The Development of a Robust Autonomous Surface Craft for Deployment in Harsh Ocean Environment

Zhi Li, *Student Member, IEEE*
Autonomous Ocean Systems Laboratory (AOSL)
Memorial University of Newfoundland
St. John's, NL, Canada
zl1634@mun.ca

Ralf Bachmayer, *Member, IEEE*
Autonomous Ocean Systems Laboratory (AOSL)
Memorial University of Newfoundland
St. John's, NL, Canada
bachmayer@mun.ca

Abstract—**In this paper, a robust Autonomous Surface Craft (ASC) that is capable of operating in harsh ocean environments near the coastal waters of Newfoundland and Labrador is introduced. The reliable Controller Area Network (CAN) protocol is implemented to build the onboard communication and control system. As a distributed system, the time synchronization between different CAN nodes is resolved using the Time Reference Message (TRM). This ASC integrates a long-distance wireless modem for wireless data logging and supervisory command updates. In addition, a MATLAB based user interface is tentatively used as the ASC control and data display terminal on the dock-side computer. Full-scale resistance and self-propulsion tests are performed at the tow tank of Memorial University, and the drag coefficient and a bilinear thruster model are generated. The sea trials are performed at Holyrood Arm, Conception Bay, Newfoundland, for the validation of the tow tank experimental results.**

Keywords—Autonomous Surface Craft (ASC); Controller Area Network (CAN); resistance test; self-propulsion test

I. Introduction

An Autonomous Surface Craft (ASC) or Unmanned Surface Vehicle (USV) can be operated autonomously, or remotely controlled in lakes, rivers and oceans. With fast improvement of the ASC in the past few years, different prototypes and applications have been proposed and built.

The Massachusetts Institute of Technology (MIT) started their research of the ASC since 1993. In their first design, a 1/17 scale replica trawler boat was used for the validation of navigation and control system architecture [1] [2]. Following that, a small catamaran-shaped ASC [2] was developed, and it demonstrated better roll stability during the bathymetric survey than the trawler boat. After that, they changed the combustion engine propulsion system to electric powered motors to achieve better controllability over the thruster [3]. In 1998, a large SWATH type ASC [4] was produced in Germany for human rescue and ocean survey research. Meanwhile, the "ASIMOV" project [5], which was supported by the Commission of the European Communities, concentrated on the coordinated operation between the ASC and the Autonomous Underwater Vehicle (AUV) during the ocean exploration tasks. In Italy, the "Charlie" project [6] introduced a small ASC that is capable of performing sea surface sampling tasks in Antarctica. The "Springer" ASC [7] from the UK could perform the environmental monitoring and pollutants tracking tasks. From 2004, several new kayak-type ASCs [8] were introduced by the MIT Sea Grant College Program for exploration of the multi-ASC coordination and advanced sensors integration techniques. In 2010, a SWATH-type ASC [9] was proposed by the Autonomous Ocean Systems Laboratory at Memorial University for underwater gliders recovery.

Based on these aforementioned ASC projects, it can be concluded that the ASC is capable of performing various research tasks including ocean survey, environmental monitoring and AUV assistance. Therefore, many scientists could benefit from using these intelligent ASCs to perform their ocean exploration tasks in an autonomous way. Unfortunately, there are still limitations with deploying the ASC under different weather conditions. It is clear that the environmental factors including strong winds, waves and currents will have a significant effect on the behaviour of the ASC. To the author's knowledge, however, there are few discussions about the design and evaluation of an ASC especially for operation in harsh ocean environments.

In this research, a robust ASC that is capable of operating in harsh ocean environments near the coastal waters of Newfoundland is introduced. Section II provides an overview of the system and system architecture. Section III introduces the Controller Area Network (CAN) based low-level communication protocol. Then, Section IV highlights the long-range wireless data logging and control system. Section V shows the full-scale resistance and self-propulsion test results, from which the ASC hull drag coefficient and thruster model are generated. Finally, Section VI presents the sea trial experimental results, and Section VII provides a conclusion and future work.

