Proceedings of the ASME 2021
International Mechanical Engineering Congress and Exposition
IMECE2021
November 1-4, 2021, Virtual, Online

IMECE2021-69563

CONSTRUCTION AND TESTING OF SMALL-SCALE TRANSFORMABLE-HULL CONCEPT BOAT

Phillip Whitworth
Washington State University
Pullman, WA, USA

Cole James
Washington State University
Pullman, WA, USA

Konstantin I. Matveev
Washington State University
Pullman, WA, USA

ABSTRACT

Practically all marine vessels have fixed-geometry hulls. This limits their capabilities and high-performance regimes to a limited set of operational conditions. Having a transformable or adaptive hull structure can help maximize ship's operational performance for various scenarios. In this work, a transformable concept boat is conceived that can change its configuration from monohull to twin-hulled configuration. A catamaran is desirable for carrying volumetric cargo or creating a large deck space that can serve, for example, as a launch pad for aircraft, while more compact monohulls can be more easily stored or operated in restricted environments. A monohull and a catamaran also have different stability, hydrodynamic, maneuvering and seakeeping characteristics. In the present effort, a small-scale model boat has been constructed with two hulls that can be brought together or separated using an expansion mechanism driven by a servo motor. This model setup has been equipped with propulsors, batteries, and control and communication modules for radio-controlled operations. In addition, a remote data acquisition system was assembled for measuring boat's kinematic and powering characteristics. Results of initial tests with the small-scale transformable boat in an open water reservoir are reported and discussed in this paper.

1. INTRODUCTION

Most ships and boats have rigid hulls with constant geometry. However, performance characteristics of marine vehicles, including stability, resistance, seaworthiness, maneuvering, etc. are quite sensitive to ship's speed, loadings, and sea state conditions [1]. Moreover, depending on operational scenarios, a wide deck or large cargo area may be required to carry volumetric payload or serve as a launch pad for VTOL aircraft. On the other hand, for operating in narrow passages or being stored in ports or on motherships, compact narrow hulls are more desirable. Having a transformable hull configuration would be very attractive for some applications, but it would also come at extra cost for additional machinery and more demanding hull structural requirements.

In this study, a transformable concept boat has been envisioned that can change its shape from a monohull to a catamaran using an expanding mechanism between hulls. An illustration of two states of such a boat is schematically shown in Fig. 1. A very important property of a catamaran is much greater lateral stability, as the restoring moment on a heeled twin-hull is much bigger due to larger variations of hydrostatic forces and longer moment arms of these forces acting on separated hulls in comparison with a monohull (Fig. 1d). In addition, high-speed multi-hulls can take advantage of aerodynamic lift on the platform between hulls [2].

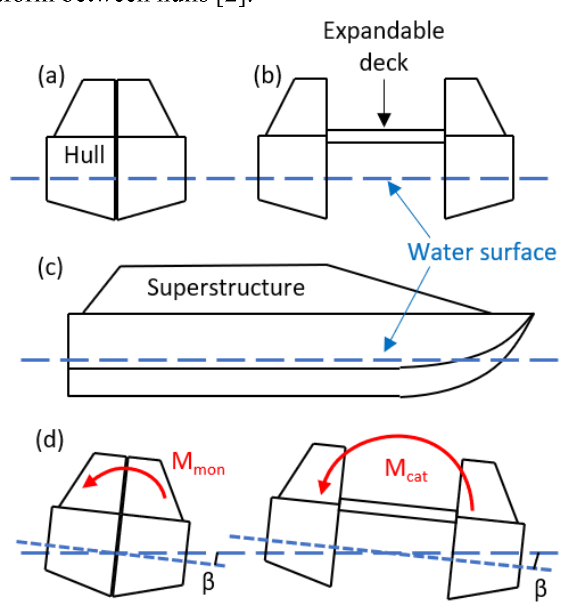

Fig. 1 (a) Front view of monohull, (b) front view of catamaran, (c) side view of both hulls, (d) front view of heeled hulls illustrating restoring moments.

There were previous conceptualizations and undertakings aimed at developing large-scale transformable boats. A rapidly deployable intermodal facility (RDIF) with pivotal hulls forming a spar configuration was considered in [3]. A heavy lift ship concept that can produce a wide platform by deploying vertical deck extensions mounted on the hull sides was presented in [4]. A self-transforming ship with SWATH and barge modes was described in [5]. However, publications on transformable ships usually focus on particular design aspects without providing complete analysis or test data. Some recent luxury yachts and speed boats also include foldable hull features allowing owners to significantly expand usable deck areas or operate in different hydrodynamic regimes [6,7]. Again, reported technical details are rather incomplete.

