Short Papers

System Identification of a Model Ship Using a Mechatronic System

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and David Parsons

Abstract—**This paper describes a mechatronic system for a model ship that is developed as a validation platform for ship maneuvering control system research. The model ship is a free-running system that is propelled and steered by two propulsion motors and two rudder motors, respectively, powered by batteries packed onboard. Real-time control is performed by an embedded processor, with control algorithm being programmed on a hosting PC and communicated through a wireless network. Sensors for the ship motion are integrated for feedback control and data acquisition. The hardware description, software development, and system integration efforts will be delineated. The mechatronic system has been used to develop a dynamic mathematical model for the ship to facilitate future control work. System identification results are presented to demonstrate the utility of the hardware and software presented in this paper.**

Index Terms—**Control systems, marine vehicle control, mechatronics.**

I. INTRODUCTION

Path following and tracking control of surface vessels are important control problems that have attracted the attention of the control community for many years. The underactuated nature of these problems, namely, with more degrees of freedom to be controlled than the number of control actuators, coupled with actuator dynamic constraints, strict safety requirements, and the nonlinear characteristics of the hydrodynamics associated with the ship motion, make the control problems very challenging. Much of the ship control work [1], [2] to date has been limited to simulations because the use of full-size vehicles to test advanced nonlinear control methodologies is often expensive and risky. To remedy this situation, a scaled-model experimental apparatus is developed to evaluate the ship controller designs. Such apparatus features a mechatronics system with integrated sensors for signal measurement and control implementation, thereby providing a platform for ship control research, such as ship guidance and navigation, tracking and way-point following, and formation control of marine vessels.

Researchers have been studying scaled vehicles for different reasons, such as vehicle dynamics, performance on rough terrain, and to determine vehicle turning radius [3]. More recently, work has been reported on vehicle dynamics and controls [4]–[6], to study the lateral/longitudinal motion and design of steering controller [7], [8], and to study vehicle rollover [9], [10]. Interested readers are referred to the survey article [11] for many additional references on the use of scaled mechatronic systems.

This paper addresses the development of the mechatronic system for a scaled-model ship. As an illustration of the utility for the developed system, a mathematical model for the scaled-model ship is developed through system identification using the data acquired by the mechatronic system.

The main research contributions are summarized as follows: First, the real-time control capability with the mechatronic system is enhanced by reducing the signal processing delay. To this end, the camera data and the carriage speed have been designed to be directly transmitted to the onboard computer while in [12] and [13], the camera PC and the host PC are connected in a local area network (LAN) using the Ethernet interface. This design can incur some delay in processing the data by communicating via wireless LAN. Second, to supply a safe powering environment, the electronic and mechanical components are grouped into three groups: sensors, actuators, and onboard PC. Each group is powered by an individual power supply. This modularization has made significant contributions to the reliable operation of the autonomous ship in the water tank test. Third, lacking a rotary arm facility and a device known as a planar motion mechanism (PMM) [14], we proposed a viable system ID technique by which the velocity, acceleration, and yaw-dependent hydrodynamic coefficients are determined subsequently. The validity of this mathematical model has been proved to be effective in control development works through several successful model-based controller development and tests [15], [16]. While similar model ships, such as the Cybership [12], have been used for control research for many years, to the best of the authors' knowledge, the full accounts of the development and construction of such complex mechatronic system are not readily found in open literature.

This paper is organized as follows. In Section II, the hardware and software platforms of the model ship are presented. Model testing experiments using the mechatronic system are reported in Section III. The collected data are used in Section IV for system identification to determine the hydrodynamic coefficients. Finally, conclusions are outlined in Section V.