II. System Overview

A. *Main Specification*

To increase the Autonomous Surface Craft (ASC) roll stability, a catamaran-type hull form was chosen. Figure 1 shows this original design. In the figure, the two streamline bodies are the ASC hulls, and two electric outboard motors are fixed at the rear part of each hull. The effective capacity of

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each hull is around 4.3 L, which is enough for the storage of battery systems and necessary electrical components. The plastic hatch covers provide the waterproofness for each hull. Two front through holes were designed to connect the bottom mounted sensors. The aluminum superstructure was added to install the antenna system and other electrical modules.

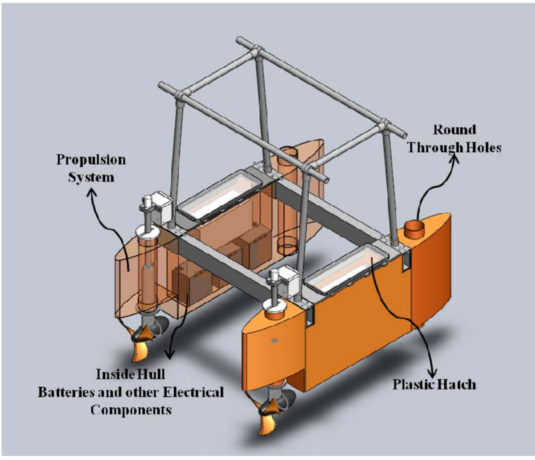

Fig. 1. The ASC original design

The ASC robustness is supported by its strong hull bodies. These hulls were manufactured by the plywood covered with fibreglasses. In addition, the two connection beams and the superstructure used aluminum material, which provided satisfactory strength and corrosion resistance to the salty water.

Figure 2 shows the ASC setup with the whole electrical system. To guarantee the robustness of this onboard communication and control system, all enclosures were chosen by following the IP 67 standard [10]. The sturdiness of the wiring system is supported by the NMEA 2000 [11] recommended cables and connectors. More details of this wiring system will be provided in the following sections.

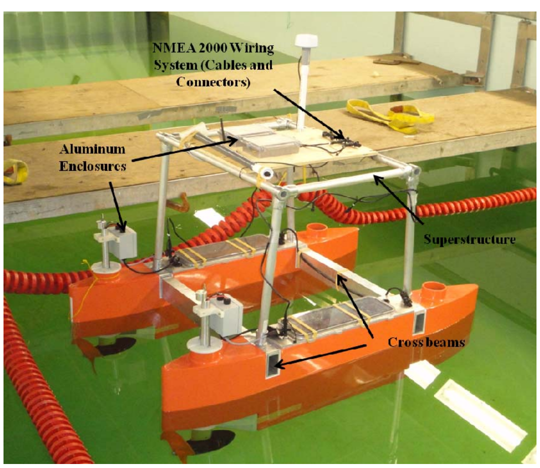

Fig. 2. The ASC setup

The ASC propulsion system consists of two commercially available outboard electric motors which are produced by Torqeedo Incorporation. Although this ASC features no rudder system, by applying the differential thrust from the two thrusters, the ASC can be easily steered. The primary parameters of this ASC are summarized in Table I.

TABLE I. THE ASC MAIN SPECIFICATION

Parameters	Value
Length	1.5 m
Width	1 m
Hull Height	0.5 m
Superstructure Height	0.66 m
Draft	0.37 m
Mass	146 kg
Maximum Speed	1.0 m/s

B. System Architecture

Using the Controller Area Network (CAN) protocol, a distributed communication and control system was realized. Comparing with a centralized system, a distributed system can provide better system robustness and fault tolerance capability. A centralized system always has a main processing unit that is responsible for all control and sensor data analysis tasks. A potential downside of this architecture, however, is if a small error occurs, the whole system can be frozen. Contrarily, in a distributed system, tasks are distributed into separate processing units. Therefore, even if one module fails, the remaining system functions, which are supported by the rest modules, will still potentially work [12].

