A Solar Tracking System Using Feedback Controller and State Estimation Filter

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Abstract—In this paper, a solar tracking system with feedback controller and state estimation filter is designed with consideration of unpredictable disturbance and feedback sensor noise and verified through various computer simulations. It is verified that the designed solar tracking system with PI controller and Kalman filter has the ability to reject disturbance and reduce feedback sensor noise.

Index Terms—Feedback Control, State Estimaion Filter, Solar Tracking System, Disturbance, Noise.

I. Introduction

The physical system of the solar tracking system consists of an electric motor and a solar panel. A voltage is supplied to the electric motor to generate a torque and then this torque moves the solar panel. Thus, it is needed to design a controller to set the correct voltage so that the solar tracking system tracks the sun well. However, even if the solar tracking system works accurately in normal situations, it may undergo unpredictable uncertainties such as disturbance and feedback sensor noise. These uncertainties, whether large or small, must be addressed because they adversely affect the performance of the solar tracking system. A feedback control can be considered for disturbance rejection. For example, the feedback control with the PID controller takes action to force the plant variable back toward the desired output whenever a disturbance on the plant causes a deviation [1]- [5]. The estimation filter can be considered for noise reduction. For example, the state estimation filter such as the well-known Kalman filter adjusts the currently measured sensor value by considering the past sensor data to reduce noise in the measured value [6]- [9].

This paper designs a solar tracking system with feedback controller and state estimation filter for disturbance rejection and noise reduction when there are disturbance and feedback sensor noise. Each detailed design process is verified through computer simulations. The performance degradation due to sun's moving and unpredictable disturbance in the basic open-loop control is shown. To resolve this problem, a proportional-integral controller based feedback system is designed for the solar tracking system. To improve the performance degradation due to feedback sensor noise that may occur during the feedback process, the Kalman filter as a state estimation filter is applied for the solar tracking system. It is verified that the designed solar tracking system with feedback controller and state estimation filter has the ability to reject disturbance and reduce feedback sensor noise.

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II. Feedback Controller Design for Solar Tracking System

The physical system of the solar tracking system consists of an electric motor and a solar panel. With a voltage source, the electric motor generates torque to rotate the solar panel as follows:

$$\begin{aligned} L\dot{i}(t) + Ri(t) + K_g K_f \dot{\theta}(t) &= V(t), \\ T(t) &= K_g K_t i(t). \end{aligned} \quad (1)$$

The solar tracking system consists of many kinds of variables and parameters.

TABLE I
Variables for solar tracking system

Variable	Notation	Unit
Panel position (Azimuth angle)	$\theta(t)$	rad/s
Current	$i(t)$	A
Voltage source	$V(t)$	V
Torque	$T(t)$	N

As shown in (1), a voltage $V(t)$ is supplied to the motor to generate a torque $T(t)$ and then this torque moves the solar panel. Thus, it is needed to design a controller to set the correct voltage $V(t)$ so that the panel tracks the sun well. It is wanted that the panel pointing at the sun, so the difference between these two positions is the error. The controller applies a voltage to the motor to make that error as small as possible. And if the sun moves, the controller will react accordingly to keep the panel pointing at the sun.

In PID controller, the derivative term helps respond to quick changes. Thus, the derivative term might not

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be needed because the sun moves steadily across the sky. Hence, the PI controller can be considered. The PI controller with $K_i = 180$ is applied while maintaining $K_p = 240$.

Sometimes the sun is obscured by clouds, and also does not appear during rain. Then suddenly the sun may appear, in which case the sun tracker will move in search of the sun. In order to consider this situation, the reference for the moving sun's position is emulated by an unit step function as shown in 1 for the PI controller. When the proportional-integral(PI) controller is applied, the solar tracking system tracks the sun position with the overshoot as shown in Fig. 1.

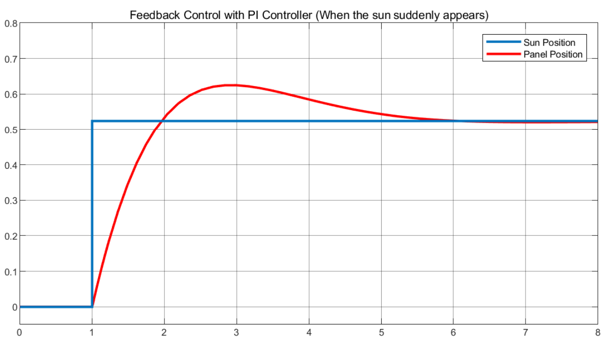

Fig. 1. Feedback control with PI controller when the sun suddenly appears

However, in environments where a solar tracking system is installed, it is general that the sun steadily across the sky for a long time. Thus, in order to consider this situation, the reference for the moving sun's position is emulated by a ramp type as shown in Fig. 2 for the PI controller. When the PI controller is applied, the solar tracking system tracks the sun well overall except for the initial time.

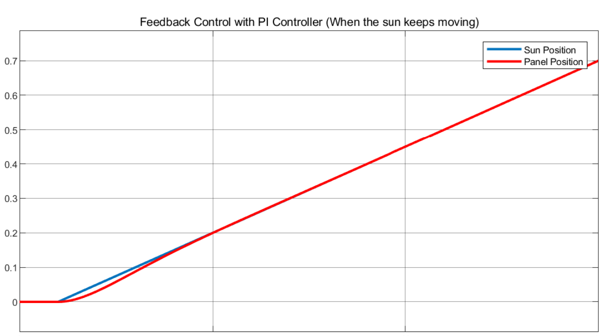

Fig. 2. Feedback control with PI controller when the sun keeps moving

Moreover, there can be a disturbance issue. In real situations, there can be unknown disturbance which is often in the form of unpredicted variations on the system that can lead to inaccurate positioning of the solar panel. To address this, it is assumed in this paper that the disturbance affects the voltage source and can drop the voltage. So, to see the effect of the disturbance in simulation, the disturbance is assumed to act at $15sec$ and simulation time is extended to $30sec$. It is shown that the feedback control with the PI controller compensates for the unpredicted disturbance as shown in Fig. 3.