II. MECHATRONIC SYSTEM DEVELOPMENT

This section is devoted to the description of the mechatronic system that runs the model ship autonomously. To support the theory development and algorithm validation for ship maneuvering controls, the mechatronic system is designed with the following requirements in mind: 1) the model ship should be run autonomously and untethered in the towing tank where GPS position feedback signal is not available; 2) it should have the control functions of maneuvering and course keeping. Furthermore, it should have sufficient control authority to support our future work on coordinated maneuvering and seakeeping, where 4-DOF (surge, sway, yaw, and roll) motion dynamics are of interest; 3) the option of manual operation should be available where the model ship can take propeller and rudder commands from an operator; and 4) communication between the onboard controller and ground control station must be real-time to allow monitoring and interaction functions.

A model ship, a replica of an offshore supply vessel with overall length $L = 1.6$ m and scale 1:50 is chosen for this study. The main geometric parameters of the ship are summarized in Table I. The ship is installed with two twin-screw propellers, each with four blades and independently controlled. The rudders have a movement range of 30° each way with approximate dimensions of 10 cm × 15 cm × 1 cm.

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TABLE I
PRINCIPAL PARAMETERS OF THE SCALED-MODEL SHIP

Item	Symbol	Value
Scale		1:50
Length	L	1.6 m
Breadth	B	0.38 m
Height	H	0.17 m
Mass	m	38 kg
Inertia	I_z	2.7 kgm^2
Nominal Speed	u_n	0.4 m/sec

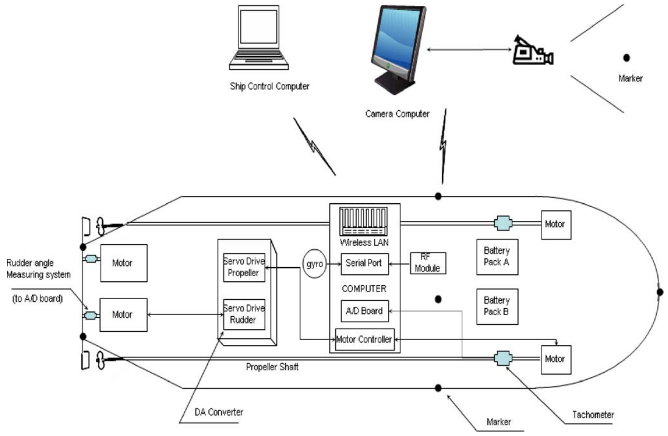

Fig. 1. System architecture showing hardware components.

TABLE II
SPECIFICATION OF FREE-RUNNING SYSTEM

Item	**Model**	**Spec**
Tachometer	DC-Tach DC22	0.25V/1000 RPM
Encoder	HEDL 5540, 3CH	500 CPR
MRU	XSens MTi DK -3D Orientation -3D Acceleration -3D Rate of Turn	(accuracy: 0.05deg) (5g) 300deg/s
Motor Controller	Maxon ADS 50/5	
Servo Motor	Propeller: Maxon RE30, 90Watt Gear Head	Rudder: Maxon RE30, 60Watt
PC104: Data I/O Modules	DM6814 DM4620 -	3 16-Bit Encoder 8CH, 12-Bit ADC 2CH, 12-Bit DAC
PC104: Serial Interface	CM310HR -	RS-232/422/485 111K Baudrate
PC104: CPU Module	Onboard processor	AMD 400MHz CPU 64MB Memory
Battery Pack	Polymer Li-Ion Battery Water-proof Fire Fire Retardant Enclosure	18V, 180Watt
RF Modem	9XTend RS-232/485	40 mile range

The rudders are mounted on a 0.75-cm-diameter steel shaft, which is fastened to the motor coupling.

The mechatronic system that operates the model ship consists of four key modules: sensors, motors and their associated controllers, embedded processors for control and communication, and power supplier, as featured in Fig. 1.

