Kateter Tahrik Sisteminin Kayma Kipli Kontrolü ve Bulanık Mantık ile Performans İyileştirmesi Sliding Mode Control of Catheter Drive System and Performance Improvement via Fuzzy Logic

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***Özetçe*—Kateterler bronkoskopi, kolonoskopi, anjiyografi gibi medikal uygulamalarda kullanılmaktadır.Kateterler bu işlemlerde direk olarak doku ile temas ettiklerinden dolayı hareketlerinin kontrollü olması gerekmektedir. Bu çalışmada kateterin ilerlemesinin kontrol etmek için kullanılabilecek üç farklı kayan kipli kontrolcü önerilmiştir. Bunlar klasik kayan kipli kontrolcü, yarı kayan kipli kontrolcü ve asimtotik kayan kipli kontrolcü yapılarıdır.Kontrolcülerin performans karşılaştırılması kapalı çevirim sistem cevabı incelenerek yapılmıştır. Sonuçlar yarı kayma kipli kontrolcünün performansının diğer kontrolcülerden daha iyi olduğunu göstermiştir. Yarı kayma kipli kontrolcünün performansının iyileştirilmesi için bulanık mantık tabanlı bir üst seviye kontrolcüsü kullanılması önerilmiştir. Önerilen kontrolcü yapısı tahmin edilen bozucu girdi genligi ve pozisyon hatasına baglı olarak kontrolcü parametrelerini güncellemektedir. Elde edilen sonuçlar yarı kayma kipli kontrolcünün gerçek zamanlı performansının önerilen kontrol yapısı değişikligi ile iyileştigini göstermektedir.**

Anahtar Kelimeler*—Minimal invaziv cerrahi; Kateter; Sürtünmeli Sürüş; Kayma Kipli Kontrolü; Bulanık Mantık

***Abstract*—Catheters are used in medical applications such as bronchoscopy, colonoscopy, angiography. Due to the catheters are in direct contact with the tissue in these procedures, their movements must be controlled. In this study, three different sliding-mode controllers that can be used to control the movement of the catheter have been proposed. These are the classical sliding mode controller, quasi sliding mode controller , and asymptotic sliding mode controller structures. Performance comparison of the controllers was made by assessing the closed-loop system response. The results indicated that the performance of the quasi sliding mode controller was better than the other controllers. It has been proposed to use a fuzzy logic-based highest controller to improve the performance of the quasi sliding mode controller. The proposed controller structure updates the controller parameters depending on the predicted disturbance magnitude and position error. The results show that the real-time performance of the quasi sliding mode controller is improved by the change of the proposed control structure.**

Keywords*—Minimally invasive surgery; Catheter; Frictional Driving; Sliding Mode Control; Fuzzy Logic

I. INTRODUCTION

Minimally invasive surgery has drawn attention because it reduces the patient's physical pain and becomes increasingly popular in medical practice, both for diagnosis and surgery [1], [2]. Endoscopy is one of the most common practices of minimally invasive methods to view or intervene the organs via catheters like in operations: bronchoscopy, angiography, and colonoscopy. Hence, the control of the catheter has a critical role in such operations since uncontrolled actions may result in damages in organs. The catheter control setups consist of two subsystems for catheter driving and guidance. The guidance setups are used for changing the direction of catheters and the driving system is used for feeding the catheter into a human body. The main concerns in catheter driving are precise motion [3], force limitations [4], and the robustness of controllers [5]. In such systems, one of the most common actuator is the frictional drive. The frictional drive systems [6]–[8] are actuator systems that transfer force or torque to the output port via a friction pulley coupled to any force/torque source. They can be considered as two link (motor-driven friction wheel and catheter) mechanism with standard kinematic pair according to degree of freedom in contact point. In this case, the torque or force on the drive shaft is transmitted to the catheter without any loss or slippage [9]. The frictional catheter driving systems has the advantage of controlling and limiting the interaction force directly which makes them preferable as actuators in continuum robotic systems [10] and biomedical devices [11]. The major disadvantage of the frictional drive systems is the slippage that should be carefully handled in control design.

