ICIC Express Letters ICIC International ©2024 ISSN 1881-803X
Volume **18**, Number **3**, March **2024** pp. **247–254**

A SOLAR TRACKER WITH CONSIDERATION OF UNPREDICTABLE DISTURBANCE AND FEEDBACK SENSOR NOISE

Pyung Soo Kim

System Software Solution Lab.
Department of Electronic Engineering
Tech University of Korea
237 Sangidaehak-ro, Siheung-si, Gyeonggi-do 15073, Korea
pskim@tukorea.ac.kr

Received June 2023; accepted August 2023

Abstract. *In this paper, a solar tracker with feedback controller and state estimation filter is designed with consideration of unpredictable disturbance and feedback sensor noise and verified through various computer simulations. First, a couple of mathematical models, panel model and motor model, for the solar tracker is derived. Second, the performance degradation due to sun's steady moving and unpredictable disturbance in the basic proportional control is shown. To resolve this problem, a proportional-integral controller based feedback system is designed for the solar tracker. Third, to improve the performance degradation due to feedback sensor noise that may occur during the feedback process, a state estimation filter is applied for the solar tracker. Ultimately, it is verified that the designed solar tracker with feedback controller and state estimation filter has the ability to reject disturbance and reduce feedback sensor noise.*
Keywords: PID controller, Kalman filter, Solar tracker, Disturbance, Noise

1. **Introduction.** In these days, there are emerging technologies focused on harvesting solar power. For example, solar panels, also known as "photovoltaic (PV) panels", are used to convert light from the sun, which is composed of particles of energy called "photons", into electricity that can be used to power electrical loads. Many of solar panels face south and are positioned with the fixed angles. This means that they produce more electricity when the sun is shining directly on them in the middle of the day, and less power when the sun is to the east or west, early and late in the day. Therefore, the automatic solar tracker has been researched and developed for better utilization of the renewable solar energy source. The solar tracker positions the solar panel in a hemispherical rotation to track the movement of the sun and thus increase the total electricity generation as compared to the static solar panel [1, 2, 3, 4].

The physical system of the solar tracker 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 tracker tracks the sun well. However, even if the solar tracker 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 tracker. A feedback control can be considered for disturbance rejection. For example, the feedback control with the Proportional-Integral-Derivative (PID) controller takes action to force the plant variable back toward the desired output whenever a disturbance on the plant causes a deviation [5, 6, 7, 8]. 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

DOI: 10.24507/icicel.18.03.247

sensor value by considering the past sensor data to reduce noise in the measured value [9, 10, 11, 12]. In existing researches for solar tracker systems, approaches to rejecting disturbance and reducing feedback sensor noise at the same time were lacking. Therefore, a new design approach is required to resolve these two problems simultaneously.

This paper designs a solar tracker 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. A couple of mathematical models, panel model and motor model, for the solar tracker is introduced. The performance degradation due to sun's moving and unpredictable disturbance in the basic proportional control is shown. To resolve this problem, a proportional-integral controller based feedback system is designed for the solar tracker. 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 tracker. It is verified that the designed solar tracker with feedback controller and state estimation filter has the ability to reject disturbance and reduce feedback sensor noise.

This paper has the following structure. In Section 2, the problem statement of solar tracker is described. In Section 3, the feedback controller is designed for disturbance rejection. In Section 4, the state estimation filter is designed for noise reduction. Then, concluding remarks are given in Section 5.

2. **Mathematical Models for Solar Tracker.** To obtain maximum efficiency from solar panel, minimum two axis of solar tracker is required. One axis rotates the tracker around a vertical axis through all possible azimuth angles and the other axis rotates the tracker face about a horizontal axis through all possible elevation angles. The azimuthal rotation axis allows the tracker to point the tracker face through a range of azimuth angle (θ) defined in the same manner as sun position. The elevation rotation axis allows the tracker to point the tracker face through a range of elevation angle (α) defined as the angle between the horizontal vector in the direction of the tracker azimuth. As the solar tracker is a non-interacting system, a controller designed for single axis will be the replica for another axis also. Therefore, this paper considers a single-axis solar tracker and thus the elevation angle (α) is assumed to be adjusted manually at certain intervals during the year.

