Automatic Ship Handling of the Maritime Search Mission using a Self-Tuning Fuzzy Gain Scheduling PD Controller

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In this paper, the ship manoeuvring problems particular to maritime search and rescue are investigated. A solution to such problems is necessary for successful ship handling to save human life. A fuzzy gain scheduling Proportional Derivative (PD) controller, using a back-propagation algorithm, is developed to solve these maritime search and rescue problems. The parameters of the proposed PD controller are determined on-line by fuzzy rules and adjustable fuzzy reasons. The proposed controller is self-adaptive and can accommodate the effects caused by wave or wind disturbance. Some computer simulations are provided to illustrate the use of the main ideas.

1. INTRODUCTION. As is well known, ship manoeuvring is critical to marine safety. In the past, several design methods have been proposed for autopilots; for example: classical control, adaptive control, proportional-integrate derivative control (PID), and other modern control techniques.[1–5] The manoeuvring problems including course keeping, course tracking, berthing, and anti-collision were considered in these papers. However, to the best of our knowledge, no automatic control strategy for maritime search has been discussed in any open literature. In fact, the solution to such problems is urgent and absolutely necessary for ship handling to save human life. The International Maritime Organization (IMO) suggests two standard search patterns, namely the sector and the square search patterns. In this paper, both search patterns will be investigated.

PID controllers are most widely used in marine engineering control systems; for example steering systems, propulsion systems, and so on. Traditionally, the parameters of a conventional PID controller, i.e. K_p, K_i and K_d, are fixed. Consequently, the conventional PID controller is inefficient for control of a system while the system is disturbed by unknown factors. Several methods for parameter tuning of a non-fixed PID controller have been proposed.[6–15]

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Fuzzy theory has been applied to a wide variety of real engineering and business areas. Unlike traditional control techniques, precise information on the system is not necessary before a suitable fuzzy controller is designed. However, it is not so easy to design a good fuzzy controller for very complex nonlinear systems, if highly accurate performance of the system is desired. Parameters of the fuzzy controller may need to be tuned, while the system suffers some disturbances in the process.

In this paper, a fuzzy gain scheduling Proportional Derivative (PD) controller, using a back-propagation algorithm, is developed to solve the ship handling problems of maritime search and rescue. A back-propagation algorithm[16–17] is utilized to adjust the membership functions of the fuzzy gains based on the error signal and its derivative of the system. The schematic diagram of the feedback system is shown in Figure 1.

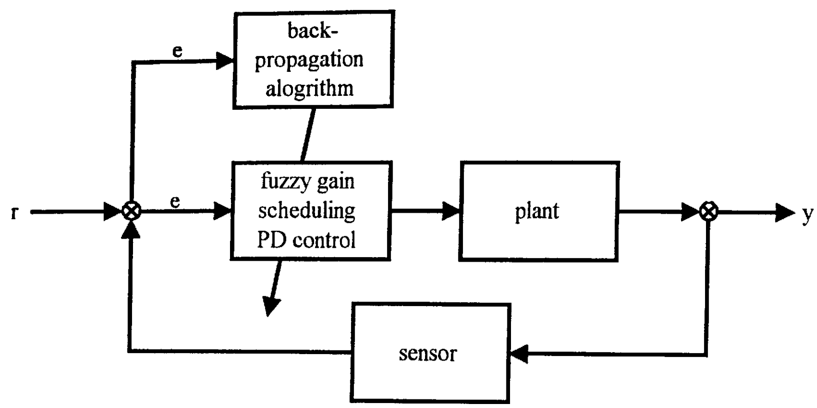

Figure 1. Architecture of the feedback system.