The catheters move inside living organisms and they interact with tissues and body fluids [12]. As a consequence, the

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effects of inner body interactions are observed as the unknown disturbances in the system model. However, the bounds for uncertain interaction forces can be predicted using the characteristics of tissues and body fluids. In the formulation of any practical control problem, there will always be a discrepancy between the actual plant and its mathematical model used for controller design. These inconsistencies can be called briefly from unknown external factors [13], [14], model parameters [15], [16], and parasitic or unmodified dynamics [17]. In the presence of these disturbances or uncertainties, designing control laws that provide the desired performance to a closed-loop system [18] is a very difficult task for a control engineer. For this reason, a robust controller [19] should be designed by considering these factors in the control of the catheter. A special approach to robust controller design is the sliding mode control technique.

Sliding Mode Control is a controller that can handle the nonlinear conditions of the facility. The advantages of the sliding mode controller can be designed for robustness [20], the ability to deal with nonlinear systems [21], time-varying systems [22], and fast dynamic responses [23]. The sliding mode controller reaches the desired output in the system by turning the input signal on and off at high frequency [24], [25]. As a result, the implementation of sliding mode control requires high frequency switching control input. When some part of the system dynamics is unknown, the chattering phenomenon is observed [13], [26], [27]. This phenomenon can lead to a decrease in system efficiency and can cause damage to the system [28].

In this study, we focused on frictional catheter driving system control. To obtain an appropriate controller scheme, we first derived a classical sliding mode control law afterwards, two chattering reduction methodologies were implemented: Quasi sliding mode control and Asymptotic sliding mode control. The performance of each of the controllers is analyzed experimentally and the controller parameters are tuned by trial and error. We presented the performance comparison of the controllers using metrics: Mean Absolute Error(MAE), rise time, settling value, and overshoot value. The paper is organized as follows. Section 2 shows a mathematical model of the frictional drive system, which is the designing process of the system and system modeling of the frictional driving of the catheter. Section 3 presents applying the process of the Sliding Mode Control approach to the frictional driving system. In this section first, the classical sliding mode approach is applied. After that chattering attenuation approach which is two other sliding mode approach is presented for elimination to chattering phenomena. Section 4 introduces the experimental result. In this section first, frictional drive equipment and frictional driving system controlling program is mentioned. Later that experimental result process is mentioned and sliding mode performance is compared and the best controller is chosen. Finally, Section 5 presents the conclusions and future work for this paper.

II. MATHEMATICAL MODEL OF FRICTIONAL DRIVE

The proposed friction drive consists of two silicon-coated cylinders which are active and passive rollers. The active roller is coupled to a motor (the torque source) and the passive one is placed to create a pressure point for the catheter. The catheter is fed between the rollers (Figure 1a) and translates via frictional force.

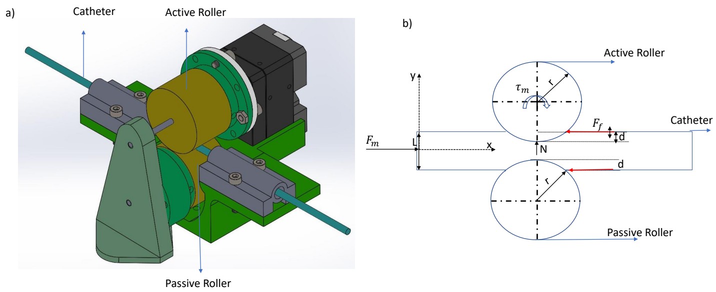

Figure 1: a) Frictional Catheter Driving System, b) Frictional Catheter Driving Diagram

The force transferred to the catheter(F_m) can be calculated concerning the radius of the active roller(r) as given in Equation 1.

$$F_m = \frac{\tau_m}{r} \tag{1}$$

It should be noted that Equation 1 is only valid when F_m is smaller than the frictional force(F_f) between the catheter and the rollers. The friction force can be calculated using the coefficient of friction (μ) and the normal force (N) at the contact point (Equation 2).

$$F_f = 2\mu N \tag{2}$$

As it can be seen in Figure 1b, the rollers squeeze the catheter and cause the elastic deformation in shape. Therefore the normal force causing friction can be calculated by assuming that the catheter is a spring with an equivalent coefficient (k) and is compressed by the amount of d (Equation 3).

$$F_f = 2\mu k d \tag{3}$$

If the driving force is less than the friction force ($F_m > F_f$), the catheter and friction pulley movement will be independent and the system will make a two degree of freedom movement. If otherwise ($F_m \leq F_f$)), the movement of the catheter and the friction pulley will be dependent and the system will make a single degree of freedom movement as given in Equation 4.

$$m\ddot{x} = F_m - f(\dot{x}, t) \tag{4}$$

As a consequence of the catheter motion in the living organism, the effects of inner body interactions are observed as the unknown disturbances in the system model ($f(x, \dot{x}, t)$). However, the bounds for uncertain interaction forces can be predicted using the characteristics of tissues and body fluids.

