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Design a Robust PI Controller for Line of Sight Stabilization System

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ABSTRACT
Based on the minimization of integral of time-weighted absolute error index (ITAE), a robust proportional-integral (PI) controller is designed to achieve high performance and high stabilization precision for the line of sight (LOS) stabilization system. The system ability to reject outer disturbance, attenuate the measurement noise and its robustness are investigated. The proposed model exhibits a simplicity and applicability for designing a robust control system. Simulation results demonstrate the effectiveness of the designed controller, which offers an excellent performance in the presence of uncertainty and nonlinearity, Improves the outer carrier disturbance rejection, attenuates the measurement noise.

***Keywords* - integral of time-weighted absolute error index (ITAE), proportional-integral (PI), line of sight (LOS).**

1. INTRODUCTION
In recent years, modern control systems are commonly uses the optical sensors such as CCD cameras, optics, laser seekers for target tracking. Due to the disturbance from the carrier, the electro- optical equipment can not work normally and finally lose the target. The line of sight (LOS) stabilized technology is used to isolate the sensor's LOS from carrier disturbance in order to guarantee accurate aiming and tracking for the target at the inertial space [1-4].

Physical systems and external environment is somewhat difficult to model precisely. The external environment may change in an unpredictable manner, and may be subject to significant disturbances. The design of the control systems in the presence of significant uncertainty requires the designer to seek about a robust system. A robust control system exhibits the desired performance despite the presence of significant process uncertainty [5]. The control system is described robust when it has low sensitivity to process change, stable over the range of parameter variations, and the performance continues to meet the specifications in the presence of a set of changes in the system parameters [6].

One of the most popular controllers widely used in the control field is the proportional-integral-derivative (PID) controller [7-9]. Several methods have been proposed for the LOS stabilization control system using PID and other types of controller, however, most of these methods are either concern only with achieving the required performance regardless the effect of process change, uncertainty of the system[10,11], or it is complex and can not be realized easily[12-16].

In this paper, a robust PI controller is applied in order to achieve high control system performance with high robustness in a simple and applicable method based on the minimization of integral of time-weighted absolute error (ITAE) index.

2. ROBUST PI CONTOLLER
2.1. Error signal analysis and system sensitivity
The tracking error $E(s)$ for a closed loop feedback control system shown in Fig. 1 can be defined as:

$$E(s) = R(s) - Y(s) \tag{1}$$

Where $R(s)$ and $Y(s)$ are the system input and output signals, respectively.

For a unity feedback system the output signal $Y(s)$ can be defined as:

$$Y(s) = \frac{G_c(s)\,G(s)}{1+G_c(s)\,G(s)} R(s) + \frac{G(s)}{1+G_c(s)\,G(s)} T_d(s) - \frac{G_c(s)\,G(s)}{1+G_c(s)\,G(s)} N(s) \tag{2}$$

Where $G(s)$ is the motor and platform transfer function, $G_c(s)$ is the controller transfer function, $T_d(s)$ and $N(s)$ are the disturbance and measurement noise signals, respectively.

For $L(s) = G_c(s)\,G(s)$ and using (1) the tracking error can be defined as:

$$E(s) = \frac{1}{1+L(s)} R(s) - \frac{G(s)}{1+L(s)} T_d(s) + \frac{L(s)}{1+L(s)} N(s) \tag{3}$$

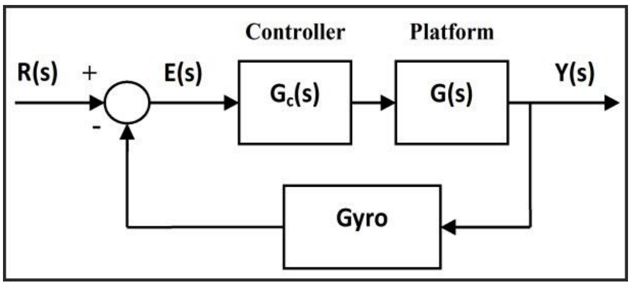

Fig.1. System configuration

System sensitivity is defined as the ratio of the change in the system transfer function to the change of a process transfer function (or parameters) for a small incremental change.

$$S = \frac{\partial T / T}{\partial G / G} = \frac{\partial \ln T}{\partial \ln G} \quad (4)$$

