Modelling and Identification of a Robust Autonomous Surface Craft for Deployment in Harsh Ocean Environment

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Abstract—In this paper, the procedures for modelling and identification of a displacement style catamaran differentially driven Autonomous Surface Craft (ASC) are introduced. A three degrees of freedom mathematical model that includes the surge, sway and yaw motion of the vehicle is used. The surge motion tests were performed at the towing tank of Memorial University. In this indoor experiment, the full scale ASC model was used and it was equipped with the Hagisonic StarGazer™ indoor localization system for measurement of the position and velocity. Following this, the zig-zag tests were performed in the sea trials. All the experimental data were collected using the existed ASC control and communication system and available onboard sensors. The identified ASC model is evaluated and compared with the collected measurement data.

Keywords—Autonomous Surface Craft (ASC), system modelling, parameter identification, StarGazer indoor localization sensor.

I. INTRODUCTION

The Autonomous Surface Craft (ASC) SeaCat (Fig. 1) was designed at the Autonomous Ocean Systems Laboratory (AOSL) at Memorial University [1]. This platform was developed focusing on its deployment in harsh ocean environment in the coastal waters of Newfoundland and Labrador. A summary of the main specification of the SeaCat ASC is shown in Table I. This catamaran-type ASC provides good roll stability when working in the water. With a total weight of around 60 kg, the battery system lowers the center of gravity of the whole system which also increases the stability. To obtain the best strength-weight ratio, the aluminium cross beams and superstructure are chosen. Electrical circuits, microcontrollers and sensors are included in four separately located enclosures (labeled in Fig. 1) which follow the IP 67 [2] standard. The connection between these boxes is based on the NMEA 2000 [3] marine standard cables and connectors. The propulsion system consisting of two fixed electric outboard motors, is installed at the rear part of each hull. Although there are no rudders on this ASC, the steering motion can be achieved by applying differential thrust from the two propellers.

The ASC SeaCat’s onboard control commands and sensor data are transmitted based on the Controller Area Network (CAN) protocol [4]. The CAN protocol has been widely used in automobile industry because it has reliable data transmission and error detection mechanism. Established on CAN protocol, a distributed onboard communication and control system with four CAN nodes is realized. This system layout is depicted in Fig. 2, in which the labelled CAN nodes are related to those from Fig. 1. CAN node 3 and 4 are thruster junction boxes, and they are controlled separately to adjust the rotational speed, direction and power level of the two propellers. CAN node 2 collects the navigation data from the Global Positioning System (GPS) and an Attitude Heading and Reference System (AHRS) module. CAN node 1 is an interface between the

TABLE I. THE ASC SPECIFICATION

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Width</td>
<td>1.0 m</td>
</tr>
<tr>
<td>Height</td>
<td>1.25 m</td>
</tr>
<tr>
<td>Draft</td>
<td>0.37 m</td>
</tr>
<tr>
<td>Mass (6 batteries)</td>
<td>146 kg</td>
</tr>
<tr>
<td>Maximum Speed</td>
<td>1.0 m/s</td>
</tr>
</tbody>
</table>
SeaCat and the shore-side computer. Integrated with a 900 MHz wireless modem, CAN node 1 can transmit the onboard sensor data back to the operator for logging; meanwhile, receive the control commands from the operator and generate the proper motor commands for the thruster control nodes 3 and 4. In addition, the weather station module, Airmar\textsuperscript{T M} PB200, is connected with the CAN node 1 microcontroller using NMEA 2000 communication protocol [3]. This sensor can also provide the GPS and AHRS data as a backup if sensor failure happens in node 2. PB200 also provides measurement of wind data, temperature and barometric pressure.