III. Sliding Mode Control

The sliding mode control strategy is an appealing method for mechanical control systems with bounded uncertainty [29]. First, the classical sliding mode control method is applied to the system. After that two chattering attenuation methods are applied which are quasi and asymptotic sliding mode controllers.

A. Classical Sliding Mode Controller Design

Using the mathematical model(Equation 4), the position and velocity error of the catheter tip can be defined as in Equations 5, 6, 7, and 8.

$$x_1 = x - x_d \tag{5}$$

$$x_2 = \dot{x} - \dot{x}_d \tag{6}$$

$$\dot{x}_1 = x_2 \tag{7}$$

$$\dot{x}_2 = u + f(x_2, t) \tag{8}$$

u is a time-dependent input function of the system, and to generates the function that minimizes the tracking error defined in Equations 7 and 8.

In Equation 8, u is the control input and f(x_2,t) is the viscous friction arising from the mucus fluid. Accordingly, it is assumed that the viscous friction acting on the catheter tip in all conditions will be lower than a certain limit value.

$$|f(x_2, t)| \ \leq \ F_d \tag{9}$$

To calculate the robust controller the sliding surface is defined as follows:

$$\sigma(x_1, x_2) = x_2 + cx_1 \qquad c > 0 \tag{10}$$

To guarantee the stability of the controller, a Lyapunov Function candidate is suggested in Equation 11, which is widely used for the sliding mode controller design.

$$v = \frac{1}{2}\,\sigma^2 \tag{11}$$

The system is said to be asymptotically stable in sense of Lyapunov if v(x) is greater than or equal to zero and the time derivative of this Lyapunov Function is less than zero for all values of x. To ensure negativeness of $\dot{v}$, a limiting function introducing design parameter α is defined as follows:

$$\dot{v} \leq -\alpha\sqrt{v} \tag{12}$$

Equations from below are obtained if the system model for stability analysis is written in terms of the new variable σ and the time response of the Lyapunov Function is calculated accordingly. To relate condition given in Equation 12 with system dynamics, time derivative of sliding surface (Equation 10) and Lyapunov function candidate (Equation 11) as follows:

$$\dot{\sigma} = \dot{x}_2 + c\dot{x}_1 = u + \ f(x_2, t) + cx_2 \tag{13}$$

$$\dot{v} = \sigma\dot{\sigma} = \sigma(u + \ f(x_2, t) + cx_2) \tag{14}$$

Without loss of generality, the control input u can be defined as in Equation 15, and new expression for $\dot{v}$ can be obtained as in Equation 17 [30].

$$u = -cx_2 + \theta \tag{15}$$

$$\dot{v} = \sigma(\ f(x_2, t) + \theta) \tag{16}$$

$$\dot{v} = \sigma\ (\ f\ (x_2, t) + \theta) \leq |\sigma|\, F_d + \sigma\theta \tag{17}$$

The absolute value of the function representing the sliding surface can be obtained as in Equation 18.

$$|\sigma| = \mp\sqrt{2v} \tag{18}$$

The time derivative of the Lyapunov function candidate can be obtained by rearranging and combining Equations 12 and 18.

$$\dot{v} = \frac{-\alpha\,|\sigma|}{\sqrt{2}} \tag{19}$$

As seen in Equation 19, the design parameter (α) can be included in the Lyapunov base design procedure. To proceed in controller design, an arbitrary switching function to keep the system states on sliding surface is given as in Equation 20 with $\theta > 0$. The equations are updated by considering Equation 20 as follows:

$$\theta = -\ \varphi\ sgn\,(\sigma) \tag{20}$$

$$\dot{v} \leq -\,|\sigma|\,(\varphi + F_d) \tag{21}$$

The amplitude of the switching function (φ) can be calculated using Equation 25 by considering the Equations 9, 16, and 19.