The current paper aims at presenting comprehensive information on construction and testing of a small-scale transformable boat. The vessel configuration comprises two hulls which can be brought together or separated using an expansion mechanism. The hulls were fabricated using strong and light-weight materials, which helped produce a low-weight, buoyant, and very durable marine platform, similar to those in our previous projects with marine and amphibious craft [8,9]. This setup was equipped with electronics for powering, propulsion, control, communication, sensing, and data acquisition. The next sections of this paper elaborate on the construction of hulls, assembly of all components, and data obtained in initial tests on open water.

2. EXPERIMENTAL SETUP

2.1 Hull construction

The unmanned surface vehicle (USV) fabricated for this project was based on a hard-chine prismatic hull form with deadrise of about 20° [10]. Dimensions of hulls after manufacturing resulted in the total width of about 20.3 cm, hull length of 71 cm and height from keel to deck of 11.7 cm. Hull core was made of two 3-inch-thick pieces of extruded polystyrene foam glued together with a light coating of spray adhesive. The shape of the hull was formed through multiple hotwire cuts following three sets of guide templates. The templates were laser cut out of 0.32 cm birch plywood and were used to shape the deadrise, keel, and deck. Bow curves were shaped using hand tools and checked against another template. The final hotwire cut was made vertically from the keel to deck to complete the two catamaran hulls, with flat surfaces on the internal hull sides. Hulls in different stages of the construction process are shown in Fig. 2.

Each hull had 0.32 cm thick plywood plates lightly glued to the transoms and decks before the carbon fiber overlay process. This provided additional mounting substrates for attaching various mechanisms. Both hulls were then wrapped in two layers of carbon fiber fabric infused with System 2000 epoxy resin using a wet layup procedure over the shaped foam hull forms.

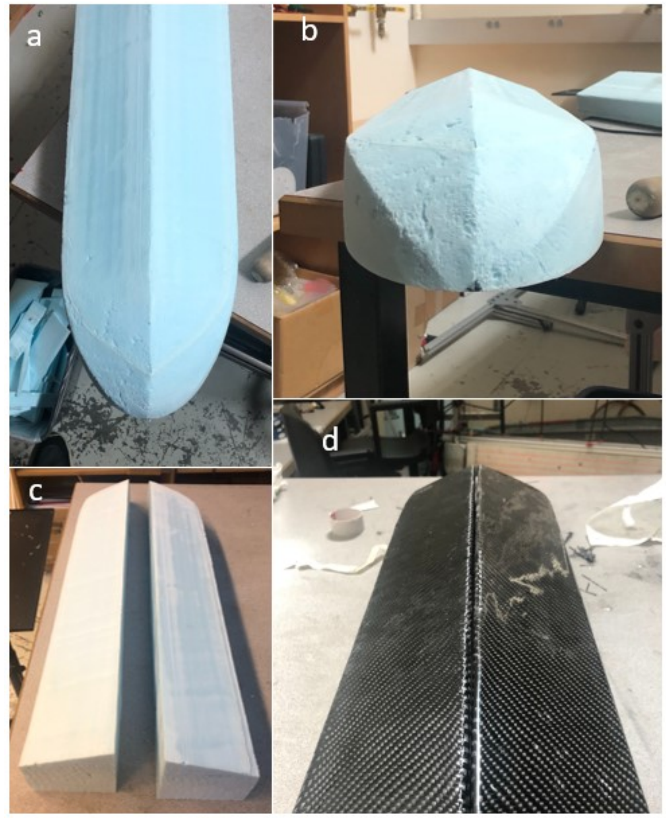

Fig. 2 Hulls during different construction stages: (a) top view of bow section, (b) front view showing deadrise, (c) hull split vertically along keel, (d) hulls covered in carbon fiber.

2.2 The expander

The requirements specified for the expansion mechanism included 19-cm spacing between the hulls, an expansion rate of about 5 cm/s, and sufficient strength to operate the boat in open-water conditions. Several expander concepts were considered. One of them involved mounting a lead screw and a sliding rail transversely to the hull. This approach would result in variable center-of-gravity positions, as well as structural elements extending beyond the deck area on a monohull. Another variant with a telescopic expander would have issues with sustaining non-axial loads. An expansion system consisting of two plates hinged together in the middle and at the edge of each hull's deck was also considered. However, the center pivot would be elevated in the monohull setup, and variable hull spacings in the catamaran mode would create structural problems. A low-profile scissor-type mechanism was eventually chosen, as a low-cost, structurally sound and easily manufacturable option. This device was assembled from six identical, 0.6-cm-thick aluminum C-channel sections, as shown in Fig. 3.

