MODELING, SIMULATION AND FEEDBACK LINEARIZATION CONTROL OF NONLINEAR SURFACE VESSELS

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Abstract: Realistic models and robust control are vital to reach a sufficient fidelity in military simulation projects including surface vessels. In this study, a nonlinear model including sea-state modelling is obtained and feedback linearization control is implemented in this model. To control the system, nonlinear analysis techniques are used. The model is integrated into a commercial framework based CGF application within a high-fidelity military training simulation.The simulation results are presented at the end of the study.

1 INTRODUCTION

The aim of this study is to observe the dynamic behaviors of the surface vessels under the effect of hydrodynamic force-moments and environmental conditions such as waves, current, wind, season that pertaining to the tactical environment.

The analysis and control of nonlinear motion model of surface vessels are obtained by using following techniques:

- Linearization by Taylor Series
- Phase Plane Analysis
  - o Course Keeping
  - o Zig Zag Maneuver
- Lyapunov Stability Theorem
- Feedback Linearization

Ship dynamics model and disturbance model are introduced in Section 2; the phase plane analysis and lyapunov stability therom in Section 3 and 4, the proposed controller is discussed in Section 5; simulation results are presented in Section 6.

2 THE SURFACE PLATFORM MOTION MODULE

2.1 Coordinate System and Vector Notation

The motion of surface vessels has 6 degrees of freedom. The description and notation of each degree of freedom has been shown on Table 1.

Table 1: DoF Description and Notation.

DOF	Description	Axis	Forces and moments	Linear and angular veloc.	Positions and Euler angles
1	Surge	x	X	u	x
2	Sway	y	Y	v	y
3	Heave	z	Z	w	z
4	Roll	x	K	p	ϕ
5	Pitch	y	M	q	θ
6	Yaw	z	N	r	ψ

SNAME's (1950) notation is used in this study. The first three parameters and time derivatives that are shown on Table define the position and the motion of the platform in x-, y-, z- axes. Last three parameters define the orientation and rotary motion of the platform. After analyzing 6 degrees of freedom motion of surface vessel, it is observed that 2 axis systems are needed to perform the motion. Therefore, North – East- Down (NED), is the local geodetic coordinate system fixed to the Earth, and Body Fixed, is fixed to the hull of ship, coordinate frames are used. Motion axis system X_0 Y_0 Z_0 has been fixed to the platform and called as Body Fixed axes system. The point O, which is the origin of this axes system, is always selected as the ship's centre of gravity. (Figure 1)

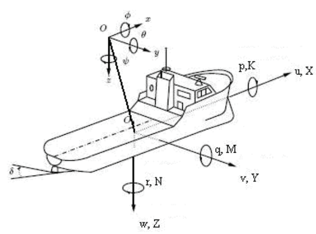

Figure 1: Coordinate System.

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2.2 Surface Platform Motion Equations

Fossen (1991), by inspiring Craig's (1989) robot model, contrary to classical representation, modeled 6 degrees of freedom motion of the surface vessel vectorially.

$$\dot{\boldsymbol{\eta}} = J(\boldsymbol{\eta})\boldsymbol{\upsilon}$$

$$M\dot{\boldsymbol{\upsilon}} + C(\boldsymbol{\upsilon})\boldsymbol{\upsilon} + D(\boldsymbol{\upsilon})\boldsymbol{\upsilon} + \mathbf{g}(\boldsymbol{\eta}) = \boldsymbol{\tau} + g_0 + w$$

Above; M is the moment of inertia including added mass, C(υ) is Coriolis matrix, D(υ) is damping matrix, g(η) is gravitational force vector and τ is the vector showing the force and moments of the propulsion system that causes motion. This representation will be used in this study.

2.2.1 Motion Equations

Representing the motion equations in the Cartesian system of coordinates (body-fixed reference frame) and defining x_G, y_G and z_G as the position of the ship's CG, the well known motion equations of a rigid body are giving by the following (Fossen, 1991):

Surge:

$$X = m[\dot{u} + qw - rv + x_G(q^2 + r^2) + y_G(pq - \dot{r}) + z_G(rp + \dot{q})]$$

Sway:

$$Y = m[\dot{v} + ru - pw - y_G(r^2 + p^2) + z_G(qr - \dot{p}) + x_G(qp + \dot{r})]$$

Heave:

$$Z = m[\dot{w} + pv - qu - z_G(p^2 + q^2) + x_G(rp - \dot{q}) + y_G(rq + \dot{p})]$$