$$\dot{v} \leq \frac{-\alpha\,|\sigma|}{\sqrt{2}} \ = \ -\,|\sigma|\,(\varphi + F_d) \tag{22}$$

$$\varphi = \frac{\alpha}{\sqrt{2}} + \ F_d \tag{23}$$

Eventually, the control effect is proposed as in Equation 24 by combining sliding mode control law with proportional control law for catheter tip position.

$$u = -cx_2 - Kx_1 - (\frac{\alpha}{\sqrt{2}} + \ F_d)sgn(\sigma) \tag{24}$$

B. Chattering Attenuation Methods for Increase Control Performance

As mentioned above, chattering is a major problem of the sliding mode control due to high-frequency switching. However, there are several methods proposed to eliminate the chattering [13], [31]. This study focuses on the quasi-sliding mode [32] and the asymptotic sliding mode [28] control methodologies to improve the accuracy of the system and reduce the chattering.

1) Quasi-Sliding Mode Control: In the quasi-sliding mode control design, the signum function in Equation 24 is replaced by a continuous function to eliminate the chattering. The quasi-sliding mode acts like conventional sliding mode control outside the boundary layer. In the boundary layer, the continuous state feedback control is used instead of discrete state feedback control due to the discontinuous switching function, which effectively reduces the chattering. However, the modification in the controller reduces the system accuracy. In quasi-sliding mode, the continuous function mimicking the signum function is given as Equation 25 [32], [33] where ϵ is a small positive scalar.

$$sgn\left(\sigma\right) \approx \frac{\sigma}{|\sigma| + \epsilon} \tag{25}$$

In that regard, the control law is updated as follows:

$$u = -cx_2 - Kx_1 - (\varphi)\frac{\sigma}{|\sigma| + \epsilon} \tag{26}$$

2) Asymptotic Sliding Mode: In asymptotic sliding mode control, a continuous control is designed using the approach for deriving a control law in terms of control function derivative. In this case, the actual control signal (u) is continuous because it is integral to high-frequency switching signal. The asymptotic sliding mode can be obtained by applying four steps [30]:

Step 1: The auxiliary sliding variable s is defined using the sliding variable and its derivative. Also, parameter c is equal to proportional gain parameter K.

$$s = \dot{\sigma} + \ \bar{c}\sigma \tag{27}$$

Step 2: According to the ideal sliding mode controller, the auxiliary sliding variable converges to zero in finite time. Therefore, the sliding variable and its derivative converge to zero.

$$s = \dot{\sigma} + \ \bar{c}\sigma = 0 \quad (\sigma, \dot{\sigma} \rightarrow 0) \tag{28}$$

Step 3: As a consequence of derivations (Equation 27 and 28), the sliding variable approaches to zero in finite time. In this regard, the disturbance effect is eliminated and the state variables approach to zero in finite time.

$$\sigma = \ x_2 + cx_1 \rightarrow \ c > 0 \tag{29}$$

$$\dot{\sigma} = \ \dot{x_2} + c\dot{x_1} \tag{30}$$

Step 4: The control input derivative (ζ) is calculated concerning the stability of the sliding mode and the cancelation of bounded uncertainties using a similar approach in Equation 14.

$$\dot{u} = \zeta \tag{31}$$

$$\zeta = -c\bar{c}x_2 - (c + \bar{c})\, u - \zeta_1 \tag{32}$$

$$\zeta_1 = \ \varphi \ sign(s) \tag{33}$$

$$\varphi = \frac{\alpha}{\sqrt{2}} + \bar{F_d} + (c + \bar{c})\, F_d \tag{34}$$

$$\zeta = -c\bar{c}x_2 - (c + \bar{c})\, u - \varphi \ sign(s) \tag{35}$$

3) Sliding Mode Parameter Tuning: The parameter selection in sliding mode control is a trial and error procedure containing several steps. In this study, switching gain(φ), proportional control gain (K) and velocity state gain (c) are controller parameters to be defined. Each parameter should be considered in a given aspect concerning its effect on motion dynamics. The switching gain must have a minimum value to compensate the disturbance when all states(x_1,x_2) are equal to zero. The proportional constant (K) and velocity state gain (c) should be tuned for shaping controlled system response. For the tuning process, the performance metrics overshoot value and rise time are used for evaluating transient response and the mean absolute error value(MAE) and steady-state value are used for evaluating system accuracy.

