A study on the autonomous control system for an unmanned surface vessel

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Abstract: Recently, the applications of unmanned system are steadily increasing. Unmanned automatic system is suitable for routine mission such as reconnaissance, environment monitoring, resource conservation and investigation. Especially, for the ocean environment monitoring mission, many ocean engineers had scoped with the routine and even risky works. The automatic system can replace the periodic and routine missions: water sampling, temperature and salinity measuring, etc. In this paper, an unmanned surface vessel was designed for routine and periodic ocean environmental missions. An autonomous control system was designed and tested for the unmanned vessel. A GPS and gyro compass was used for navigation. A linear autopilot model for course control can be derived from the maneuvering model. Nomoto's 2nd-order response equation was derived. The design methodologies and performance of the surface vessel were illustrated and verified with this linearized equation of motion. A linear controller was designed and automatic route tracking performance was verified for yaw subsystem.

Keywords: Unmanned Surface Vessel, Onboard Sensors, Automatic route Tracking Control.

1. Introduction

The unmanned surface vessels are remotely piloted or self-piloted ships. Recently, their abilities are much more that they carry GPS, radar, sonar, cameras, sensors, communication equipments, or other payloads. Such unmanned automatic vessel system is suitable for routine mission such as reconnaissance, environment monitoring, resource conservation and investigation. Especially, for the ocean environment monitoring mission, many ocean engineers had scoped with the routine and even risky works. The automatic system can replace the periodic and routine missions: water sampling, temperature and salinity measuring, etc. Some day several unmanned system will be operated in military purposes such as reconnaissance, surveillance, and intelligence of enemy forces without risking the lives of crews. These actual applications need more versatile performance. Among these abilities autonomous stabilization, collision avoidance and navigation abilities are necessarily needed. It is necessary to design a feedback control system with adequate closed loop bandwidth.

This paper was concentrated on describing the functional design, electronic equipments and their interconnections for acquiring autonomous navigation. The autopilot or *automatic pilot* is a device for controlling an aircraft, ship or other vehicles without constant human intervention. For ships, course-keeping capabilities were the first applications. Modern autopilots can execute complex maneuvers like turning, docking operations, or make possible the control of inherently unstable vessels. Autopilots are used to steer surface ships, submarines, torpedoes, missiles, rockets, and spacecraft among others. The design methodologies and performance of the surface vessel were illustrated and verified with a linearized equation of motion. A linear autopilot model for course control can be derived from the maneuvering model. Nomoto's 2nd-order response equation was derived. A linear controller was designed and automatic route tracking performance was verified for yaw subsystem.

2. Equation of the Surface Vessel Motion

2.1 Equation of Motion Yaw autopilot Model

Generally, control dynamic equation of ship is described by nonlinear equation owing to the nonlinear fluid force produced by ship hull, thruster and rudder or the effect of interference of fluid viscosity and inertia. The linearized equation of control dynamic equation is widely used. The 2nd order Nomoto ship dynamic equation is that yaw angle velocity is only function of rudder control input, δ . The resulting equation is as following equation (1).

$$T_1 T_2 \ddot{\gamma} + (T_1 + T_2)\dot{\gamma} + \gamma = K\delta + KT_3\dot{\delta} \tag{1}$$

where, T_1 , T_2 are command following and, stability coefficients respectively. T_3 is coefficient which affects on the rudder of differential control effect and increases path stability. K is coefficient related to rotation ability.

From equation (1), in a non-periodic motion such as control motion, low frequency motion, a simplified 1st order Nomoto response model can be used as following equation (2).

$$\dot{\gamma} = -\frac{1}{T}\gamma + \frac{K}{T}\delta \tag{2}$$

where, γ is yaw angle velocity, δ is rudder control angle, K and T are characteristic constants of the ship.

2.2. Yaw Angle Command Generation

Figure 1 represents the coordinate system used for ship motion control. Coordinate system OX_0Y_0 is inertia coordinate. The ship path and ship motion with respect to this inertia coordinate system.