Roll :

$$K = I_X\dot{p} + (I_Z - I_y)qr + m[y_G(\dot{w} + pv - qu) - z_G(\dot{u} + ru - pw)]$$

Pitch:

$$M = I_y\dot{q} + (I_x - I_Z)rp + m[z_G(\dot{u} + qw - rv) - x_G(\dot{w} + pv - qu)]$$

Yaw:

$$N = I_Z\dot{r} + (I_y - I_x)pq + m[x_G(\dot{v} + ru - pw) - y_G(\dot{u} + qw - rv)]$$

2.2.2 Simplifying Assumptions

Simplifying assumptions used in this study are following:

- The rotational velocity and acceleration about the y-axis are zero (q, = 0).
- The translational velocity and acceleration in the z direction are zero. (w, = 0).
- The vertical heave and pitch motions are decoupled from the horizontal plane motions.
- The vertical centre of gravity, (VCG), is on the centerline and symmetrical (yG=0)

2.2.3 Simplified Motion Equations

Applying simplifying assumptions to the general motion equations, the following simplified equations of motion are obtained

Surge: $$X = m[\dot{u} - rv - x_G r^2 + z_G rp] \quad (1)$$

Sway: $$Y = m[\dot{v} + ru - z_G\dot{p} + x_G\dot{r}] \quad (2)$$

Roll: $$K = I_X\dot{p} - mz_G(\dot{u} + ru)] \quad (3)$$

Yaw: $$N = I_Z\dot{r} + mx_G(\dot{v} + ru) \quad (4)$$

2.2.4 Force and Moments Acting on Surface Vessel

Basically force and moments acting on surface vessel can be divided to four as; hydrodynamics force and moments, external (environmental) loads, control surface forces (rudder, fin..) and propulsion (propeller) forces. Force and moments can be expressed according to axis system;

Surge: $X = X_H + X_R + X_E + T$

Sway: $Y = Y_H + Y_R + Y_E$

Roll: $K = K_H + K_R + K_E$

Yaw: $N = N_H + N_R + N_E$

Description of indices is; H, Hydrodynamic force and moments originating from fluid-structure interaction, R , forces that affects control surface are, E, environmental external loads (Wave, current, wind), T, propulsion force.

Hydrodynamic Forces and Moments

Integration of the water pressure along the wetted area of the surface vessel causes hydrodynamic force and moments within the platform. These force and moments can be defined, with the velocity and acceleration terms as a nonlinear axes system, by using Abkowitz method.

Most important step on developing maneuver model is expanding force and moment terms in Taylor's series. This way, nonlinear terms act as independent variables and form a polynomial equation. The function and its derivatives have to be continuous and finite in the region of values of the variables to use the Taylor's expansion. Certainty of the model alters depending on where the expansion is finished.

Force and moments, which were obtained by expanding Taylor series until third power, are under mentioned (Abkowitz, 1969; Sicuro, 2003)

$$X_{hid} = X_{\dot{u}}(\dot{u}) + X_{vr}vr + X_{uu}v^2 \quad (5)$$

$$\begin{aligned} Y_{hid} &= Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_{\dot{p}}\dot{p} + Y_{\phi|uv|}\phi|uv| + Y_{\phi|ur|}\phi|ur| \\ &+ Y_{\phi|uu|}\phi|uu| + Y_{|u|v}|u|v + Y_{ur}ur + Y_{v|v|}v|v| \\ &+ Y_{v|r|}v|r| + Y_{r|v|}r|v| \end{aligned} \quad (6)$$

$$
\begin{aligned}
K_{hid} = & K_{\dot{v}}\dot{v} + K_{\dot{p}}\dot{p} + K_{|u|v}|u|v + K_{ur}ur + K_{v|v|}v|v| \\
& + K_{v|r|}v|r| + K_{r|v|}r|v| + K_{|uv|\phi}|uv|\phi \\
& + K_{|ur|\phi}|ur|\phi + K_{uu\phi}uu\phi + K_{|u|p}|u|p \\
& + K_{|p|p}|p|p + K_p p + K_{\phi\phi\phi}\phi\phi\phi - \Delta G_z(\phi)
\end{aligned} \tag{7}
$$

Obtaining Hydrodynamic Derivatives

In order to obtain hydrodynamic derivatives three basic methods can be used.

