MODELING, GUIDANCE AND CONTROL OF "ESSO OSAKA" MODEL

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Abstract: A guidance and control system is introduced and applied to ship path following using two controls. The guidance system is derived through a waypoint guidance scheme based on line-of-sight projection algorithm and speed is controlled by a state feedback controller. An approach concerning the calculation of a dynamic line-of-sight vector norm is presented and the results are compared with the traditional line-of-sight scheme. It is intended that the complete system will be implemented in a scale model of the "Esso Osaka" tanker. The results of simulations are presented here showing the effectiveness of the system.

Keywords: Path following, Ship control systems, Guidance system, Model ship.

1. INTRODUCTION

The motivation for the development of the work presented here is the need to develop a control system to steer an autonomous vessel along reference trajectories defined in a given reference frame. Systems for way-point guidance consist of a way-point generator with human interface. One solution to design this type of system is to store the selected way-points in a way-point database and use them to generate a trajectory (path) for the ship. Other systems can be linked to this way-point guidance system as the case of weather routing, collision and obstacle avoidance, mission planning, etc. (Fossen, 2002). With the rapid advances in computer signal processing technology, modern control theory, accurate positioning and navigation systems, there is a growing interest in the development of intelligent ship guidance and control systems which automates the procedure of determining the course, attitude and speed to be followed by the vehicle, and the associated control law for operating the ship to perform the task commanded by the guidance system (Harris *et al.*, 1999).

The objective of the development of a trajectory tracking control system is to track the position and velocity of the vessel to a desired time-varying position and velocity reference signals. Traditionally, trajectory tracking control systems for autonomous vehicles are functionally divided into three subsystems that must be implemented on board the platforms: Guidance, Navigation and Control (Fossen, 2002). One approach is to use a conventional autopilot, controlling the heading ψ using yaw moment control, and to combine this with a Line-of-Sight (LOS) algorithm. However, it is important to minimize the cross-track error, i.e., the shortest distance between the ship and the straight line (Pettersen and Lefeber, 2001).

Trajectory tracking control based on LOS for marine surface vessels has been adopted by Fossen *et al.* (2003) in which a 3 DOF (surge, sway, and yaw) nonlinear controller for path following of marine craft is derived using only two controls. In this case the path following is achieved by a geometric assignment based on a LOS projection algorithm for minimization of the cross-track error to the path and the desired speed along the path can be specified independently. Breivik and Fossen (2004) presents a guidance-based approach whose main idea is to explicitly control the velocity vector of the vehicles in such a way that they converge to and follow the desired geometrical paths in a natural and elegant manner.

In this paper a practical guidance and control system is introduced for the path following of the model of the tanker “Esso Osaka”. The paper main contribution is the vessel maneuvering design based on a waypoint guidance algorithm by LOS (Healey and Lienard, 1993), which is used to compute the desired heading angle. A different approach concerning the calculation of a dynamic LOS vector norm is presented in order to improve the convergence of the LOS algorithm. Also, a tracking controller including a feedforward term and speed controller obtained through state feedback linearization are developed.

To avoid large bumps in the computed desired heading angle and speed and to provide the necessary derivatives to the respective controllers, the commanded LOS heading and vessel speed are fed through 3rd and 2nd order reference models, respectively. A PID heading controller is derived and its gains are obtained after linearization of the non-linear maneuvering mathematical model of “Esso Osaka” in a 2 DOF (sway-yaw) linear maneuvering model. The linearized model is used for the purpose of identification of the heading controller parameters. A feedforward term to achieve accurate and rapid course-changing maneuvers is also added to the controller. A speed controller is designed through state feedback linearization.

