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New Applications

From Auto Control of Vessels Designed for Offshore Conditions to Auto Control of Large Barge Convoys in a River/Canal – Lessons Learned

Anselmo Pontes,
Symmetry, Ltda

Edson Mesquita dos Santos
Marinha do Brasil

FROM THE AUTOMATIC CONTROL OF VESSELS DESIGNED FOR OFFSHORE OPERATING CONDITIONS TO THE AUTOMATIC CONTROL OF LARGE BARGE CONVOYS IN A RIVER/CANAL: LESSONS LEARNED

Anselmo Carvalho Pontes[1]
Edson Mesquita dos Santos[2]

Summary

This paper presents the results obtained during the development of an automatic navigation control, positioning and maneuvering system for a large scale river convoy. The organizations that participated in this project are:

- **The Brazilian Navy** - the coordinating entity that worked through the Merchant Marine Training center (CIAGA) where the numerical simulations were preformed and the commanders trained.
- **Marin** (Maritime Research Institute Netherlands) - location where the reduced model tests and measurement of the shallow-water coefficients for were preformed.
- **IPT-SP** (Technology Research Institute) - provided support to the operational assessment of the river and the convoy, thus making it possible to improve the process for evaluating its maximum dimensions.
- **Symmetry -** the only Brazilian dynamic-positioning system developer and manufacturer. The company contributed its technology, which is 100% Brazilian, to the endeavor, thereby enabling the integration of the new control modules.

The barge convoy, specially designed to navigate the Paraná-Paraguai Rivers, can, when deployed in its largest configuration, reach a length of 305m, a width of 63 meters and a 5 meter draught. The convoy is pushed by a push boat with three azimuth propellers, specially designed for confined

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[1] Matematician – Symmetry, Ltda.

[2] Naval Engineer – Marinha do Brasil

waters. It also has a tug boat with a cycloidal Voith Schneider propeller in the bow that is responsible for changing the vessel's heading.

This study is divided into three main parts:

- Presenting the problem: the distinctive hull geometry, shallow waters, banks, water density variations, non-uniform current fields and vortexes, etc.
- Description of the adaptive control technique adopted that made use of modern and robust control techniques currently used in dynamic positioning systems in the offshore industry.
- Analysis of the applicability of these new technological resources as part of a new solution, to enable transportation/shipping in Brazil's rivers and channels, as well as to provide feedback for new applications in the offshore sector.

Two basic lessons are explored:

- The system must be equipped with a control module that can take advantage of the captain's ship handling ability. The actions of a well trained captain can minimize precious operation time.
- The remote radio control of an unmanned tug boat can optimize costs and increase safety and could eventually be employed to solve other offshore operation problems.

Abstract

The waterway transportation sector, despite its problems and bottlenecks, is continually seeking alternatives to improve its operations. With goals of increased efficiency, safety and cost reduction, the sector is modernizing and acquiring new technology. The Dynamic Position control system for a large barge convoy is one of the new technology highlights. This innovation may make development in the Brazilian waterway transportation sector feasible by permitting navigational safety and greater flexibility in transport and distribution not only for mined products but for petroleum and its derivatives.

This paper presents the development process of The Dynamic Position control system for a large barge convoy in the Parana-Paraguay Rivers, for Rio Tinto Mining Company. The hydrodynamic effects in a river are quite different than those of the traditional offshore environment. The degree of difficulty involved in solving this problem is highly dependent on a ship's characteristics, which can be analyzed in terms of their hydrodynamic coefficients. Model tests in towing tanks were made to adjust the hydrodynamic coefficients and characteristics of the thrusters. The choice of the "Backstepping" control law and observer (state estimator) presented in this paper is a result of these

particular conditions. The authors point out the advantage of using this technique, since all the properties of the hull, propeller and thruster coefficients have already been tested and tuned and make it possible to create a reliable set-up that optimizes navigation in restricted waterways.

1. Introduction

The mathematical model that describes the movement of a vessel is essentially defined by the set of equations of the rigid body dynamics and the hydrodynamic forces that act upon them. The dynamics involved are complex. When describing the differential equation of a vessel's movement, there are terms which are highly dependent on its particularities and are evaluated through the hydrodynamic coefficients.