- By means of basin test using the realistic model
- By using CFD (Computational Fluid Dynamics) software
- By using empirical formulae

In this study third method was used. Hydrodynamic derivatives have been used by the empirical formulae of the source Inoue et al. (1981). To have an opinion about validity and fidelity of the empirical formulae, parameters of a merchant ship that was chosen from literature was used. By using these parameters and related formulae hydrodynamic derivatives were calculated and compared with the equivalent in the literature.(Table 2)

Table 2: Comparing the hydrodynamic derivatives obtained from the model data and empirical formulae.

	Model (Son and Nomoto, 1982)	Emprical Formulas (Inoue et. al, 1981)
Yv	-0.0116	-0.0118
Nv	-0.0038	-0.0041
Yr	0.0024	0.0022
Nr	-0.0022	-0.0020
Yrvv	0.0214	0.0216
Nrvv	-0.0424	-0.0427
Yrrv	-0.0405	-0.0426
Nrrv	0.0016	0.0017

The Environmental Disturbances

The environmental disturbances acting on the surface vessels can be grouped into two main categories; the wave model, the current and wind models.

The Wave Model

When real data regarding the complicated seas lacks, idealized mathematical spectrum functions are generally used for marine calculations. One of the easiest and commonly used of these calculations is the Pierson – Moskowitz spectrum where a wave spectrum formula is provided for winds blowing over an infinite area and at a constant speed for over a sea of full state. In this study this spectrum is used while a wave model is created.(Berteaux, 1976)

This spectrum is expressed as follows due to the wave frequency and wind speed.

$$
S_{\xi} = \frac{0.0081 g^2}{\omega^5} \exp\left[-0.74\left(\frac{g}{V\omega}\right)^4\right] \tag{8}
$$

where, ω : Wave Frequency [rad/sec], V: Wind Speed (at 19,5 m above sea) [m/s]

The Current and Wind Models

Typically wind models only treat the force and moments that are directly related to surge, sway and yaw motions. In this study, the wind model is obtained by using Isherwood Method.(Isherwood 1972)

Wind forces and moments acting on a surface platform are usually defined in terms of relative wind speed V_R (knots) and relative angle γ_R (deg). The wind forces for surge and sway and the wind moment for yaw as is shown.

$$
X_{wr} = \frac{1}{2} C_X(\gamma_R)\rho_w V_R^2 A_T \tag{9}
$$

$$
Y_{wr} = \frac{1}{2} C_Y(\gamma_R)\rho_w V_R^2 A_L \tag{10}
$$

$$
N_{wr} = \frac{1}{2} C_N(\gamma_R)\rho_w V_R^2 A_L L \tag{11}
$$

where C_X, C_Y and C_N are the force and moment coefficients, ρw is the density of the air, AT and AL are the transverse and lateral projected areas and L is the overall length of the ship. (Isherwood, 1972). The equations of current forces and moments are similar with wind forces and moments.

2.3 Nonlinear Equations of Motion

When the simplified 4 degrees of freedom motion model, which was obtained in previous section, was associated with hydrodynamic forces and environmental external loads a nonlinear maneuver model can be obtained. To behave like independent variables and become coefficients of a polynomial motion equation, hydrodynamic derivatives are derived by another software that makes use of ship geometry. As well, terms of ship motion equations are normalized relative to the ship velocity. (Fossen, 1991)

$$
\begin{aligned}
X' = & X'(u') + (1-t)T'(J) + X'_{vr}v'r' + X'_{vv}v'^2 \\
& + X'_{rr}r'^2 + X'_{\phi\phi}\phi'^2 + c_{RX}F'_N \sin\delta'
\end{aligned} \tag{12}
$$

$$
\begin{aligned}
Y' = & Y'_v v' + Y'_r r' + Y'_p p' + Y'_\phi \phi' + Y'_{vvv}v'^3 + Y'_{rrr}r'^3 \\
& + Y'_{vvr}v'^2 r' + Y'_{vrr}v'r'^2 + Y'_{vv\phi}v'^2\phi' + Y'_{v\phi\phi}v'\phi'^2 \\
& + Y'_{rr\phi}r'^2\phi' + Y'_{r\phi\phi}r'\phi'^2 + (1+a_H)F'_N \cos\delta'
\end{aligned} \tag{13}
$$