As shown in Figure 1, the physical system of the solar tracker consists of an electric motor and a solar panel. With a voltage source, the electric motor generates torque to

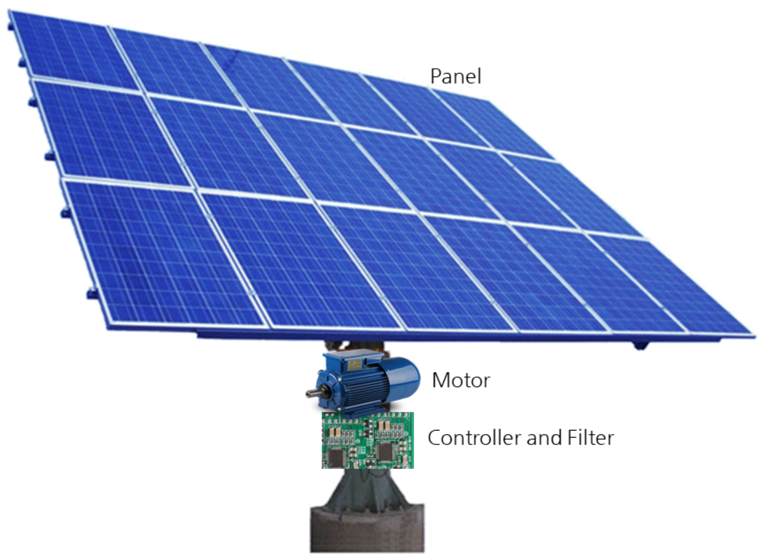


FIGURE 1. Solar tracker with solar panel and electric motor

rotate the solar panel as follows:

$$L\dot{i}(t) + Ri(t) + K_g K_f \dot{\theta}(t) = V(t),$$
$$T(t) = K_g K_t i(t). \tag{1}$$

The torque produced from the motor is applied in the solar panel. The following panel model demonstrates the equation of motion for the solar panel rotating about its central post:

$$J\ddot{\theta}(t) + K_d \dot{\theta}(t) = T(t), \tag{2}$$

where the moment of inertia is calculated by

$$J = m/12 \cdot \left(l^2 \cdot \cos(\alpha)^2 + d^2 \cdot \sin(\alpha)^2 + w^2\right).$$

As shown in Equations (1) and (2), the solar tracker consists of many kinds of variables and parameters, which are defined in Table 1 and Table 2. Values of physical parameters used for computer simulations are obtained from [13] and set as shown in Table 2.

Table 1. Variables for solar tracker

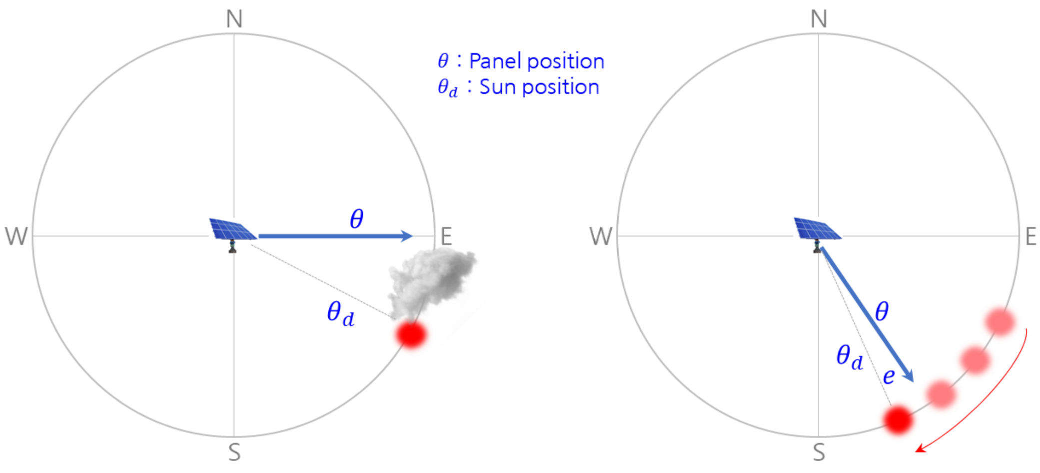
Variable	**Notation**	**Unit**
Panel position (Azimuth angle)	$\theta(t)$	rad/s
Current	$i(t)$	A
Voltage source	$V(t)$	V
Torque	$T(t)$	N