2. DYNAMIC MODEL. The nonlinear ship dynamic model[18] relates the yaw angle $_r$ to the rudder angle δ_r, as shown in Figure 2, according to:

$$\ddot{}_r + \frac{K}{T}H(\dot{}_r) = \frac{K}{T}\delta_r, \tag{1}$$

where K is the gain, T is a time constant and $H(\dot{}_r) = \alpha\dot{}_r + \beta\dot{}_r^3$ (α and β are constants) is a nonlinear function in $\dot{}_r$ determined experimentally from the standard spiral test. Furthermore, for a more complete description of the ship model, the rudder servo-mechanism has to be taken into account. For instance, the natural constraints of the steering machine are given as:

$$\delta_{max} = 35\,(\text{deg}),\ 2\tfrac{1}{3} \leqslant \Delta\delta_{max}(\text{deg/sec}) \leqslant 7,$$

where δ_{max} is maximum rudder angle and $\Delta\delta_{max}$ is the maximum rudder angle change rate when the rudder operates in the linear characteristic region.

In general, the environmental disturbance of the ship steering should be considered, especially waves, which can affect the yaw angle of ship's heading. Hence, the actual yaw angle of the ship can be expressed by:

$$= {}_r + {}_w,$$

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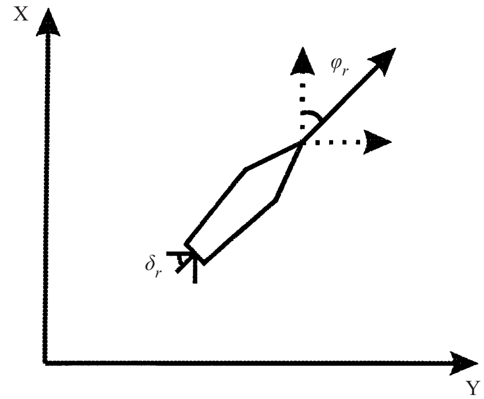

Figure 2. Motion in the horizontal plane.

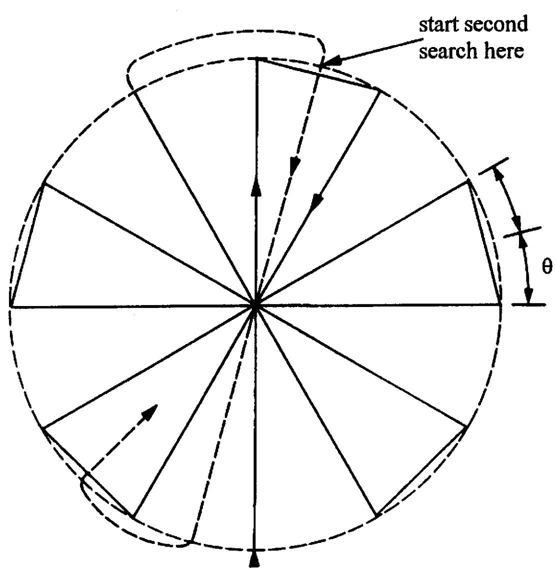

Figure 3. Sector search pattern.

where $_r$ and $_w$ are the yaw angles produced by the rudder and a wave, respectively. For simplicity of illustration, a linear model for the yaw angle produced by a wave is used in this study, namely:

$$_w(s) = h(s)\,\omega(s),$$

where $\omega(\cdot)$ is a zero-mean Gaussian white noise, and the transfer function $h(s)$ is given by:

$$h(s) = \frac{K_\omega s}{s^2 + 2\zeta\omega_0 s + \omega_0^2}. \tag{2}$$

In (2), ζ is the damping coefficient, ω_0 is the dominating wave frequency, and $K_\omega = 2\zeta\omega_0\,\delta_\omega$ is the gain constant with δ_ω representing the wave intensity.[5]

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3. MARITIME SEARCH PATTERNS. IMO suggests the standard procedures of a maritime search mission in Model Course 3.14 – Compendium for Maritime Search and Rescue Mission Co-ordinator. In particular, two standard search patterns are suggested when an emergency occurs, namely: the sector search pattern, and the square search pattern, as shown in Figures 3 and 4. In general,