When developing a system to control the movement of a vessel, the need arises to find various possible solutions for different speed ranges in different types of operations. Modern control methodologies make use of non-linear control methods that permit an understanding of the complexity of the vessel's dynamics and make use of the favorable non linearity for its control. One of the techniques that stands out is called "Backstepping".

With the above considerations in mind, Symmetry developed its dynamic positioning system (IDP) using the "Backstepping" control technique, which enables it to determine a vessels position using only navigational systems that generate horizontal plane coordinates

The resistance and propulsion forces were evaluated at IPT-SP (Instituto de Pesquisas Tecnológicas de São Paulo). The hydrodynamic derivatives were validated by the Maritime Research Institute of Netherlands (Marin).

In order to better evaluate the problem and its limitations in different applications, the dynamic positioning control system was integrated into the bridge simulator at the Brazilian Navy training center - CIAGA (Centro de Instrução Almirante Graça Aranha). This integration was crucial toward evaluating the control conditions to be used in accordance with the convoy's maneuverability in the local working conditions (current, wind, shallow water, etc.), It also allowed the training process, development and equipment installation aboard the vessels to be conducted simultaneously, creating the perfect integration of the designers, builders and operators.

2. The Mathematical Model

This section presents the low velocity model of the vessel's dynamics that was used on the control project; this model describes the vessel's movement in its three primary degrees of control on the horizontal plane.

The movement equations are described using the same position reference system as the vessel and are described by:

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

Where u, v, r are the respective surge, sway and yaw speeds, $\dot{u}, \dot{v}, \dot{r}$, denote the accelerations, and x, y, ψ , the positions and heading of the vessel.

X, Y, N are the external forces:

$$\begin{aligned} X &= X_{H_{low}} + \tau_x + \tau_{env} \\ Y &= Y_{H_{low}} + \tau_y + \tau_{env} \\ N &= N_{H_{low}} + \tau_n + \tau_{env} \end{aligned} \qquad (2)$$

$X_{H_{LOW}}, Y_{H_{LOW}}, N_{H_{LOW}}$ Are the hydrodynamic forces that depend upon the vessel's movement in the water and are assumed to be a function of the ship's velocity and its acceleration, or:

$$\begin{aligned} X_{H_{LOW}} &= f_1(u, v, r, \dot{u}, \dot{v}, \dot{r},) \\ Y_{H_{LOW}} &= f_2(u, v, r, \dot{u}, \dot{v}, \dot{r},) \\ N_{H_{LOW}} &= f_3(u, v, r, \dot{u}, \dot{v}, \dot{r}) \end{aligned} \qquad (3)$$

The functional dependence of the above equations is complex. As a result, simplifications are commonly made in maneuverability studies. There is an interest in evaluating the ship's response under a given equilibrium condition, normally in a straight line and at a constant speed. Expanding these forces in a Taylor series and around an initial speed value, it is possible to select coefficients according to the hull's geometry, thereby obtaining the forces of resistance to the ship's movement, as follows:

$$
\begin{aligned}
X_{H_{LOW}} &= X_{uu_{LOW}} u^2 + X_{uvr_{LOW}} \frac{u}{|u|}|v||r| \\
Y_{H_{LOW}} &= Y_{vu_{LOW}} vu + Y_{ru_{LOW}} ru + Y_{vv_{LOW}} ru + Y_{vv_{LOW}} v|v| + Y_{rr_{LOW}} r|r| \qquad (4) \\
N_{H_{LOW}} &= N_{vu_{LOW}} vu + N_{ru_{LOW}} ru + N_{v|v|_{LOW}} v|v| + N_{rr_{LOW}} r|r|
\end{aligned}
$$

τ_x, τ_y, τ_n, are the forces and momenta given by the vessel control system, for example, propellers, rudders and impellers.