2. MANEUVERING MODEL OF “ESSO OSAKA”

For the simulation and verification of the guidance and control designs, a good mathematical model of the ship is required to generate typical input/output data. The model of the “Esso Osaka” was chosen because this tanker hull has been studied in detail in various comparative studies by different authors and detailed information is available on its maneuvering model. The dynamics of the “Esso Osaka” tanker is described by a model based on the horizontal motion with the motion variables of surge, sway and yaw (Abkowitz, 1980). The model was scaled 1:100 (k = 100) from the real “Esso Osaka” ship. The form of the simulation equations given in this section is the one presented in Abkowitz (1980), where δ is the rudder deflection; m is the ship’s mass; I_z is the yaw moment of inertia; x_G is the location of the center of gravity relative to midship; Δu is the change in forward speed (negative Δu is a speed loss); X, Y and N with subscripts u, v, r and δ are the hydrodynamic coefficients, such as N_v.

Realism calls for accepting the possibility of wind, current and waves during the model operation. As “Esso Osaka” has relatively little abovewater structure, a mild to moderate wind would not cause substantial external excitation. However, even moderate currents could produce substantial external forces on the hull, especially when the current velocity becomes a reasonable fraction of the components of the model ship’s speed during the maneuver. If u_c is the current’s magnitude, α the current’s spatial direction (heading), ψ the ship’s heading angle, u the ship’s spatial forward component of velocity over the ground, and v the ship’s spatial transverse component of velocity, the forward component of relative velocity u_r and the transverse component of relative velocity v_r are given by

$$u_r = u - u_c \cos(\psi - \alpha) \tag{1}$$

$$v_r = v + u_c \sin(\psi - \alpha) \tag{2}$$

and the resulting advance speed of the vessel is given by

$$U_r = \sqrt{u_r^2 + v_r^2} \tag{3}$$

In the simulation equations, presented from (4) up to (10), the nondimensional form of the coefficients is indicated by a prime superscript, that is, $\eta_1^{'}$ is the nondimensional form of η_1, etc.. The velocities u and v with subscript r refer to the relative velocity between the ship and the water and thereby include the effect of water currents on the forces. This simulation model was validated with real data in Abkowitz (1980) and shown to be a good formulation for the “Esso Osaka” and ships of its type. The derivatives with respect to time of u_r, v_r and r given by

$$\dot{u}_r = \frac{f_1}{m - X_{\dot{u}_r}} \tag{4}$$

$$\dot{v}_r = \frac{1}{f_4}\left[(I_z - N_{\dot{r}})f_2 - (mx_G - Y_{\dot{r}})f_3\right] \tag{5}$$

$$\dot{r} = \frac{1}{f_4}\left[(m - Y_{\dot{v}_r})f_3 - (mx_G - N_{\dot{v}_r})f_2\right] \tag{6}$$

where

$$\begin{aligned} f_1 = {} & \eta_1^{'}\left[\frac{\rho}{2}L^2\right]u_r^2 + \eta_2^{'}\left[\frac{\rho}{2}L^3\right]nu_r + \eta_3^{'}\left[\frac{\rho}{2}L^4\right]n^2 - \dots \\ & \dots - C_R^{'}\left[\frac{\rho}{2}Su_r^2\right] + X_{v_r}^{'2}\left[\frac{\rho}{2}L^2\right]v_r^2 + X_{e^2}^{'}\left[\frac{\rho}{2}L^2c^2\right]e^2 + \dots \\ & \dots + \left(X_{r^2}^{'} + m^{'}x_G^{'}\right)\left[\frac{\rho}{2}L^4\right]r^2 + \left(X_{v_r r}^{'} + m^{'}\right)\left[\frac{\rho}{2}L^3\right]v_r r + \dots \\ & \dots + X_{v_r^2 r^2}^{'}\left[\frac{\rho}{2}L^4U^{-2}\right]v_r^2 r^2 \end{aligned} \tag{7}$$

