IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received 11 August 2023, accepted 16 August 2023, date of publication 23 August 2023, date of current version 7 September 2023.
Digital Object Identifier 10.1109/ACCESS.2023.3307738

RESEARCH ARTICLE

Disturbance Observer-Based Control to Guarantee a Sliding Mode Without Sliding Mode Control

KEONWOO LEE, JAEJUN CHA, AND SEUNGKYU PARK
Department of Electrical Engineering, Changwon National University, Changwon-si 51140, South Korea
Corresponding author: Seungkyu Park (skpark@changwon.ac.kr)

This work was supported by Changwon National University (2023–2024).

ABSTRACT This paper presents a novel disturbance observer (DOB)-based control method to prevent the deterioration of transient response due to disturbances. The proposed method uses sliding mode dynamics without a sliding mode control (SMC) structure and does not require an upper bound of disturbance (UBD), which is needed for SMC. The proposed DOB focuses on maintaining sliding mode dynamics while minimizing the estimation error. The sliding function and disturbance estimation error are considered simultaneously in a Lyapunov candidate function. By modifying the dynamics of the auxiliary variable in the DOB model, the proposed DOB system ensures that the states remain close to the sliding surface and preserve the desired control system characteristics. In contrast, existing DOB models focus only on disturbance estimation and suffer from control performance deterioration during transient estimation time. The proposed DOB-based control method adopts an integral sliding mode and shows better ability to maintain the sliding mode than integral SMC (ISMC).

INDEX TERMS Disturbance observer, robust control, sliding mode.

I. INTRODUCTION

Among the robust control methods for managing uncertainty in actual control systems, the representative controllers are H_∞ control [1], [2], sliding mode control and disturbance observer (DOB)-based control [3]. Sliding mode control (SMC) preserves the desired dynamics under bounded disturbances [4], [5], and DOB-based control decouples the disturbances directly [6], [7], [8]. DOB-based control is considered to be a powerful robust control method because it includes other nominal controllers.

SMC was developed to maintain the sliding mode dynamic, which is the prescribed desired dynamic in the case of bounded uncertainties. It cannot be used with other control methods because its dynamic order is lower than that of the original system to be controlled. Hence, ISMC was developed to eliminate the reaching phase, and its ability to preserve the nominal system dynamics allows it to be used with various nominal controllers [9], [10]. A similar result was obtained in [11]. However, as in other SMC systems, ISMC is not free from UDB.

DOB-based control was developed in the frequency domain by utilizing an inverse transfer function that can compute the disturbance by subtracting the input from the output, including the disturbance and control input [12], [13], [14]. Frequency-domain DOB schemes have various applications because their intuitive concept is easily understood. However, they must be used with low-pass filters (Q-filters) to ensure the strictness of the inverse system and can allow only low-frequency disturbances. Recently, the allowable range of disturbances has been expanded, and consequently, this kind of DOB scheme has become easier to use for actual systems [15], [16], [17], [18]. Various types of state space DOB models have been developed utilizing state measurement and estimation [16], [19], [20]. Among these, DOB with auxiliary variables is the most commonly used method because of its simple structure [21], [22], [23].

DOB-based controllers have a DOB in the inner control loop and the outer loop of the nominal controller. The nominal controller design and DOB design are separated under the

The associate editor coordinating the review of this manuscript and approving it for publication was Xiwang Dong.

assumption of complete disturbance decoupling. However, this assumption cannot be satisfied during estimation, that is, before the complete estimation of the disturbance, and this causes the deterioration of the nominal control performance. Recently, a DOB considering residual estimation errors has shown improved control performance [22]. However, preserving nominal system characteristics through disturbance decoupling is difficult in existing DOB-based control. The SMC can apply DOBs to decouple a disturbance and reduce the size of the UBD [24], [25], [26], [27]. However, the problems of the UBD and residual errors remain.

In this paper, we derive a novel DOB through a Lyapunov stability that considers a integral sliding function and disturbance estimation error. We then develop a DOB-based control system using this novel DOB without the ISMC structure.

The controller consists of a nominal control input and the novel disturbance decoupling input, which focuses on preserving integral sliding mode while decoupling disturbances. Our proposed DOB-based control system achieves sliding mode preservation by introducing the integral sliding function to the DOB algorithm.

As a result, the proposed novel DOB-based control method has the advantage of ISMC without the problem of UBD that is commonly associated with ISMC. By preserving the integral sliding mode, the proposed novel DOB has a superior ability to maintain nominal system dynamics during transient estimation time compared to existing DOB-based controls.

There are many studies for the combination of ISMC and DOB, where DOB is used to reduce the maximum size of the nonlinear gain in the SMC structure [28], [29], [30]. However, our proposed controller does not utilize the SMC structure and should not be classified as a combination of ISMC and DOB.

The rest of the paper is organized as follows. Section II explains the existing state-space DOB-based control method and ISMC, and Section III proposes a novel DOB model that guarantees sliding mode dynamics. Section IV demonstrates the validity of the theory through numerical examples and simulation results, and Section V presents the conclusion.