The closed-loop system transfer function T(s) is:

$$T(s) = \frac{G_c(s)G(s)}{1 + G_c(s)G(s)H(s)} \quad (5)$$

For unity feedback system, that is, $H(s)$ =1 and using (4), the sensitivity of the feedback system is:

$$S_G^T = \frac{1}{1 + G_c(s)G(s)} \quad (6)$$

2.2. Disturbance rejection and Measurement noise attenuation

For zero input and zero noise signals, $R(s) = N(s) = 0$, the equation (3) becomes:

$$E(s) = -S(s)G(s)T_d(s) = \frac{G(s)}{1 + L(S)} T_d(s) \quad (7)$$

For good disturbance rejection, the loop gain should be large over the frequencies of interest that associated with the expected disturbance signals.

For zero input and zero disturbance signals, $R(s) = T_d(s) = 0$, the equation (3) becomes:

$$E(s) = C(s)N(s) = \frac{L(s)}{1 + L(S)} N(s) \quad (8)$$

Where $C(s)$ is the complementary sensitivity.

The effect of noise signal on the tracking error can be decreased by increasing the loop gain L(s).

If the controller is designed such that $L(s) \ll 1$, the complementary sensitivity function $C(s)$ will be small and $C(s) \approx L(s)$, then the noise will be attenuated.

In practice, the disturbance signals are often low frequency, while the measurement noise signals are often high frequency. In order to design a robust controller that can reject the disturbance signals and attenuate the measurement noise, the controller should be high gain at low frequencies and low gain at high frequencies.

2.3. Design of Robust PI Controller

The robust PI controller design is done through three steps: The first step is done by selecting the natural frequency ω_n and the damping ratio ζ of the closed loop system which specify the required settling time and percent over shoot, respectively. From Fig. 2 [5] or (9). The damping ratio ζ is decided to specify the percentage of overshoot.

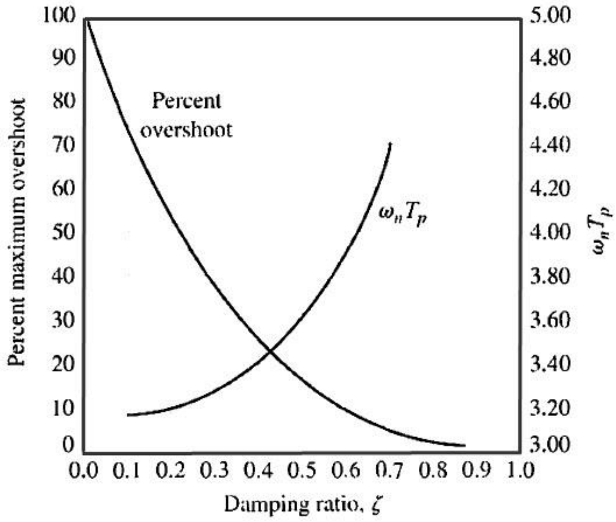

Fig.2. Percent overshoot versus damping ratio.

$$P.O = 100 \exp(-\zeta\pi / \sqrt{1 - \zeta^2}) \quad (9)$$

The natural frequency of the closed loop system is calculated using (10) for the required settling time and damping ratio,

$$T_s = 4\tau = \frac{4}{\zeta\omega_n} \quad (10)$$

Where T_s is the settling time, τ is the time constant, ζ is the Damping ratio, and ω_n is the closed loop natural frequency.

Secondly, the two PI coefficients are calculated by using the appropriate optimum equation (Table (1)) and the calculated natural frequency ω_n to obtain $G_c(s)$.

Table 1
The optimum coefficient of $T(s)$ based on the ITAE criterion.

$s + \omega_n$
$s^2 + 1.4\omega_n s + \omega_n^2$
$s^3 + 1.75\omega_n s^2 + 2.15\omega_n^2 s + \omega_n^3$
$s^4 + 2.1\omega_n s^3 + 3.4\omega_n^2 s^2 + 2.7\omega_n^3 s + \omega_n^4$
$s^5 + 2.8\omega_n s^4 + 5.0\omega_n^2 s^3 + 5.5\omega_n^3 s^2 + 3.4\omega_n^4 s + \omega_n^5$
$s^6 + 3.25\omega_n s^5 + 6.60\omega_n^2 s^4 + 8.60\omega_n^3 s^3 + 7.45\omega_n^4 s^2 + 3.95\omega_n^5 s + \omega_n^6$

Finally, a pre-filter $G_P(s)$ is designed to eliminate the zeros in the closed-loop system transfer function and convert it to the general closed loop transfer function in the form:

$$T(s) = \frac{Y(s)}{R(s)} = \frac{b_0}{s^n + b_{n-1} s^{n-1} + \cdots + b_1 s + b_0} \quad (11)$$

The coefficients that will minimize the ITAE performance criterion for a step input have been determined for the general closed loop transfer function [17].