$$
\begin{aligned}
f_2 &= Y_0'\left[\frac{\rho}{2}L^2\left(\frac{u_{A\infty}}{2}\right)^2\right] + \left\{Y_{v_r}'\left[\frac{\rho}{2}L^2U_r\right]v_r + \ldots\right. \\
&\ldots + Y_\delta'(c-c_0)\frac{\rho}{2}L^2v_r\Big\} + \left\{\left(Y_r' - m'u_r'\right)\left[\frac{\rho}{2}L^3U_r\right]r - \ldots\right. \\
&\ldots - \frac{Y_\delta'}{2}(c-c_0)\frac{\rho}{2}L^3r\Big\} + Y_\delta'\left[\frac{\rho}{2}L^2c^2\right]\delta + \ldots \\
&\ldots + Y_{r^2v_r}'\left[\frac{\rho}{2}L^4U_r^{-1}\right]r^2v_r + Y_{e^3}'\left[\frac{\rho}{2}L^2c^2\right]e^3
\end{aligned} \tag{8}
$$

$$
\begin{aligned}
f_3 &= N_0'\left[\frac{\rho}{2}L^3\left(\frac{u_{A\infty}}{2}\right)^2\right] + \left\{N_{v_r}'\left[\frac{\rho}{2}L^3U_r\right]v_r - \ldots\right. \\
&\ldots - N_\delta'(c-c_0)\frac{\rho}{2}L^3v_r\Big\} + \left\{\left(N_r' - m'x_G'u_r'\right)\left[\frac{\rho}{2}L^4U_r\right]r + \ldots\right. \\
&\ldots + \frac{1}{2}N_\delta'(c-c_0)\frac{\rho}{2}L^4r\Big\} + N_\delta'\left[\frac{\rho}{2}L^3c^2\right]\delta + \ldots \\
&\ldots + N_{r^2v_r}'\left[\frac{\rho}{2}L^5U_r^{-1}\right]r^2v_r + N_{e^3}'\left[\frac{\rho}{2}L^3c^2\right]e^3
\end{aligned} \tag{9}
$$

$$
\begin{aligned}
f_4 &= \left(m' - Y_{\dot{v}_r}'\right)\left[\frac{\rho}{2}L^3\right]\left(I_z' - N_{\dot{r}}'\right)\left[\frac{\rho}{2}L^5\right] - \ldots \\
&\ldots - \left(m'x_G' - N_{\dot{v}_r}'\right)\left[\frac{\rho}{2}L^4\right]\left(m'x_G' - Y_{\dot{r}}'\right)\left[\frac{\rho}{2}L^4\right]
\end{aligned} \tag{10}
$$

where ρ is the mass density of water; L is the length of the ship between perpendiculars; n are the propeller rps; C_R is the resistance coefficient of the vehicle (including the drag of windmilling propeller); S is the wetted surface area of the ship; and c is the weighted average flow speed over rudder; c_0 is the value of c when the propeller rotational speed and ship forward speed are in equilibrium in straight-ahead motion (when $u = u_0$ and $n = n_0$); A_P is the propeller area; A_R is the rudder area; w is the wake fraction; $u_{A\infty}$ is the induced axial velocity behind the propeller disk; K_T is the propulsive coefficient; D is the propeller diameter; and e is the effective rudder angle.

3. CONTROL PLANT MODEL

In order to design the steering autopilot it is necessary to simplify the mathematical model described in the previous section to a 2 DOF (sway-yaw) linear maneuvering model. This simplified model should contain only the main physical properties of the process. A linear maneuvering model is based on the assumption that the cruise speed of the ship u is kept constant ($u = u_0 \approx$ constant) while v and r are assumed to be small. A 2 DOF linear maneuvering model can be expressed by:

$$M\dot{\nu} + N(u_0)\nu = b\delta \tag{11}$$

with

$$M = \begin{bmatrix} m - Y_{\dot{v}} & mx_G - Y_{\dot{r}} \\ mx_G - Y_{\dot{r}} & I_z - N_{\dot{r}} \end{bmatrix} \tag{12}$$

$$N(u_0) = \begin{bmatrix} -Y_v & (m - X_{\dot{u}})u_0 - Y_r \\ (X_{\dot{u}} - Y_{\dot{v}})u_0 - N_v & (mx_G - Y_{\dot{r}})u_0 - N_r \end{bmatrix} \tag{13}$$

$$b = \begin{bmatrix} -Y_\delta \\ -N_\delta \end{bmatrix} \tag{14}$$

where $\nu = [v, r]^T$ is the sway and yaw state vector. Notice that in this representation the nonlinear damping matrix is neglected.