For further improvement, a fuzzy logic based supervisory control scheme is proposed concerning the estimated disturbance magnitude and magnitude of error. The supervisory control enables automated update of controller parameters: Switching gain and proportional control gain.

IV. Experimental Results

Using the experimental setup given in Figure 2, the performance of the proposed controllers in real-time was evaluated. The performance analysis was carried out by assuming that the catheter moves under the effect of bounded unknown friction force ($|F_d|>f(x_2,t)$).

A. Test setup

As an actuator for driving the active roller, the Dynamixel XM430-W350 type smart servo motor is exploited. The controller mode for the actuator is selected as the current control mode in which the controlled motor operates as a torque source. The motor is also capable of giving position, velocity, and current feedback. The proposed controllers are implemented using the Python3.6 with the Robotic Operating System(ROS) [34] interface was designed using a computer which has a Ubuntu18.04.

B. The Controller Performance Tests

The performance tests were carried out for tuning the control parameters φ,c and K given in Table 1. The reference input was given for catheter tip position as 200mm and 5mm. During the test, position, speed, and control signals were logged. The rise time, MAE, overshoot value, and steady-state value were calculated using the logged signals to determine the best-performing controller parameters. The MAE value is calculated between the desired value to present values which are the position values above 95% of desired position value. Also reaching 95% of the desired position is give the rise time of the system performance. During the experiments, the upper bound of unknown friction force is estimated for 1N and the switching gain(φ) is kept constants as 2. The performance evaluation of trial and error tuning is presented in Table 1 with the selected set of controller parameters.

The first three rows of Table 1 show that all sliding mode controllers have underdamped responses when the reference

SMC TYPE	c	K	x_d	Rise Time(s)	Overshoot Value(mm)	Steady-state error (mm)	MAE Value
Classical Sliding Mode	0.1	0.1	200	1.770	1.18	0.8	0.56
Quasi Sliding Mode	0.05	0.3	200	1.740	5.80	0.03	0.18
Asymptotic Sliding Mode	0.05	0.4	200	1.770	11.14	0.03	1.02
Classical Sliding Mode	0.1	0.1	5	0.156	Can not be calculated	Oscillatory	0.8
Quasi Sliding Mode	0.05	0.3	5	0.228	No over-shoot	0.28	0.28
Asymptotic Sliding Mode	0.05	0.4	5	0.432	Can not be calculated	Oscillatory	0.34

Table I: Sliding Mode Control Performance

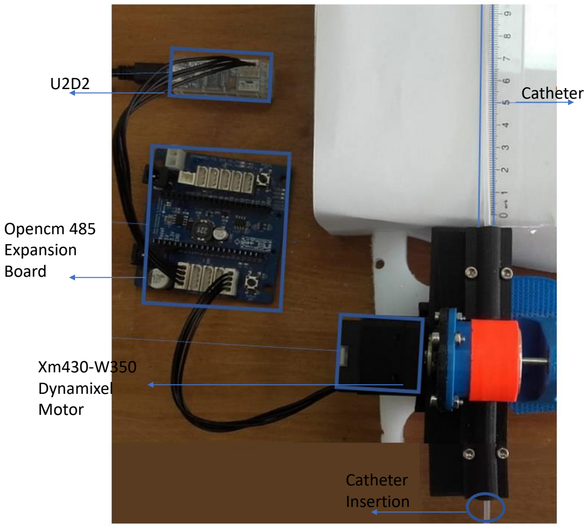

Figure 2: Frictional Catheter Driving System

is 200mm. The control input and position signals obtained during the experiment are given in Figure 3. It can be seen that all catheter tip position signals look similar. Nevertheless, high magnitude chattering was observed in the classical and asymptotic sliding mode control signals in Figure 3 a1,c1 when the position signal reached the steady-state. Both controllers have a chattering magnitude larger than the disturbance force bound. It is also observed that the quasi-sliding mode controller accomplishes the chattering attenuation and compensates the disturbance force. As a consequence, it can be dedicated that the chattering attenuation performance of quasi-sliding mode control is better than asymptotic sliding mode control for the given application. When the performance test result with 5 mm reference, the effect of steady-state chattering in control signals of classic and asymptotic sliding mode controllers became evident also in position signals(Figure 4 a1, a2, c1 and c2). However, the quasi-sliding mode control accomplishes the chattering attenuation and compensate the disturbance force. Besides, the quasi-sliding mode controller has also the best performances in terms of transient and steady-state performance as seen in Table 1.