$$
\begin{aligned}
K' = & K'_v v' + K'_r r' + K'_p p' + K'_\phi \phi' + K'_{vvv}v'^3 + K'_{rrr}r'^3 \\
& + K'_{vvr}v'^2 r' + K'_{vrr}v'r'^2 + K'_{vv\phi}v'^2\phi' + K'_{v\phi\phi}v'\phi'^2 \\
& + K'_{rr\phi}r'^2\phi' + K'_{r\phi\phi}r'\phi'^2 - (1+a_H)z'_R F'_N \cos\delta'
\end{aligned} \tag{14}
$$

$$\begin{aligned} N' &= N'_v v' + N'_r r' + N'_p p' + N'_\phi \phi' + N'_{vvv} v'^3 + N'_{rrr} r'^3 \\ &+ N'_{vvr} v'^2 r' + N'_{vrr} v' r'^2 + N'_{vv\phi} v'^2 \phi' + N'_{v\phi\phi} v' \phi'^2 \\ &+ N'_{rr\phi} r'^2 \phi' + N'_{r\phi\phi} r' \phi'^2 + (x'_R + a_H x'_H) F'_N \cos\delta' \end{aligned} \tag{15}$$

3 PHASE PLANE ANALYSIS

3.1 Phase Portrait of Course Keeping

Phase portraits of surface platform are shown. Yaw angle (psi) versus its derivative yaw rate (r) in Figure 2 and Roll angle versus roll rate in Figure 3 are used to obtain the phase portraits. If the real part of the eigenvalues is positive, then x(t) and x(t) both diverge to infinity, and the singularity point is called an unstable focus.

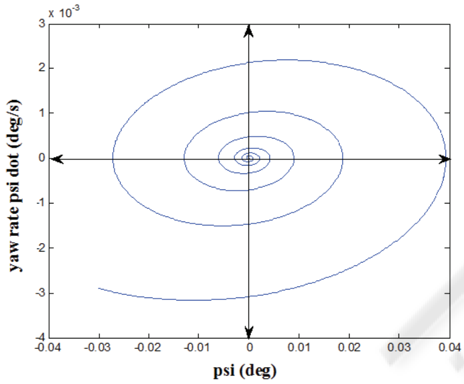

Figure 2: The Phase Portrait (Yaw vs Yaw rate).

The phase portrait in Figure 3 demonstrates that the unstable free motion of the surface platform.

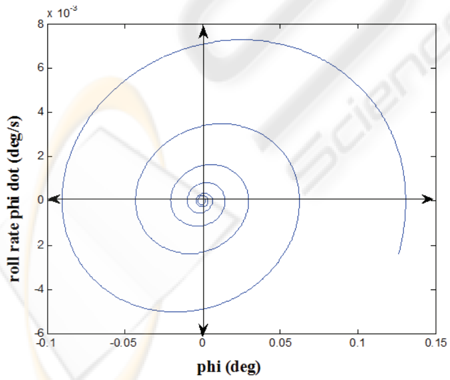

Figure 3: The Phase Portrait(Roll angle vs Roll rate).

3.2 Phase Portrait of Zig Zag Maneuver

It is intended that the surface platform makes zig-zag maneuvers of 45° with a velocity of 8 m/s with 20° rudder angle. For a zig-zag maneuver, when the angular acceleration plotted is against angular velocity it shows how non-linear ship response can be (Figure 4).

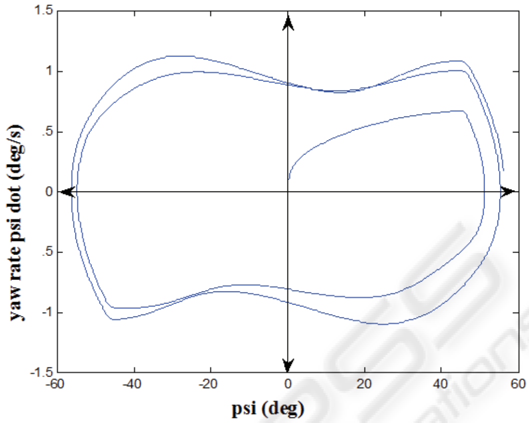

Figure 4: Phase Portrait of Zig Zag Maneuver.