3. SIMULATION STUDY

In this model, the plant under consideration consists of a gimbaled payload of 0.05 $kg.m^2$ moment of inertia. A rate gyro with scale factor (SF) 500 mV/ °/s is used to measure the angular rate of the gimbal in azimuth, the open loop transfer function of motor and gimbal with payload is 50/ (0.05s+1).

3.1. Parameter tuning and design of controller and prefilter

Based on these parameters, simulation of the stabilization loop that controlled by robust PI controller is carried out on the azimuth axis. The PI controller parameters (K_P, K_I) are calculated using the optimization algorithm based on the minimization of integral of time-weighted absolute error (ITAE) index. The desired dynamic performance of system imposes that: T_s=0.02s, $P.O < 5\%$, and zero steady state error. The optimal PI controller with best ITAE is designed as:

$$G_c = 0.76 + \frac{163.3}{s} \tag{12}$$

The closed loop transfer function without pre-filter is:

$$T(s) = \frac{163260(0.0047s+1)}{s^2+400s+81640} \tag{13}$$

To eliminate the zeros in the closed-loop system transfer function, improve the over shoot and system performance, a pre-filter $G_P(s)$ should be designed as:

$$G_P = \frac{0.5}{0.0047s+1} \tag{14}$$

Then the overall system transfer function with pre-filter is:

$$T_o = \frac{81630}{s^2+400s+81630} \tag{15}$$

Fig. 3 shows the system response to a unit step without disturbance and noise. As the figure shows, settling time and percent overshoot satisfy the required performance, and zero steady state error is also satisfied.

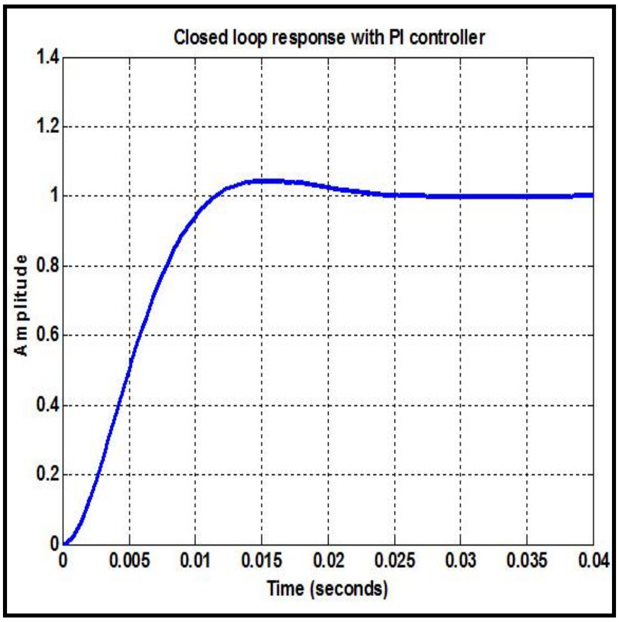

Fig.3. Step response of the PI controlled system without disturbance and noise.

Fig. 4 shows the bode diagram of the closed loop system with the robust PI controller (continuous line) and the output sensitivity (dashed line). As shown in the figure, the output sensitivity is very low at low frequencies. This means that the sensitivity of the system to the process change is very low.