Figure 3 shows the ASC onboard distributed communication system structure that is based on the CAN-bus topology. As indicated in this picture, four separate CAN nodes are connected with the same communication media: the CAN-bus cables (center line). A primary advantage of this bus topology is that important information can be broadcasted to all connected CAN modules. In other words, control command or sensor data can be exchanged between any connected CAN nodes.

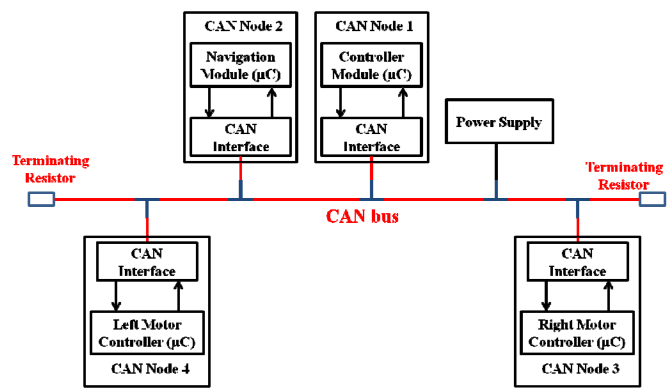

Fig. 3. The ASC communication system architecture

III. CONTROLLER AREA NETWORK

A. Controller Area Network (CAN) Overview

The Controller Area Network (CAN) protocol was introduced by Bosch Inc. in 1986. Due to its communication robustness, this protocol was extensively used in building an automobile's communication and control system. Until now, this protocol was also implemented in trains and even airplanes [13].

Figure 3 has shown the implemented CAN-bus system architecture. In order to make each CAN node work on the same CAN-bus, a couple of factors have to be considered. Firstly, the CAN interface chip is needed for the voltage conversion. In addition, each CAN node has to have a microcontroller that can process different CAN messages. More importantly, the communication rate has to be configured to be the same. In this application, the communication rate is configured to be the maximum: 1Mbps.

Figure 4 provides a top view of the layout of the CAN-bus system implemented on the ASC. It can be seen that the CAN-bus runs from one hull to the superstructure, and then into the other hull. The initial configuration has the following four CAN nodes that are labeled from 1 to 4 as shown in Fig. 4. Two actuator CAN nodes (3 and 4) are responsible for motor control; the controller CAN node (label 1) exchanges data with the dock-side computer using the wireless radio; the navigation node (label 2) gathers the Attitude and Heading Reference System (AHRS) and Global Position System (GPS) information.

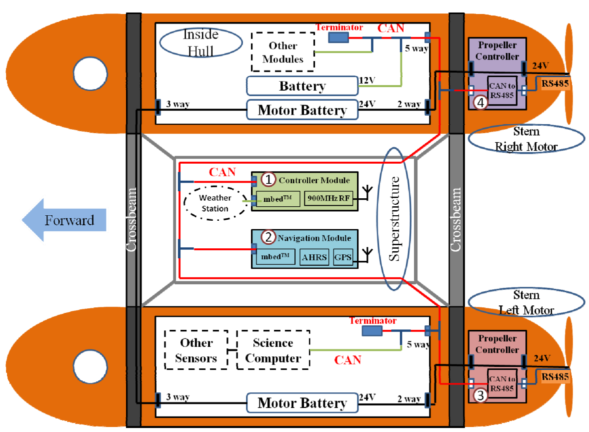

Fig. 4. CAN-bus layout on the ASC

The CAN protocol is based on a message-oriented communication mechanism [13]. Each transmitted CAN message is started with a unique identifier (ID), and a message filtering system inside every CAN node decides if this unique ID message should be accepted. This unique identifier is an integer, and its value denotes the priority that a message can access the CAN-bus (low value with high priority). In a message transmission confliction, the high priority message will be transmitted instantly, while the transmission of the low priority message will be delayed. In this case, the high priority messages will be guaranteed with the shortest transmission latency.