The control system developed has internal routines for the propellers, rudders and impellers. The model of propeller forces is initially based upon the Kt, Kq – J diagram divided into four quadrates (speed of the ship x rotation of the propeller). The propulsion forces are defined as a function of the vessel's instantaneous speed (*u*) and the rotation of the propeller (*n*), through:

$$
\begin{aligned}
X_{PROP} &= c_p 1 * u^2 + c_p 2 * u * n + c_p 3 * n^2 \\
Y_{PROP} &= b_p 1 * u^2 + b_p 2 * u * n + b_p 3 * n^2 \qquad (5) \\
N_{PROP} &= a_p 1 * u^2 + a_p 2 * u * n + a_p 3 * n^2
\end{aligned}
$$

The rudder forces are included by the means of the data obtained from experimental results, short wing theory and the effects of the interference with the propellers. The rudder forces are a function of the instantaneous position of the rudder angle, vessel speed and propeller rotation, through:

$$
\begin{aligned}
X_{RUD} &= [c_1 * u^2 + c_2 * u * n + c_3 * n^2] * \delta^2 \\
Y_{RUD} &= [b_1 * u^2 + b_2 u * n + b_3 n^2]\delta + [b_4 * u^2 + b_5 u * n + b_6 n^2]\delta^3 \qquad (6) \\
N_{RUD} &= [a_1 * u^2 + a_2 u * n + a_3 n^2]\delta + [a_4 * u^2 + a_5 u * n + a_6 n^2]\delta^3
\end{aligned}
$$

τ_{env} Are the forces and momenta that act on the hull due to environmental disturbances such as wind, currents and waves.

3. The Observer

The idea of the state observers is to reproduce in the mathematical model (virtually) a state that accurately reflects the reality. There are some differences between the real output and the model output, this error is fed back into the mathematical model to correct the difference and bring the mathematical model closer to the reality.
The technique of the state observer consists in developing a model for the system under analysis and comparing the estimated outputs with the measured ones. The estimate between the two present signals results in a difference that is used for analysis. A state observer should also reconstruct the system's non-measured states, provided they are observable.

The observer chosen was constructed on the basis of the Lyapunov Stability Theory. The mathematical model was based on the vessel model developed for the simulator, and the observer equations were chosen so as to emulate the vessel's dynamics and include gains for the position error estimation filter.

The main reason this observer was selected was the fact that it wouldn't be necessary to "learn" to identify the vessel, the dynamic positioning system (IDP) explores the vessel's dynamics, few calibration parameters are needed and it is adaptive and can be used in directionally stable and unstable vessels [2].

The observer was constructed by means of the following equation:

$$\begin{aligned}
\dot{\hat{x}} &= \hat{u}\cos(\psi) - \hat{v}\sin(\psi) + k_1\tilde{x} + k_2\tilde{y} + k_3\tilde{\psi} \\
\dot{\hat{y}} &= \hat{u}\sin(\psi) + \hat{v}\cos(\psi) + k_4\tilde{x} + k_5\tilde{y} + k_6\tilde{\psi} \\
\dot{\hat{\psi}} &= \hat{r} + k_7\tilde{x} + k_8\tilde{y} + k_9\tilde{\psi} \\
\dot{\hat{u}} &= -a_1\hat{x} - a_2\hat{u} + b_1\tau_1 + k_{10}\tilde{x} + k_{11}\tilde{y} + k_{12}\tilde{\psi} \\
\dot{\hat{v}} &= -a_3\hat{y} - a_4\hat{v} - a_5\hat{r} + b_2\tau_2 + b_3\tau_3 + k_{13}\tilde{x} + k_{14}\tilde{y} + k_{15}\tilde{\psi} \\
\dot{\hat{r}} &= -a_6\hat{y} - a_7\hat{v} - a_8\hat{r} + b_2\tau_2 + b_3\tau_3 + k_{16}\tilde{x} + k_{17}\tilde{y} + k_{18}\tilde{\psi}
\end{aligned} \qquad (7)$$

$\dot{\hat{u}}, \dot{\hat{v}}, \dot{\hat{r}}, \hat{u}, \hat{v}, \hat{r}, \hat{x}, \hat{v}, \hat{\psi}$, are the state variables.