The connection points are attached with M3 bolts with nylon locking nuts and a nylon washer between the links to help minimize friction. The connections to the hulls are made through custom 3D-printed PLA brackets over standard ball-mounted pillow block bearings. Two scissor end points, one each side, are attached with fixed pivot points. On the starboard (right) hull, another pillow block bearing allows the scissor mechanism to slide on a linear motion shaft. On the port (left) hull, the remaining scissor end is attached to a screw nut which is threaded on the 0.8 cm lead screw. This provides the mechanical movement for the opening and closing of the expander. The lead screw is directly connected to a Parallax Feedback 360° high speed servo without gearing. The power supplied to the servo was from a 2S LiPo battery (7.2 V).

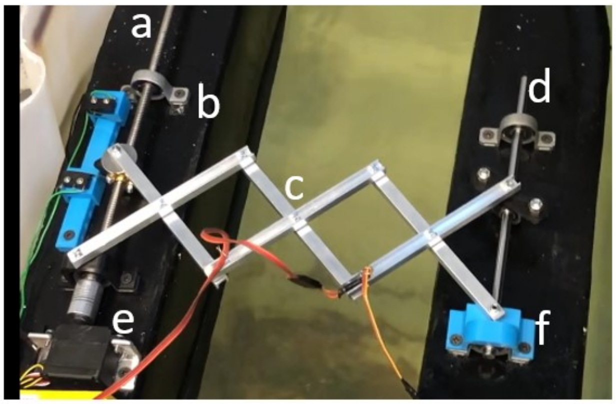

Fig. 3 Scissor-type expansion mechanism: (a) lead screw, (b) pillow block bearing, (c) scissor device, (d) linear motion shaft, (e) servo, (f) scissor pivot mount.

2.3 Propulsion and control

The propulsion system for the boat is comprised of two thrusters, two electronic speed controllers (ESCs), and a one-way communications system. Two T100 propulsors from Blue Robotics provided both forward and reverse thrust, each with a range of thrust between -1.85 and 2.36 kg force in static conditions. The propellers have a diameter of 7.6 cm and have different configurations, clockwise and counter clockwise. The propulsors were mounted on aluminum angles attached to the hull transoms (Fig. 4). The thrusters are controlled through two 30-amp brushless electronic speed controllers (ESCs) that read pulse-width-modulated (PWM) signals and appropriately vary a power output to achieve desirable thrust. The ESCs are connected in parallel to the single 3S LiPo battery.

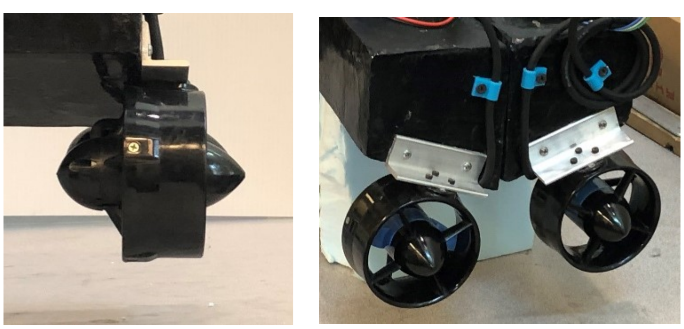

Fig. 4 Thrusters mounted on USV: left image, side view; right image, rear view.

The PWM signals are provided to the ESCs through a Futaba R2008SB receiver. This receiver is bound to a Futaba T6J transmitter which enables the pilot to remotely control the onboard systems. Three channels were used on the transmitter to control the two thrusters and the servo that operated the expander. Steering was accomplished through differential thrust, and the transmitter was configured accordingly. An Arduino Uno microcontroller was programmed to manage the servo operation for the expanding mechanism based a PWM signal sent from the transmitter. The Uno also regulated the position of the expander through two digital signals from limit switches that reported the position of the screw nut (Fig. 3). A custom 3D printed rail and slider setup was arranged to allow for adjustment points in 1 cm increments, fine-tuned through the arms of the limit switches. Bending the thin metal arms proved to be effective for the limit switches to achieve minor position adjustments. The monohull and catamaran configuration of the boat achieved with this mechanism are illustrated in Fig. 5.

