THEORETICAL AND EXPERIMENTAL INVESTIGATION OF GAIN SCHEDULING AND ADAPTIVE AUTOPILOTS FOR A MODEL BOAT

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Abstract:
In this paper Gain scheduling PD controller and Adaptive PD controller are adopted as autopilot systems for a boat model. The control design is based on Nomoto’s first order mathematical model. Adaptive controller is based on model reference adaptive controller theory. Similar test runs are conducted on a model boat with the above controller algorithms. The effectiveness of the two controllers are compared numerically and graphically. The results show that both controllers are well for reaching the desired heading angle. The adaptive controller has some notable advantage over gain scheduling controller.

Keywords: Adaptive PD controller, Gain scheduling controller, Model Reference Adaptive controller, Model reference adaptive control systems, autopilot systems, heading angle.

1. Introduction

Autopilot is one of the most important equipment used in ships. Autopilots are not just used to lead the ship on a desired trajectory, but also raise the safety level of the journey and control the ship economically. An optimal pilot can shorten 3-5% length of the journey and reduce the fuel consumption. A good autopilot can help to avoid undesired situations on maneuvering and remarkably reduce the numbers of ship operators. In the last few decades, taking the advantage of drastic development of electronics and control theory several new and effective methods have been proposed and developed for designing ship-autopilots [9],[3],[4]. Autopilots designed based on PD and PID controllers are simple, reliable and easy to construct, however their performance in various environmental conditions is not as good as desired. These autopilots require aid from operators for parameter adjustment based on navigation conditions. The main disadvantage of PID type autopilot is that they are difficult to adjust manually. The number of controller settings is too large and there is no clear relation between the settings and the operation demands or the environmental changes.

In recent years a large number of publications about new autopilot designs has appeared various algorithms have been proposed to give these autopilots optimizing and self adjusting (adaptive) properties. Adaptive autopilot designs for an unmanned aerial vehicle have been presented by Calise [7]. The work summarizes the application of two adaptive approaches to an autopilot design and presents an evaluation and comparison of the two approaches in simulation for an unmanned aerial vehicle. Autopilots based on the theory of model reference adaptive systems developed different techniques to implement the model reference adaptive system on working models of boat and the hardware used was simple. Monitoring of the environmental conditions as a basis for adjustment of the autopilot has been described by Oldenburg, Sugimoto, Kajina and Kannanam [6], where the controller settings were adjusted by measuring the frequency of waves and intensity of wind. Using the measured data, models are developed and incorporated into the controller adjustment mechanism.
A number of studies have shown that PID controllers may compensate any unknown constant uncertainties, but the closed system stability is still questionable. It was shown that the PID controller is very stable provided the gain matrices satisfy a complex rotation ship [1]. Based on [1] a PID controller was introduced, so that positioning accuracy is improved and the local stability is proven [2]. A nonlinear adaptive PD controller, which is valid globally in the presence of uncertainties in the gravity and buoyancy [8].

Ships operating in seawater are strongly influenced by unpredictable environmental disturbances such as wind, wave and current frequently. Hence, to navigate safely and economically, the ship must have a robust autopilot system with good steering characteristics. To design such a robust computer based autopilot system, a suitable mathematical model for ship steering dynamics should be constructed.

2. Mathematical Modeling
A mathematical model that describes the dynamics of the process is essential for the design of a controller. In order to construct a desired controller the ship’s steering behavior and influence of all the disturbances (Fig.1) on steering is to be known exactly. Some of the disturbances are real, not controllable in anyway, while other are influenced, but their control can be estimated.

To analyze the dynamics of ship, a coordinate system is shown in Fig.2. The ship’s center of gravity G is chosen as the origin of this coordinate system and the axis of symmetry are chosen as x-, y- and z-axis.

In general there are six degrees of freedom, motions in the x, y and z directions and rotations around these axes. For surface ships, it is common practice to consider only motions in the horizontal plane. This reduces the number of degrees of freedom to three such as motion in x-direction (surge), y-direction (sway) and rotation around z-axis (yaw).

Hence, ship maneuvering is treated as a horizontal plane motion, and only the surge, sway and yaw models are considered. To take advantage of the properties of the ship hull, a moving coordinate system is considered.
The basic equations of motion are obtained by Newton’s law.

\[
\frac{d^2 x_0}{dt^2} = X_0 \\
\frac{d^2 y_0}{dt^2} = Y_0 \\
\frac{d^2 \psi}{dt^2} = N
\]

In order to determine the influence of forces and moments directly acting on the hull of the ship, a ship fixed coordinates system is very useful. Transformation of above Eq. (1)-(3) gives

\[
m(u - vr) = X \\
m(v + ur) = Y \\
I_{oz} \ddot{r} = N
\]

where \(X\) and \(Y\) are the sum of all forces in the \(x\) and \(y\) directions, \(N\) is the moment caused by these forces. \(u\) and \(v\) are speeds in \(x\) and \(y\) directions. \(r\) is rate of turn. \(m\) is mass of ship. \(I_{oz}\) is moment of inertia about \(z\)-axis.