A. Hardware Development

The main actuation mechanism is composed of four dc servomotors that operate the two propeller shafts and the two rudders. They are fitted with a tachometer and an encoder to measure the speed at propeller shaft and the rudder deflection, respectively. A motion reference unit (MRU) is installed at the center of the model ship to measure the 3-D orientations and local acceleration of the ship. These data are collected by the onboard PC through a serial port and A/D board. The rest of A/D converter channel is used to measure 6-DOF load cell signal during the captive model test. The specifications of the major hardware components are shown in Table II. PC104 includes three A/D or digital-to-analog (D/A) converters (24 channel (CH) and 6 CH), two encoder board (6 CH), and six serial ports.

A PC104 computer, running the real-time operating system (RTOS) of QNX, is selected as the target onboard processor. PC104 is a compact size computer, typically used for data acquisition and real-time control applications such as those in vehicles. PC104 modules (3.8 in × 3.9 in) are much smaller than industry standard architecture (ISA) bus cards found in regular PCs, and the requirements for power and signal drivers are reduced to meet the needs of an embedded system. On the other hand, most of the program development tools for regular PCs can be used for a PC104 system, thereby reducing the learning curve for programmers and hardware designers. PC104 modules include common functions such as CPUs, serial I/O ports, and video controllers; special purpose modules such as GPS receivers, vehicle power supplies, and wireless communications can also be incorporated. A list of PC104 modules is shown in Table II.

B. Control Software Development

Simulation software was developed on a host PC under Opal RT-Lab, which makes it possible, without writing a single line of code, to run Simulink models in real time for experiments within the laboratory.

RT-Lab works together with MATLAB, Simulink, Real-Time Workshop, and LabView. The guidance, navigation, and control (GNC) system for the experiment is implemented in the Simulink environment. RT-Lab generates the C-code, and transfers it to the target PC where it is compiled. RT-Lab also handles the communication between the host, target, and GUI. The host PC is connected to a LAN using the Ethernet interface. The target accesses the LAN through a wireless communication link (LinkSys). Through the main console, the operator can switch between different modes of operation (manual and automatic), supervise the experiment, and log data.

C. Sensors Integration

Qualisys motion measuring system is adopted to provide the position feedback for laboratory tests, where GPS signals are not available. It uses optical tracking technology to capture the movements of a model ship. Six DOF (surge, sway, heave, roll, pitch, and yaw) are measured. For our test bed, six passive infrared markers and four cameras (1000 Hz ProReflex MoCap) are mounted on the model ship and the towing carriage, respectively, as shown in Fig. 1. Each camera identifies the markers as the part of the body, and captures its movement by sending infrared lights and processing the signal reflected by the markers. This setup provides a camera view field that spans a width of over 6.7 m (the width of the towing tank) and a length of 6 m, which provides enough space for the carriage operator to adjust the carriage position to keep the ship in sight. The PC104 onboard the ship provides a GPS receiver I/O, and thus, the position information can be also measured using the GPS in the outdoor test.

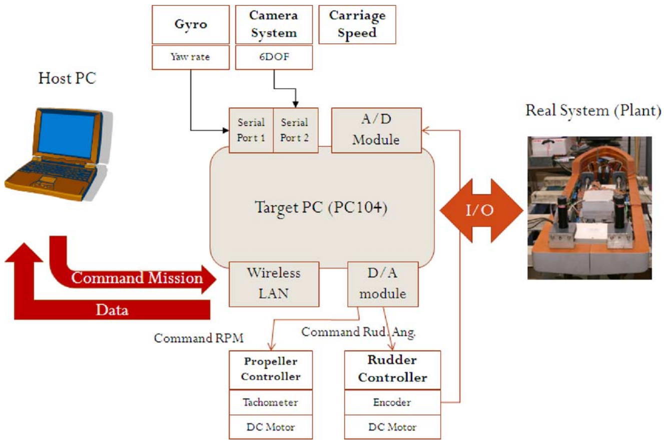

Fig. 2. Test setup of the free-running system.

2-D digital measurement data captured by the camera are then sent to a dedicated laptop through a RS422 interface, where QTM (a motion capture software by Qualisys) is running to process the data, and to provide the 3- or 6-DOF position information for the control system.