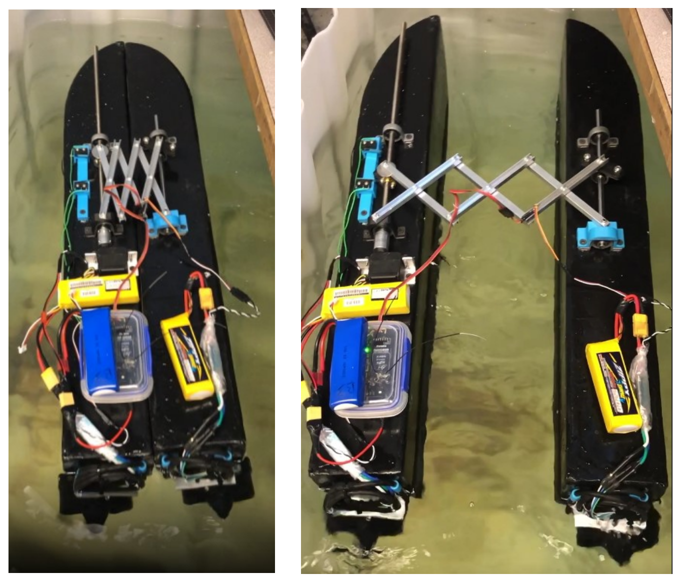

Fig. 5 Two configurations of USV: left image, monohull (contracted state); right image, catamaran (expanded configuration).

2.4 Data acquisition system

A small-scale data logger was assembled using an Arduino-based Feather M0 microcontroller main board with micro-SD card. A GPS attachment ('wing' or daughter board) was configured for 5-Hz serial communication with the main board, reporting date, time, position, speed, number of satellites and position accuracy. A BNO055, 9-DOF inertial measurement unit (IMU) was also configured to provide orientation of the logging system. Additional analog inputs from a power monitoring module reported current and voltage of the main battery. A 3.7-V lithium-ion battery was used to power the Arduino board and its associated components. The battery, IMU, GPS and main board were placed into a watertight plastic container and supported using small pieces of foam. (Fig. 6). The overall diagram of the propulsion and expander system components is given in Fig. 7, whereas the wiring diagram for the DAQ is shown in Fig. 8.

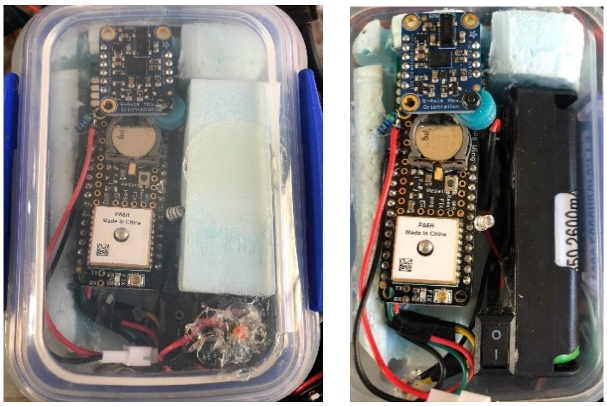

Fig. 6 Data logger in watertight case with and without lid.

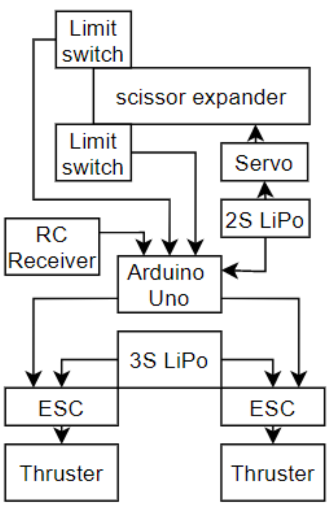

Fig. 7 Components of propulsion-expander system.

Programming for the DAQ was done in the Arduino IDE environment and based on C/C++ style language. An initial setup routine is run to ensure all components are operating and the log file is created. The main loop updates and records the time in milliseconds, GPS data (time, latitude, longitude, speed in knots, number of satellites used, fix quality), IMU data (angles and accelerations), current flow, and battery voltage.

Accuracy of the GPS position improved as the number of satellites increased, but still demonstrated small consistent offset from the actual location. Since the performance data relies on the change in position instead of absolute position, data was processed with a consistent number of satellites as the offset in actual position would remain consistent. The IMU uses a sensor fusion algorithm, blending accelerometer, magnetometer, and gyroscopic data into a stable three-axes orientation output, and communicates the results upon request from the main board through an I2C communication protocol. The power monitor reported scaled the output signals to 3.3 V logic level. A calibration was completed on the power module to obtain conversion equations for rescaling during post processing. Batteries ranging from 9 to 12.5 volts were read through the DAQ and compared to multimeter readings taken at the same time. The calibration of the current signal was completed while operating the USV in a large water tank. A multimeter was wired in series between the battery and the parallel splitter and the measurement was compared to the DAQs reading. Trim and list were set at 0 deg using a digital sensor under lab-controlled conditions. The IMUs orientation, relative to the boats resting position once in the water was completed at the start of each test. The resulting offsets were used during post processing to match the data to the boat's orientation. Finishing the main loop, the gathered information is stored in a comma separated (CSV) file on the microSD card.