4 LYAPUNOV STABILITY THEOREM FOR SURFACE PLATFORM DYNAMIC

A fully actuated surface platform can be described by

$$M\dot{\boldsymbol{\upsilon}} + C(\boldsymbol{\upsilon})\boldsymbol{\upsilon} + D(\boldsymbol{\upsilon})\boldsymbol{\upsilon} + \mathbf{g}(\boldsymbol{\eta}) = Bu = \boldsymbol{\tau}$$
$$\dot{\boldsymbol{\eta}} = J(\boldsymbol{\eta})\boldsymbol{\upsilon}$$

where J(η) is singular for θ = ±90 degrees (Euler angles), M= M^T>0 and D(v) = D^T(v) > 0. The position is controlled by

$$u = B^T (BB^T)^{-1}\left[g(\eta) - J^T(\eta) K_P \eta\right]$$

where Kp = K^Tp > 0. Let $V = \frac{1}{2}\left(\upsilon^T M \upsilon + \eta^T K_P \eta\right)$

be a Lyapunov function candidate for the closed-loop system (4.1), (4.2) and (4.3). We take the time derivative of the Lyapunov function candidate to obtain

$$\begin{aligned} \dot{V} &= \upsilon^T \left(M\dot{\upsilon} + J^T(\eta) K_P \eta\right) \\ &= \upsilon^T \left(Bu - C(\upsilon)\upsilon - D(\upsilon)\upsilon - g(\eta) + J^T(\eta) K_P \eta\right) \\ &= \upsilon^T \left(-C(\upsilon)\upsilon - D(\upsilon)\upsilon\right) \\ &= -\upsilon^T D(\upsilon)\upsilon \end{aligned}$$

which is ***negative semidefinite***. Asymptotic stability can then be established by applying LaSalle's invariance principle, but the equilibrium point (η, ν)=(0, 0) is only ***locally asymptotically stable*** since J(η) is singular for θ = ±90 degrees.

5 FEEDBACK LINEARIZATION

The basic idea with feedback linearization is to transform the nonlinear systems dynamics into a linear system (Freund (1973). Conventional control techniques like pole placement and linear quadratic optimal control theory can then be applied to the linear system. Feedback linearization allows us to design the controller directly based on a nonlinear dynamic model that better describes a ship maneuvering behavior. Consider Norrbin's nonlinear ship steering equations of motion in the form (Fossen 1992):

$$m\ddot{\psi} + d_1\dot{\psi} + d_3\dot{\psi}^3 = \delta \qquad (16)$$

here m = T/K, d_1 = n_1/K and d_3 = n_3/K. Taking the control law to be:

$$\delta = \hat{m}a_{\psi} + \hat{d}_1\dot{\psi} + \hat{d}_3\dot{\psi}^3 \qquad (17)$$

where the hat denotes the estimates of the parameters and a, can be interpreted as the commanded acceleration, yields:

$$m(\ddot{\psi} - a_{\psi}) = \tilde{m}a_{\psi} + \tilde{d}_1\dot{\psi} + \tilde{d}_3\dot{\psi}^3 \qquad (18)$$

Here $\tilde{m} = \hat{m} - m$, $\tilde{d}_1 = \hat{d}_1 - d_1$ and $\tilde{d}_3 = \hat{d}_3 - d_3$ are the parameter errors. Consequently, the error dynamics can be made globally asymptotically stable by proper choices of the commanded acceleration a_ψ. (Fossen 1992) In the case of no parametric uncertainties, equation (18) reduces to: $\ddot{\psi} = a_{\psi}$ which suggests that the commanded acceleration should be chosen as:

$$a_{\psi} = \ddot{\psi}_d - K_d\dot{\tilde{\psi}} - K_p\tilde{\psi} \qquad (19)$$

where ψ_d is the desired heading angle and $\tilde{\psi} = \psi - \psi_d$ is the heading error. This in turn yields the error dynamics:

$$\ddot{\tilde{\psi}} + K_d\dot{\tilde{\psi}} + K_p\tilde{\psi} = 0 \qquad (20)$$

The block diagram of the control system is shown in Figure 5.

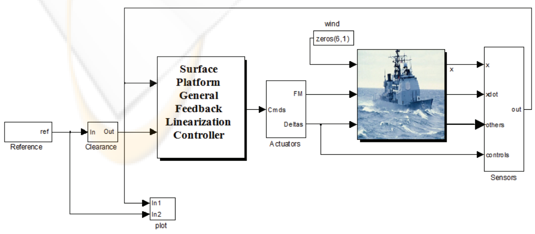

Figure 5: Block Diagram of System.

6 EXPERIMENTAL RESULTS

The crucial parameters of the surface platform chosen for the illustration have been displayed in Table 3.

Table 3: The main parameters of the surface platform.