The two sets of XStream 2.4 GHz RF modems have been used to send the 6 DOF measurement of the boat and the speed of the towing carriage to PC104. The stand-alone RF modems provide an outstanding range up to 20 miles in a low-cost wireless solution. The modem is coupled with a dual in-line package (DIP) switchable RS-232/RS-422/RS-485 interface board. In our test, the RF data rate and interface data rate are set to 9.6 and 57.6 Kbps, respectively.

D. Power Systems

Two 18-V auxiliary battery packs, designed to power user-installed equipments (RF modem, MRU, dc motor, and encoder) and the onboard control computer, are installed at the front of the PC104. These battery packs can provide 180 W for 2 h of continuous operation, powering all the four motors and their controllers.

III. TESTING

In order to test the mechatronic system, the instrumented model ship shown in Fig. 2 was tested in the Marine Hydrodynamics Laboratory at the University of Michigan. The model ship was run both in manual and autonomous modes for different speed profiles and maneuvering operations. The actuator functions and wireless communications are tested and verified. The model ship traveled the distance of 100 m at a constant propeller speed of 300 r/min without any problem in wireless communication. The ship slowed down near the end of the water tank. The list of collected data is as follows: rudder deflections and propeller speeds, ship positions, and heading angles. The towing carriage speed and ship's position data from the motion tracking system are transmitted in real time to the onboard PC104 through two pairs of wireless RF modems. In the manual operation, an operator using a joystick sends the command signals of propeller speeds and rudder angles to PC104 through wireless communication channels. Proportional–integral (PI) controllers are implemented for the motor speed and position inner-loop control, using the measured propeller shaft speed and rudder angle as feedback. The actuator PI gains are $K_{\mathrm{prop}} = (0.05, 1.0)$ and $K = (3, 5)$.

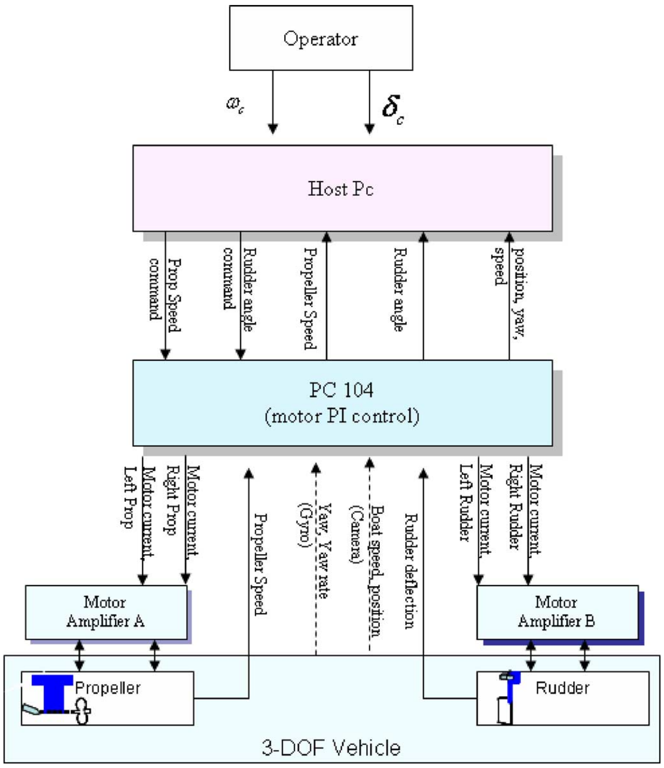

Fig. 3. Manual-mode control system layer.