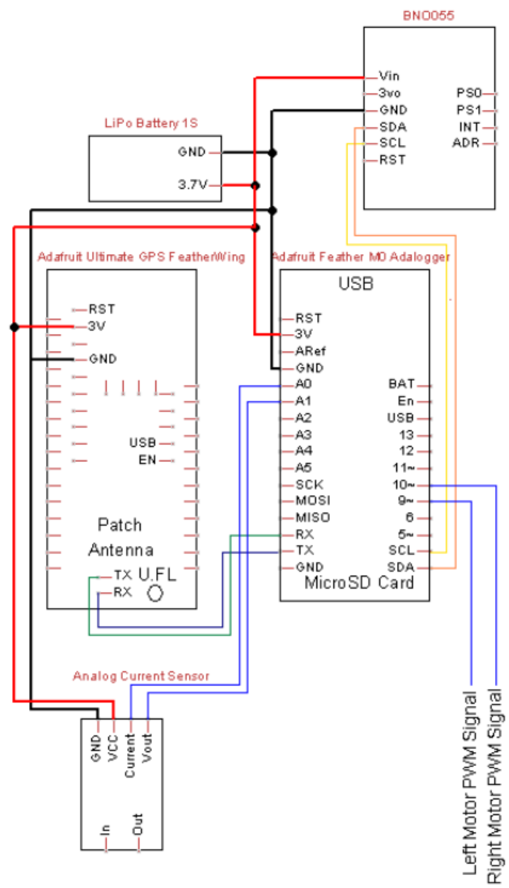

Fig. 8 Wiring diagram of data acquisition system.

3. OPEN-WATER TEST RESULTS

Initial tests with the constructed boat were conducted to characterize some propulsive, maneuvering, and seakeeping properties by running the boat in the remotely controlled mode and gathering measurements using sensors installed on the boat.

The testing area was an open water pond next to Valley Road Playfields near Washington State University in Pullman, Washington. Photographs of the boats sailing in calm water are shown in Fig. 9. The spacing between hulls in the catamaran mode was 19 cm. The slopes of the transverse restoring moment on heeled hulls were measured as 0.03 and 0.45 N·m per degree of roll for the monohull and the catamaran, respectively, thus confirming much greater lateral stability of the twin-hull configuration.

Fig. 9 Monohull and catamaran on a pond in calm weather.

In the first test series, both the monohull and catamaran configurations were run along straight paths in calm water at different throttle positions. The main measured variables were the electrical power drawn from a battery, boat speed, and trim angle. The collected data are presented in Fig 10. The power usage is small up to speed of 1 m/s (Fig. 10a), as the boat generates little waves at low speeds and most resistance comes from the frictional drag. At higher speeds, water resistance and thus consumed power rise faster with speed, since more significant waves are produced increasing pressure drag of the boat. In the speed ranges 0.5-1.0 m/s and 1.5-2.5 m/s, the catamaran shows slightly larger power requirement to sail at the same speed as a monohull, which can be caused by larger wetted surface area of the twin-hull configuration and possibly unfavorable interference between wave patterns produced by separated hulls at higher speeds.

The trim angles generally increase with speed but there is a dip at a low speed (Fig. 10b), which is similar to other boats operating in broad speed ranges. At rest, boats have near-zero trim. At relatively low speeds, negative trim may appear due to suction force on the bow, as water flow accelerates (relative to the hull) under the curved bow section. This effect was more pronounced for the catamaran in the present tests (Fig. 10b). With continuing speed increase, the stagnated pressure region at the bow causes significant positive trim, which again was more pronounced for the twin-hulled setup and was correlated with higher drag (or required power) of the catamaran in the speed range 1.5-2.5 m/s.