C. *Performance Improvement*

Results from the above indicated that controller performance is good when the system moving to a single position. However, when the desired position is dynamically changed, a large amplitude of chattering occurs in the system which is shown in Figure 7 a2. In addition, as seen in Figure 7 a1, there is a difference in system accuracy between the forward and the reverse motion. To solve this problem, two fuzzy supervisory controllers have been added to adjust the quasi sliding mode controller parameters for reducing the amplitude of the chattering and increasing the precision.

Two fuzzy controllers have been proposed for these control structures. The input signal of the first fuzzy logic controller is the magnitude of the disturbance, the output signal is the quasi sliding mode controller switching gain parameter. The input signal of the second fuzzy logic controller is position error, the output signal is the quasi sliding mode controller proportional gain parameter. Membership functions defined for the first fuzzy controller are given by Figure 5. Membership functions defined for the second fuzzy controller are given by Figure 6. Using the rules given below, the system parameters are calculated instantaneously using the Mamdani decision making method. The responses of the position signal and input signal of the modified controller are given in Figure 7 b. Figure7 b1 shows that the fuzzy controller increases the controller precision. Figure 7 b2 indicated that the amplitude of the chattering value has decreased, but the magnitude value of chattering has increased.

First fuzzy logic controller rules are given as follows:

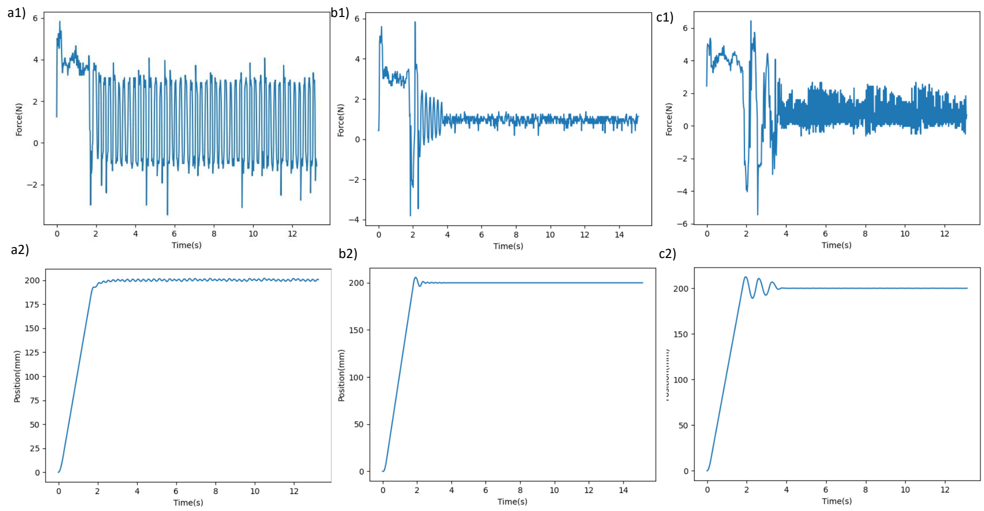

Figure 3: Sliding Mode Controller Control Actions and Position State Result when Desired Position 200mm a) Classical Sliding Mode b) Quasi Sliding Mode, c) Asymptotic Sliding Mode