II. EXISTING DOB-BASED CONTROL AND SMC

In this section, a state space DOB using an auxiliary variable is presented, and its limitations in DOB-based control are explained. Let us consider a nonlinear system in the presence of a disturbance:

$$\dot{x}(t) = f(x) + g(x)(u(t) + d(t)) \tag{1}$$

where $f(x) \in R^{n\times 1}$ and $g(x) \in R^{n\times 1}$ are the system vector and the control input vector, respectively; $x(t) \in R^n$ is the state vector; $u(t) \in R$ is the input; and $d(t) \in R$ is the disturbance with the bounded rate of change below.

$$|\dot{d}(t)| \leq \mu \tag{2}$$

where μ is the maximum rate of change of the disturbance. There exists a DOB model that considers time-varying disturbances [21].

The existing DOB model considered in the paper is a state space DOB model that utilizes auxiliary variables.

A. EXISTING STATE SPACE DOB

The disturbance estimation is derived in terms of an auxiliary variable and the state of the system as follows [8]:

$$\hat{d}(t) = v(t) - q(x) \tag{3}$$

where $\hat{d}(t) \in R$ is the estimate of $d(t)$ and $q(x)$ is a function that satisfies $\frac{\partial q(x)}{\partial x} g(x) < 0$. $v(t) \in R$ represents the auxiliary variable that is derived from

$$\dot{v}(t) = \frac{\partial q(x)}{\partial x}(f(x) + g(x)(u(t) + \hat{d}(t))). \tag{4}$$

The estimation error is defined as

$$e_s(t) = \hat{d}(t) - d(t) \tag{5}$$

The derivative of (3) illustrates the estimation procedure. The dynamics of the estimation error are obtained as follows:

$$\dot{e}_s(t) = \frac{\partial q(x)}{\partial x} g(x) e_s(t) + \dot{d}(t) \tag{6}$$

Equation (6) shows that $e_s(t)$ can be bounded if $q(x)$ is chosen to satisfy $\frac{\partial q(x)}{\partial x} q(x) < 0$ and the rate of change of the disturbance is bounded. Usually, $\frac{\partial q(x)}{\partial x} g(x)$ is set as a negative constant by choosing $q(x)$ appropriately.

It is noted that the existing DOB model does not consider the overall stability of the DOB-based control system using the estimation results. It focuses only on the performance of the disturbance estimation without considering the control performance of the DOB-based control system. The final goal of disturbance estimation is to decouple the disturbance and preserve the nominal system characteristics. However, this has been overlooked in the existing DOB systems. This is a limitation of existing DOBs.

B. DOB-BASED CONTROL

The DOB-based control input is composed of the nominal control input and disturbance decoupling input as follows:

$$u(t) = u_0(t) - \hat{d}(t) \tag{7}$$

where $u_0(t)$ is the nominal control input, which is designed for a nominal system without considering disturbance.

Applying (7) to system (1), the dynamics of the closed-loop system are as follows:

$$\dot{x}(t) = f(x) + g(x)(u_0(t) + e_r(t)) \tag{8}$$

where $e_r(t) = d(t) - \hat{d}(t)$, which is called the residual disturbance in this paper. It is noted that $e_r(t) = -e_s(t)$, where e_s is given in (5).

It should be noted that the nominal system is affected by $e_r(t)$, which cannot be zero in the transient estimation time. This means that the response of the nominal system deteriorates due to the residual error caused by the disturbance estimation error. In general, for DOB-based control, the DOB model in the inner loop cannot effectively handle this challenge.

The main aim of this paper is to develop a DOB model that preserves the nominal control performance by utilizing the sliding mode.

C. INTEGRAL SLIDING MODE CONTROL

In this section, ISMC, which has no reaching phase problem and preserves the nominal control performance, is explained. For the system in (1), the sliding surface of ISMC is defined as follows [9]:

$$s(t) = x(t) - z(t) = 0 \tag{9}$$

$z(t)$ represents the auxiliary variable that is obtained from

$$\dot{z}(t) = f(x) + g(x)u_0(t) \tag{10}$$

where $u_0(t)$ is the nominal control input. The sliding surface (9) is a well-known sliding surface of ISMC. Compared with the other sliding surfaces, this sliding surface has dynamics of the same order as the original system and preserves the nominal system dynamics. This is shown as follows. Taking the derivative of the sliding function $s(t)$ in (9) yields

$$\dot{s}(t) = \dot{x}(t) - \dot{z}(t) \tag{11}$$

and when $s(t)$ remains at zero and $\dot{s}$ is zero, the following equation is satisfied:

$$\dot{x}(t) = f(x) + g(x)u_0(t) \tag{12}$$

This shows that the sliding mode of (9) has the dynamics of the nominal system. If the system satisfies the matching condition, the dynamics on the sliding surface are free from disturbances.

To derive the ISMC input that ensures the states remain on the sliding surface, the following Lyapunov candidate function is used.

$$V(t) = \frac{1}{2}s^T s \tag{13}$$

If $\dot{V}(t)$ is negative, then s converges to zero, and the states remain on the sliding surface.