Based on the aforementioned discussion, the ASC SeaCat is designed as a robust electrical and mechanical system. In order to operate the SeaCat autonomously in the coastal waters of Newfoundland and Labrador for ocean exploration and environmental monitoring tasks, though, a mathematical model that can accurately describe the vehicle’s planar motion is necessary for development of the control and navigation algorithm [5] and [6]. In this paper, the procedures for modelling and parameter identification of the ASC SeaCat are discussed. The remaining part of the paper is arranged as follows. Section II introduces the three degrees of freedom modelling of the SeaCat. In Section III, the parameter identification of the straight-line and steering motion model is performed. Section IV provides the comparison of the measured data and the simulated data from the identified mathematical model, and Section V presents the conclusion and future work.

II. SYSTEM MODELLING

A. Thrusters

The propulsive force and steering torque come from the two thrusters on the ASC SeaCat; therefore, a proper model of the propulsion system is necessary for our further analysis. Based on the towing tank resistance and self-propulsion tests, a bilinear thruster model has been identified in [1]. In Eq. 1, \( T(\Omega, V_a) \) stands for the total thrust force from the two propellers as a function of the rotational speed of the propellers (\( \Omega \)) and the advance velocity (\( V_a \)). A summary of the variables and coefficients used in Eq. 1 is provided in Table II. For simplicity, we use \( T \) instead of \( T(\Omega, V_a) \) in the following modelling process. Note that we will also assume that the hull influence on the flow speed into the two propellers is negligible. Therefore, \( V_a \) also defines the ASC relative moving speed (surge speed) in water.

\[
T(\Omega, V_a) = T_{\Omega^2} \Omega^2 + T_{\Omega V_a} \Omega V_a 
\]

Using Eq. 1, we could also achieve the mathematical model for the steering torque which is shown in Eq. 2. In Eq. 2, \( \tau \) represents the torque generated by the left and right thrusters \( T_L \) and \( T_R \). \( L \) is the perpendicular distance between the center axis of each thruster to the ASC centerplane, and it is measured as 0.41 m.

\[
\tau = (T_L - T_R) \times L 
\]

B. SeaCat Planar Motion Model

In the planar motion modelling process, we will assume the ASC’s motion is restricted in three degrees of freedom, i.e. surge, sway and yaw. Then, a definition of the direction of the three axes of the body frame \( \{B\} \) is followed (Fig. 3) such that surge points from aft to fore of the vehicle (x axis), sway points to the starboard (y axis) and the positive heave motion points downwards (z axis). In Fig. 3, \( O_B \) is the origin of \( \{B\} \), and it coincides with the ASC center of gravity. In addition, \( \{I\} \) defines the inertial coordinate frame (North-East-Down) fixed on the earth’s surface.

In order to generate the planar motion model, the notation in Table III is used, where \( y \) and \( \psi \) are the time derivative of surge and sway speed, \( m \) stands for the ASC mass (kg) with full payload and \( I_Z \) is ASC’s moment of inertia (kg \( \cdot \) m\(^2\)) around z axis. Note that term \( -vr \) and \( ur \) exist

![Fig. 2. The SeaCat ASC onboard communication and control system layout](image)

![Fig. 3. Inertial and body frame](image)

<table>
<thead>
<tr>
<th>Variable/Coefficient</th>
<th>Definition/Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T(\Omega, V_a) )</td>
<td>Total propulsive force</td>
<td>N</td>
</tr>
<tr>
<td>( \Omega )</td>
<td>Propeller rotational speed</td>
<td>rpm</td>
</tr>
<tr>
<td>( V_a )</td>
<td>Advance velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>( T_{\Omega^2} )</td>
<td>( \frac{0.0014}{\Omega^2} )</td>
<td>( \text{rpm}^{-2} )</td>
</tr>
<tr>
<td>( T_{\Omega V_a} )</td>
<td>( 0.2758 )</td>
<td>( \Omega V_a )</td>
</tr>
</tbody>
</table>
because the Newton’s Law is applied on a moving frame.

\[
\begin{align*}
X &= m(u - vr) \\
Y &= m(\dot{v} + ur) \\
N &= IZ\dot{r}
\end{align*}
\] (3)