$\tilde{x}, \tilde{y}, \tilde{\psi}$, are the position estimate errors.

$k_1, k_2, \ldots k_9$, are the arbitrary gains.

$k_{10}, k_{11}, \ldots k_{18}$, are the gains calculated in accordance with of the KYP-Kalmann-Yakubovich-Popov theory [3].

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4. The Controller

When developing a controller, attention is given to defining the forces to be supplied by the actuators so as to guarantee that the vessel will accompany or maintain itself at the desired status variables. The concept of "Backstepping" control consists in choosing one of the state variables as a virtual control; the selection is performed during the calculation process of the state observer variables. The desired state variables are established according to the dynamic maneuverability limitations of the vessel and the geometric restrictions of the trajectory to be followed.

The following control law was used:

$$\begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix} = -S^{-1} \begin{bmatrix} c_2 z_2 + \phi_2 + d_2(\omega_{21}^2 + \omega_{22}^2 + \omega_{23}^2 + \omega_{26}^2) z_2 + z_1 \\ c_4 z_4 + \phi_4 + d_4(\omega_{41}^2 + \omega_{42}^2 + \omega_{43}^2 + \omega_{46}^2) z_4 + z_3 \\ c_6 z_6 + \phi_6 + d_6(\omega_{61}^2 + \omega_{62}^2 + \omega_{63}^2) z_6 + z_5 \end{bmatrix} \qquad (8)$$

Where:

$$S = \begin{bmatrix} b_1 \cos\psi & -b_2 \sin\psi & -b_3 \sin\psi \\ b_1 \sin\psi & b_2 \cos\psi & b_3 \cos\psi \\ 0 & b_4 & b_5 \end{bmatrix}$$

5. The Equipment

The dynamic positioning system used in this job was the IDP, developed and produced in Brazil by Symmetry, Ltda.

To make this method of river navigation possible, Symmetry developed and supplied a solution consisting of:

- Customized IDP for river navigation.
- VMS (Vessel Management System) integrated with the IDP.
- Telemetry system via radio for remote control and alarm monitoring.
- Remote video system via radio
- Simulator for training and tests
- Instrumentation of a conventional convoy for comparative tests.

6. Construction, Installation and results

The construction and remodeling of the push boat began in Louisiana, USA. However, due to hurricane Katrina in 2005, the work schedule was delayed and the construction was transferred to Argentina. After a year, the construction ended and the boats were towed to Asunción, Paraguay, where the commissioning took place.