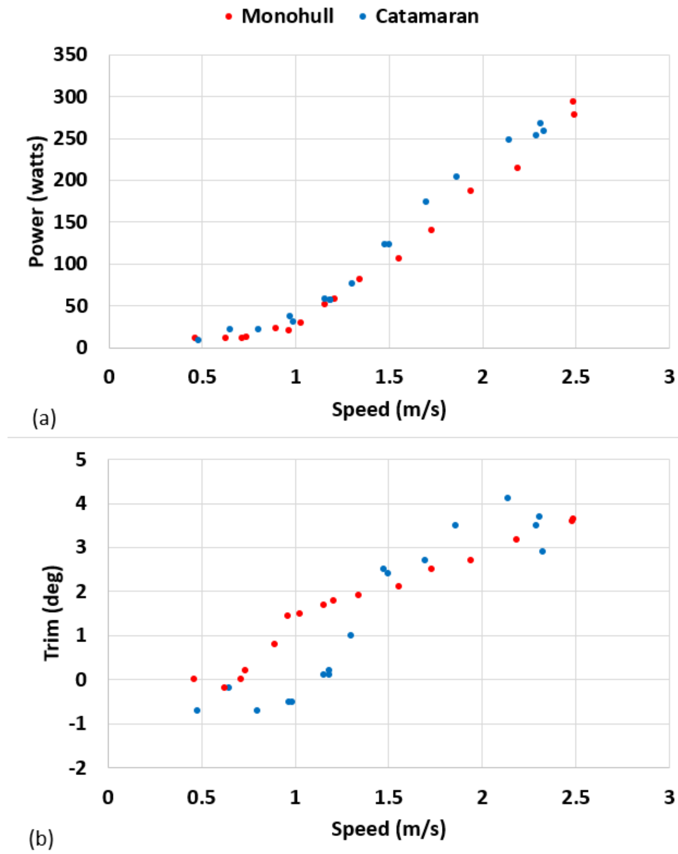

Fig. 10 (a) Power curves and (b) trim angles for straight path. tests.

The second test series was conducted to establish circulation radii of two hull configurations at approximately the same amount of average and differential power supplied to the propulsors. (the differential thrust is needed to generate a yaw moment that turns the boat). The boat trajectories recorded with GPS sensors are given in Fig. 11 for three levels of the average power drawn from a battery. The numerical values of averaged kinematic characteristics of two configurations are listed in Table 1. As one can see, moving at larger power results in higher speeds in circulation. Increase of the turning radius is caused by both higher speed and lower differential power in these tests. The circulation radius is smaller for a catamaran, as larger yaw moment is produced by thrusters displaced further from the boat centerline in the twin-hull setup.

The monohull roll angle is also more pronounced, as the recovering transverse moment in heel is smaller than for wider catamaran. The speeds of both geometric variations of the boat are almost the same in this circulation maneuver, while trim of a catamaran is slightly greater at higher speeds.