Taking the derivative of $V(t)$ with the sliding function in (13) yields

$$\dot{V}(t) = s^T(\dot{x}(t) - \dot{z}(t)) = s^T(g(x)(u(t) + d - u_0(t)) \tag{14}$$

From (14), the ISMC input needed to obtain a negative $\dot{V}$ is derived as follows:

$$u(t) = u_0(t) - d_m \text{sign}(s^T(t)g(x)) \tag{15}$$

where d_m is the known UBD.

From the ISMC input, it is indicated that the UBD must be known, and input chattering is inevitable because of the sign function. The initial value of $s(t)$ can be set to zero by setting $z(0) = x(0)$. This is one of the advantages of ISMC in eliminating the reaching phase problem.

Remark 1: Disturbance observer-based control decouples disturbances by estimating them (as in Eq.(7)), while sliding mode control uses a nonlinear switching input maintain the states on a sliding surface that is not affected by disturbances (as described in Eq.(14)). The motivation of this paper is to take advantages of DOB-based control and SMC without their disadvantages, which are deterioration of transient response and requiring UBD, respectively.

III. NOVEL DOB-BASED CONTROL

To use the advantage that ISMC preserves the nominal dynamics through a sliding surface, a novel DOB model is proposed by adding a sliding function in the auxiliary variable dynamic equation. Therefore, the performance of the DOB-based control system can be improved by utilizing a sliding mode that has nominal system dynamics.

A. PROPOSITION OF A NOVEL DOB

To derive a novel DOB that utilizes the sliding surface through Lyapunov stability, the Lyapunov candidate function, which includes the sliding function and estimation error, is considered as follows:

$$V_s(t) = \frac{1}{2}s^T(t)Ps(t) + \frac{1}{2}e_s^2(t) \tag{16}$$

where P is a symmetric positive definite weighting matrix and $s(t)$ is a sliding function of (9) used in ISMC. If $\dot{V}_s(t)$ is negative, then $s(t)$ can remain at zero and $e_s(t)$ can converge to zero. This means that the states remain on the sliding surface, achieving the prescribed nominal system dynamics. To obtain a negative $\dot{V}_s(t)$, the DOB-based control needs a novel DOB. In this paper, the following DOB model is proposed:

$$\hat{d}_s(t) = v_s(t) - q(x) \tag{17}$$

$v_s(t)$ is derived from the dynamics of the auxiliary variable as follows:

$$\dot{v}_s(t) = \frac{\partial q(x)}{\partial x}(f(x) + g(x)(u(t) + \hat{d}_s(t)) + g^T(x)Ps(t) \tag{18}$$

In the following subsection, the above dynamics of the auxiliary variable are used to derive the estimation error dynamics, and it is shown how the novel DOB-based control scheme guarantees the sliding mode and preserves the nominal system dynamics. It is expected that the additional term $g^T(x)Ps(t)$ in (18) will have an important role in guaranteeing the sliding mode.

B. NOVEL DOB-BASED CONTROL WITH A SLIDING MODE

The proposed DOB-based control input is composed of the nominal control input and disturbance decoupling input as follows:

$$u(t) = u_0(t) + u_{ds}(t) \tag{19}$$

where $u_{ds}(t) = -\hat{d}_s(t)$ is the disturbance decoupling input and $\hat{d}_s(t)$ is the estimate of $d(t)$ in (17).

The decoupling input is used to make $\dot{V}_s(t)$ negative and ensure that the states remain close to a sliding surface that is free from the effect of disturbance. This is presented as Theorem 1.

Theorem 1: The DOB-based control scheme (19) with the proposed DOB (17) ensures that the states of the system in (1) remain sufficiently close to the sliding surface (9) and have almost the same dynamics as the nominal system (12).

Proof: When the proposed input (19) is applied to system (1), the time derivative of $s(t)$ is

$$\dot{s}(t) = \dot{x} - \dot{z} = g(x)(d(t) - \hat{d}_s(t)) = g(x)e_r(t). \quad (20)$$

Considering (17) and taking the derivative of $e_s(t)$ yields

$$\dot{e}_s(t) = \frac{\partial q(x)}{\partial x}e_s(t) + g^T(x)Ps(t) + \dot{d}(t) \quad (21)$$

where $e_s(t) = \hat{d}_s(t) - d(t)$.
Taking the derivative of $V_s(t)$ in (16) and substituting (20) and (21) yields

$$\begin{aligned}\dot{V}_s(t) &= s^T(t)P(\dot{x}(t) - \dot{z}(t)) + e_s(t)\dot{e}_s(t) \\ &= s^T(t)Pg(t)e_r(t) \\ &\quad + e_s(t)(\frac{\partial q(x)}{\partial x}g(x)e_s(t) + g^T(t)Ps(t) + \dot{d}(t)) \quad (22)\end{aligned}$$

From the above equation, under the assumption $|\dot{d}(t)| \leq \mu$, the following inequalities are satisfied because $e_r(t) = -e_s(t)$ and $q(x)$ is chosen so that $\frac{\partial q(x)}{\partial x}g(x)$ is negative.