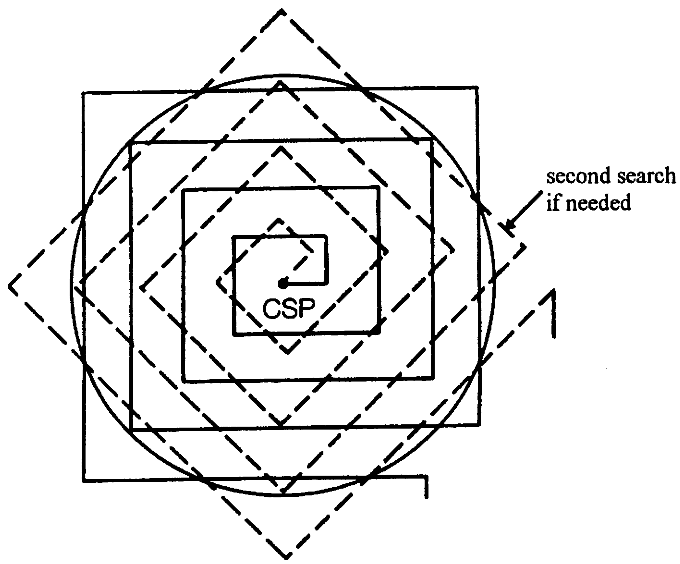

Figure 4. Square search pattern.

patterns ought to be selected that require fewer turns and longer search legs, thus reducing turning errors and making navigation easier and more accurate. The goal of this paper is to find a feasible control mechanism to accomplish the required search pattern.

The path of the required search pattern could be expressed as a set of assembled course lines, as shown in Figures 3 and 4. Consequently, the maritime search problem can be treated as a course-tracking problem. It is noted that the course of the rescue ship should be changed immediately the yaw angle is disturbed by, say, waves.

Suppose the coordinate of the rescue ship is (x, y), and the target position of the desired search pattern is (T_x, T_y), then the desired yaw angle ($_d$) from the rescue ship to the target is designed as:

$$_d = \tan^{-1}\left(\frac{T_x - x}{T_y - y}\right), \quad T_x - x \geqslant 0, \quad T_y - y \geqslant 0,$$

$$_d = \tan^{-1}\left(\frac{T_x - x}{T_y - y}\right), \quad T_x - x \leqslant 0, \quad T_y - y \geqslant 0,$$

$$_d = 90 - \tan^{-1}\left(\frac{T_y - y}{T_x - x}\right), \quad T_x - x \leqslant 0, \quad T_y - y \leqslant 0,$$

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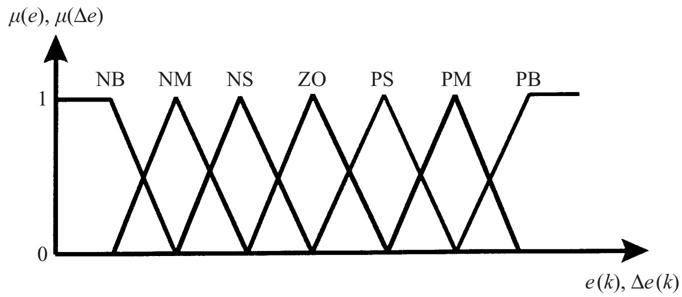

Figure 5. Fuzzifier membership functions of $e(k)$ and $\Delta e(k)$.

4. FUZZY GAIN SCHEDULING PD CONTROLLER. PID controllers are currently used in ship control systems, and the steering machines of autopilot systems. The discrete-time PD controller used in this paper is given as:

$$u(k) = K_p e(k) + \frac{K_d}{T_s}[e(k) - e(k-1)] \equiv \delta_r(k),$$

where the error is the difference between actual ship yaw angle and desired yaw angle, i.e. $e(k) \equiv \;_d(k) - \;(k)$. The controller design procedure is described as follows.

(i) The PD controller parameters are calculated according to

$$K_p = (K_{p,\max} - K_{p,\min}) \cdot K'_p + K_{p,\min}, \tag{3a}$$

$$K_d = (K_{d,\max} - K_{d,\min}) \cdot K'_d + K_{d,\min}, \tag{3b}$$

where the values of $K_{p,\min}$, $K_{p,\max}$, $K_{d,\min}$ and $K_{d,\max}$ can be set by designer's experience. In general, a higher value of K_p results in faster system response, but a larger over-shoot, and a higher value of K_d results in slower system response, but a smaller over-shoot.