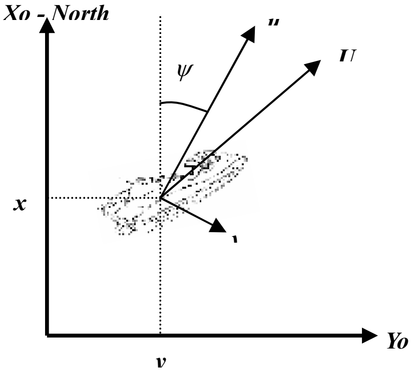

Fig. 1. Coordinate System for Ship Motion

ψ is yaw angle, the angle between true north and heading of the ship. u and v are forward and transverse velocity respectively. x and y are position of the ship. The motion equation can be derived from above figure 1.

$$\begin{aligned} \dot{x} &= u\cos\psi - v\sin\psi \\ \dot{y} &= u\sin\psi + v\cos\psi \\ \dot{\psi} &= \gamma \end{aligned} \tag{3}$$

An automatic route tracking control algorithm is represented in figure 2. If the vessel is off the desired target path, position error between present and target position of the ship is occurred by calculation of the GPS signals. To navigate exact path of the ship, appropriate yaw angle command which reduce this position error must be generated.

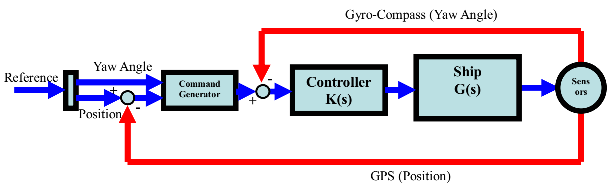

Fig. 2. Function Diagram of Unmanned Surface Vessel

In straight navigation path, the position error (P_e) between the desired target position (P_d) and present poison of the ship (P) can be defined by the following equation.

$$P_e = P_d - P = \begin{bmatrix} x_d - x \\ y_d - y \end{bmatrix} \tag{4}$$

By using equation (3), the equation can be described in the function of desired yaw angle ψ_d and present yaw angle ψ of the ship.

$$\dot{P}_e = \begin{bmatrix} \dot{x}_d - \dot{x} \\ \dot{y}_d - \dot{y} \end{bmatrix} = \begin{bmatrix} u\cos\psi_d - u\cos\psi \\ u\sin\psi_d - u\sin\psi \end{bmatrix} \tag{5}$$

Summarize with respect to ψ,

$$\psi = \psi_d - \psi_{P_e} \tag{6}$$

$$\psi_{P_e} = \cos^{-1}\left(1 - \frac{\dot{P}_e^T \dot{P}_e}{2u^2}\right) \tag{7}$$

where, differentiate position error P_e with respect to time the following equation is acquired. The position error can be reduced by adding this ψ_{P_e} to the yaw angle.

2.3. Wind Models

Wind is defined as the movement of air relative to the surface of the Earth. Mathematical models of wind forces and moments are used in vessel control systems to improve the performance and robustness of the system in extreme conditions. In order to implement wind compensation for a surface vessel, a 3 DOF wind model as function of relative wind speed and direction is needed. For this purpose, the generalized force vector is:

$$w_{wind} = [X_{wind}, Y_{wind}, N_{wind}]^T \tag{8}$$

Two models for numerical computation of X_{wind}, Y_{wind}, N_{wind} will now be discussed.

$$X_{wind} = \frac{1}{2} C_X(\gamma_r)\rho_a V_r^2 A_T \quad \text{(N)} \tag{9}$$

$$X_{wind} = \frac{1}{2} C_Y(\gamma_r)\rho_a V_r^2 A_L \quad \text{(N)} \tag{10}$$

$$X_{wind} = \frac{1}{2} C_Z(\gamma_r)\rho_a V_r^2 A_L L \quad \text{(N m)} \tag{11}$$

where C_X and C_Y are the empirical force coefficients, C_N is a moment coefficient, ρ_a (kg/m^3) is the density of air, A_T (m^2) and A_L(m^2) are the transverse and lateral projected areas, and L (m) is the overall length of the ship. Notice that V_r is given in knots.

2.4. Linear Wave Response Models

The wave-induced forces and moments on a marine vessel in closed loop can be simulated by assuming a linear wave response mode. If accuracy of the vessel motion is critical, a more detailed model for the wave loads should be applied. Linear approximations well suited for this purpose are discussed below. Linear wave response approximations are usually preferred by ship control systems engineers, owing to their simplicity and applicability. This model is written:

$$h(s) = \frac{K_w s}{s^2 + 2\lambda\omega_0 s + \omega_0^2} \tag{12}$$

and it is convenient to define the gain constant according to:

$$K_w = 2\lambda\omega_0\sigma \tag{13}$$

where, σ is a constant describing the wave intensity, λ is damping coefficient, and ω_0 is the dominating wave frequency.

