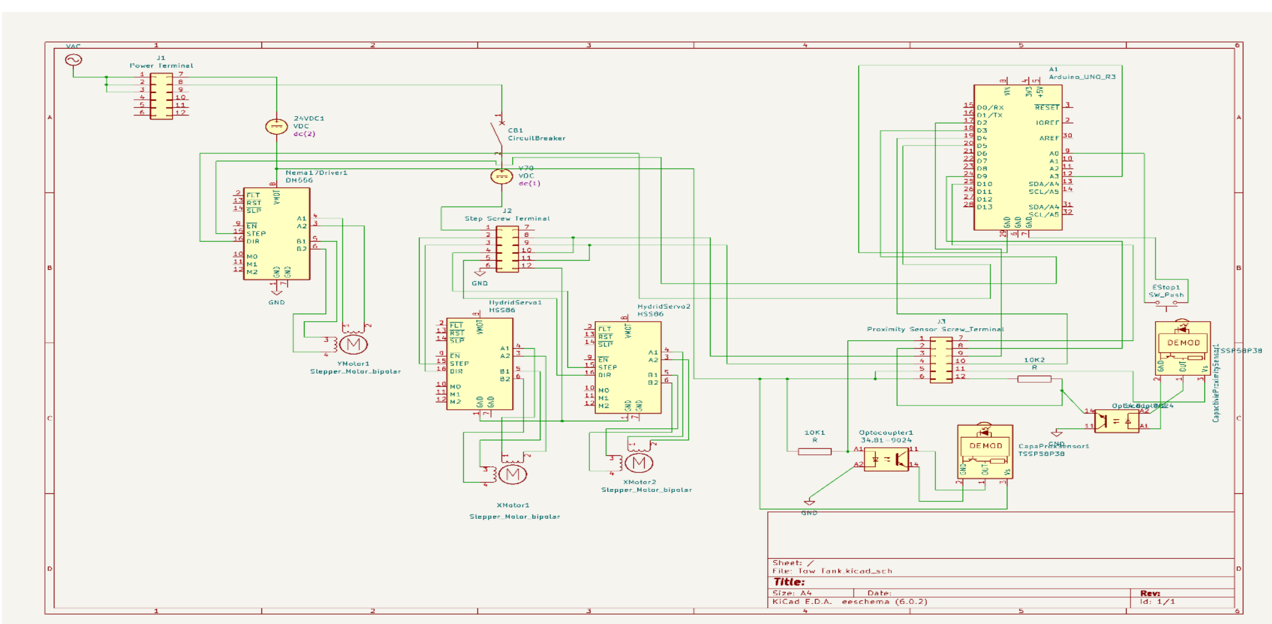


Figure 1: Circuit Diagram of Electrical and Electronic System

are housed in a separate control box, fabricated similarly to the other one. The load cell was calibrated by mounting it on a table and sequentially loading it with a series of known weights. Voltage values were plotted against the known weights, and a linear regression was carried out to obtain the relation between the two. The calibration was conducted for all three axes. The load cell responded by producing a corresponding change in the voltage value while all other axes' voltage values remained the same. This step was repeated ten times on all axes with ten known weights. The R squared values from calibration were 1, 1, and 0.9998 for the X, Y, and Z force axis, and the equations of the lines were $y = 1068.5x - 11.665$, $y = 1068.5x - 11.665$, and $y = 877.88x + 2.1545$ respectively. Components y and x are the output (force value) and input (voltage value). The CAD model of the three-axis load cell and the load cell control box is depicted in Figures 1(c) and **Error! Reference source not found.**), respectively.