If we assume the ASC motion is not affected by the environmental forces or moments from wind, wave or ocean current. The terms on the left of Eq. 3 can be extended including the added mass forces \((X_A\text{ and } Y_A)\) and moments \((N_A)\), hydrodynamic damping forces \((X_D\text{ and } Y_D)\) and moments \((N_D)\), and the input force \((T)\) and torque \((\tau)\) as shown in Eq. 4.

\[
\begin{align*}
X &= X_A + X_D + T \\
Y &= Y_A + Y_D \\
N &= N_A + N_D + \tau
\end{align*}
\] (4)

We can rewrite Eq. 4 including the hydrodynamic coefficients to get Eq. 5. Note for the damping force and moment, we combine the quadratic and linear damping terms.

\[
\begin{align*}
X &= X_u\dot{u} + X_u^2u^2 + X_uu + T \\
Y &= Y_v\dot{v} + Y_v^2v^2 + Y_vv \\
N &= N_r\dot{r} + N_r^2r^2 + N_r\tau + \tau
\end{align*}
\] (5)

For completeness, we combine Eq. 3 and Eq. 5 together to get our three degrees of freedom ASC planar motion model as shown in Eq. 6.

\[
\begin{align*}
(m - X_u)\dot{u} &= X_u^2u^2 + X_uu + mvr + T \\
(m - Y_v)\dot{v} &= Y_v^2v^2 + Y_vv - mvr \\
(IZ - N_r)\dot{r} &= N_r^2r^2 + N_r\tau + \tau
\end{align*}
\] (6)

For simplicity, we express Eq. 6 in a lumped form as in Eq. 7, where the coefficients \(A_{11}\) to \(A_{33}\) are defined in Eq. 8. The coefficients \(A_{11}\) to \(A_{33}\) will be identified in the parameter identification part.

\[
\begin{align*}
\dot{u} &= A_{11}u^2 + A_{12}u + A_{13}mvr + A_{14}T \\
\dot{v} &= A_{21}v^2 + A_{22}v + A_{23}mvr \\
\dot{r} &= A_{31}r^2 + A_{32}r + A_{33}\tau
\end{align*}
\] (7)

III. PARAMETER IDENTIFICATION

A. Straight-line Motion Model Identification

The experiments were performed indoor at the towing tank of Memorial University. One reason is to conduct the experiments in a controlled environment; and the other is to increase the location data update rate and increase the location measurement accuracy.

The indoor ASC position is measured using the off-the-shelf Hagisonic StarGazer\textsuperscript{TM} indoor mobile robot localization sensor. The StarGazer\textsuperscript{TM} projects the infra red light to passive uniquely identifiable landmarks and uses a camera to detect position and heading. The system can reach up to 2 cm and 1.0 degree location and heading angle measurement accuracy. By using multiple landmarks, a larger measurement area can be achieved. In our case, we put all the landmarks along one straight line in the towing tank, which is appropriate for us to perform the straight-line ASC tests.

The StarGazer\textsuperscript{TM} sends out the location data through the serial interface, and we designed a circuit to read in the message and transmit it onto the onboard communication and control network using the CAN protocol. Therefore, in this experiment, the StarGazer\textsuperscript{TM} is integrated into the onboard communication system and acts as the indoor localization CAN module. The location and heading measurement data are measured at 10 Hz, and by differentiating the location data, we can get the ASC moving speed.

Fig. 4 shows the experimental setup in the towing tank. As can be seen from this picture, the StarGazer\textsuperscript{TM} has been installed on the superstructure of the SeaCat ASC right in the center plane. The system points upward to send out the infrared light to the landmarks and determines its position based on the reflected image. All landmarks are fixed on the ceiling on one straight line with a fixed interval of 2 m, and these marks are located above the towing tank’s centerline.