$$\begin{aligned}\dot{V}_s(t) &\leq \frac{\partial q(x)}{\partial x}g(x)\|e_s(t)\|^2 + \|e_s(t)\|\mu \\ &\leq -\lambda_m\|e_s(t)\|^2 + \|e_s(t)\|\mu \\ &= -\|e_s(t)\|(\lambda_m\|e_s(t)\| - \mu)\end{aligned}$$

where $\lambda_m > 0$ is the minimum size of $\frac{\partial q(x)}{\partial x}g(x)$. When $\|e_s(t)\| \geq \frac{\mu}{\lambda_m}$, $\dot{V}_s(t)$ is negative, and the disturbance estimation error is bounded as follows.

$$\|e_s(t)\| < \frac{\mu}{\lambda_m}$$

If $q(x)$ is chosen so that λ_m is sufficiently larger than μ, then $e_s(t)$ can be close to zero; $\dot{s}(t)$ is also close to zero because $\dot{s}(t) = -g(x)e_s(t)$, as in (20), and the following is satisfied.

$$\begin{aligned}\dot{s}(t) &= \dot{x}(t) - \dot{z}(t) \\ &= \dot{x}(t) - f(x) - g(x)u_0(t) \approx 0\end{aligned}$$

This means that the states remain close to the sliding surface (9) from the initial time when $z(0) = x(0)$ and have the following almost nominal dynamic characteristics.

$$\dot{x}(t) \approx f(x) + g(x)u_0(t) \quad (23)$$

Q.E.D.

The overall control input (19) has the same form as (7) but with the proposed DOB model instead of the existing DOB model. Fig. 1 shows the proposed DOB-based control system.

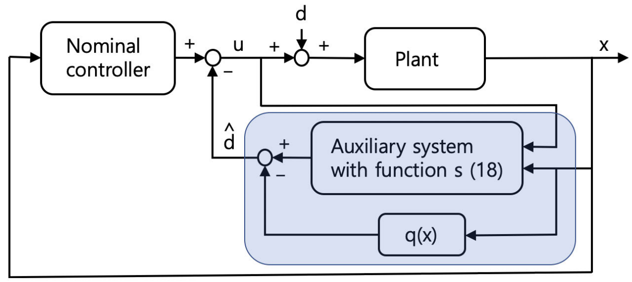

FIGURE 1. **Proposed DOB-based control system.**

Remark 2: The disturbance decoupling input in (19) ensures that $V_s(t)$, which includes the sliding function and the disturbance estimation error, converses close to zero. Therefore, as demonstrated in Theorem 1, the states remain close to the sliding surface and have almost nominal dynamics described by (23) controlled only by $u_0(t)$ without the influence of disturbances.

Remark 3: The derivative of $\dot{V}_s(t)$ includes the term $s^T PBe_r(t)$, which cannot be eliminated by the existing DOB model. Compared with the auxiliary variable dynamic equation of the existing DOB model, that of the proposed DOB model (equation (17)) has an additional $PB^T s$ term that is used to eliminate the $s^T PBe_r(t)$ term in equation (22) and achieves a negative $\dot{V}$. In addition, the observer gain $\frac{\partial q(x)}{\partial x}$ in equation (18) is used to enlarge the negative $\dot{V}(t)$. This is verified through simulations.

Remark 4: The proposed DOB-based control and ISMC models use the same sliding surface in (9) and the same nominal control input u_0, but they use different strategies to ensure that the states remain on the sliding surface. The ISMC input (15) requires the UBD information to be known and needs a sign function that causes SMC input chatter. In contrast, the novel DOB-based control input (19) does not need UBD information and does not use the SMC structure. Therefore, the chattering problem of SMC can be avoided.

IV. SIMULATION RESULTS

To demonstrate the effectiveness of the novel DOB approach proposed in this paper, a one-link manipulator is considered in the simulation. The state equation of the one-link manipulator is given by:

$$\begin{aligned}x_1(t) &= x_2 \\ x_2(t) &= -\frac{mgl\sin(x_1(t))}{J_1} - \frac{B}{J_1}x_2(t) + \frac{1}{J_1}(u(t) + d(t))\end{aligned}$$

where $x_1(t)$ is the joint angle and $x_2(t)$ is the joint angular velocity. The parameters are as follows:
$m = 1$, $g = 9.8$, $J = 18$, and $B = 2$.