(ii) The values of K'_p and K'_d are computed according to:

$$K'_p = \sum_{i=1}^{2}\sum_{j=1}^{2} \mu_{i,j} \cdot K'_{p,i,j}, \quad K'_d = \sum_{i=1}^{2}\sum_{j=1}^{2} \mu_{i,j} \cdot K'_{d,i,j}, \quad \sum_{i=1}^{2}\sum_{j=1}^{2} \mu_{i,j} = 1.$$

(iii) The values of $\mu_{i,j}$, $K'_{p,i,j}$, and $K'_{d,i,j}$ are determined by the error signal $e(k)$ and error change $\Delta e(k) = e(k) - e(k-1)$ through a suitable fuzzy inference. The membership function of $e(k)$ and $\Delta e(k)$ are shown in Figure 5 and the membership value of $\mu_{i,j}$, $i, j = 1, 2$, is given by:

$$\mu_{i,j} = \mu_{A,i} \cdot \mu_{B,j}, \quad \mu_{A,i} \equiv \mu_i(e(k)), \quad \mu_{B,j} \equiv \mu_j(\Delta e(k)).$$

The defuzzifier membership functions of $K'_{p,i,j}$ and $K'_{d,i,j}$, $i, j = 1, 2$, as shown in Figure 6, are sigmoid functions given as:

$$K'_{p,i,j}(\mu) = 1 - \frac{1}{1 + e^{-r_1 \times (\mu_{i,j} - 0\cdot 5)}} \quad \text{for B}, \quad K'_{p,i,j}(\mu) = \frac{1}{1 + e^{-r_2 \times (\mu_{i,j} - 0\cdot 5)}} \quad \text{for S}, \tag{4a}$$

$$K'_{d,i,j}(\mu) = 1 - \frac{1}{1 + e^{-r_3 \times (\mu_{i,j} - 0\cdot 5)}} \quad \text{for B}, \quad K'_{d,i,j}(\mu) = \frac{1}{1 + e^{-r_4 \times (\mu_{i,j} - 0\cdot 5)}} \quad \text{for S}, \tag{4b}$$

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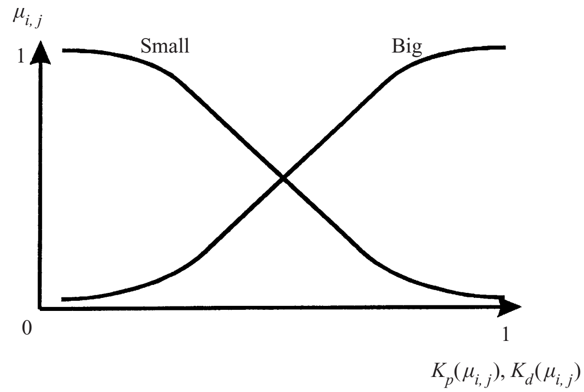

Figure 6. Defuzzifier membership functions of $K_p(\mu_{i,j})$ and $K_d(\mu_{i,j})$.

Table 1. Rule base of $K'_{p,i,j}$

$K'_{p,i,j}$		$\Delta e(k)$						
		NB	NM	NS	ZO	PS	PM	PB
$e(k)$	NB	B	B	B	B	B	B	B
	NM	S	B	B	B	B	B	S
	NS	S	S	B	B	B	S	S
	ZO	S	S	S	B	S	S	S
	PS	S	S	B	B	B	S	S
	PM	S	B	B	B	B	B	S
	PB	B	B	B	B	B	B	B

Table 2. Rule base of $K'_{d,i,j}$

$K'_{d,i,j}$		$\Delta e(k)$						
		NB	NM	NS	ZO	PS	PM	PB
$e(k)$	NB	S	S	S	S	S	S	S
	NM	B	B	S	S	S	B	B
	NS	B	B	B	S	B	B	B
	ZO	B	B	B	B	B	B	B
	PS	B	B	B	S	B	B	B
	PM	B	B	S	S	S	B	B
	PB	S	S	S	S	S	S	S

where r_i, $i = 1, \ldots 4$, are positive real numbers. The rule bases for $K'_{p,i,j}$ and $K'_{d,i,j}$ are listed in Tables 1 and 2, respectively.