2.4. MATLAB-Based Control Application

No existing, zero-cost system to simultaneously control the motors and read data was found. Hence, the authors designed and implemented a custom application in-house using MATLAB App Designer. This application controls the motion in both axes, reads force data, and plots it. The application was created with two tabs. The design tab enables the user to design an experiment by setting operation parameters such as the physical parameters (fluid in use, length of specimen, speed) and the motion trajectory (linear or sinusoidal) and checking the trajectory plot generated before commencing the experiment. The design tab also performs connection to the Arduino, jogs the system, and homes it. The command buttons on the design tab can be used to jog the linear stage to the side of the tank for easier user access to mount the test object. Figure 3 depicts the MATLAB application user interface, showcasing the design tab, where parameters are selected to design the experiment. It also contains a trajectory plot, axis control buttons, and key control commands such as home, start, pause, specimen load position (for mounting the specimen), set home position, go home, upload a file, and reset. The analysis tab displays plots of the time series force data collected. A flow chart of how the MATLAB-Based Control Application works with the towing tank is shown in

Figure *2* below.

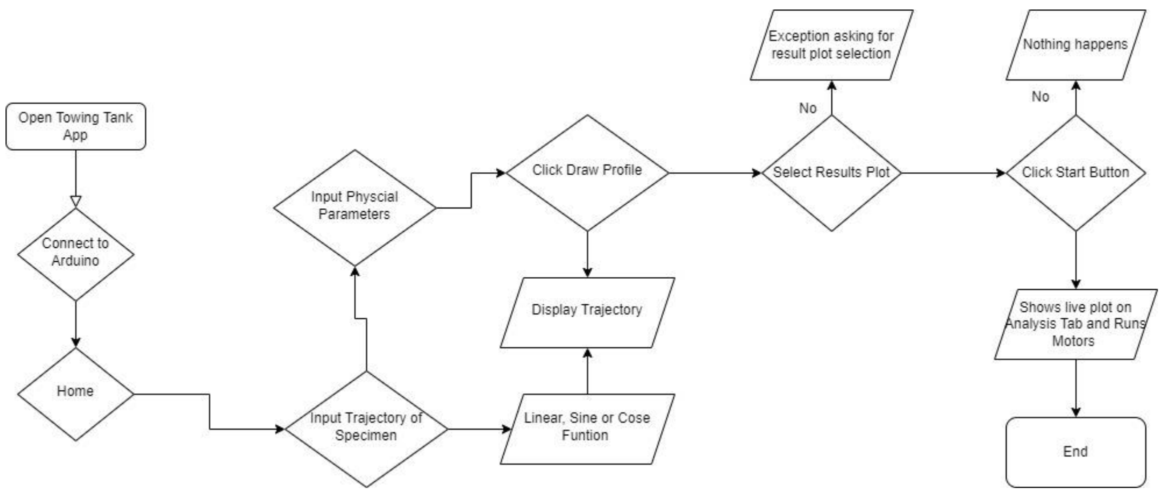


Figure 2: Simplified flowchart of MATLAB-Based Application for Controlling Towing Tank