Table 2. Parameters for solar tracker

Parameter	**Notation**	**Unit**	**Values for simulations**
Panel mass	m	kg	50
Panel width	w	m	1.04
Panel length	l	m	1.4
Panel depth	d	m	0.1
Elevation angle	α	rad	$\pi/4$
Damping constant	K_d	N·m/(rad/s)	5
Inductance	L	H	1e-5
Resistance	R	Ω	10
Gear ratio	K_g	N	2000
Back EMF constant	K_f	V/(rad/s)	0.07
Torque constant	K_t	N·m/A	0.07

3. **Feedback Controller Design for Solar Tracker.** As shown in Equations (1) and (2), 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. As shown in Figure 2, it is wanted that the panel points 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.

There are a lot of options for a controller, but a common approach is some form of PID control which stands for proportional-integral-derivative, because the control output is some function of the error, the integrated error, and the derivative of the error. The PID controller is widely employed because it is very understandable and because it is quite effective. One attraction of the PID controller is that all engineers understand conceptually differentiation and integration, so they can implement the control system even without a



(a) when the sun suddenly appears (b) when the sun keeps moving

FIGURE 2. Two cases of sun's motion

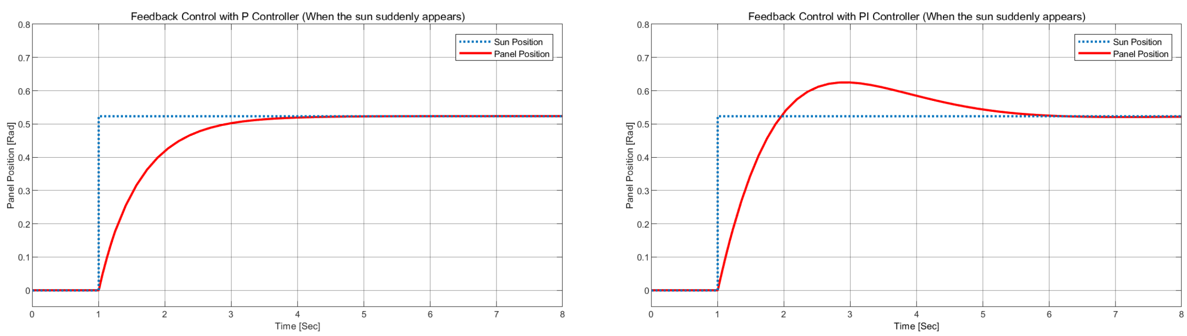
deep understanding of control theory. Further, even though the compensator is simple, it is quite sophisticated in that it captures the history of the system through integration and anticipates the future behavior of the system through differentiation.

From Equations (1) and (2), the open-loop transfer function of the solar tracker can be represented by

$$G(s) = \frac{\Theta(s)}{V(s)} = \frac{K_g K_t}{s\left[(Js + K_d)(Ls + R) + K_f K_t K_g^2\right]} \left[\frac{\text{rad}}{\text{V}}\right]. \tag{3}$$

For the open-loop transfer function (3), there are a lot of ways to customize the PID controller. In PID controller, the derivative term helps respond to quick changes. Thus, the derivative term might not be needed because the sun moves steadily across the sky. Hence, the P controller and the PI controller can be considered. First, the P controller is applied with a gain of $K_p = 240$. Then, the PI controller with $K_i = 180$ is applied while maintaining $K_p = 240$.