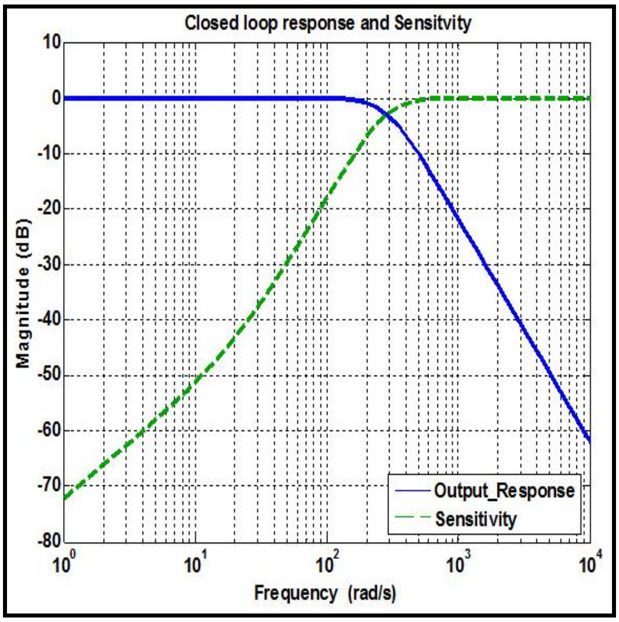

Fig.4. Bode diagram of the robust PI controlled system.

3.2. Performance of disturbance rejection and noise attenuation

Fig. 5 shows the line of sight precision with gyro noise signal shown in Fig. 6 under no outer disturbance. As the figure shows, the stabilization precision of PI controller is less than 0.02 °/s, which indicates that this kind of controller can attenuates the nonlinear gyro measurement noise.

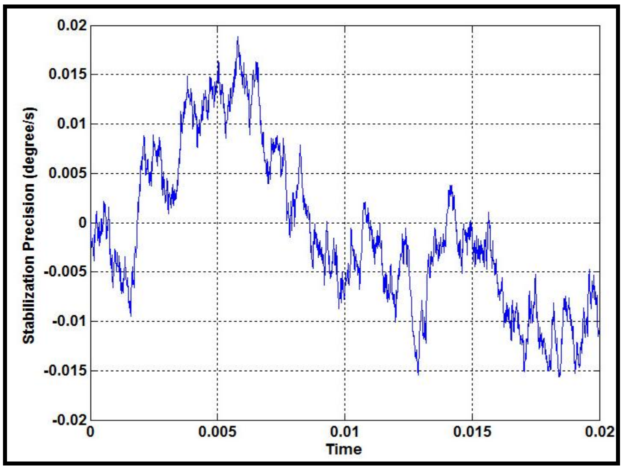

Fig.5. LOS stabilization precision without disturbance.

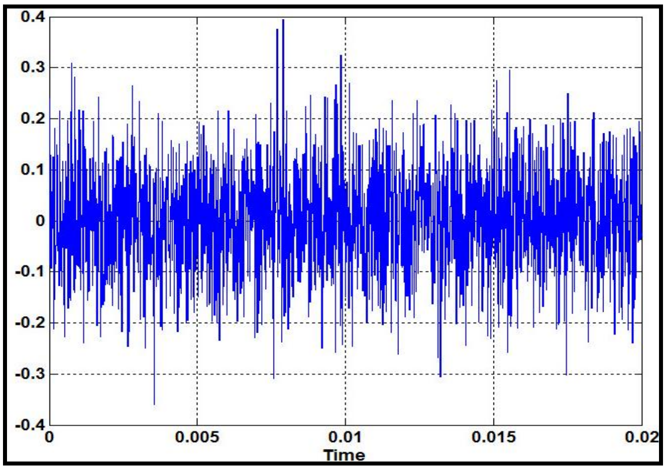

Fig.6. Gyro signal noise.

Fig. 7 shows the line of sight precision with gyro noises under the disturbance of sinusoidal signal with amplitude of 30º/s and frequency 1 Hz. It can be seen that PI controller provides a good stabilization precision.

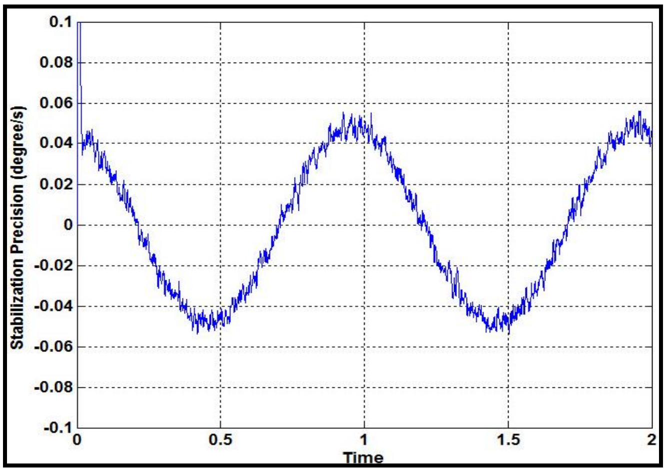

Fig.7. LOS stabilization precision with sinusoidal disturbance.