A linear state-space model can be obtained from by transforming this expression to the time-domain by defining,

$$\dot{x}_{w1} = x_{w2} \text{ and } x_{w2} = y_w$$

$$\dot{x}_w = A_w x_w + e_w w_w \tag{14}$$

$$y_w = c_w^T x_w \tag{15}$$

where w_w is a zero-mean white noise process. Writing this expression in component form, yields:

$$\begin{bmatrix} \dot{x}_{w1} \\ \dot{x}_{w2} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\omega_0^2 & -2\lambda\omega_0 \end{bmatrix} \begin{bmatrix} x_{w1} \\ x_{w2} \end{bmatrix} + \begin{bmatrix} 0 \\ K_w \end{bmatrix} w_w \tag{16}$$

$$y_w = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} x_{w1} \\ x_{w2} \end{bmatrix} \tag{17}$$

2.5. 1 DOF autopilot Model (Yaw Subsystem)

A linear autopilot model for course control can be derived from the maneuvering model

$$M\dot{\nu} + N(u_0)\nu = b\delta \tag{18}$$

where, $\nu = [u, v, w, p, w, r]$, by defining the yaw rate r as output:

$$r = c^T \nu, \quad c^T = [0,1] \tag{19}$$

Hence, application of the Laplace transformation yields :

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

This is referred to as Nomoto's 2nd-order response equation. In figure 3, the result of automatic route tracking control for yaw subsystem was represented. This yaw angle control system showed reasonable performance. Solid blue line is target and dashed red line is controlled yaw response.

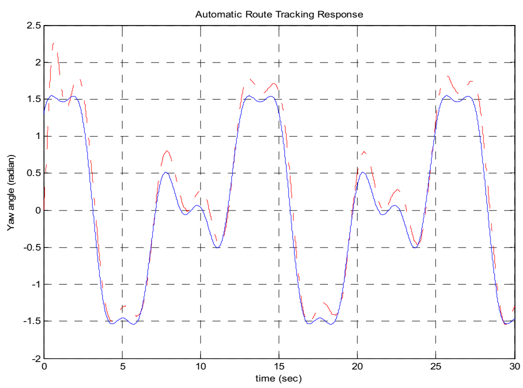

Fig. 3. Automatic Route Tracking control(Yaw Subsystem)

3. System Design of the Unmanned Vessel

3.1. System Design

The test unmanned surface vessel was made by modifying and installing necessary navigation sensor on a water- jet ski. The vessel has a 85 horsepower 718 cc 2 cylinder engine. The dry weight is 174 kg and has Length 254 cm. Figure 4 represents that the overall shape and on board equipments design of the unmanned vessel. It had equipped many navigation sensors, such as, GPS, DGPS, sonar, speed meter and so on. Also, it had many onboard environmental sensors, such as, anemometer, water temperature sensor, salinity sensor, OCM(Ocean Color Monitoring) sensor and so on. In Figure 5, data link and GCS System is shown for maritime mission. Figure 6 illustrates the Ocean Sensor and Unmanned Vessel System. Figure 7 illustrates Orbcomm satellite communication system which prevents form loss of the vessel system.