As shown in Figure 2(a), 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 a unit step function as shown in Figure 3 for the proportional (P) controller and the PI controller. When the P controller is applied, the solar tracker tracks the sun position well without any overshoot. On the other hand,

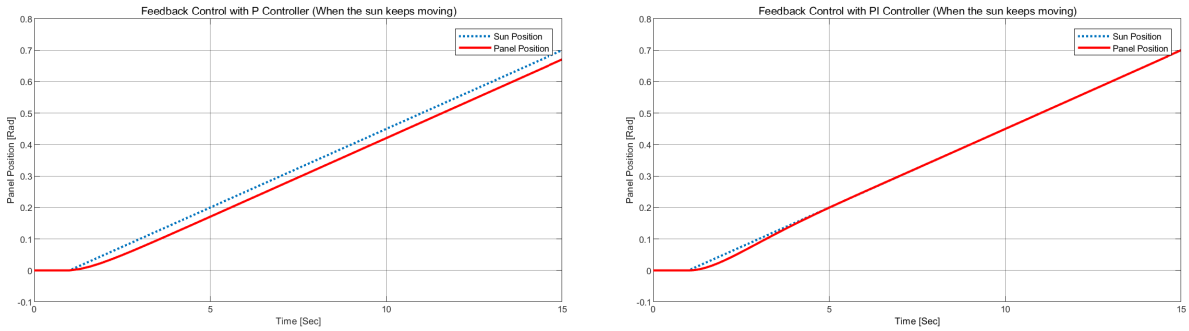


(a) P controller (b) PI controller

FIGURE 3. Feedback control with PID controllers when the sun suddenly appears

when the proportional-integral (PI) controller is applied, the solar tracker tracks the sun position with the overshoot.

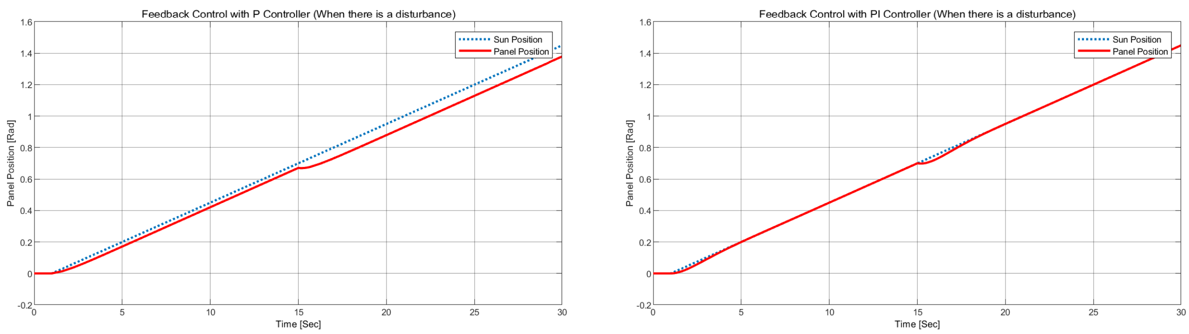
However, in environments where a solar tracker is installed, it is general that the sun steadily across the sky for a long time as shown in Figure 2(b). Thus, in order to consider this situation, the reference for the moving sun's position is emulated by a ramp type as shown in Figure 4 for the P controller and the PI controller. When the PI controller is applied, the solar tracker tracks the sun well overall except for the initial time. On the other hand, when the P controller is applied, there can be tracking error.