The initial states of the system are selected as $x(0) = \begin{bmatrix}1 & 2\end{bmatrix}^T$. Both a square wave with a frequency of 0.5 rad/sec and a magnitude of 5, and a chirp signal with a frequency range of 0 to 10 rad/sec and a magnitude of 5, are applied together as the disturbance. The nominal controller in the

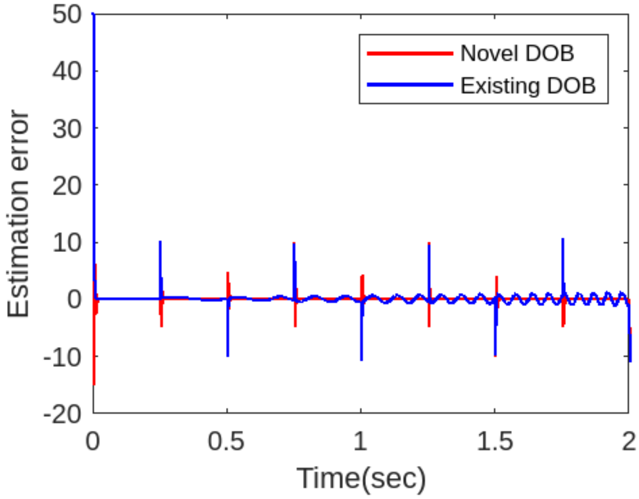

FIGURE 2. Disturbance estimation performance.

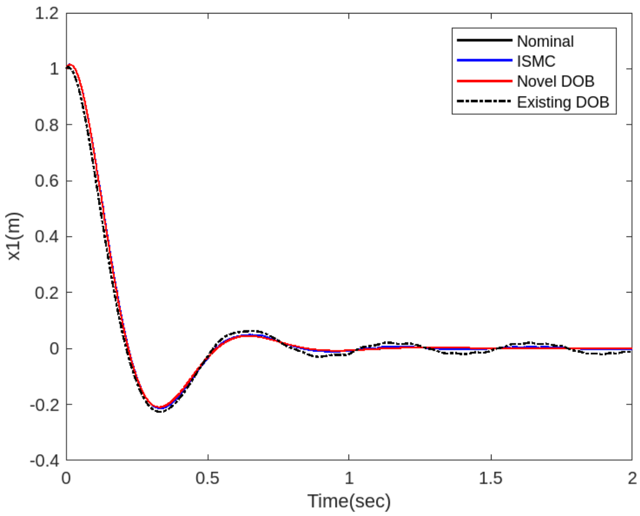

FIGURE 3. State response of $x_1(t)$.

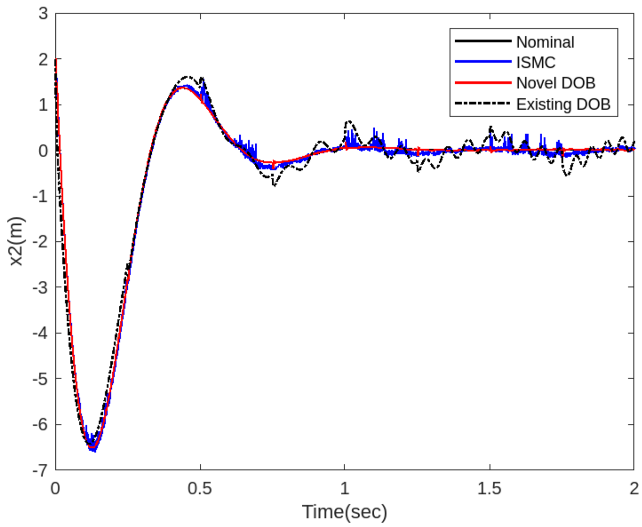

FIGURE 4. State response of $x_2(t)$.

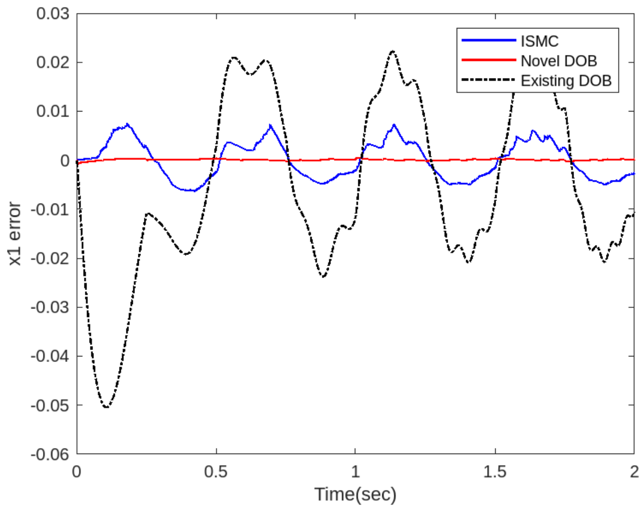

FIGURE 5. State error of $x_1(t)$.

simulation consists of nonlinear decoupling input and state feedback input as follows:

$$u_0(t) = mgl\sin(x_1(t)) + K\left[x_1(t)\ x_2(t)\right]^T$$

where $K = \left[-10\ -15\right]$ is the state feedback gain to place the eigenvalues of the closed system at $-5 \pm 10i$.

The novel DOB-based control is compared with ISMC to demonstrate its ability to preserve integral sliding mode and achieve a nominal response from the inintial time without relying on ISMC. To make $\frac{\partial q(x)}{\partial x}g(x) < 0$, a value of $q(x) = [-50x_1(t) - 50x_2(t)]$ is chosen, which results in $\frac{\partial q(x)}{\partial x}g(x) = -10$. The ISMC uses an UBD of $d_m = 21$. The matrix P, which weights on the sliding function, is chosen as $P = \begin{bmatrix} 100 & 0 \\ 0 & 100 \end{bmatrix}$. A larger value of P results in better transient response, but it must be limited because of the constraints on the control input's size. Therefore, the choice of P is ultimately up to the designer to determine this weighting matrix.