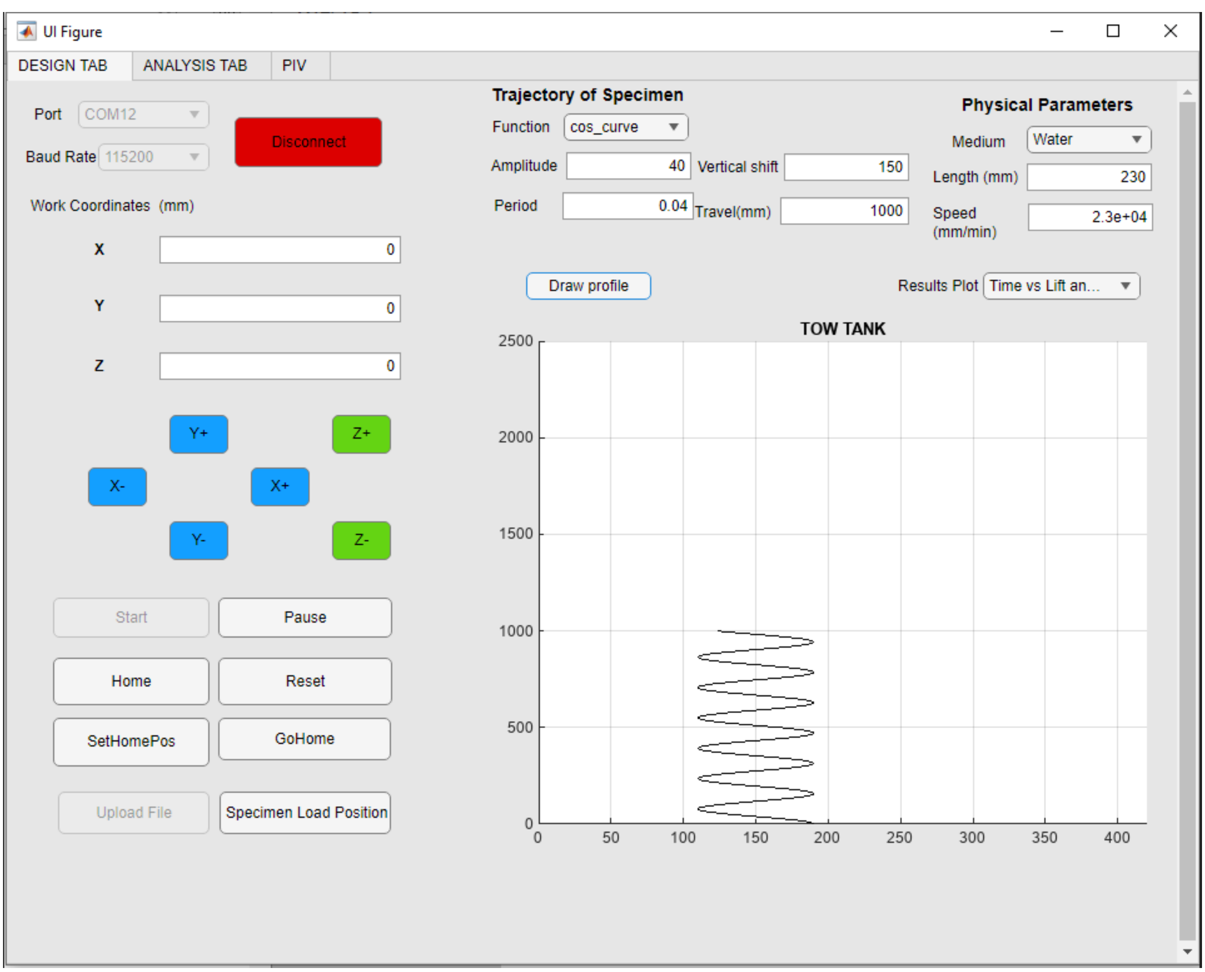


Figure 3: Screenshot of the MATLAB-based application designed in-house to control carriage motion and collect data.

Table 1 shows the key specifications of the system designed, and

Figure 4 displays the fully fabricated system, including the desktop housing the MATLAB application.

Table 1: Towing Tank Specifications

Specifications	
Dimensions of Tank	2.75*m* L x 1.23*m* W x 0.77*m* D
Speed	0*m/s* - 0.75*m/s*
Drive Mechanism	2GT Synchronous Wheel 2M 20T Belt and Pulley 6*mm* (X-Axis) and RATTMMOTOR EBX1605 400mm Lead screw drive (Y-Axis)
System Control	MATLAB Application
Motion Profiles	Linear and Sinusoidal motion
Data Acquisition	Force Data (Lift and Drag Forces in *Newtons*) via Load Cell and Arduino Uno