The overall control signal flow is shown in Fig. 3. The control system comprises three levels (operator, PC104, and actuator/sensor). At the lowest level, the onboard computer controls and coordinates the motion of two propeller motors and two rudder motors, while in the highest level, an operator (or a user-written control program) prescribes the desired speed and rotation of the ship. The towing carriage speed and boat position data from the motion tracking system are transmitted in real time to the onboard PC104 through two pair of wireless RF modems. An operator using a joystick sends the command signals of propeller speed ω_c and rudder angles δ_c to PC104. PI controllers are implemented for the motor speed and position control using measured propeller shaft speed and rudder angle as feedback. The actuator PI gains are tuned to be $K_{\mathrm{prop}} = (0.05, 1.0)$ and $K_{\mathrm{rudder}} = (3, 5)$. The control system runs at sample rate of 1 ms.

The ship position and turning rate from one of the tests are plotted in Fig. 4, along with the rudder angle and the propeller speed. We see small discrepancy (10 r/min) between the speed profiles of two propellers. This is because propellers are actuated independently by two servomotors with nonidentical characteristics. The rudder motions show an excellent match with each other. The heading rates obtained from the camera and the MRU are plotted in the third plot. The MRU and camera system provide complementary ship orientation information. While MRU does not have the accuracy of the camera system, its measurement is more robust in the sense that it is not affected by the performance of the wireless communication and the ship–camera relative position. In addition, this dual measurement setup can also be used to evaluate the performance of the MRU sensor during dynamic maneuver.

The rate gyro can provide the reliable heading information in the event of the camera malfunction whether due to the ship out of the camera's field of view or the wireless communication network. The ship position has been detected by the camera without any loss or

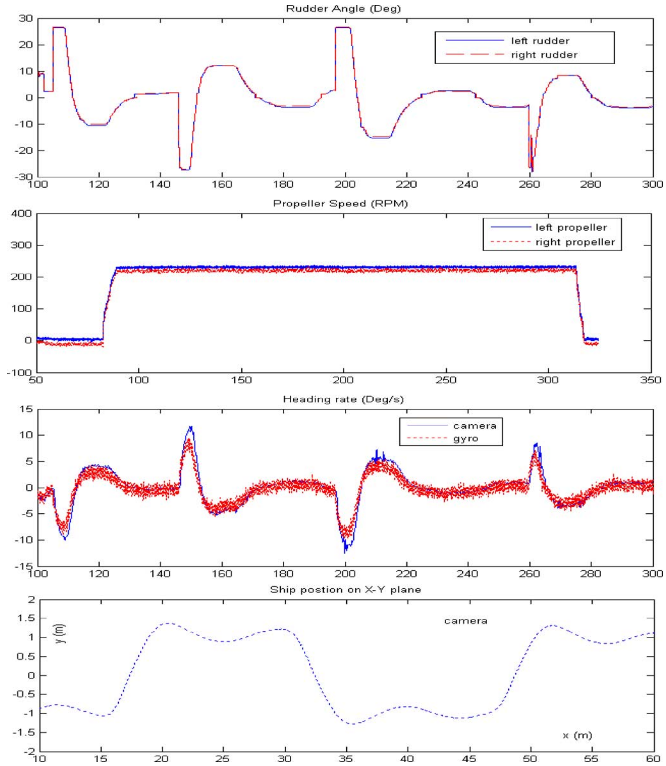

Fig. 4. Measured data in a zig-zag maneuvering test.

distortion. In our test, the camera's field of view spans the whole width of the towing tank and up to 6 m distance to the ship, which provides enough space for an operator to adjust the distance between the carriage and the ship.

IV. SYSTEM IDENTIFICATION

The main purpose to develop the mechatronic system described in this paper is to support the maneuvering control research activities. The development of an effective maneuvering model is an important step in solving marine control problems. A good model of the ship dynamics will facilitate model-based design, allowing applications of control design and analysis tools. This section presents a systematic procedure of the system identification using the mechatronic system, aimed at developing a control-oriented dynamic model for the model ship that will be used as the main platform for control algorithm rapid prototyping and validation.