The simulation results are presented in Figures 2–8. Figure 2 shows the estimation performance of DOB. The estimation exhibits some oscillations due to the high frequency of the disturbance, but this does not pose a problem as it is used as a disturbance decoupling input because of the low-pass filter characteristic of the system. Additionally, the role of the DOB is not limited to estimating the disturbance; it also serves to reduce the size of the sliding function, albeit at the cost of potentially degrading its estimation performance. Figures 3 and 4 illustrate the state responses of the control systems. Figures 5 and 6 compare the state errors of the proposed DOB-based control and ISMC with the nominal system. Figure 7 displays the size of the sliding functions, and Figure 8 compares the control inputs of the ISMC and the proposed control.

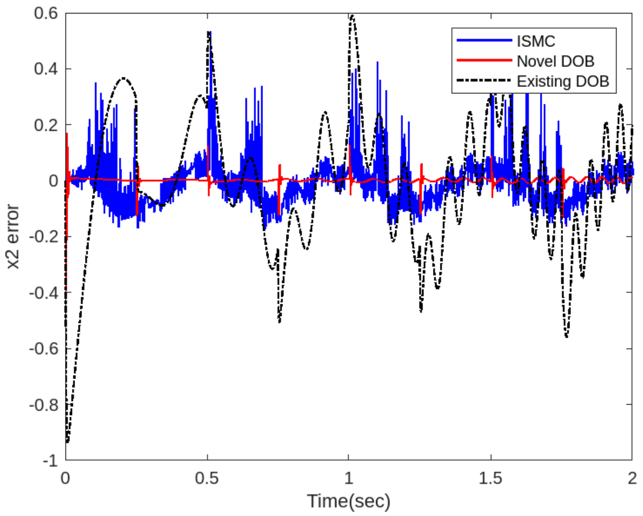

FIGURE 6. State error of $x_2(t)$.

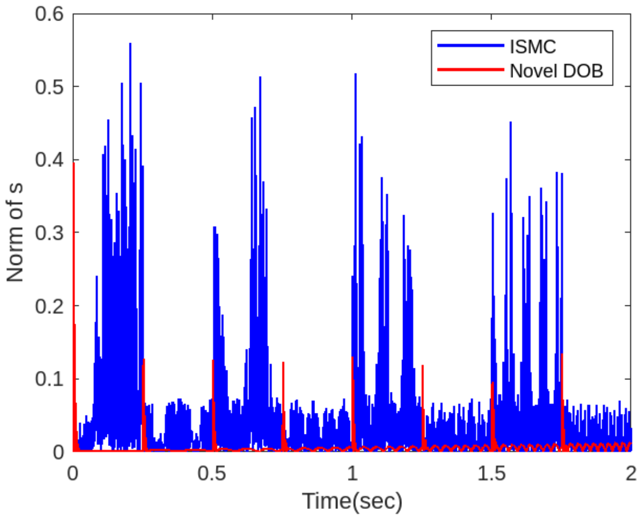

FIGURE 7. Size of the sliding function.

As shown in Fig. 3, the x_1 responses of the novel DOB-based control and ISMC are similar to those of the nominal control system. This verifies that their responses are not deteriorated by the disturbance. In Fig. 4, the x_2 response of the novel DOB-based control is closer to the nominal control system than the ISMC response, which exhibits chatter. This shows that these resposes are not affected by the disturbance, but the response of the ISMC is affected by the inevitiable input chattering. Fig. 5 and Fig. 6 display the state errors of the proposed DOB-based control and ISMC in comparison to the nominal states. The errors, taking into account the scales of the states, indicate that the states of the novel DOB-based control and ISMC are similar enough to those of the nominal system.

Fig. 7 compares the novel DOB-based control and ISMC in terms of the size of the sliding function. The results show that the size of the novel DOB-based control converges close

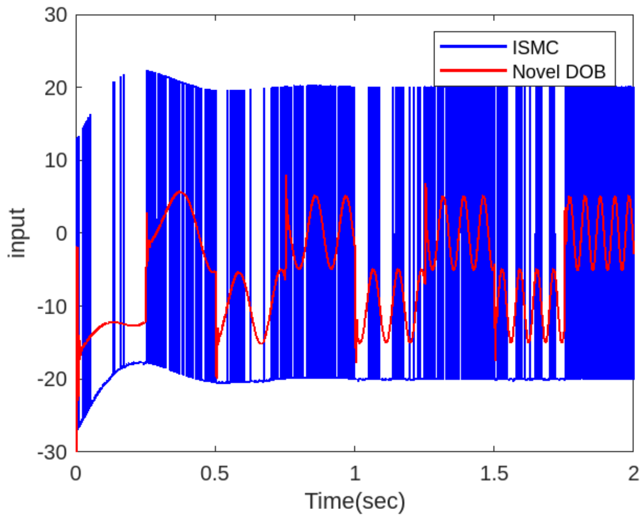

FIGURE 8. Inputs of the proposed DOB-based control and ISMC models.

to zero and is significantly smaller than that of ISMC. This confirms the bounded stability established in Theorem 1.