3.1. Nomoto Linear Model.

Nomoto *et al.* (1957) proposed a linear model for the ship steering equations that is obtained by eliminating the sway velocity from (11). The resulting model is named the Nomoto's 2nd order model and is given by a simple transfer function between r and δ

$$\frac{r}{\delta}(s) = \frac{K(1 + T_3 s)}{(1 + T_1 s)(1 + T_2 s)} \tag{15}$$

where T_i (i = 1, 2, 3) are time constants and K is the gain constant. A 1st order approximation to (15) is obtained by defining the *effective time constant*:

$$T = T_1 + T_2 - T_3 \tag{16}$$

such that

$$\frac{r}{\delta}(s) = \frac{K}{1 + Ts} \tag{17}$$

where T and K are known as the Nomoto time and gain constants, respectively. Neglecting the roll and pitch modes ($\phi = \theta = 0$) such that $\dot{\psi} = r$ finally yields

$$\frac{\psi}{\delta}(s) = \frac{K(1 + T_3 s)}{s(1 + T_1 s)(1 + T_2 s)} \approx \frac{K}{s(1 + Ts)} \tag{18}$$

Journée (2001) and Clarke (2003) showed that the 1st order Nomoto equation can be used to analyze the ship behavior during zigzag maneuvers, to find the values of K and T. If the 1st order Nomoto equation of motion is integrated with respect to time t, the following equation results,

$$T[r]_o^t + [\psi]_o^t = K\int_0^t \delta dt \tag{19}$$

Applying (19) to the first two heading overshoots of the zigzag maneuver, as shown in Figure 1, where the shaded area gives the integral term and at points delimited by the crosses (1 and 2), the yaw rate r is equal to zero. The term K is found immediately from the following expression,

$$K = -\frac{\psi_1 - \psi_2}{\int_{t_1}^{t_2} \delta dt} \tag{20}$$

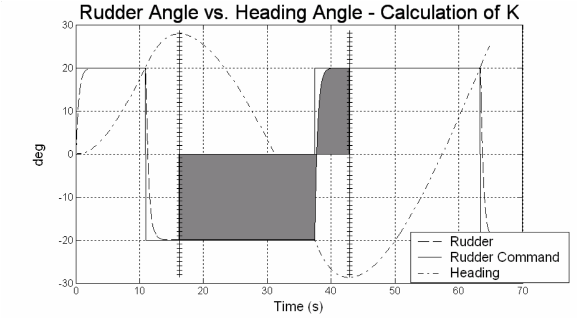

Fig.1. Derivation of *K* from 20-20 zigzag maneuver

Similarly, (19) is applied to the first two zero crossing points of the heading record of the zigzag maneuver, as shown in Figure 2, where again the integral term is given by the shaded area.

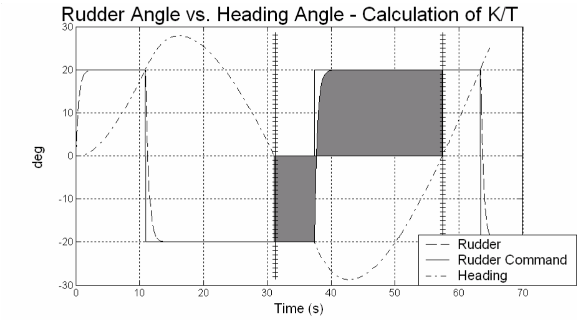

Fig.2. Derivation of *K/T* from 20-20 zigzag maneuver

In this case, at the two points delimited by the crosses (3 and 4), the heading ψ is equal to zero and T may be calculated from,

$$\frac{K}{T} = -\frac{r_3 - r_4}{\int_{t_3}^{t_4} \delta dt} \tag{21}$$

The values obtained for K and T of the 1st order Nomoto model, considering a speed u_0 equal to 0.4 m/, are $K = 0.1705\ s^{-1}$ and $T = 7.1167$ s

3.2.PID Heading Controller.