(a) P controller (b) PI controller

FIGURE 4. Feedback control with PID controllers 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 15 sec and simulation time is extended to 30 sec. As shown in Figure 5, it can be seen that the disturbance causes additional performance degradation in the solar tracker with the P controller. This means the feedback control system with the P controller fails if there is an unpredicted disturbance acting on the solar tracker. On the other hand, it is shown that the feedback control with the PI controller compensates for the unpredicted disturbance.



(a) P controller (b) PI controller

FIGURE 5. Feedback control with PID controllers when there is a disturbance

4. State Estimation Filter Design for Solar Tracking System.

4.1. **Performance degradation due to feedback sensor noises.** In order that the feedback control in the solar tracker 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. As shown in Figure 6, 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 getting the noise reduction of panel's position.

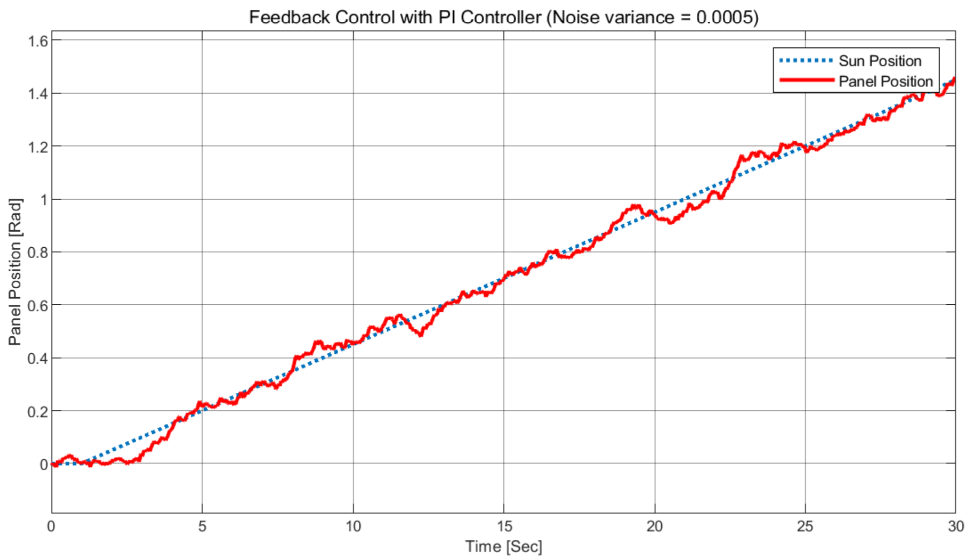


FIGURE 6. Feedback control with PI controller when there is a noise

4.2. **Kalman filtering.** 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 [9, 10, 11, 12]. To apply the state estimation filtering, the state-space realization is required for the solar tracker. 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. Mathematical models (1) and (2) of the solar tracker can be represented in the continuous-time state-space model as follows:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t), \\ y(t) &= Cx(t), \end{aligned} \tag{4}$$

with variables and matrices

$$x(t) \triangleq \begin{bmatrix} \theta(t) \\ \dot{\theta}(t) \\ i(t) \end{bmatrix}, \; A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -K_d/J & K_gK_t/J \\ 0 & -K_gK_t/L & -R/L \end{bmatrix}, \; B = \begin{bmatrix} 0 \\ 0 \\ 1/L \end{bmatrix}, \; C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix},$$

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 $\theta(t)$, and $u(t)$ is control input variable with voltage source $V(t)$.

For the state-space model (4), the Kalman filter provides an optimal state estimate $\hat{x}(t)$ for the system state $x(t)$ as follows:

$$\dot{\hat{x}}(t) = A\hat{x}(t) + P(t)C^T R^{-1} [y(t) - C\hat{x}(t)] + Bu(t),$$
$$P(t) = AP(t) + P(t)A^T + GQG^T - P(t)C^T R^{-1} CP(t),$$

with the initial state $\hat{x}(t_0) = \bar{x}(t_0)$. $P(t)$ is the error covariance of the estimate $\hat{x}(t)$ with initial value $P(t_0)$. Q and R are useful design parameters for the Kalman filter. These parameters can make the tradeoff between the noise reduction and the tracking speed of the state estimation. In this paper, how to properly set these parameters will not be discussed.