B. *Time Reference Message (TRM)*

The time synchronization of different CAN nodes is realized by using the Time Reference Message (TRM). As introduced in Section III.A, the navigation CAN node can collect data from the GPS module. Therefore, the Coordinated Universal Time (UTC) time from the GPS can be extracted and redistributed through the whole CAN network. The TRM is a standard CAN message that carries the UTC time information. By receiving the TRM, the UTC time can be decoded by each CAN node, and they will know their working time cycle.

Since the update of the UTC time is 1 Hz, the time interval of the two adjacent TRMs is close to be 1 second. Figure 5 shows a basic cycle which is defined by the TRM. It can be seen the transmission of other CAN messages will only happen after the reception of the time synchronization message. To provide a robust time synchronization, the TRM is assigned with the highest priority among all the transmitted CAN messages. Therefore, the latency of the TRM transmission in the CAN network is calculated to be 76 µs.

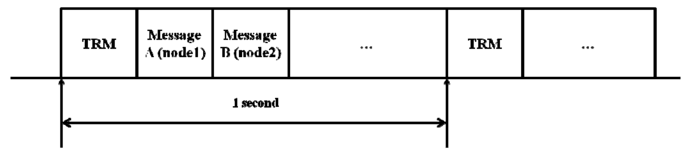

Fig. 5. Time synchronization based on Time Reference Message

C. *CAN-bus Wiring System*

The selection of the CAN-bus wiring system is significant in improving the overall communication system's robustness and performance. The NMEA 2000 standard is a high-level marine communication standard [14] that is created based on the CAN protocol. Currently, this standard is widely used to build the boat onboard communication system. As recommended by the NMEA 2000 standard, the Micro-type cables and connectors were chosen [11]. Figure 6 shows the application of this wiring system on the superstructure of the ASC. In the 5-pin connectors, pin 1 is the shield wire, pin 2 and 3 are defined as power and ground, and pin 4 and 5 are CANH and CANL pins for CAN message transmission.

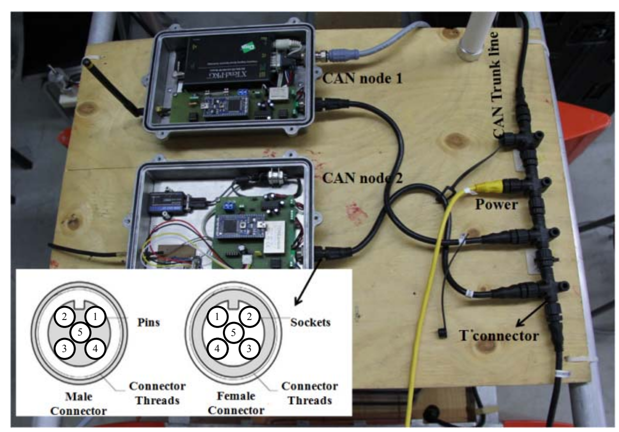

Fig. 6. CAN-bus wiring system

A couple of advantageous features are achieved by using this NMEA 2000 suggested wiring system:

- Cable consists of one shield wire and two pairs of shielded-twisted wires (data and power transmission) which increase the internal signal's resistance to external interference as well as reduce the RF emission.

- The NMEA 2000 cables and connectors are designed to be used in the marine environment with corrosion and reliability in mind.
- CAN nodes shown in Fig. 6 can be connected with the CAN-bus trunk line through the use of three-port "T" connectors which simplifies the connection pattern and brings great convenience for CAN node extension.
- Power transmission line is included in this wiring system, which makes the whole system compact. The maximum total power can be transmitted is around 36 W (12V, 3A), which is sufficient for all CAN devices in this application.

IV. WIRELESS DATA LOGGING AND CONTROL SYSTEM

A. *Long-range Wireless Data Logging and Control system*

The long-range wireless communication is supported by the XTend-PKG RF modems from the Digi International Incorporation. This wireless modem uses the 900 MHz band for data transmission, and the outdoor line-of-sight communication range is up to 64 km (high gain antenna). The modem used in this application is an industrial version, and its operation temperature range is from -40 °C to 85 °C.