Assuming that both ψ and r will be measured by a compass and a rate gyro the PID-controller for full state feedback is given by (Fossen, 2002):

$$\begin{aligned}\tau_N(s) &= \tau_{FF}(s) - \tau_{PID}(s) = \\ &= \tau_{FF}(s) - K_p\tilde{\psi} - K_d\tilde{r} - K_i\int_0^t \tilde{\psi}(\tau)d\tau =\end{aligned} \tag{22}$$

where $\tilde{\psi} = \psi - \psi_d$, $\tilde{r} = r - r_d$, $K_d = K_p T_d$, and $K_i = \dfrac{K_p}{T_i}$. τ_N is the controller yaw moment, τ_{FF} is the feedforward term, K_p (> 0) is the proportional gain constant, T_d (> 0) is the derivative time constant, and T_i (> 0) is the integral time constant. The feedforward term τ_{FF} is added to the controller to achieve accurate and rapid course-changing maneuvers and is determined such that perfect tracking during course-changing maneuvers is obtained. Using Nomoto's 1st-order model as basis for feedforward, suggests that reference feedforward should be included according to:

$$\tau_{FF} = \frac{T}{K}\dot{r}_d + \frac{1}{K}r_d \tag{23}$$

3.3.Speed Controller using State Feedback Linearization.

The basic idea with feedback linearization is to transform the nonlinear systems dynamics into a linear system. Conventional control techniques like pole placement and linear quadratic optimal control theory can then be applied to the linear system (Fossen, 2002). Combining Eqs.(1) and (4) the model of the ship in surge is given by

$$\dot{u} = \frac{f_1}{m - X_{\dot{u}_r}} - u_c.r.\sin(\psi - \alpha) \tag{24}$$

with

$$f_1 = T(u_r, n) + f_1^*(u_r, v_r, u, v, r, \delta) \tag{25}$$

The thrust term is given by

$$\begin{aligned}T(u_r, n) &= \eta_1^{'}\left[\frac{\rho}{2}L^2\right]u_r^2 + \ldots \\ &\ldots + \eta_2^{'}\left[\frac{\rho}{2}L^3\right]nu_r + \eta_3^{'}\left[\frac{\rho}{2}L^4\right]n^2\end{aligned} \tag{26}$$

and f_1^* is given by

$$\begin{aligned}f_1^*(u_r, v_r, u, v, r, \delta) &= -C_R^{'}\left[\frac{\rho}{2}Su_r^2\right] + \ldots \\ &\ldots + X_{v_r}^{'2}\left[\frac{\rho}{2}L^2\right]v_r^2 + X_{e^2}^{'}\left[\frac{\rho}{2}L^2c^2\right]e^2 + \ldots \\ &\ldots + \left(X_{r^2}^{'} + m^{'}x_G^{'}\right)\left[\frac{\rho}{2}L^4\right]r^2 + \ldots \\ &\ldots + \left(X_{v_r r}^{'} + m^{'}\right)\left[\frac{\rho}{2}L^3\right]v_r r + \ldots \\ &\ldots + X_{v_r^2 r^2}^{'}\left[\frac{\rho}{2}L^4U^{-2}\right]v_r^2 r^2\end{aligned} \tag{27}$$

The commanded acceleration can be calculated through (Fossen, 2002)

$$a^b = \dot{u}_d - K_p(u_r - u_d) - K_i\int_0^t (u_r - u_d)d\tau \tag{28}$$

Thus, the speed controller can be computed by:

$$\tau_T = (m - X_{\dot{u}_r})[\dot{u}_d - K_p(u_r - u_d) - \dots$$
$$\dots - K_i \int_0^t (u_r - u_d)d\tau + u_c.r.\sin(\psi - \alpha)] - \dots \quad (29)$$
$$\dots - f_1^*(u_r, v_r, u, v, r, \delta)$$