![StarGazer sensor and landmarks](image)

In the straight line tests, the sway speed and the yaw rate is relatively small and negligible. Therefore, in this case, the
surge model of Eq. 7 will not include the term of the coupled sway speed and yaw rate \( A_{13} m v r \). However, the surge speed model is still non-linear (the term \( u^2 \) and the bilinear thruster model). In the model we assume time-invariant parameters; thus, we can perform the least-squares fit for the surge model. We can write the surge model in a lumped form as shown in Eq. 9.

\[
\begin{bmatrix} \dot{u} \end{bmatrix}_{n \times 1} = \begin{bmatrix} u^2 & u & T \end{bmatrix}_{n \times 3} \begin{bmatrix} A_{11} \\ A_{12} \\ A_{14} \end{bmatrix}_{3 \times 1}
\]

(9)

From Eq. 9, as long as the vehicle moving speed, and the thrust force from the propulsion system can be measured (calculated), the unknown parameters \( \theta \) can be identified using Eq. 10

\[
\theta = (\Phi^T \Phi)^{-1} \Phi^T \left[ \dot{u} \right]
\]

(10)

B. Steering Motion Model Identification

Similar ideas can be used to identify the sway and yaw motion model parameters. A further insight of the sway model in Eq. 7 reveals that there is no direct control input for the sway motion; however, the coupled terms from the surge speed and yaw rate acts as the control forces for the sway motion. Since the towing tank is not wide enough for us to perform the steering tests, we performed the zig-zag tests in the sea trials at the Holyrood Arm, Conception Bay South, Newfoundland and Labrador.

As shown in Fig. 5, in a steering motion, the sideslip angle (\( \beta \)) can be calculated with the magnetic heading (measured with a magnetometer aligned with the surge direction) and the course over ground (COG measured using the onboard GPS). In this case, the sideslip angle is calculated as shown in Eq. 11. In Eq. 11, \( \theta_{MH} \) and \( \theta_{MD} \) represents the magnetic heading angle and magnetic declination angle respectively (\( +19.1^\circ \) in this case), and \( \theta_{COG} \) is course over ground with respect to true north.

\[
\beta = \theta_{MH} - \theta_{MD} - \theta_{COG}
\]

(11)

Therefore, the surge and sway speed can be calculated using the speed over ground (SOG) measured from the GPS module as indicated in Eq. 12. The yaw rate can be directly measured using the onboard gyroscope.

\[
u = \cos(\beta) \times V_{SOG} \\
\]

(12)

IV. Experimental Data Analysis

A. Straight-line Experiments

Straight-line experiments were performed in the controlled environment of the towtank using the previously described indoor localization system. In [1], the ASC SeaCat’s self-propulsion points were found. Following these experimental results, in this test, we will use the same group of propeller settings and record each acceleration process of the ASC.

The parameter identification was performed for each acceleration process, and a summary of the identified parameters is shown in Table IV. Figure 6 depicts the measured surge speed and the simulation results which implements the identified parameters from Table IV. Note that in Table IV, RMSE stands for the root mean squares error, and it is calculated using the practical and simulated surge speed.

<table>
<thead>
<tr>
<th>Propeller (rpm)</th>
<th>( A_{11} ) (m/s)</th>
<th>( A_{12} ) (s^-1)</th>
<th>( A_{14} ) (kg/s^-1)</th>
<th>RMSE (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>99</td>
<td>-0.7693</td>
<td>0.3145</td>
<td>0.0011</td>
<td>0.0102</td>
</tr>
<tr>
<td>128</td>
<td>-0.7403</td>
<td>0.3831</td>
<td>0.0010</td>
<td>0.0147</td>
</tr>
<tr>
<td>142</td>
<td>-0.7278</td>
<td>0.4439</td>
<td>0.0010</td>
<td>0.0285</td>
</tr>
<tr>
<td>166</td>
<td>-0.6995</td>
<td>0.5150</td>
<td>0.0007</td>
<td>0.0375</td>
</tr>
<tr>
<td>188</td>
<td>-0.6700</td>
<td>0.5256</td>
<td>0.0009</td>
<td>0.0179</td>
</tr>
<tr>
<td>216</td>
<td>-0.6459</td>
<td>0.5773</td>
<td>0.0009</td>
<td>0.0403</td>
</tr>
<tr>
<td>237</td>
<td>-0.6163</td>
<td>0.6275</td>
<td>0.0005</td>
<td>0.0332</td>
</tr>
</tbody>
</table>