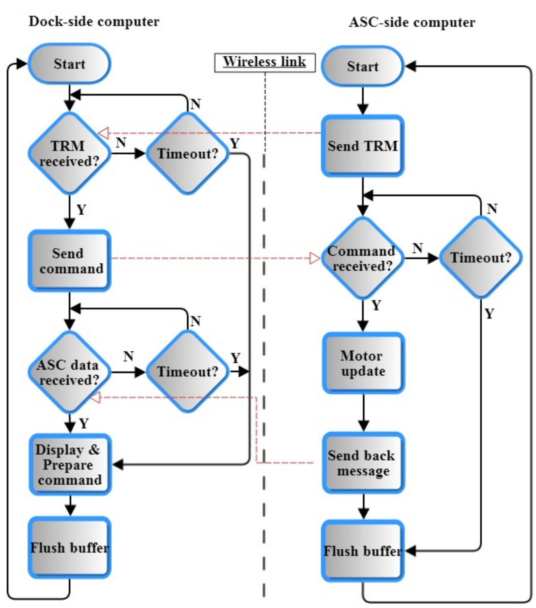

Fig. 7. Wireless communication program flow chart

To best conduct an effective ASC test requires the ASC to be remotely controlled and its sensor information can be transmitted back to and logged by the dock-side computer wirelessly. To realize this, the program execution on both sides (dock side and ASC side) has to be coordinated using the wireless link. Figure 7 shows this coordinated program flow chart. The flow chart on the left indicates: the MATLAB program running on the dock-side computer firstly accepts the Time Reference Message (TRM) (Section III.B), and then issues the command to control the motors of the ASC, and finally receives the ASC sensor data packages and displays it on the user interface. The flow chart on the right is the program running in the controller CAN node (Section III.A). This CAN node, on the one hand, receives the TRM from the CAN network, and on the other hand, sends the TRM through the wireless modem to synchronize the time on the dock-side computer. The dotted arrow in Fig. 7 represents the three handshakes between the dock-side and ASC-side computers in one second.

B. *MATLAB Based User Interface*

A MATLAB-based Graphic User Interface (GUI) was developed on the dock-side computer to support the data logging and ASC control functions. Figure 8 shows the designed GUI. All the ASC status data, including the acceleration, angular rate, GPS location, course angle, moving speed and motor rotational speed settings, are displayed on this user interface. In this way, the ASC status information can be viewed intuitively by the users.

In addition, the ASC motor speed, direction and power can be reconfigured using the left bottom functions on the GUI. In the remote control mode, a Logitech Bluetooth gamepad was used to make ASC retrieval more convenient. Moreover, the integration of the "kml toolbox" [15] into the GUI makes it possible to show the quasi real-time position of the ASC in Google Earth.

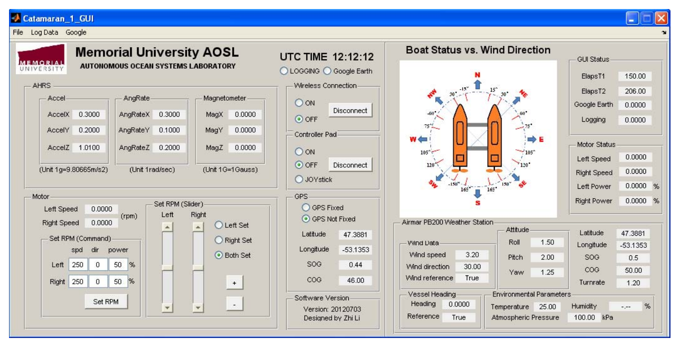

Fig. 8. MATLAB based user interface

V. TOW TANK EXPERIMENTS

A. *Resistance Test Results*

The ASC hull resistance was measured following the standard drag test procedures in the tow tank of Memorial University. To get rid of the propeller induced resistance, the propeller was substituted by a bladeless hub. In this test, the ASC was towed at the speed range of 0.3 m/s to 1.3 m/s with 0.1 m/s interval. Tow force was recorded under each situation.