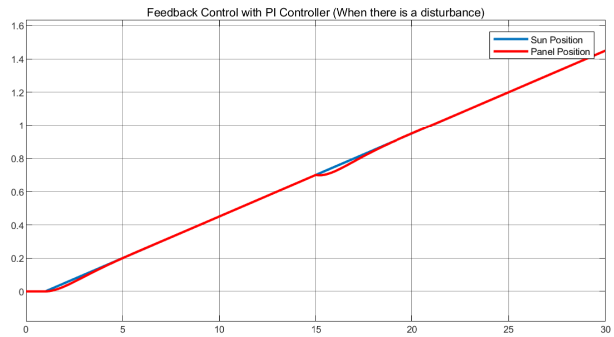

Fig. 3. Feedback control with PI controller when there is a disturbance

III. State Estimation Filter Design for Solar Tracking Syetem

In order that the feedback control in the solar tracking system can adjust the error, a feedback sensor is required to measure output i.e. the panel's actual position. Unfortunately, the feedback sensor can be often noisy. The noise coming from a sensor is thermal noise arising from thermal motions of charges within the sensor. Another low-level source of noise is shot noise related to the fact that charge is quantized. The feedback sensor noise is random variations of sensor output unrelated to variations in sensor input. Therefore, when the feedback sensor measures output imperfectly due to the noise, the control accuracy is affected in the conventional feedback control system. A noise signal with noise variances $\sigma = 0.0005$ is considered for simulations. The actual position of the panel is very noisy for both noise signals. The measured output i.e. the actual position should be corrected. Thus, the filtering should be applied to get the noise reduction of panel's position.

The Kalman filter is known to be the best linear unbiased estimator for linear systems with Gaussian process and measurement noise. The Kalman filter has been a standard choice and a beautiful reference for the state estimation filtering. The Kalman filter's closed-form recursive equations have turned it into arguably the most popular and widely used estimator, with applications ranging from the aerospace and aircraft industries to seismology and weather forecasting [6]- [9]. To apply the state estimation filtering, the state-space realization is required for the solar tracking system. The state-space approach is a generalized time domain method for modeling, analyzing and designing a wide range of control systems and is particularly well suited to digital computational technique. The mathematical model (1) of the solar tracking system can be represented in the continuous-time state-space model as follows:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t), \\ y(t) &= Cx(t), \end{aligned}$$

with variables and matrices

$$x(t) \triangleq \begin{bmatrix} \theta(t) \\ \dot{\theta}(t) \\ i(t) \end{bmatrix},$$

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -K_d/J & K_g K_t/J \\ 0 & -K_g K_t/L & -R/L \end{bmatrix},$$

$$B = \begin{bmatrix} 0 \\ 0 \\ 1/L \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix},$$

where $x(t)$ is state variable with panel position $\theta(t)$, panel speed $\dot{\theta}(t)$ and current $i(t)$, $y(t)$ is output variable with panel position $\theta(t)$, $u(t)$ is control input variable with voltage source $V(t)$.

The filtered panel position $\hat{\theta}(t)$ of the first state variable $\theta(t)$ is fed to the computation of error $e(t) = \theta_d - \hat{\theta}(t)$ where θ_d is the reference for the moving sun's position. Then, this error $e(t)$ is fed to the PID controller to compute the voltage source. Finally, it is verified from Fig. 4 that the solar tracking system with both feedback controller and state estimation filter is sufficient for meeting the given performance criteria and compensates for the unpredicted disturbance as well as the feedback sensor noise.

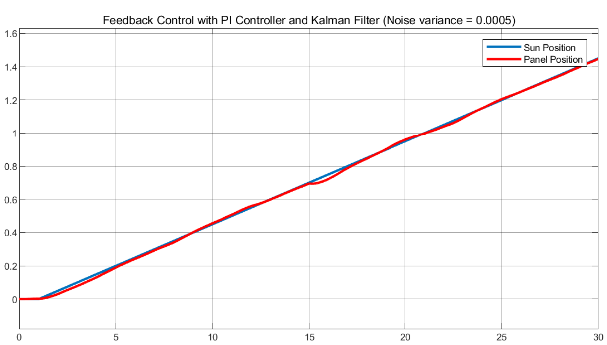

Fig. 4. Feedback control with PI controller and Kalman filter

IV. Conclusions

This paper has designed a solar tracking system with feedback controller and state estimation filter for disturbance rejection and noise reduction when there are disturbance and feedback sensor noise. Each detailed design process has been verified through computer simulations. Because there can be performance degradation due to sun's moving and unpredictable disturbance in the open-loop control, a PI controller based feedback system has been designed for the solar tracking system. To improve the performance degradation due to feedback sensor noise that may occur during the feedback process, the Kalman filter as a state estimation filter has been applied for the solar tracking system. It has been verified that the designed solar tracking system with feedback controller and state estimation filter has the ability to reject disturbance and reduce feedback sensor noise.

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