Fig. 6. Measured surge speed compared with the simulated surge speed

To achieve a generalized surge motion model that could approximate all different acceleration process, it is not possible to use the time invariant coefficients (Table IV). After trial and error, it was found out that the parameter \( A_{11} \) and \( A_{12} \) will affect the simulated surge speed greater than \( A_{14} \). Therefore, we could try to keep two coefficients as constant (\( A_{11}, A_{14} \) or \( A_{12}, A_{14} \)), but change the third parameter to make the new surge model fit all acceleration process. The model from [1] which relates each propeller’s rotational speed to the ASC steady-state moving speed (Eq. 13) can be used...
to find the relationship between the three unknown parameters \((A_{11}, A_{12},\text{ and } A_{14})\). Note in Eq. 13, the coefficient \(K=0.0043\) \(m/(s \cdot \text{rpm})\).

\[
u_{ss} = K\Omega \
\]

(13)

If we substitute Eq. 1 and Eq. 13 into the surge speed model in Eq. 7 under the steady-state conditions, Eq. 14 can be established.

\[
(2A_{14} + 0.1849A_{11})\Omega = -43A_{12} 
\]

(14)

Then an average value of \(A_{11}\) and \(A_{14}\) from Table IV can be used in Eq. 14, and finally the parameter \(A_{12}\) is calculated as a function of the propeller rotational speed. These results are summarized as \([A_{11}, A_{12}, A_{14}]=[-0.6973, 0.0029, 0.00087]\). The new model with no longer invariant coefficient \(A_{12}\) is simulated and compared with the measurement data. The results are shown in Fig. 7. Table V summaries this simulation with corresponding \(A_{11}, A_{12}\) and \(A_{14}\) values. The RMSE results can be directly compared with those of Table IV. It can be concluded that, except for the last speed setting (237 rpm), which has a relatively large discrepancy with the measured data, the generalized surge model can also be used to simulate the ASC SeaCat’s acceleration process with good agreement. A probable explanation of the large mismatch for the propeller speed of 237 rpm is that the added mass, which is governed by \(A_{14}\), is quite different from the other acceleration process.

\[
u(t) = A_{11}(\Omega^2 + 2\Omega T + T^2) + A_{12}\Omega + A_{14} \quad \text{with corresponding results are shown in Fig. 7.}
\]

Table V summarizes this simulation. The paper introduces the methods needed for the modelling and parameter identification of a robust Autonomous Surface Craft (ASC) SeaCat. The three degrees of freedom model parameters can be identified. A summary of these identified parameters is shown in Table VI. The root mean squares error for the sway and yaw model are calculated as 0.018 m/s and 0.0111 rad/s.

**TABLE V. SIMULATION RESULTS WITH \(A_{11} AND A_{14}\) CONSTANT**

<table>
<thead>
<tr>
<th>Propeller (rpm)</th>
<th>(A_{11}) ((m^{-1}))</th>
<th>(A_{12}) ((m/s))</th>
<th>(A_{14}) ((kg^{-1}))</th>
<th>RMSE ((m/s))</th>
</tr>
</thead>
<tbody>
<tr>
<td>99</td>
<td>-0.6973</td>
<td>0.2871</td>
<td>0.00087</td>
<td>0.0196</td>
</tr>
<tr>
<td>112</td>
<td>-0.6973</td>
<td>0.3538</td>
<td>0.00087</td>
<td>0.0151</td>
</tr>
<tr>
<td>142</td>
<td>-0.6973</td>
<td>0.4118</td>
<td>0.00087</td>
<td>0.0206</td>
</tr>
<tr>
<td>186</td>
<td>-0.6973</td>
<td>0.4814</td>
<td>0.00087</td>
<td>0.0440</td>
</tr>
<tr>
<td>216</td>
<td>-0.6973</td>
<td>0.5452</td>
<td>0.00087</td>
<td>0.0525</td>
</tr>
<tr>
<td>237</td>
<td>-0.6973</td>
<td>0.6264</td>
<td>0.00087</td>
<td>0.0458</td>
</tr>
</tbody>
</table>