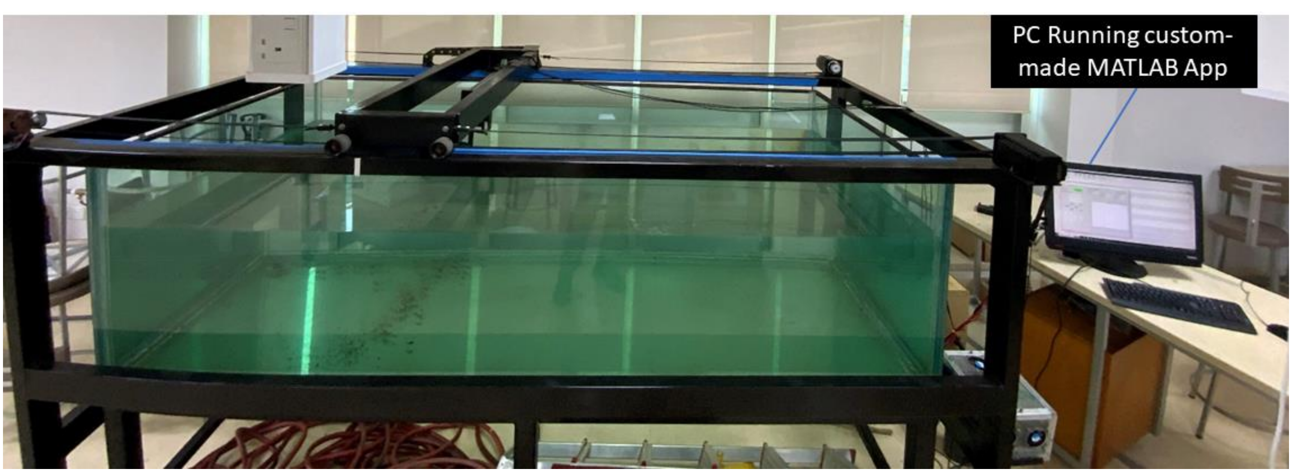


Figure 4: Fully Fabricated System

2.5. Experimental Test for System Validation

System performance was measured through a series of experiments based on accuracy and reliability. The carriage was prescribed to move to a fixed distance location at a single velocity. This was repeated ten times for each of the three different velocities. The parameters of interest were the accuracy of the distance covered and the velocity output corresponding to the velocity input in the MATLAB App. The start position, end distance distance, four-fifths of the end distance, and one-fifth of the end distance were marked, as shown in Figure 5(a).

The initial position and the final distance were employed to verify the accuracy of the distance traveled. One-fifth of the distance and four-fifths of the final distance were employed to validate the velocity. These distance positions were selected to maximize the system's velocity, as it accelerates at the start to reach the input velocity and decelerates as it approaches the goal position or distance. Another series of experiments was conducted to verify the distance traveled. These experiments were done by fixing a tape measure to the tank walls and a camera to the carriage positioned to face the front wheel, capturing distance data for each run. The starting point of the tape measure was positioned at the front wheel to serve as the reference for measurements. Distances of 750, 1000, and 1500 *mm* were selected for the carriage's travel, with the mounted tape measure serving as the benchmark against which the input distance values were compared. Ten runs for each of these three distances were conducted. Accuracy was calculated based on the percentage error between the distance traveled and the distance prescribed in the application. Reliability was calculated based on the standard deviation of each dataset.