Our test results are shown in Fig. 9. In this figure, the line with the error bar indicates the measured drag force with respect to the ASC advance speed, while the line with circles provides a quadratic fit using the measured data points between 0.3 m/s and 1.0 m/s. The reason measured drag spikes after 1.0 m/s is because the pitch and heave motion of the ASC causes the water to start overflowing the ASC bow during the towing test.

To calculate the ASC hull drag coefficient, the drag equation is used. Equation 1 is the total drag force (two hulls) of the ASC, so there is no 0.5 factor in front of the equation. A definition of the variables used in Eq. 1 is summarized in Table II. Since ρ and A are known, the drag coefficient can be calculated. During the test, it was found that the pitch angle and heave motion changed with ASC moving speed. Therefore, before calculating the drag coefficient, the reference area A is calibrated.

$$F_D=\rho A V_a^{\ 2} C_D \tag{1}$$

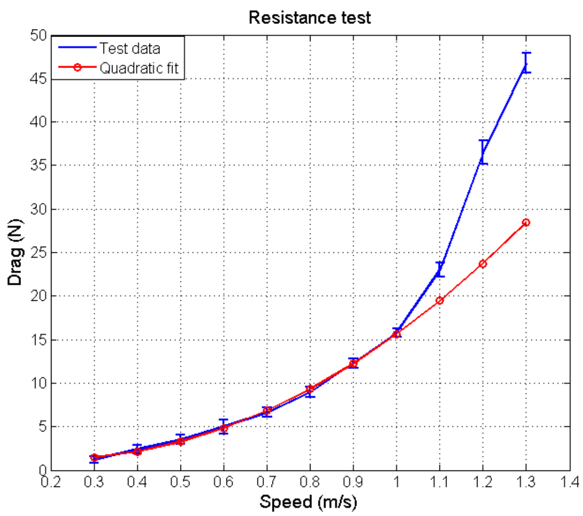

Fig. 9. Resistance test drag and advance speed curve

TABLE II. VARIABLE DEFINITION IN EQ. 1

Variable	Description	Unit
F_D	Drag force	N
ρ	Water density	Kg/m^3
A	The reference area for each hull	m^2
V_a	The ASC advance speed relative to water	m/s
C_D	Dimensionless drag coefficient	-

Figure 10 shows the calculated drag coefficient curve. It can be seen that within the speed range of 0.3 to 1.0 m/s the drag coefficient is bounded between 0.2 and 0.25; however, the drag coefficient spikes after 1.0 m/s. This clarifies the reason why there is a big discrepancy between the measured data and fitted data when the speed is over 1.0 m/s as shown in Fig. 9.

B. Self-propulsion Test Results

In the self-propulsion test, the propellers were installed back on the ASC. Before the test, the two propellers were set at the same rotational speed. Then the tow carriage towed the ASC to the predefined advance moving speed. The tow force was then recorded. To achieve the self-propulsion points, under each advancing speed condition, the propeller rotational speed has to be changed from a low value (under-propelled) to a high value (over-propelled). Figure 11 shows our self-propulsion test results. The advance speed range is chosen from 0.4 m/s to 1.0 m/s, and each curve represents one moving speed condition. The intersection of each curve with the line that indicates the tow force equals to zero is the self-propulsion point at this speed.

These test results are summarized in Table III. Using the measured data from Table III, a linear approximation model that describes the relationship between the propeller revolution rate and the ASC steady-state advance speed can be generated. Equation 2 shows this linear model, in which V_{ssa} is the ASC steady-state velocity and Ω is the propeller revolution rate.

The applicable situation of this model is: the ASC has to move in a straight line and the environmental interference is neglectable. Table III also shows the difference between the measured and the calculated advance speed based on Eq. 2.