Description		Value	Description	Value
Total Length		171 m	Volume	12000 m^3
Total Width		20.4 m	Height	12 m
Draft	Front	5.9 m	Block Coefficient	0.559
	Rear	5.7 m	Area of Rudder	28 m^2
	Middle	5.8 m	Beam/Length Ratio	1.8219

In the sample application, it is intended that the surface platform makes zig-zag maneuvers of 45° with a velocity of 8 m/s. The route information regarding this task is inputted by the VR-Forces graphical user interface (Figure 6).The results below have been produced after running the simulation for 800 seconds.

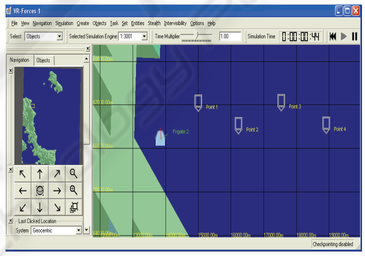

Figure 6: The route defined for the platform.

In this application, which is known as the zig zag test of Kempf in the literature (Kempf, 1932), the initial speed of the platform has been given as 0. The platform is ordered to move to the specified waypoints one by one by increasing its velocity up to 8 m/s. It takes the platform 96 seconds to reach to the first point. The first loop is accomplished in approximately 295 seconds. The results are acceptable for the motion behaviors that are supposed to be realized by a large platform and satisfactory in terms of simulation.

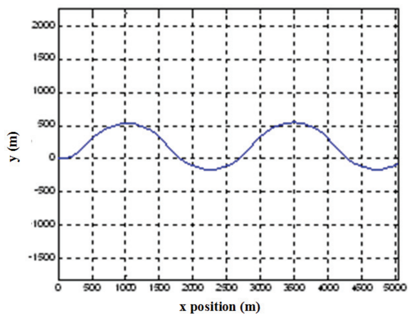

Figure 7: (a) Change of location.

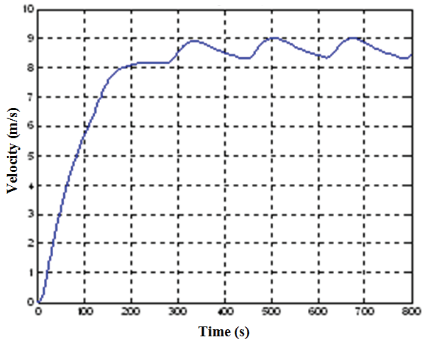

Figure 7: (b) Change of velocity.

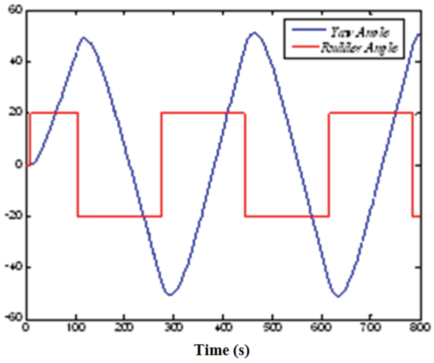

Figure 8: Changes in the yaw angle and rudder angle of the surface platform.

Controller performance can tried by some different route applications:

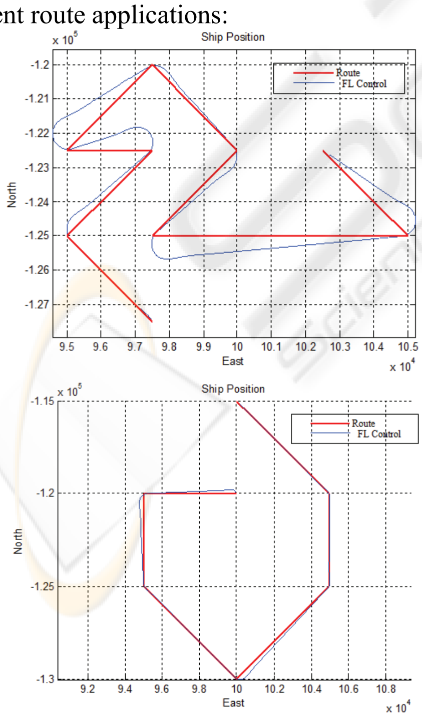

Figure 9: Controller performance in different routes.

7 CONCLUSIONS

In this study, feedback linearization control has been implemented in a nonlinear surface vessel model including sea-state modeling (wave, current, wind). The performance of the maneuver controller has been illustrated through a simulation study. The results are acceptable and satisfy for the needs of military simulation. Although we have designed our control to cover all influences, a more specified design can upgrade the performance in each different case. In the future work, the performance of the controller may be compared with an intelligent control technique.

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