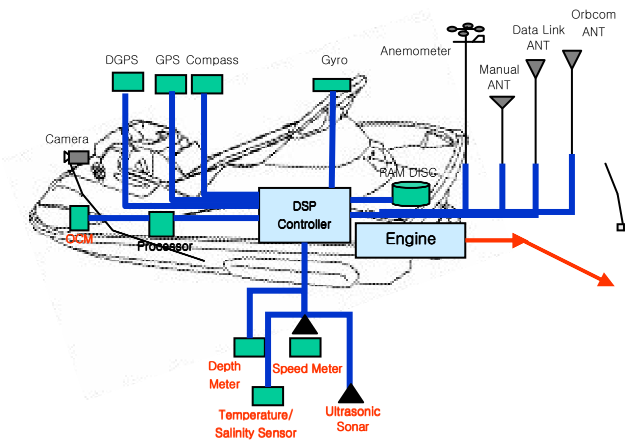

Fig. 4. Function Diagram of Unmanned Surface Vessel

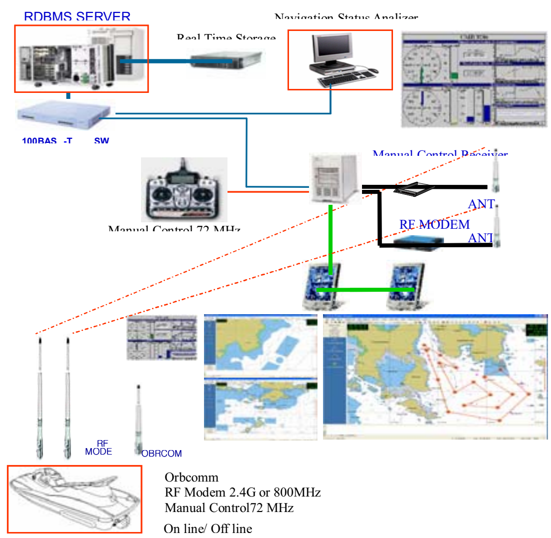

Fig. 5. Data Link and GCS System

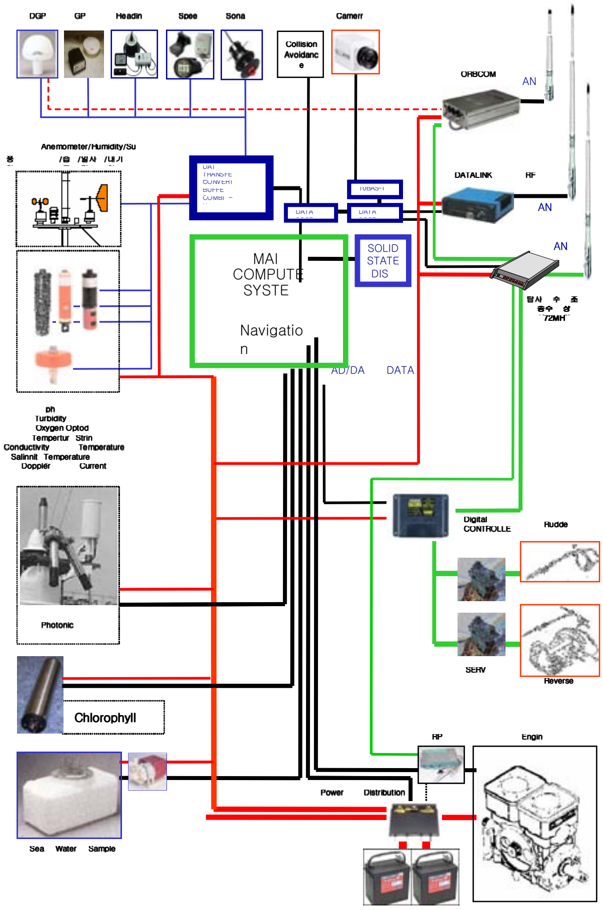

Fig. 6. Ocean Sensor and Unmanned Vessel System

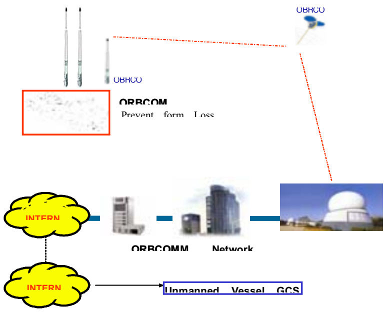

Fig. 7. Orbcomm Satellite Communication System

4. Conclusions and Further Research

The unmanned surface vessel system was design and functional system performances were studied. A computer based controller was designed and the performance of yaw angle of the vessel was simulated and tested in several wind and wave conditions. System configuration and interference was also tested for the designed unmanned vessel. And a navigation controller was implemented a DSP based controller. The design methodologies and performance of the surface vessel were illustrated and verified with a linearized equation of motion. A linear autopilot model for course control can be derived from the maneuvering model and a linear controller was designed and tested for this unmanned surface vessel. The yaw angle showed reasonable responses under offshore environmental wind and wave conditions. Therefore, designed unmanned marine vessel system and controller will be useful for advanced real embedded platform. And the nonlinear model will be used in the hardware-in-the-loop simulation to check out control software. The state estimation method such as Kalman filter is required for robust to short GPS outages. Also, it is required that the real time OS(operating system) is implemented to autopilot computer for graphical interface.

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