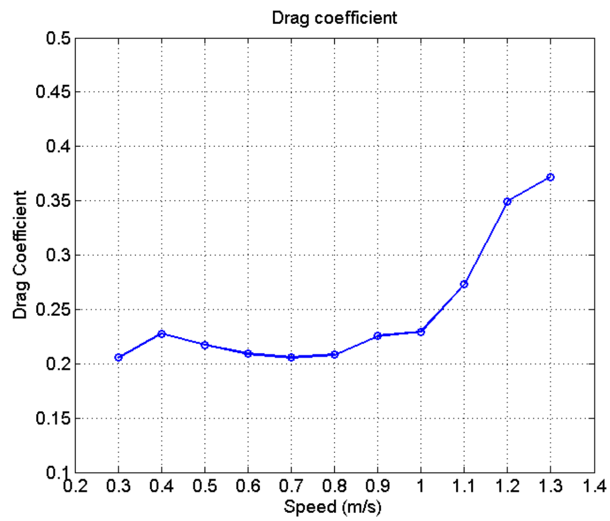

Fig. 10. Drag coefficient curve

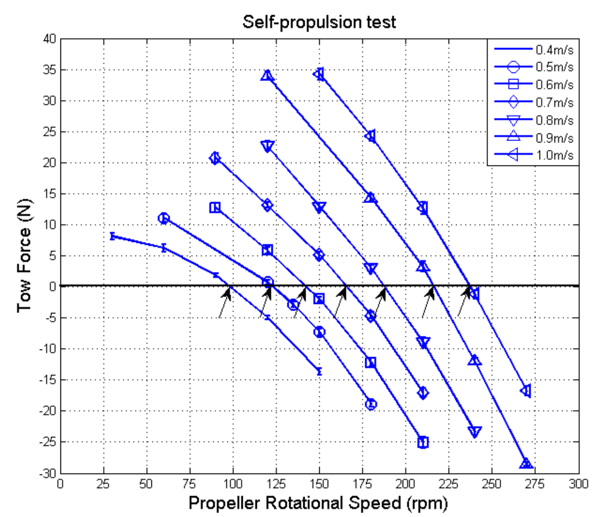

Fig. 11. Self-propulsion test results

TABLE III. SELF-PROPULSION POINTS

Measured Rotational Rate (rpm)	Advance Speed (m/s)	Approximated Advance Speed (m/s)	Difference
99	0.4	0.43	6%
122	0.5	0.53	5%
142	0.6	0.61	2%
166	0.7	0.71	2%
188	0.8	0.81	1%
216	0.9	0.93	3%
237	1.0	1.02	2%

$$V_{ssa} \approx 0.0043\Omega \quad (2)$$

C. Thruster Model

In the self-propulsion tests, the measured tow force (F_{Tow}) equaled the effective forward thrust (F_{ET}) deducted by the ASC hull drag force (F_D). This relationship is shown in Eq. 3. Therefore, combining the results from the resistance and self-propulsion tests, the forward thrust can be plotted with the rotational speed square in Figure 12 under different advance speed conditions.

From Fig. 12, it can be concluded that forward thrust is affected by both propeller rotational speed and the ASC moving speed. Moreover, under each speed conditions, the thrust value is linear with the revolution rate squared. However, the influence of the advance speed factor is nonlinear.

$$F_{TOW}=F_{ET}-F_D \quad (3)$$

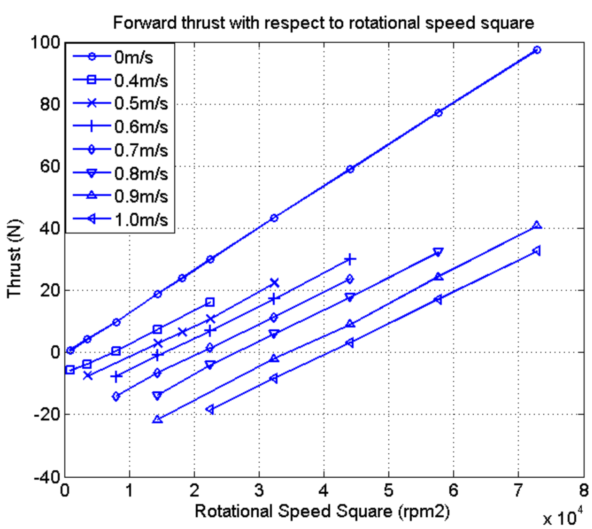

Fig. 12. Forward thrust plotted with rotational speed square

A bilinear thruster model that takes into account the influence of both moving speed and propeller rpm was chosen. This thruster model can be written as shown in Eq. 4. A definition of the variables used in Eq. 4 is summarized in Table IV.