We wish to point out that better performance can be achieved if the parameters r_1, r_2, r_3 and r_4 can be adjusted adaptively by a back-propagation tuning algorithm.

Define the error function as:

$$E \equiv 0{\cdot}5 \cdot \sum (y - r)^2,$$

where y is the actual output and r is the desired output value, i.e. and $_d$ respectively.

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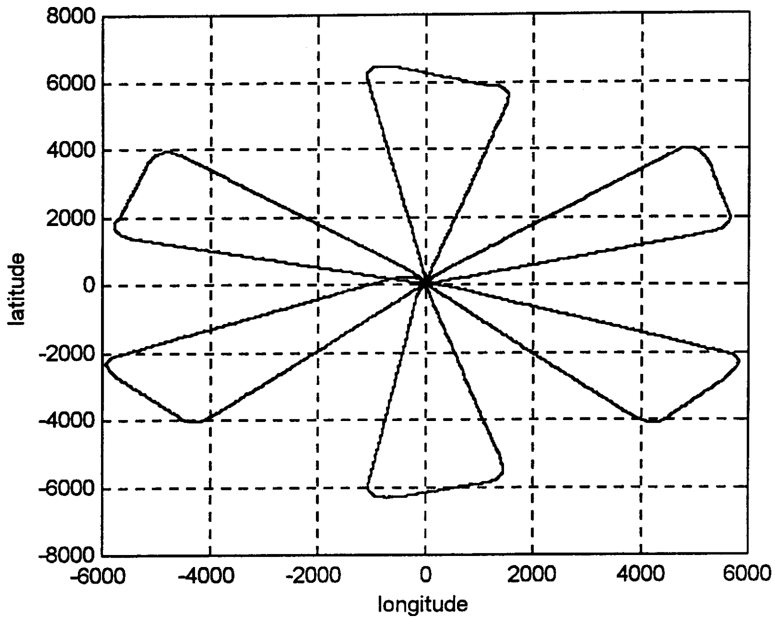

Figure 7. Simulation result of sector search pattern.

The aim of adjustment for r_i, $i = 1, 1, \ldots 4, \Lambda, 4$, is to minimize the instantaneous square error between the actual system output and the desired output. This speeds up the convergence of the system trajectory. The adaptation of each r_i is given by:

$$r_i(k) = r_i(k-1) + \delta_L w_i, \tag{5}$$

where, δ_L, $0 < \delta_L \leqslant 1$, is the learning rate and w_i, $i = 1, \Lambda, 4$, is the amount adjusted in each time interval and is given by:

$$w_i = \frac{\partial E}{\partial r_i} = \frac{\partial E}{\partial y}\frac{\partial y}{\partial u}\frac{\partial u}{\partial S}\frac{\partial S}{\partial r_i} + \frac{\partial E}{\partial y}\frac{\partial y}{\partial u}\frac{\partial u}{\partial B}\frac{\partial B}{\partial r_i}.$$

The corresponding values of $K'_{p,i,j}$ and $K'_{d,i,j}$, $i, j = 1, 2$, are also modified at each time k accordingly.

5. ILLUSTRATIVE EXAMPLES. In this simulation, the sector search pattern is performed first using the proposed PD controller. Next, the square search pattern is simulated. Finally, a successful rescue mission for *man overboard* is simulated using the proposed controller. The following set of parameters are used: $K = 0{\cdot}093$, $T = 8{\cdot}7$, $\alpha = 9{\cdot}42$, and $\beta = 2{\cdot}24$ in ship model (1), which correspond to the speed of 16 knots[18], and $\omega_0 = 1{\cdot}0$, $\zeta = 0{\cdot}1$, and $\delta_w^2 = 10$ in wave disturbance model (2); see Reference 5. In our proposed controller, we choose the parameters $K_{p,\min} = 0{\cdot}32 \cdot K_u$, $K_{p,\max} = 0{\cdot}6 \cdot K_u$, $K_{d,\min} = 0{\cdot}08 \cdot K_u \cdot T_u$, and $K_{d,\max} = 0{\cdot}15 \cdot K_u \cdot T_u$ in (3), where $K_u = 100$ and $T_u = 25$, the learning rate in (5) is chosen as $\delta_L = 0{\cdot}1$, and the initial parameters of the defuzzifier membership function in (4) are set to be $r_i = 4$, $i = 1, \ldots, 4$.