3.3. Robustness of PI controller

Fig. 8 shows step response of the PI controlled system when the payload changes $\pm 50\%$. Fig. 9 shows step response of the PI controlled system when the motor parameters changes $\pm 50\%$. It can be indicates that the PI controller that designed based on minimization of integral of time-weighted absolute error (ITAE) index has a good robustness.

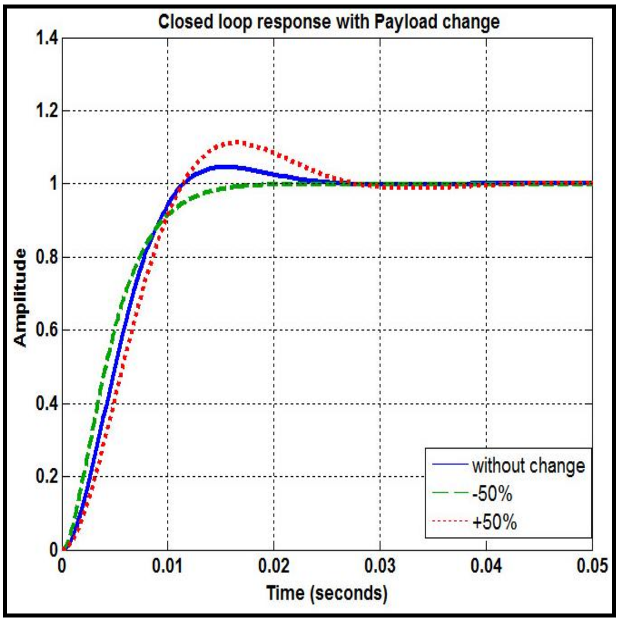

Fig.8. Step response of the PI controlled system when the payload changes $\pm 50\%$.

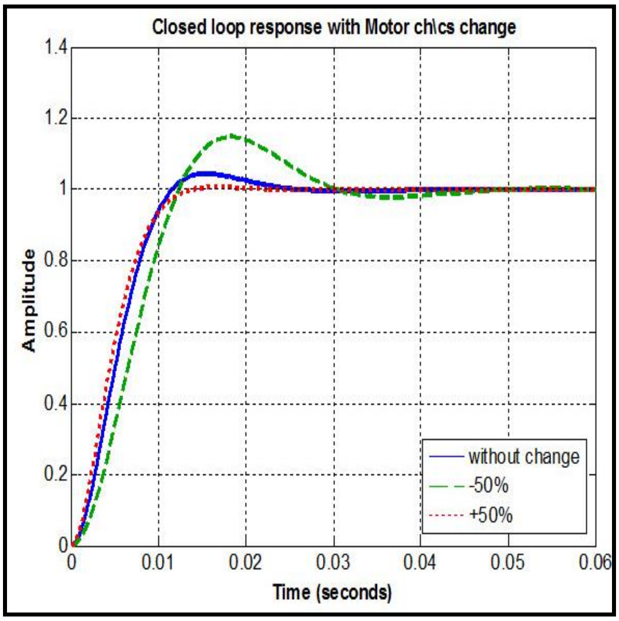

Fig.9. Step response of the PI controlled system when the motor parameters changes $\pm 50\%$.

4. CONCLUSIONS

A design of robust PI controller for the LOS stabilization system that has some nonlinearity and uncertainty is introduced. The optimization based on the minimization of integral of time-weighted absolute error (ITAE) index is used to calculate the PI parameters. The results show that the designed controller specified the required performance, 0.02s settling time, less than 5% overshoot percentage, and zero state error is achieved. The system improves the outer carrier disturbance rejection, and attenuates the measurement noise. The stabilization precision of the control system is found to be about 0.02 º/s. In addition, the system sensitivity to process change (payload, motor parameters) is low and the controller has a good robustness. The proposed design model is simple, applicable, which achieves high specification and high robustness at the same time.

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