The first order model of Nomoto’s is a compromise between the demand for a simple mathematical model and a fair approximation of the actual maneuvers of the ship.

The first order Nomoto model follows\[5\]:

\[
\ddot{\psi} + \dot{\psi} = K \delta
\]

Where

\(\ddot{\psi}\) - yaw angular acceleration (rad/s²)
\(\dot{\psi}\) - rate of turn (rad/s)
\(\delta\) - actual rudder angle
\(K\) – proportionately constant (1/sec.)
T – time constant (s)

The influence of forward speed is added to this model by the relations,

\[
T' \dot{\psi} + \psi = K' \delta
\]

Where

\(K' = K \frac{L}{U}\)
\(T' = T \frac{U}{L}\)

\(T'\) and \(K'\) are dimensionless constants with respect to speed.
\(U\) is ship’s speed.
\(L\) is ship’s length.

Linearization of Eq. (4)-(6) w.r.t. a constant speed, straight line motion condition decouples the surge equation. Taking the Laplace transform of the coupled sway-yaw system and cancelling the sway term, the following 2nd order Nomoto model is obtained.

\[
\frac{r(s)}{\delta(s)} = \frac{K(l + T_1 s)}{(1 + T_1 s)(l + T_2 s)}
\]

Where \(\delta\) is the desired heading angle,
is rate of heading,  
T time constant and  
K is the rudder gain

Further simplifying Eq. (11) and 1st order Nomoto model follows;

\[
\frac{r(s)}{\delta(s)} = \frac{K}{(1 + Ts)}
\]  
(12)

Where  \( T = (T_1 + T_2 + T_3) \) as the effective yaw mode time constant and K is rudder gain.

The Eq. (12) can be represented by differential equation in the time domain is

\[
\dot{\psi} = -\frac{1}{T} r + \frac{K}{T} \delta
\]  
(13)

With the definition \( \dot{\psi} = r \), when \( \psi \) is the heading angle. Eq. (13) can be written as

\[
\frac{\psi(s)}{\delta(s)} = \frac{K}{s(1 + Ts)}
\]  
(14)

It is to be noted that in this work the track keeping is accomplished by a sequence of course-changing maneuvers and Eq. (14) is the boat model to be used in the course changing autopilot design.

Estimation of boat parameters K and T initially user inputs the speed to both proportions with certain speed difference and this speed is maintained constant for the entire test run. The heading angle data is recorded by digital electronic compass. The same procedure is followed and several tests are conducted for different speeds. By analyzing the data parameters K and T of the Nomoto model are evaluated.

3. Design of Controller
3.1. Gain scheduling controller

Gain scheduling is very easy to implement in computer-controlled systems. Here it is possible to find auxiliary variables that correlate well with the changes in process dynamics. By changing the parameter variations, which are of functions of auxiliary variables feedback gains are adjusted.

The main problem in design of gain scheduling controller is to find suitable scheduling variables. This is normally done based on the physics of the system. When scheduling variables have been deformed, the controller parameters are calculated at a number of operating conditions using some suitable design approach. The controller is tuned for each operating condition. The stability and performance of the system are evaluated at different operating conditions.

It is necessary to have a good insight into the dynamics of the process. In the present work, the boat dynamic model parameters K and T are the variables which are to be scheduled based on the error, the difference between the actual heading of the boat and the desired headings. Not only the process parameters K and T are scheduled, the controller gains \( K_p \) and \( K_d \) are calculated based on the scheduled process variables.

The formulae for calculating \( K_p \) and \( K_d \) are as follows [11]

\[
K_p = (\omega_n^2 T / K) \left( \frac{L}{U} \right)^2
\]  
(15)

\[
K_d = 2\omega_n \left( KpKT - 1 / K \right)
\]  
(16)

Where  \( K_p \) is the proportional gain of PD controller.  
\( K_d \) is the derivative gain of PD controller.
\( \omega_n \) is the natural frequency of yawing, here it is constant as we are using propellers to control the boat yawing.

\( \zeta \) is the damping ratio.

L is length of the boat.

U is speed of the boat.

For different speeds and for various values of K and T, the values of \( K_p \) and \( K_d \) are shown in Table 1.