3.0. RESULTS

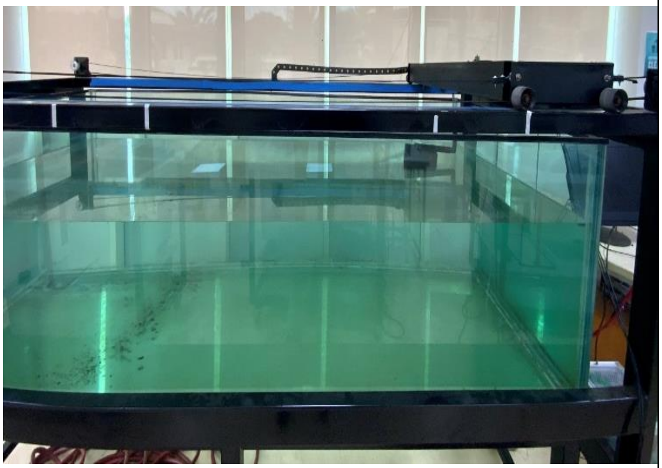
The percentage errors recorded for all the velocity experiments were below 2%. The 5,000 *mm/min*, 25,000 *mm/min*, and 45,000 *mm/min* velocities had percent errors of 0.2*%* to 2*%*, 0.46*%* to 1.82*%*, and 0.82*%* to 1.64*%,* respectively. Figure 5(e) shows a box and whisker plot of the percent error of these velocity values. The median, the most occurring value, is shown with the bold line, and the outliers, which are the values that deviate significantly from the mean, are depicted with a diamond. Figure 5(f) shows a box and whisker plot of the percent error for the distances. The percent error for the distances 750 *mm*, 1000 *mm*, and 1500 *mm* ranged from 1.06*%* to 1.33*%*, 1*%* to 1.33*%*, and 1*%* to 1.06*%* respectively. The system's reliability was determined using the standard deviation of the normalized data, where each velocity and distance value was divided by the max velocity or distance for each test. The standard deviations were obtained as 0.0086, 0.0059, and 0.0045 for velocity and 0.0012, 0.0014, and 0.0003 for distance, respectively.

Limitations

The limitations of the towing tank system are as follows:

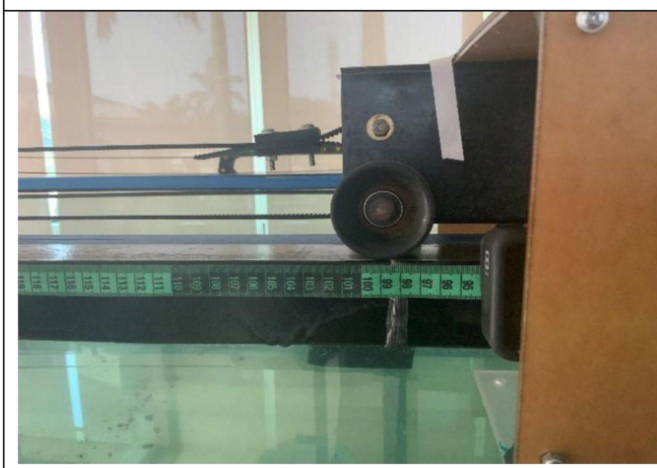
1. The system is limited to a max velocity of 0.5 m/s based on the current equipment in use.
2. The system vibrates at high speeds, resulting in noise in the sensor (force sensor) reading. Thus, obtaining the vibration frequency to create a filter for

accurate force results is a necessary improvement.