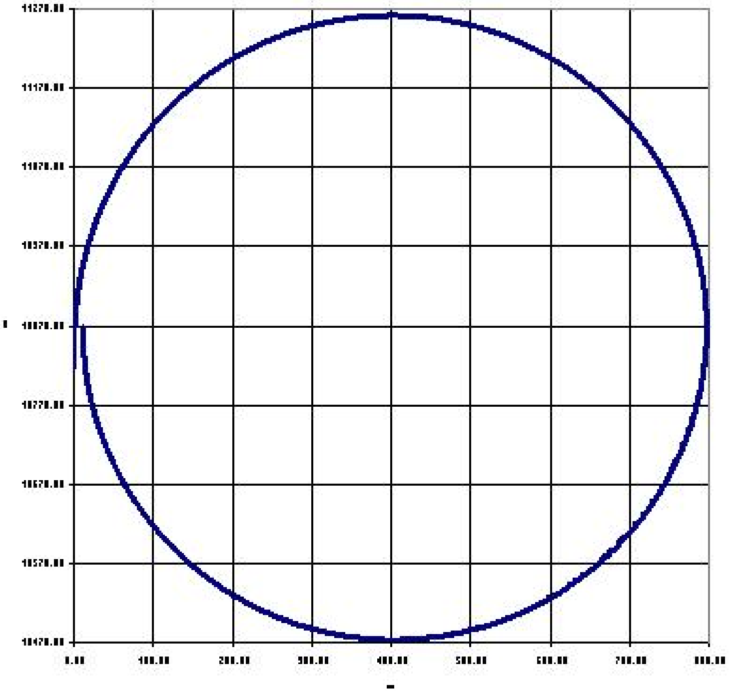
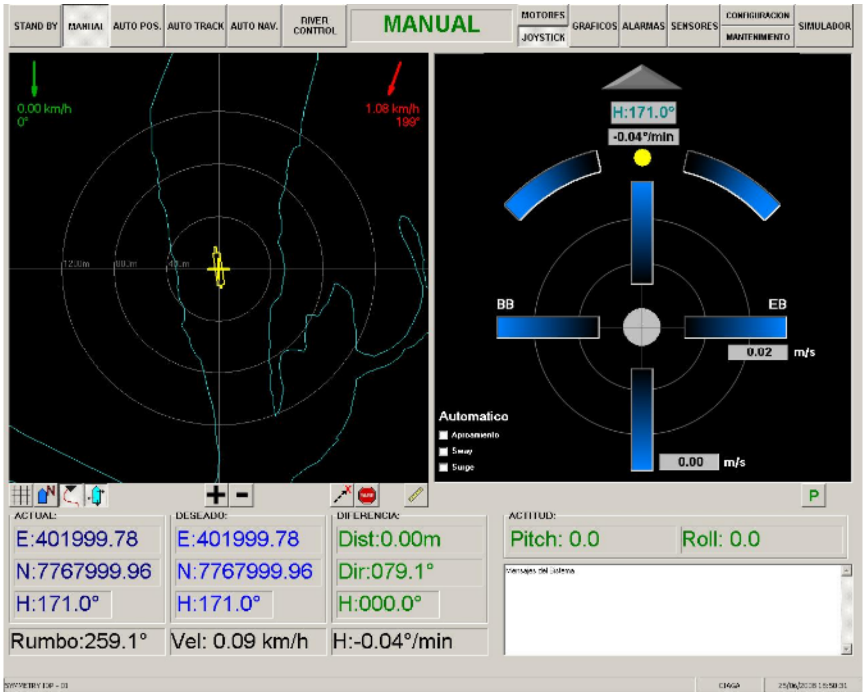


Figure 1. Rotating curve of 30 barges, 5 meters draught using BSM



ACTUAL:

E:401999.78

N:7767999.96

H:171.0°

DESEADO:

E:401999.78

N:7767999.96

H:171.0°

DIFERENCIA:

Dist:0.00m

Dir:079.1°

H:000.0°

ACTITUD:

Pitch: 0.0

Roll: 0.0

Rumbo:259.1°

Vel: 0.09 km/h

H:-0.04°/min

0.02 m/s

0.00 m/s

Figure 2. IDP operating screen

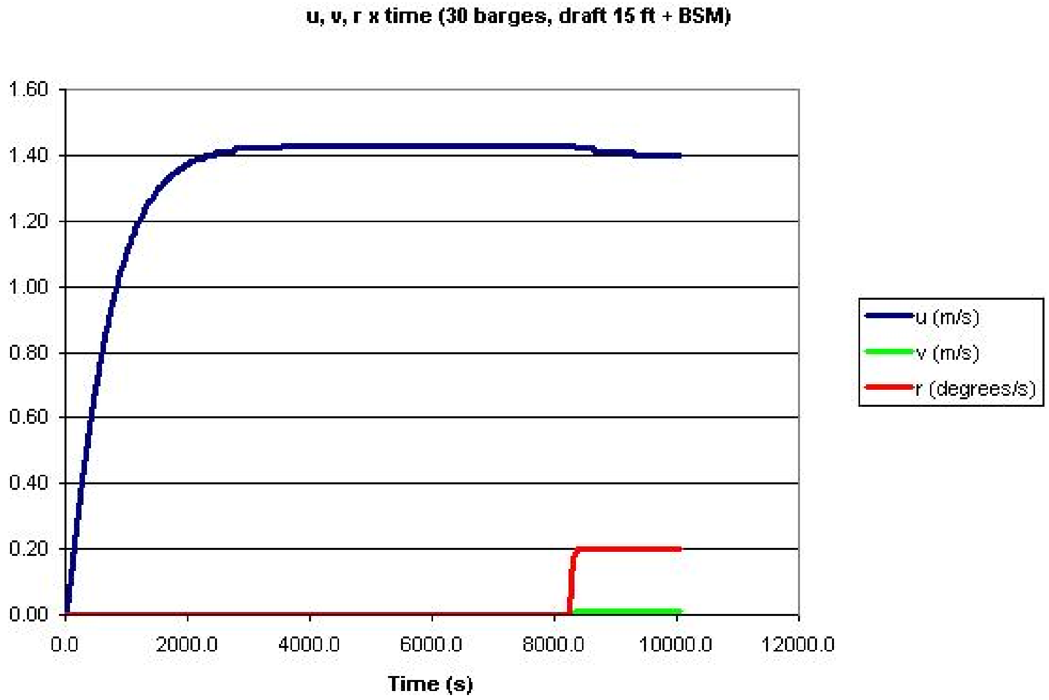


Figure 3. u,v, r curve vs. Time

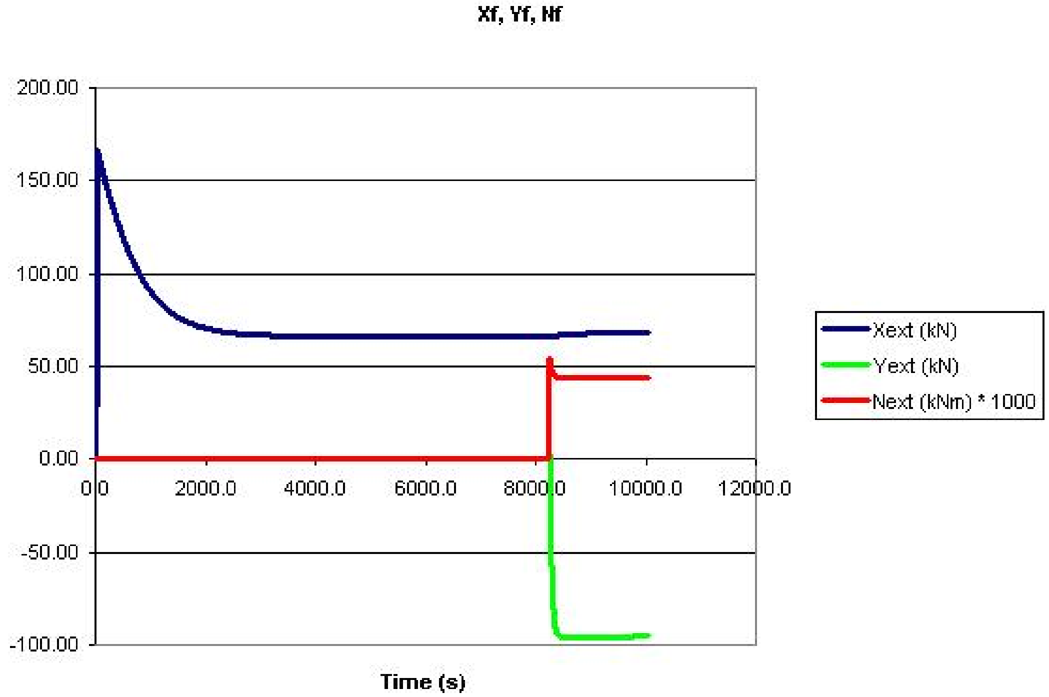


Figure 4. Longitudinal (Xf), transversal (Yf) forces and momentum (Nf) of 30 barges.

7. Conclusion

The waterway transportation sector, despite its problems and bottlenecks, is continually seeking alternatives to improve its operations. In the aim of increasing efficiency, safety and reducing costs, the sector is modernizing and acquiring new technology. The Dynamic Position control system for large barge convoys is one of the highlights of the new technology. This innovation may make development in the Brazilian waterway transportation sector feasible, as it allows for navigational safety and greater flexibility in transport and distribution not only for mined products but for petroleum and its derivatives as well.

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