The 3-DOF ship maneuvering model in the horizontal plane can be described as follows [12]:

$$\begin{aligned} m(\dot{u} - vr - x_G r^2) &= X \\ m(\dot{v} + ur - x_G \dot{r}) &= Y \\ I_z \dot{r} + m x_G (ur + \dot{v}) - m y_G vr &= N \end{aligned} \tag{1}$$

where *u*, *v*, and *r* are the surge speed, sway speed, and yaw rate, x_G and y_G are the coordinates of the vehicle center of gravity in the body-fixed local frame, and m and I_z are the vehicle mass and mass moment of inertia, respectively. *X*, *Y*, and *N* represent the total excitation surge force, sway force, and yaw moment, respectively. These quantities take into account the hydrodynamic effects from hull movements, forces exerted on the ship by the rudder, and by the propulsion system, and can also include effects induced by sea waves, wind, and currents.

TABLE III
EXPERIMENTALLY IDENTIFIED PARAMETERS

$X_{\dot{u}}$	-6.8558	X_u	3.0211
$X_{\|u\|u}$	-12.9059	X_{uuu}	2.7759
$Y_{\dot{v}}$	-17.5	Y_v	-20.5
$Y_{\|v\|v}$	-24.2	$N_{\dot{v}}$	0
N_v	1.1965	$N_{\|v\|v}$	0.0016
$Y_{\dot{r}}$	0.0	Y_r	-0.835
$Y_{\|r\|r}$	-0.63	$Y_{\|v\|r}$	0.0
$Y_{\|r\|v}$	-0.14	N_r	-1.2522
$N_{\dot{r}}$	-1.2	$N_{\|v\|r}$	0.1
$N_{\|r\|r}$	-0.3302	$N_{\|r\|v}$	0.04
c_X	$1.8902 * 10^{-5}$	c_{Y1}	-0.0298
c_{Y2}	$1.435 * 10^{-4}$	c_{N1}	0.0227
c_{N2}	$-1.0002 * 10^{-4}$		

The following model structure for the excitation terms is adopted from [12]:

$$\begin{aligned} X &= X_{\dot{u}}\,\dot{u} + X_u\,u + X_{|u|u}\,|u|u + X_{uuu}\,uuu + F_x \\ Y &= Y_{\dot{r}}\,\dot{r} + Y_{\dot{v}}\,\dot{v} + Y_v\,v + Y_r\,r + Y_{|v|v}\,|v|v \\ &\quad + Y_{|v|r}\,|v|r + Y_{|r|v}\,|r|v + Y_{|r|r}\,|r|r + F_y \\ N &= N_{\dot{r}}\,\dot{r} + N_{\dot{v}}\,\dot{v} + N_v\,v + N_r\,r + N_{|v|v}\,|v|v \\ &\quad + N_{|v|r}\,|v|r + N_{|r|v}\,|r|v + N_{|r|r}\,|r|r + M_z \end{aligned} \tag{2}$$

where F_x, F_y, and M_z stand for the actuator forces and the moment along x, y, z axis, respectively.

It should be noted that it is very difficult to identify all the parameters at once, given the limited maneuvering space constrained by the towing tank. To ensure the successful system identification, the parameters in (2) are split into three group of coefficients as follows, based on their associated motion variables:

$$\begin{pmatrix} \mathcal{P}_A \\ \mathcal{P}_B \\ \mathcal{P}_C \end{pmatrix} =: \begin{pmatrix} X_u, X_{|u|u}, X_{uuu}, Y_v, Y_{|v|v}, N_v \\ X_{\dot{u}}, Y_{\dot{v}}, N_{\dot{v}} \\ Y_r, Y_{|r|r}, N_{\dot{r}}, N_r, N_{|r|r}, N_{|v|r}, N_{|r|v}, N_{|r|u} \end{pmatrix}. \tag{3}$$