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 Figure 7 that the solar tracker 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. Figure 8 shows the ultimate block diagram for the solar tracker, which is designed with the simulation software *MathWorks Simulink*.

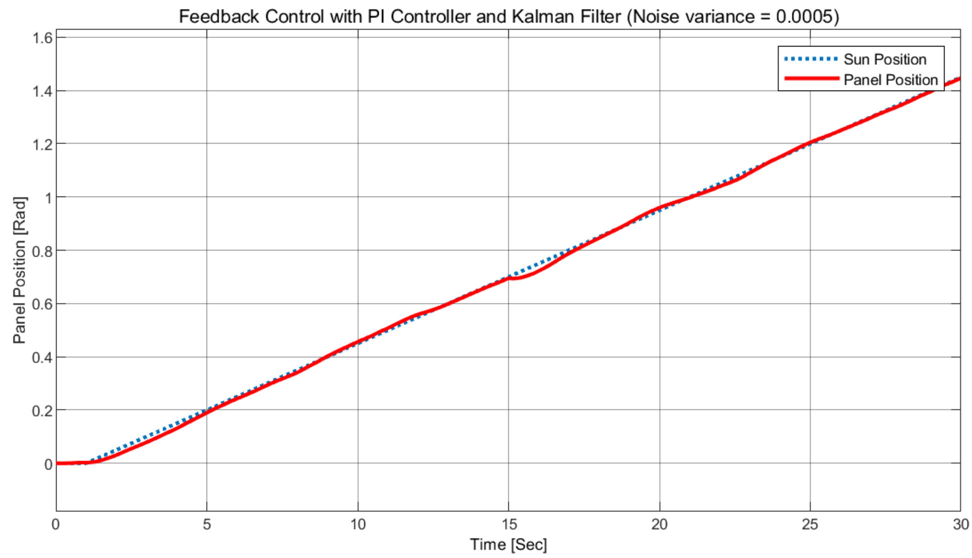


FIGURE 7. Feedback control with PI controller and Kalman filter

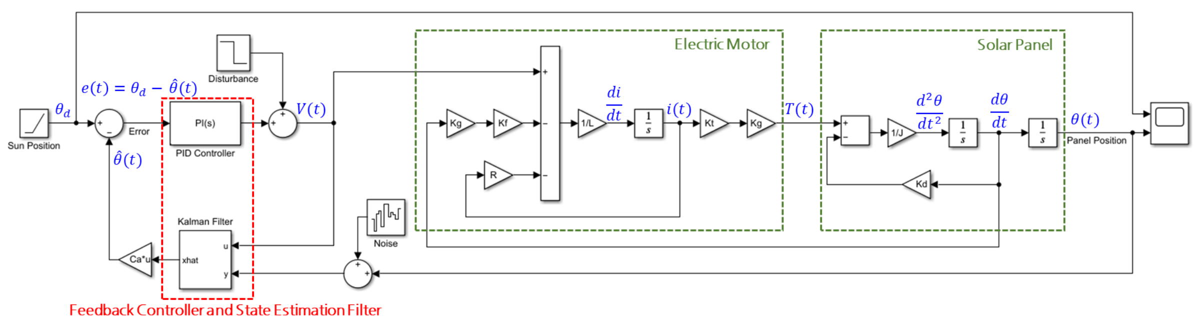


FIGURE 8. Overall block diagram for solar tracker

5. **Conclusions.** This paper has designed a solar tracker 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. A couple of mathematical models, panel model and motor model, for the solar tracker has been derived. The performance degradation due to sun's moving and unpredictable disturbance in the basic P control has been shown. To resolve this problem, a PI controller based feedback system has been designed for the solar tracker. 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 tracker. It has been verified that the designed solar tracker with feedback controller and state estimation filter has the ability to reject disturbance and reduce feedback sensor noise.