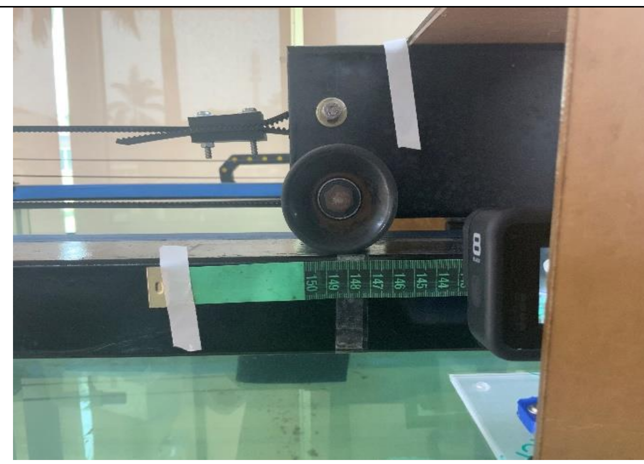


(a) Velocity makers

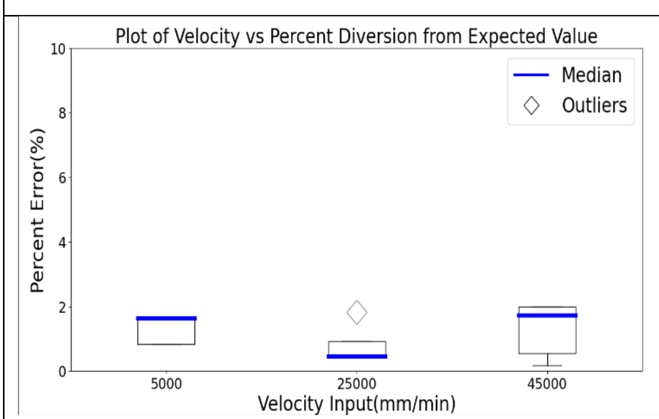
(b) Distance 750mm Experiment



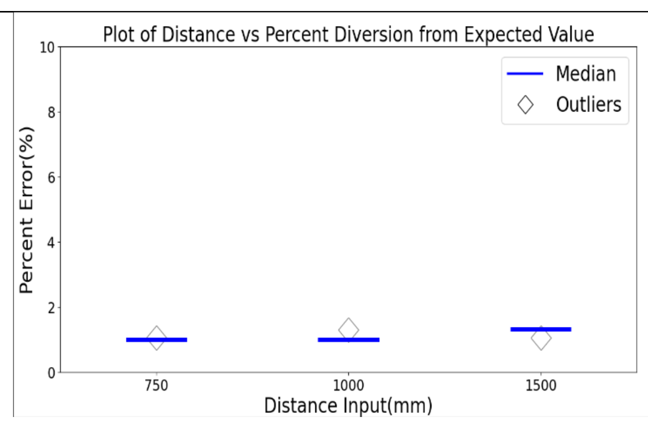
(c) Distance 1000mm Experiment



(d) Distance 1500mm Experiment



(e) Velocity Error plot



(f) Distance Error plot

Figure 5: Validated Results with the median and outlier values highlighted in the legend.

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1. The system is currently limited to force sensor readings of lift and drag.
2. Wave generating is not feasible in the current system due to the tank size (3 meters) which is insufficient to accommodate a beach for wave absorption.

Future Works

The X-axis's driving mechanism is in the redevelopment process to reduce vibration at high speeds and reduce sensor data noise. The X-axis drive system is changing into a linear screw drive (linear stage) mechanism, which is smoother and generates less vibration. Other future work includes acquiring an advanced force sensor with a high resolution for more precise force results. Other sensors on the list for improving the system include a high-precision pressure sensor, a dynamometer for torque, and rotational speed data once other axes (yaw and maybe pitch) are added to the system. With additional funding and facilities, the towing tank system can be reconstructed using the same concepts used for current use and include wave generation.

4.0. DISCUSSION AND CONCLUSION

A towing tank was designed and fabricated at Ashesi University, Ghana, fulfilling the objectives of creating a system that could be fabricated in-house, take up a reasonably small physical footprint, and produce reliable motion profiles. All critical mechanical components, such as the gantry and carriage, were fabricated in the campus workshop. The system achieves a maximum carriage travel distance of 2.75*m* and a maximum velocity of 0.75 m/s and can read force data up to 50 *Newtons* on towed test objects. The system is fully automated using an application developed in-house using MATLAB App Designer, which simultaneously collects force data.

Experiments reveal strong accuracy (< 2%) between the distance and velocity values prescribed in the MATLAB app and what the system carries out. The reliability of the carriage motion was also strong (with the max standard deviation being 0.0086 for velocity and 0.0014 for distance). These results indicate that test objects mounted to this system will undergo motion trajectories that are consistent and reliable. Future work can further enhance the capabilities of this system- incorporating additional axes of motion and collecting additional sensor data, such as pressure – and commence hydrodynamic experimentation on a range of test objects. This system serves as a proof of concept for what can be created, and it can inspire African institutions to replicate or modify this design to enhance teaching and research efforts on the continent.

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