### Table 1 Parameters lookup table for different speeds and various K and T values

<table>
<thead>
<tr>
<th>Speed of the boat in m/s</th>
<th>K</th>
<th>T</th>
<th>( K_p )</th>
<th>( K_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.3</td>
<td>6.667</td>
<td>3.15</td>
<td>0.357</td>
<td>0.917</td>
</tr>
<tr>
<td>6.0</td>
<td>6.667</td>
<td>4.8</td>
<td>0.545</td>
<td>1.46</td>
</tr>
<tr>
<td>7.4</td>
<td>6.667</td>
<td>5.7</td>
<td>0.635</td>
<td>1.73</td>
</tr>
<tr>
<td>8.2</td>
<td>6.667</td>
<td>6</td>
<td>0.68</td>
<td>1.84</td>
</tr>
</tbody>
</table>

### 3.2. Adaptive Controller

An adaptive system may be defined as follows: “An adaptive system is one in which in addition to the basic (feedback) structure, explicit measures are taken to automatically compensate for variations in the operating conditions, for variations in the process dynamics or for the variations in the disturbances, in order to maintain an optimal performance of the system” (Fig.5).

In practice it is impossible to apply gain scheduling to a lot of different process variables. Several types of adaptive systems have been developed that allow a system to be optimized without any knowledge of the causes of changing process dynamics. They are subdivided into Systems with direct adaptation and indirect adaptation. Direct adaptive systems adjust the controller parameters without explicit identification as shown in Fig.6. Model reference adaptive system is a direct adaptive system.
Indirect adaptive systems use the results of the identification of the process parameters as shown in Fig. 7.

![Fig. 7. Indirect adaptive system](image)

### 3.2.1 Model Reference Adaptive System (MRAS)

The idea behind MRAS is to create a closed loop controller, in which parameters are updated as per the response of the system. The output is compared with the desired response from a reference model. The controller parameters are updated based on this error.

![Fig. 8. Model reference adaptive system](image)

The feedback loop is called the inner loop and the parameter adjusting loop is called outer loop [1].

The reference model for the first order Nomoto’s model is chosen as [10]

\[ \psi_m(t) = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \psi_r(t) \]  

![Eqaution 17](image)

where  
\( \psi_m(t) \) is the output heading of the reference model.  
\( \psi_r(t) \) desired heading of the boat, it is the input to the reference model.  
\( \omega_n \) frequency of rudder angle fluctuations. Here it will be taken as 0.05 rad/s.  
\( \xi \) is damping ratio. Here it is equal to 1.

The above Eq. (17) is represented in differential form as

\[ \frac{d^2\psi_m(t)}{dt^2} + 2\xi\omega_n \frac{d\psi_m(t)}{dt} + \omega_n^2 \psi_m(t) = \omega_n^2 \psi_r(t) \]  

![Eqaution 18](image)

The output of Eq. (18) used in calculation of adaptive controller gains.

### 4. Experimental Setup

The experiments are performed on boat model. The boat has two propellers that can be activated to control the forward motion and also steering motion. The difference in the speeds of the two motors helps in controlling
steering torque. The setup consists of PC end and boat end. The programs are written in such a way that all the calculations are done on the PC end. Simple autopilot is constructed with the standard units available in the market. The Block diagram is shown in Fig.9.

5. Present Work

In the present work the performance of PD controllers on the heading control of a small boat is investigated. The effectiveness of the gain scheduling controller and adaptive controller is observed by implementing the above two algorithms on a working model of boat. The two controller algorithms are implemented by using C language. The message containing the heading angle data, roll data, pitch data, time stamp is sent for every 1/8th second from boat to PC. Similarly PC will sent a message for every 1/8th second to boat with the information about channel numbers and speed input, step size for the speed. In case of gain scheduling controller a set of pre determined proportional and derivative gain values are used depending on process parameters changes, where as in adaptive controller gains are estimated through online for every time step. The gain scheduling controller
as well as MRAS controller is implemented for the similar test runs. The effectiveness of the two controllers are established in the results. Performance is observed by varying the desired heading angle of boat model.

6. Results and Discussion

Performance of gain scheduling controller and Adaptive controller (MRAS) are shown in Figs 10-13. Similar test runs are conducted with the above controller algorithms for reaching the same desired angle. These figures shows for reaching the same desired angle, the heading angle vs time and rate of heading vs time for different controllers. From Fig. 10 it is known that for desired angle 10°, the Gain scheduling controller took 11 seconds and MRAS took 10.5 seconds. Also In Adaptive controller (MRAS), the rate of heading changes are very often, which cause speeds of the motors keep on changing continuously. The similar observations are observed in fig 11 – 13 for reaching desired angles 50°, 100°, 250°.
6. Conclusions

A model boat has been considered to satisfy the steering dynamics and first order Nomoto’s model. The model is found to be both controllable and observable. Two different controllers gain scheduling controller and Adaptive controller have been developed and implemented on the working model of the boat. The effectiveness of each algorithm is validated for reaching the desired heading angle. In all instances it is clear that desired angle reaches faster in case of adaptive controller.
References