**B. Zig-zag Experiments**

Zig-zag experiments were performed in the open sea conditions. The ASC on-board magnetometer and the GPS module are used to measure the magnetic heading and speed (course) over ground respectively. In these tests, the differential propeller rotational speed is set as \(\pm 100\) rpm, and the rotational speed of the two propellers is switched between 218 rpm and 118 rpm. Figure 8 shows the measured data from this experiment. The surge and sway speeds are calculated using Eq. 12, and the yaw rate is directly measured using the onboard gyroscope.

**Fig. 8. Zig-zag experimental results**

Based on these measurements, the sway and yaw motion model parameters can be identified. A summary of these identified parameters is shown in Table VI. The root mean squares error for the sway and yaw model are calculated as 0.018 m/s and 0.0111 rad/s.

**TABLE VI. IDENTIFIED PARAMETER VALUES FROM THE ZIG-ZAG TESTS**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Identified Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A_{21})</td>
<td>-0.2789</td>
<td>m/s</td>
</tr>
<tr>
<td>(A_{22})</td>
<td>-0.0143</td>
<td>m/s</td>
</tr>
<tr>
<td>(A_{23})</td>
<td>-0.1177</td>
<td>(kg^{-1}m^{-1}rad^{-1})</td>
</tr>
<tr>
<td>(A_{31})</td>
<td>-8.8115</td>
<td>rad/s</td>
</tr>
<tr>
<td>(A_{32})</td>
<td>-0.0302</td>
<td>s^{-1}</td>
</tr>
<tr>
<td>(A_{33})</td>
<td>0.0007</td>
<td>(kg^{-1}m^{-1}rad^{-1})</td>
</tr>
</tbody>
</table>

The simulated sway speed and yaw rate are compared with the measured data and the results are shown in Fig. 9. From Fig. 9, it can be seen that although the simulated sway speed follows the general trend of the experimental data, there are some regions with a large mismatch. However, since the sway speed is calculated from the GPS, and its speed measurement accuracy is 0.1 m/s, while in our simulation the maximum discrepancy is within 0.05 m/s, we think the result is acceptable. Additionally, as mentioned before, we did not include the environmental influence in our sway model, but in the experiment, the wave and wind influence can play a significant factor. In Fig. 9, the yaw rate motion model has a relatively good match with the measured data, but there is only 1 second lag in the simulated model. Therefore, when using the yaw motion model, the 1 second lag has to be considered.

**V. CONCLUSION AND FUTURE WORK**

The paper introduces the methods needed for the modelling and parameter identification of a robust Autonomous Surface Craft (ASC) SeaCat. The three degrees of freedom model
Fig. 9. Measured sway speed and yaw rate compared with the simulated results

is used to represent the ASC’s planar motion. Based on the straight-line and zig-zag test results, the corresponding model coefficients have been identified. The straight-line experiments were performed indoor, and since there was no environmental influence, satisfactory measurement data can be achieved. Based on the measured data, a generalized surge speed model was established and it can be used to simulate the acceleration process. The sway and yaw motion model simulation results shows a relatively large discrepancy with respect to the measured data. However, it is believed that the environmental influence into the sway and yaw motion can not be simulated. Therefore, more experiments in a controlled environments are needed for the validation of the sway and yaw motion models.

VI. ACKNOWLEDGEMENT

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