In Fig. 8, the input of the proposed DOB-based control model shows no chattering; in contrast, the ISMC input shows chattering, which is unavoidable in SMC because of using UBD with the sign function.

Remark 5: From all of the above simulation results, it is verified that the novel DOB-based control model can guarantee a sliding mode with better performance than ISMC. The additional term $g^T(x)Ps(t)$ in equation (18) provides this improvement.

V. CONCLUSION

A novel DOB is proposed, which considers preserving sliding mode and disturbance estimation. By using the novel DOB, A novel DOB-based control is proposed to preserve the integral sliding mode without using ISMC structure. It is theoretically proven that the states are not deteriorated by disturbance on the integral sliding mode. The proposed DOB-based control model maintains the integral sliding mode without the need for the UBD, which is required in the SMC structure. This is achieved because the proposed control model does not rely on the SMC structure. Simulation results show that the sliding function of the proposed DOB-based control system remains close to zero and verifies the validity of the novel method. There has been extensive research on DOB and SMC, but to the best of our knowledge, our work is the first to use sliding mode for DOB-based control without relying on SMC structure. The central idea can potentially be applied to systems with mismatched disturbances or unknown parameters and intelligent control systems like T-S fuzzy and neural networks [31].

REFERENCES

[1] S. Boyd, L. E. Ghaoui, E. Feron, and V. Balakrishnan, *Linear Matrix Inequalities in System and Control Theory*. Philadelphia, PA, USA: SIAM, 1994.