A subsequent identification process is performed, as described next. First, the actuator forces F_x, F_y, andM_z are modeled in terms of propeller speed and rudder angle, relying on the stationary actuator tests. In the second step, the straight-line test [14] is performed to estimate the parameters in $\mathcal{P}_A$ and $\mathcal{P}_B$, coupled with surge and sway. Specifically, $\mathcal{P}_A$ and $\mathcal{P}_B$ are excited by driving the carriage at constant speeds and constant accelerations, respectively. Finally, all the remaining terms in $\mathcal{P}_C$, coupled with yaw motion, are determined. Lacking equipment for turning experiments on the towing carriage, we choose to use free-running maneuvering experiment to find these parameters. During this test, the model ship is driven by the operator, who commands the rudder angle and propeller speed using a joystick. Due to the motion tracking camera system and sensors (MRU, tachometer, and encoder), rich sets of data concerning the boat motion are collected to determine parameters associated with yaw dynamics. The experiment tests and system identification procedures are not presented in detail here due to the limitation of space. The identified model ship parameters are listed in Table III.

The validation of the developed ship model is done in two steps. A simulation of the scaled model is carried out as a first step, and the simulation result is compared to the experimental tests with the scaled vehicle hardware. The results, which are presented in Fig. 5, show a good agreement between the model predictions and the experimental data. The yaw angle shown in Fig. 5 was calculated by double integration of the yaw dynamic equation. Hence, one potential source of the

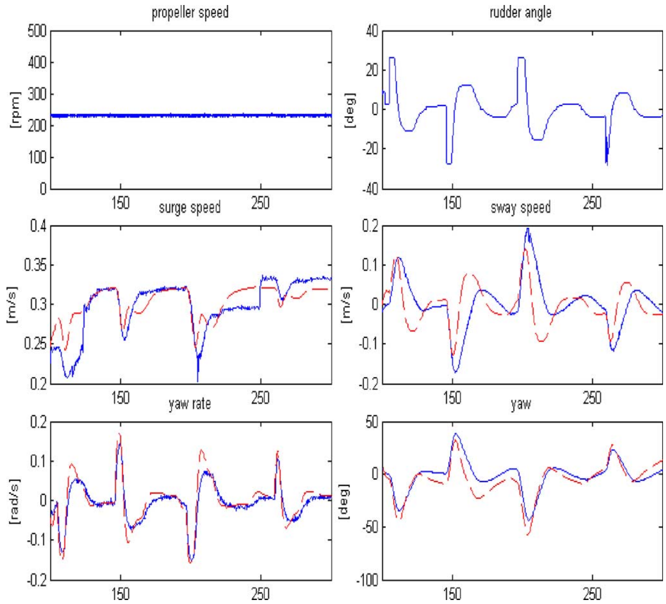

Fig. 5. Comparison between predicted (dashed line) and measured response (solid line) for the propeller and rudder inputs (top plots).

yaw error between the measured signal and the predicted value is due to the nature of the error accumulation over the time. In real experiment, however, since the model can be reset every sampling instance periodically with latest measurements, the cause of the error related to numerical integration over long period of time can be eliminated.

V. CONCLUSION

We have addressed the system integration and identification of the fully instrumented scale ship for the task of ship maneuvering control development. The real-time test bed is made of advanced instrumentation systems, including: the motion tracking system, MRU, high-precision actuator with dc servomotors, and RF module providing reliable and long-range wireless data communications.

An effective method of finding hydrodynamic coefficients, specially in the constrained test environment, was applied to derive a control-oriented model that will facilitate the model-based research on ship maneuvering and path-following control. The simulation results showed the suitability of the identified ship model for model-based control strategy development. Moreover, the model developed and the test bed constructed have been used recently in developing and validating nonlinear control algorithm by this research group, with promising results. Detailed control work based on this model can be found in [15] and [16].

REFERENCES

[1] R. Skjetne and T. I. Fossen, "Nonlinear maneuvering and control of ships," in *Proc. MTS/IEEE Oceans*, Honolulu, HI, 2001, pp. 1808–1815.