For the search pattern, the target coordinate (T_x, T_y) in x–y plane is given by:

$$T_x = L \cdot \cos(\theta_T), \quad T_y = L \cdot \sin(\theta_T),$$

where L is the desired search range and θ_T is the target angle to the reference direction (North). We assume that the desired search range of the sector pattern is given by $L = 6000$. Six sectors for a complete sector search pattern are suggested by IMO. For instance, three target points with polar coordinates $(L, \theta_{T_1}) = (6000, -10)$ (target 1), $(L, \theta_{T_2}) = (6000, 10)$ (target 2), and the centre of search pattern (CSP) (target 3) form one sector. Figure 7 shows the simulation result of a sector search using the proposed controller.

For the square search pattern, the desired target points are the vertices of the search path, as shown in Figure 4. The simulation result is shown in Figure 8.

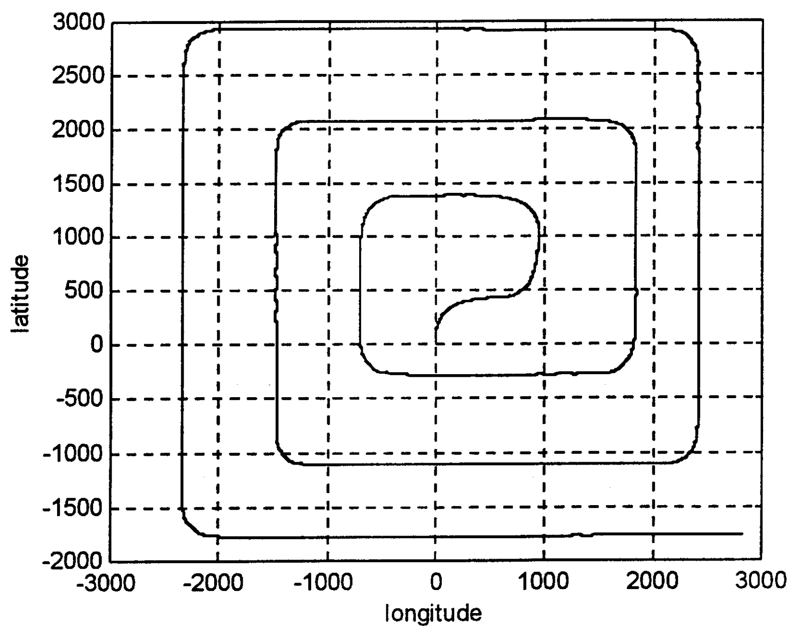

Figure 8. Simulation result of square search pattern.

From the simulation results, it is obvious that the proposed controller can successfully perform the mission of both the sector search and the square search.

In order to show the flexibility of the proposed controller, the special problem of a *man overboard* was investigated. Suppose that one of the crew falls in the water on the starboard side of the ship. Usually, single turning, or double turning, or Willison turning can be used to steer the ship and return to the original position to complete a rescue. As is well known, single turning is the most effective and faster technique. However, even for an experienced pilot, it is usually difficult to reach the original position due to the constraints caused by the turning capability of the ship. Figure 9 shows a successful, single turning manoeuvre using our proposed controller with a setting target coordinate $(T_x, T_y) = (0, 0)$.

6. CONCLUSION. In this study, we have developed a fuzzy gain scheduling PD controller with a back-propagation algorithm to solve some maritime search problems, including: the sector search problem; the square search problem; and the rescue of a *man overboard*. The parameters of the PD controller are updated by fuzzy reasoning. It is our firm belief, that the proposed controller is useful, not only for

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Figure 9. Simulation result of single turning manoeuvre to the original position.

maritime search problems, but also for other ship manoeuvring problems, such as the course-keeping problem, course-tracking problems, and other rescue problems.

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KEY WORDS

1. Marine. 2. Search and Rescue. 3. Automation.