$$T(\Omega,V_a)=T_{\Omega\Omega}*\Omega^2+T_{\Omega Va}*\Omega(1-\omega)V_a \quad (4)$$

TABLE IV. VARIABLE DEFINITION IN EQ. 4

Variable	Description	Unit
$T(\Omega,V_a)$	Forward thrust	N
$T_{\Omega\Omega}$	Coefficient for Ω^2	N/rpm^2
$T_{\Omega Va}$	Coefficient for ΩV_a	N/(rpm • m/s)
ω	Wake fraction number	-
V_a	The ASC advance speed	m/s
Ω	Propeller rotational speed	rpm-

Using the experimental data gathered from the resistance and self-propulsion tests. The coefficients can be fitted, and the final identified model is shown in Eq. 5. Figure 13 depicts the fitted curve in 3D space.

$$T(\Omega,V_a)=0.0014\Omega^2-0.2758\Omega V_a \quad (5)$$

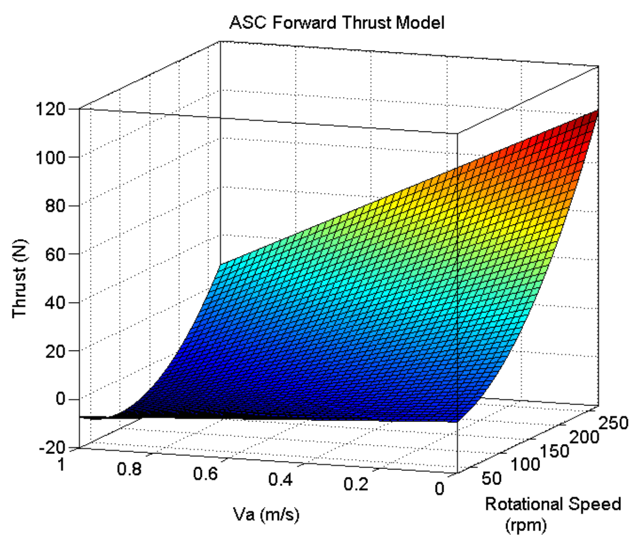

Fig. 13. Fitted bilinear thruster model curve

VI. SEA TRIALS

Sea trials in Holyrood Arm, Conception Bay, NL, were performed for the validation of the tow tank test results. In real sea conditions, the ASC motion will be affected by winds, currents and waves. Therefore, a heading PI controller was used to make the vehicle move in straight line. However, no speed controller was used in this validation process.

To validate the self-propulsion test results in this experiment the propeller revolution rate was chosen from the self-propulsion points (Table III). The ASC propeller rotational speed was first set at a constant value, and then the steady state moving speed was recorded. Table V shows the comparison between the tow tank test results and sea trials results. As can be seen, the discrepancy is quite small.

VII. CONCLUSION AND FUTURE WORK

We introduced the overall system design of a robust catamaran-style Autonomous Surface Craft (ASC) with the associated control and communication infrastructure. The system was evaluated and tested in the tow tank of Memorial University and under open water conditions. From the full-scale resistance and self-propulsion experiments, the ASC hull drag coefficient and a bilinear thruster model were generated. The sea trails performed at Holyrood Arm validated the tow tank experimental results. The next step will be the identification of a more complete system model. Mission planning and an advanced control algorithm can be developed based on this model.

TABLE V. SEA TRIALS COMPARED WITH THE TOW TANK TEST RESULTS

Propeller (rpm)	**Speed Sea trials (m/s)**	**Speed Tow tank (m/s)**	**Difference (%)**
99	0.4187	0.40	0.05
122	0.4946	0.50	1.08
142	0.6065	0.60	1.08
166	0.7162	0.70	2.31
188	0.7978	0.80	0.28
216	0.9201	0.90	2.23
237	1.0195	1.00	1.95

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