[2] K. D. Do, Z. P. Jiang, and J. Pan, "Universal controllers for stabilization and tracking of underactuated ships," *Syst. Contr. Lett.*, vol. 47, pp. 299–317, 2002.

[3] M. G. Bekker, *Introduction to Terrain Vehicle System*. Ann Arbor, MI: Univ. of Michigan Press, 1969.

[4] S. N. Brennan and A. Alleyne, "A scaled testbed for vehicle control: The IRS," in *Proc. IEEE Int. Conf. Contr. Appl.*, 1999, pp. 327–332.

[5] S. N. Brennan, "Modeling and control issues associated with scaled vehicles" Master's thesis, Univ. Illinois Urbana-Champaign, Urbana, IL, 1999.

[6] S. R. Burns, R. T. O'Brien, and Jr, J. A. Piepmeier, "Steering controller design using scale-model vehicles," in *Proc. 34th Southeastern Symp. Syst. Theory*, 2002, pp. 476–478.

[7] R. Verma, D. D. Vecchio, and H. K. Fathy, "Development of a scaled vehicle with longitudinal dynamics of an HMMWV for an ITS testbed," *IEEE/ASME Trans. Mechatronics*, vol. 13, no. 1, pp. 46–57, Feb. 2008.

[8] S. Brennan and A. Alleyne, "The illinois roadway simulator: A mechatronic testbed for vehicle dynamics and control," *IEEE/ASME Trans. Mechatronics*, vol. 5, no. 4, pp. 349–359, Dec. 2000.

[9] W. E. Travis, R. J. Whitehead, D. M. Bevly, and G. T. Flowers, "Using scaled vehicles to investigate the influence of various properties on rollover propensity," in *Proc. Amer. Contr. Conf.*, 2004, pp. 3381–3386.

[10] R. J. Whitehead, D. M. Bevly, and B. Clark, "ESC effectiveness during property variations on scaled vehicles," presented at the ASME IMECE, Orlando, FL, 2005, vol. 5.

[11] S. Shladover, "Review of the state of development of advanced vehicle control systems (AVCS)," *Veh. Syst. Dyn.*, vol. 24, pp. 551–595, 1995.

[12] R. Skjetne, O. N. Smogeli, and T. I. Fossen, "A nonlinear ship manoeuvering model: Identification and adaptive control with experiments for a model ship," *Model., Identification Contr.*, vol. 25, no. 1, pp. 3–27, 2004.

[13] D. A. Sveen, "Robust and adaptive tracking control of surface vessel for synchronization with an ROV: Practical implementation on cybership II," Master's thesis, Norwegian Univ. Sci. Technol. (NTNU), Trondheim, Norway, 2003.

[14] E. V. Lewis, *Principles of Naval Architecture: Volume II-Resistance, Propulsion, and Vibration*. vol. 2, 2nd ed. Jersey City, NJ: SNAME, 1988.

[15] Z. Li, J. Sun, and S.-R. Oh, "A robust nonlinear control design for path following of a marine surface vessel," presented at the 2007 IFAC Conf. Contr. Appl. Marine Syst., Bol, Croatia, Sep. 19–21.

[16] S.-R. Oh, J. Sun, and Z. Li, "Path following control of underactuated marine vessels via dynamic surface control technique," presented at the 2008 ASME Dyn. Syst. Contr. Conf., Ann Arbor, MI, Oct. 20–22.

[17] T. I. Fossen, *Guidance and Control of Ocean Vehicles*. New York: Wiley, 1994.

[18] T. Perez, T. I. Fossen, and A. Sørensen, "A discussion about sea keeping and maneuvering models for surface vessels," Marine System Simulator Group, Norwegian Univ. Sci. Technol. (NTNU), Trondheim, Norway, Tech. Rep. MSS-TR-001, 2004.