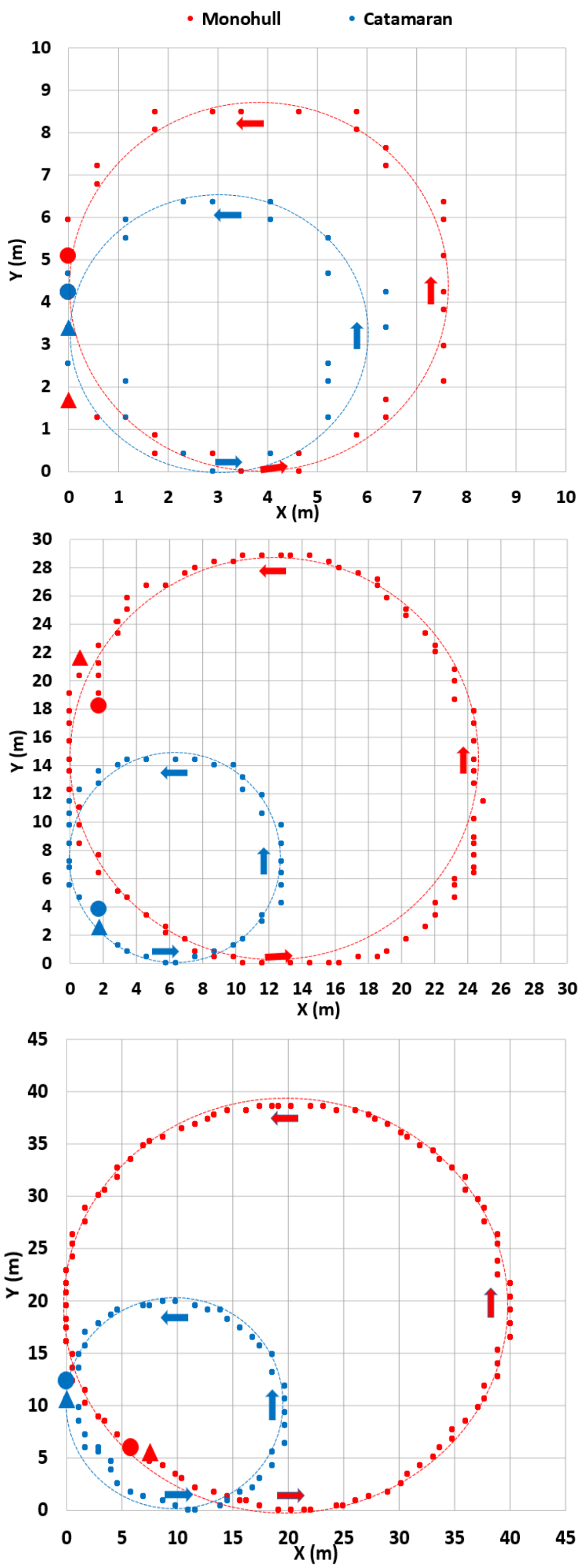

Fig. 11 Boat trajectories in circulation tests. Point symbols show GPS data. Triangles indicate the starting positions and large circles give the end points. The dashed lines represent idealized circular trajectories manually superimposed on test data. Arrows indicate direction of travel (in the counter-clockwise direction).

Table 1 Kinematic characteristics recorded in circulation tests.

	Monohull	Catamaran
Low speed circulation		
Power (watts)	17	
Diff. power (%)	36%	
Radius (m)	4.30	3.19
Speed (m/s)	0.74	0.79
Roll (deg)	2.82	1.99
Trim (deg)	0.35	0.31
Medium speed circulation		
Power (watts)	47	
Diff. power (%)	29%	
Radius (m)	13.45	6.80
Speed (m/s)	1.08	1.05
Roll (deg)	3.02	1.85
Trim (deg)	0.06	0.28
High speed circulation		
Power (watts)	75	
Diff. power (%)	25%	
Radius (m)	19.66	9.92
Speed (m/s)	1.24	1.29
Roll (deg)	3.24	1.90
Time (deg)	0.50	1.39

The third test was performed on a windy day to gather sample information about boat motions in waves. The characteristic wind speed was about 8 m/s, while the wave heights were within 4 cm. Photographs of the boat from those tests are given in Fig. 12. These tests were not comprehensive or well controlled, and results shown below represent sample data obtained in arbitrary selected time intervals.

Kinematic data gathered in rough water for two hull configurations are shown in Fig. 13. These data sets were collected at average boat speeds of roughly 1.2 m/s, but there was some variation during this interval resulting in time-evolving pitch (Fig. 13a). The pitch angles in waves were lower than equilibrium trim angles in calm water, especially for the monohull, as the boats encountered water surface disturbances preventing them to achieve steady states. These encounters happened several times per second, consistent with waves visible in Fig. 12 and oscillations in Fig. 13a. The propulsive power in the presence of waves was about 35% and 15% greater than at similar speeds in calm water for the monohull and catamaran, respectively.

The monohull exhibits more significant roll motions (Fig. 13b), as its restoring transverse moment is smaller (due to narrower hull). The catamaran and monohull data were recorded at different orientations of the boat with respect to the wind. The twin-hull was moving against the wind, while the single-hull sailed at some angle, resulting in additional heeling moment caused by wind, which was reflected in non-zero average roll angle (Fig. 13b). Vertical accelerations, shown in Fig. 13c, were larger for a catamaran and were also affected by signal noise.

Fig. 12 Monohull and catamaran in wave conditions.

4. CONCLUDING REMARKS

A boat concept that can transform between monohull and catamaran configurations has been proposed and constructed on the model scale. This platform was equipped with propulsion, control and data acquisition modules. The boat operations were demonstrated in open water, and sample data were collected. Both configurations demonstrated similar power requirements, with monohull being slightly more efficient in specific speed intervals. The catamaran was able to make sharper turns in circulation tests, while turn radii increased at higher speeds. Sample data for the boat angular motions and accelerations were also obtained in random wave conditions.

Possible future directions of this work can include making the boat autonomous so it can adapt its hull shape to specific conditions/missions, conducting more comprehensive tests in rough water, optimizing hydrodynamic properties, and equipping the boat with additional sensors and effectors to perform a variety of practical tasks.

ACKNOWLEDGEMENTS

This material is based upon work supported in part by the by the National Science Foundation under Grant No. 1800135.

REFERENCES

[1] Faltinsen, O.M.: Hydrodynamics of High-Speed Marine Vehicles. Cambridge University Press, New York (2005).