4. LINE-OF-SIGHT GUIDANCE

A widely used method for path control is LOS guidance which has been used in missile guidance for many years and also in ship guidance (Healey and Lienard, 1993, McGookin *et al.*, 1998, Fossen *et al.*, 2003, Breivik and Fossen, 2004). In this methodology a LOS vector is computed from the ship to the next way-point (or a point on the path between two way-points) for heading control. If the ship has a course autopilot the angle between the LOS vector and the predescribed path can be used as a set-point for the autopilot, forcing the ship to track the path (Fossen, 2002).

4.1. 2-Dimensional LOS Guidance System for Surface Ships.

In many applications the LOS vector is taken as a vector from the body-fixed origin (x, y) to the next way-point (x_k, y_k). This suggests that the set-point to the course autopilot should be chosen as:

$$\psi_d(t) = a\tan 2(y_k - y(t), x_k - x(t)) \quad (30)$$

where (x, y) is the ship position measurement. The four quadrant inverse tangent function $a\tan2(y, x)$ is used to ensure that $a\tan 2(y, x) \in [-\pi, \pi]$. A 3rd order reference model will generate the necessary signals required by the heading controller as well as smoothing the discontinuous way-point switching to prevent rapid changes in the desired yaw angle fed to the controller.

The drawback of a LOS vector pointing to the next way-point is that a way-point located far away from the ship will result in large cross-track errors in the presence of wind, current and wave disturbances. Therefore, the LOS vector can be defined as the vector from the vessel coordinate origin (x, y) to the intersecting point on the path (x_{los}, y_{los}) a distance n ship lengths L_{pp} ahead of the vessel. Thus, the desired yaw angle can be computed as:

$$\psi_d(t) = a\tan 2(y_{los} - y(t), x_{los} - x(t)) \quad (31)$$

where the LOS coordinates (x_{los}, y_{los}) are given by:

$$(y_{los} - y(t))^2 + (x_{los} - x(t))^2 = (nL_{pp})^2 \quad (32)$$

$$\left(\frac{y_{los} - y_{k-1}}{x_{los} - x_{k-1}}\right) = \left(\frac{y_k - y_{k-1}}{x_k - x_{k-1}}\right) = \text{constant} \quad (33)$$

The pair (x_{los}, y_{los}) can be solved from Eqs.(32) and (33). When moving along the path a switching mechanism for selecting the next way-point is needed. Way-point (x_{k+1}, y_{k+1}) can be selected on a basis of whether the ship lies within a *circle of acceptance* with radius R_0 around way-point (x_k, y_k). Moreover if the vehicle positions $(x(t), y(t))$ at time t satisfies:

$$[x_k - x(t)]^2 + [y_k - y(t)]^2 \leq R_0^2 \quad (34)$$

the next way point (x_{k+1}, y_{k+1}) should be selected, i.e., k should be incremented to $k = k+1$. A guideline can be to choose R_0 equal to two ship lengths, that is $R_0 = 2L_{pp}$ (Fossen, 2002).

4.2. LOS – Alternative Method Using Dynamic Circle.

The idea in this approach is to find the optimal circle, i.e., the minimum radius of the circle of the second term of Eq.(32) in order to improve the convergence of the LOS algorithm. This alternative method has the advantage of being adaptive and dynamic and is not necessary anymore to establish an initial value for the distance n. Figure 3 illustrates the principle to achieve the minimum radius to solve the LOS equations.