[2] K. Zhou and J. C. Doyle, *Essentials of Robust Control*. Upper Saddle River, NJ, USA: Prentice-Hall, 1998.
[3] G. A. Garcia, S. Keshmiri, and D. Shukla, ''Nonlinear control based on H-infinity theory for autonomous aerial vehicle,'' in *Proc. Int. Conf. Unmanned Aircr. Syst. (ICUAS)*, Miami, FL, USA, Jun. 2017, pp. 336–345.
[4] K. D. Young, V. I. Utkin, and U. Ozguner, ''A control engineer's guide to sliding mode control,'' *IEEE Trans. Control Syst. Technol.*, vol. 7, no. 3, pp. 328–342, May 1999.
[5] V. Utkin, J. Guldner, and J. Shi, *Sliding Mode Control in Electro-Mechanical Systems*. London, U.K.: CRC Press, 2009.
[6] S. H. Li, J. Yang, W. H. Chen, and X. S. Chen, *Disturbance Observer Based Control: Methods and Applications*. Boca Raton, FL, USA: CRC Press, 2014.
[7] H. Shim, G. Park, Y. Joo, J. Back, and N. H. Jo, ''Yet another tutorial of disturbance observer: Robust stabilization and recovery of nominal performance,'' *Control Theory Technol.*, vol. 14, no. 3, pp. 237–249, Aug. 2016.
[8] E. Sariyildiz, R. Oboe, and K. Ohnishi, ''Disturbance observer-based robust control and its applications: 35th anniversary overview,'' *IEEE Trans. Ind. Electron.*, vol. 67, no. 3, pp. 2042–2053, Mar. 2020.
[9] Y. Pan, C. Yang, L. Pan, and H. Yu, ''Integral sliding mode control: Performance, modification, and improvement,'' *IEEE Trans. Ind. Informat.*, vol. 14, no. 7, pp. 3087–3096, Jul. 2018.
[10] G. P. Incremona, L. Mirkin, and P. Colaneri, ''Integral sliding-mode control with internal model: A separation,'' *IEEE Control Syst. Lett.*, vol. 6, pp. 446–451, 2022.
[11] S. K. Park and H. K. Ahn, ''Robust controller design with novel sliding surface,'' *IEE Proc., Control Theory Appl.*, vol. 146, no. 3, pp. 242–246, May 1999.
[12] E. Sariyildiz and K. Ohnishi, ''A guide to design disturbance observer,'' *J. Dyn. Syst., Meas., Control*, vol. 136, no. 2, pp. 11–21, Mar. 2014.
[13] W.-H. Chen, J. Yang, L. Guo, and S. Li, ''Disturbance-observer-based control and related methods—An overview,'' *IEEE Trans. Ind. Electron.*, vol. 63, no. 2, pp. 1083–1095, Feb. 2016.
[14] K. Kong and M. Tomizuka, ''Nominal model manipulation for enhancement of stability robustness for disturbance observer-based control systems,'' *Int. J. Control, Autom. Syst.*, vol. 11, no. 1, pp. 12–20, Feb. 2013.
[15] N. Paine, S. Oh, and L. Sentis, ''Design and control considerations for high-performance series elastic actuators,'' *IEEE/ASME Trans. Mechatronics*, vol. 19, no. 3, pp. 1080–1091, Jun. 2014.
[16] K. Ohnishi, M. Shibata, and T. Murakami, ''Motion control for advanced mechatronics,'' *IEEE/ASME Trans. Mechatronics*, vol. 1, no. 1, pp. 56–67, Mar. 1996.
[17] M. Nakao, K. Ohnishi, and K. Miyachi, ''A robust decentralized joint control based on interference estimation,'' in *Proc. IEEE Int. Conf. Robot. Autom.*, Raleigh, NC, USA, Mar./Apr. 1987, pp. 326–331.
[18] M. T. White, M. Tomizuka, and C. Smith, ''Improved track following in magnetic disk drives using a disturbance observer,'' *IEEE/ASME Trans. Mechatronics*, vol. 5, no. 1, pp. 3–11, Mar. 2000.
[19] C. Johnson, ''Accomodation of external disturbances in linear regulator and servomechanism problems,'' *IEEE Trans. Autom. Control*, vol. AC-16, no. 6, pp. 635–644, Dec. 1971.
[20] E. Sariyildiz, R. Mutlu, and C. Zhang, ''Active disturbance rejection based robust trajectory tracking controller design in state space,'' *J. Dyn. Syst., Meas., Control*, vol. 141, no. 6, Jun. 2019, Art. no. 061013.
[21] E. Sariyildiz, G. Chen, and H. Yu, ''Robust trajectory tracking control of multimass resonant systems in state space,'' *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9366–9377, Dec. 2017.
[22] S. Park and T. S. Yoon, ''State space disturbance observer considering residual disturbance,'' *IEEE Access*, vol. 8, pp. 213882–213886, 2020.
[23] X. Yang, W. Deng, and J. Yao, ''Disturbance-observer-based adaptive command filtered control for uncertain nonlinear systems,'' *ISA Trans.*, vol. 130, pp. 490–499, Nov. 2022.
[24] J. Hui and J. Yuan, ''Disturbance observer based adaptive sliding mode control for power tracking of PWRs,'' *Nucl. Eng. Technol.*, vol. 52, no. 11, pp. 2522–2534, Nov. 2020.
[25] J. Wang, C. Shao, X. Chen, and Y. Chen, ''Fractional-order DOB-sliding mode control for a class of noncommensurate fractional-order systems with mismatched disturbances,'' *Math. Methods Appl. Sci.*, vol. 44, no. 10, pp. 8228–8242, Jul. 2021.
[26] I. Ullah and H.-L. Pei, ''Fixed time disturbance observer based sliding mode control for a miniature unmanned helicopter hover operations in presence of external disturbances,'' *IEEE Access*, vol. 8, pp. 73173–73181, 2020.
[27] D. Guha, P. K. Roy, and S. Banerjee, ''Adaptive fractional-order sliding-mode disturbance observer-based robust theoretical frequency controller applied to hybrid wind–diesel power system,'' *ISA Trans.*, vol. 133, pp. 160–183, Feb. 2023.
[28] Y. Wei and G. Gao, ''Disturbance observer–based adaptive integral sliding mode control for the hybrid automobile electro-coating conveying mechanism,'' *Int. J. Adv. Robot. Syst.*, vol. 16, pp. 1–12, May 2019.
[29] J. Zhang, X. Liu, Y. Xia, Z. Zuo, and Y. Wang, ''Disturbance observer-based integral sliding-mode control for systems with mismatched disturbances,'' *IEEE Trans. Ind. Electron.*, vol. 63, no. 11, pp. 7040–7048, Nov. 2016.
[30] Y. Lee, S. H. Kim, and C. C. Chung, ''Integral sliding mode control with a disturbance observer for next-generation servo track writing,'' *Mechatronics*, vol. 40, pp. 106–114, Dec. 2016.
[31] J. Fei, Z. Wang, and Y. Fang, ''Self-evolving recurrent Chebyshev fuzzy neural sliding mode control for active power filter,'' *IEEE Trans. Ind. Informat.*, vol. 19, no. 3, pp. 2729–2739, Mar. 2023.

KEONWOO LEE received the B.S. and M.S. degrees in electrical engineering from Changwon National University, in 2020 and 2022, respectively. He is currently an Engineer with the Research Institute, Higen Motor Company, South Korea. His research interests include motor control and mobile robots.

JAEJUN CHA received the B.S. and M.S. degrees in electrical engineering from Changwon National University, in 2020 and 2022, respectively. He is currently an Engineer with the Research Institute, Higen Motor Company, South Korea. His research interests include robot control and robust control.

SEUNGKYU PARK received the B.S. and Ph.D. degrees in electrical engineering from Korea University, in 1984 and 1990, respectively. He was a Visiting Scholar with the University of Strathclyde, in 1995; University of Wisconsin, in 2003; and The University of Texas at Austin, in 2011, each for a period of one year. He is currently a Professor with the Department of Electrical Engineering, Changwon National University. His research interests include robust control and whole-body control of robots.