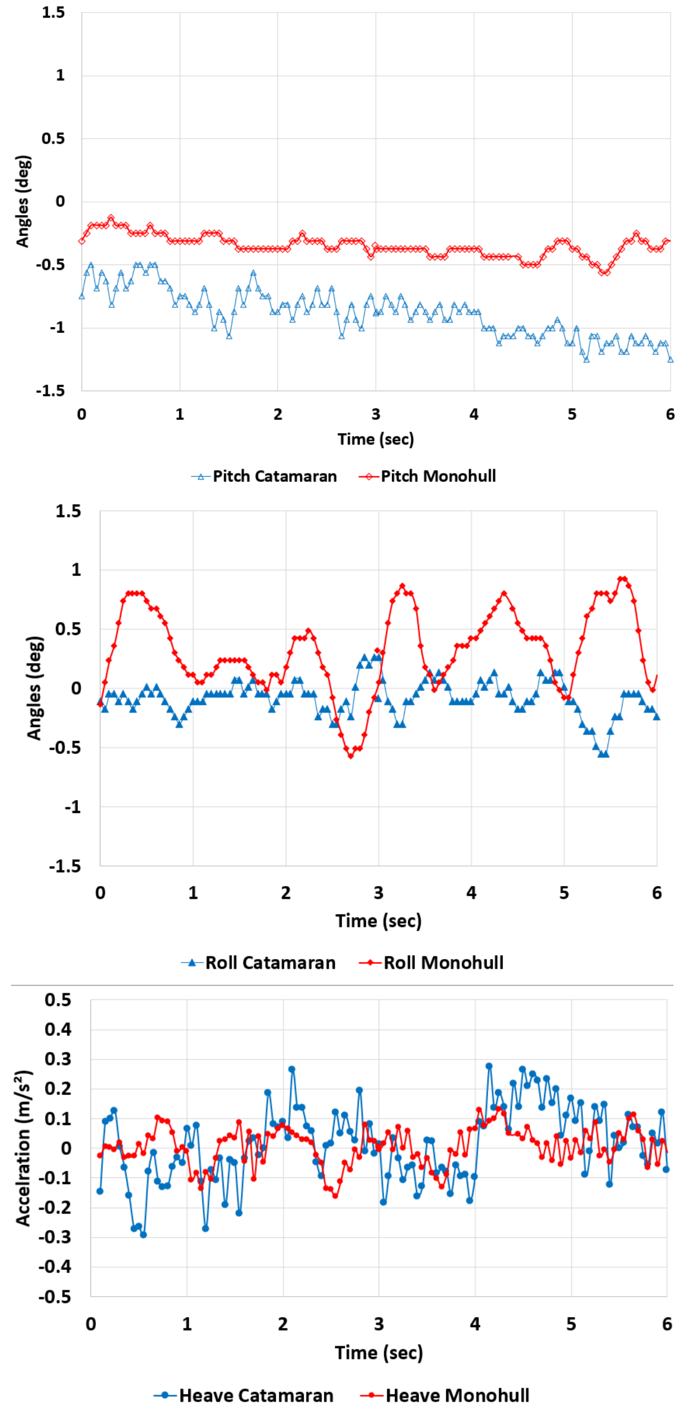

Fig. 13 Sample data collected in wave conditions.

[2] Matveev, K.I., Dubrovsky, V.A.: Aerodynamic characteristics of a hybrid trimaran model. Ocean Engineering 34, 616-620 (2007).

[3] Buck, J.: Rapidly deployable intermodal facility (RDIF): a new ship systems technology. 23rd International Conference on

Offshore Mechanics and Arctic Engineering, ASME paper OMAE2004-51342, Vancouver, Canada (2004).

[4] Bloxom, A., Cohen, L., Loeffler, J.: Transformable Heavy Lift Ship. Technical report NSWCCD-CISD-2007/009, Naval Surface Warfare Center Carderock Division, West Bethesda, MD, USA (2007).

[5] Rispin, P.: E-craft, a self-transforming vessel. International Maritime Conference, Sydney, Australia (2010).

[6] http://www.evoyachts.com

[7] https://kormaran.com/

[8] Matveev, K.I.: Static thrust recovery of PAR craft on solid surfaces. Journal of Fluids and Structures 24, 920-926 (2008).

[9] Thompson, N., Whitworth, P.R., Matveev, K.I.: Development of small-scale unmanned hydrofoil boats. Journal of Unmanned Vehicle Systems 9, 21-32 (2021).

[10] Fridsma, G.: A Systematic Study of the Rough-Water Performance of Planing Boats, Report No. 1275. Davidson Laboratory, Stevens Institute of Technology, Hoboken, NJ (1969).