As a future work, to verify the feasibility of hardware implementation of the proposed solar tracker system, a light-weight rapid control prototyping (RCP) system based on open source hardware will be researched.

Acknowledgment. This research was supported by the MSIT (Ministry of Science and ICT), Korea, under the ICAN (ICT Challenge and Advanced Network of HRD) program (IITP-2024-RS-2022-00156326) supervised by the IITP (Institute of Information & Communications Technology Planning & Evaluation).

REFERENCES

[1] A. Awasthi, A. K. Shukla, M. Manohar, C. Dondariya, K. Shukla, D. Porwal and G. Richhariya, Review on sun tracking technology in solar PV system, *Energy Reports*, vol.6, pp.392-405, 2020.

[2] A. Aktas and Y. Kircicek, Eliminate the disadvantages of renewable energy sources, in *Solar Hybrid Systems*, A. Aktas and Y. Kircicek (eds.), Academic Press, 2021.

[3] K. Kumar, L. Varshney, A. Ambikapathy, R. K. Saket and S. Mekhilef, Solar tracker transcript – A review, *International Transaction on Electrical Energy Systems*, vol.31, no.12, e13250, 2021.

[4] P. S. Kim and S. Y. Kim, A solar tracking system using feedback controller and state estimation filter, *2023 14th International Conference on Ubiquitous and Future Networks (ICUFN)*, Paris, France, pp.898-900, 2023.

[5] L. Wang, *PID Control System Design and Automatic Tuning Using MATLAB/Simulink*, Wiley-IEEE Press, 2020.

[6] A. Kaleem, I. U. Khalil, S. Aslam, N. Ullah, S. Otaibi and M. Algethami, Feedback PID controller-based closed-loop fast charging of lithium-ion batteries using constant-temperature-constant-voltage method, *Electronics*, vol.10, no.22, 2021.

[7] H. Zhang, W. Assawinchaichote and Y. Shi, New PID parameter autotuning for nonlinear systems based on a modified monkey multiagent DRL algorithm, *IEEE Access*, vol.9, pp.78799-78811, 2021.

[8] S. Zakaria, J. Q. Ong, E. A. R. E. Ariff, R. Hamidon, Z. A. Zailani, M. S. Bahari and H. Azmi, Implementation of PID controller for solar tracking system, in *Intelligent Manufacturing and Mechatronics*, M. S. Bahari, A. Harun, Z. Zainal Abidin, R. Hamidon and S. Zakaria (eds.), Singapore, Springer Singapore, 2021.

[9] F. Auger, M. Hilairet, J. M. Guerrero, E. Monmasson, T. Orlowska-Kowalska and S. Katsura, Industrial applications of the Kalman filter: A review, *IEEE Transactions on Industrial Electronics*, vol.60, no.12, pp.5458-5471, 2013.

[10] Y. S. Shmaliy, S. Zhao and C. K. Ahn, Unbiased finite impulse response filtering: An iterative alternative to Kalman filtering ignoring noise and initial conditions, *IEEE Control Systems Magazine*, vol.37, no.5, pp.70-89, 2017.

[11] H. Liu, F. Hu, J. Su, X. Wei and R. Qin, Comparisons on Kalman-filter-based dynamic state estimation algorithms of power systems, *IEEE Access*, vol.8, pp.51035-51043, 2020.

[12] P. S. Kim, Diverse derivation methods and expressions of discrete-time finite memory structure filter, *Engineering Letters*, vol.29, no.2, pp.658-667, 2021.

[13] B. Neiswander, *Getting Started with Simulink for Controls, MATLAB Central File Exchange*, https://www.mathworks.com/matlabcentral/fileexchange/73257-getting-started-with-simulink-for-controls-example-files, 2023.