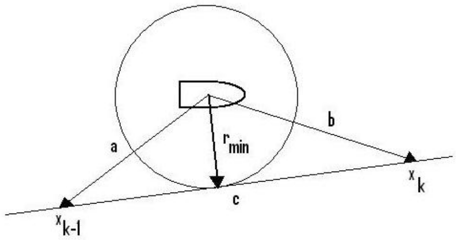

Fig.3. Geometry to obtain the minimum circle

The parameters shown in Figure 3 are given by

$$a(t) = \sqrt{(x(t) - x_{k-1})^2 + (y(t) - y_{k-1})^2} \quad (35)$$

$$b(t) = \sqrt{(x_k - x(t))^2 + (y_k - y(t))^2} \quad (36)$$

$$c(t) = \sqrt{(x_k - x_{k-1})^2 + (y_k - y_{k-1})^2} \quad (37)$$

$$r_{\min}(t) = \sqrt{a(t)^2 - \left(\frac{c(t)^2 - b(t)^2 + a(t)^2}{2c(t)}\right)^2} \quad (38)$$

Eq.(38) provides the minimum circle according with Fig.3 but doesn't behave well as $b \to 0$ and $a \to c$. To avoid $r_{\min} \to 0$ it is assumed that

$$n(t)L_{pp} = r_{\min}(t) + L_{pp} \quad (39)$$

that is equivalent to assume that n is higher than 1, i.e., $r_{\min} > L_{pp}$. Thus, the LOS coordinates (x_{los}, y_{los}) are now given by:

$$(y_{los} - y(t))^2 + (x_{los} - x(t))^2 = (r_{\min}(t) + L_{pp})^2 \quad (40)$$

5. CASE STUDY: SIMULATION RESULTS

Euler's numerical integration method was used for the discretization with a sampling time $T_s = 0.1$s. The desired path consists of a total of 9 way-points:

$Wpt_1 = (0, 0)$ $\quad Wpt_4 = (-25, 20)$ $\quad Wpt_7 = (0, 80)$
$Wpt_2 = (20, 10)$ $\quad Wpt_5 = (25, 60)$ $\quad Wpt_8 = (-20, 70)$
$Wpt_3 = (-20, 10)$ $\quad Wpt_6 = (20, 70)$ $\quad Wpt_9 = (0, 70)$

The ship's initial states are:

$$(x_0, y_0, \psi_0) = (0 \text{ m}, 0 \text{ m}, 0 \text{ rad})$$
$$(u_0, v_0, r_0) = (0.41 \text{ m/s}, 0 \text{ m/s}, 0 \text{ rad/s})$$

The desired speed is

$$r^b = \begin{cases} 0.21 m/s & if \quad t_1 \le t \le t_3 \\ 0.43 m/s & if \quad t_3 < t \le t_6 \\ 0.27 m/s & if \quad t_6 < t \le t_9 \end{cases}$$

The radius of acceptance for all way-points was set to two ship lengths. Figure 4 shows a *xy*-plot of the simulation of the "Esso Osaka" model position together with the desired geometrical path consisting of straight line segments for the two different methods.

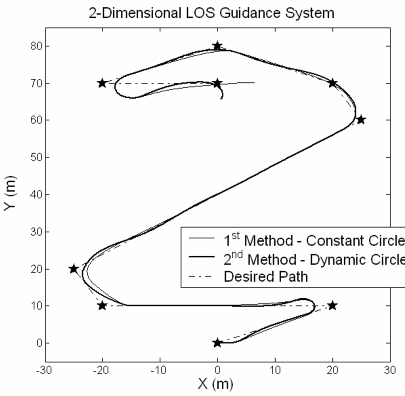

Fig.4. *xy*-plot of the simulated and desired geometrical path using the 2 different methods

More tests and respective results are described in more detail in Moreira *et al.* (2005).

6. FINAL REMARKS

In this paper a practical guidance and control system for an autonomous vehicle is introduced, using a waypoint guidance algorithm based on LOS. An approach concerning the calculation of a dynamic LOS vector norm is presented in order to improve the convergence of the vehicle to the desired trajectory and turning the scheme independent of initial design value for the LOS distance (radius). Moreover, a PID heading controller including feedforward action and a speed controller obtained through state feedback linearization were developed. Simulation results based on the mathematical model of the "Esso Osaka" tanker are included to demonstrate the performance of the system. The presented approach can be readily applied to other vehicles or extended to higher dimensional control and guidance problems.

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