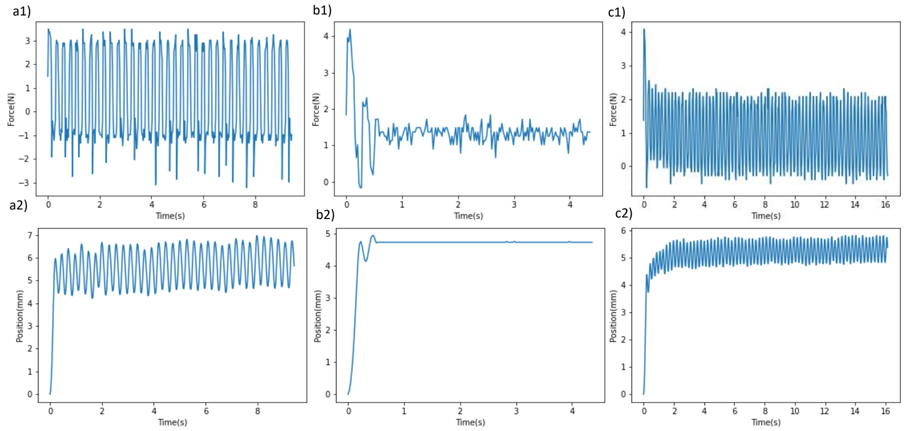

Figure 4: Sliding Mode Controller Control Actions and Position State Result when Desired Position 5mm a) Classical Sliding Mode b) Quasi Sliding Mode, c) Asymptotic Sliding Mode

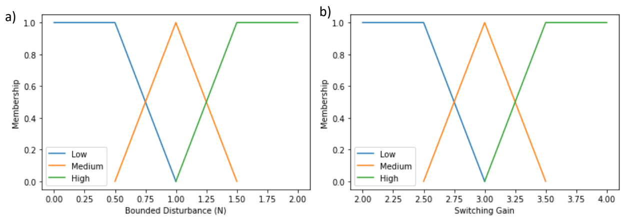

Figure 5: Frictional Catheter Driving System

- If Bounded Disturbance is Low then Switching Gain is Low
- If Bounded Disturbance is Medium then Switching Gain is Medium
- If Bounded Disturbance is High then Switching Gain is High

Second fuzzy logic controller rules are given as follows:

- If Position Error is Negative then Proportional Gain Value is Medium
- If Position Error is Zero then Proportional Gain Value is Low
- If Position Error is Positive then Proportional Gain Value is High

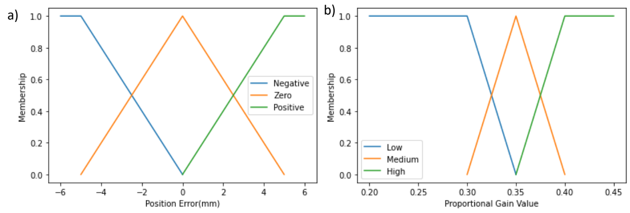

Figure 6: Frictional Catheter Driving System

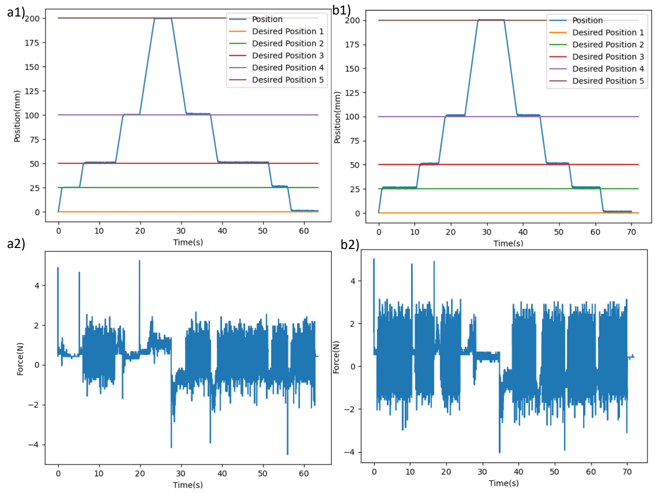

Figure 7: Frictional Catheter Driving System

V. Conclusion

In this paper, three nonlinear sliding mode control methods are proposed to control the frictional catheter driving system. The proposed controllers are classical sliding mode controller, quasi sliding mode controller, and asymptotic sliding mode controller. The sliding mode controllers are examined experimentally. The main objective of the sliding mode controllers was to improve the robustness in the presence of chattering. The experimental results were compared based on performance metrics and they indicated that the quasi-sliding mode control is superior in eliminating the chattering without degenerating the accuracy of the system. Moreover, a better disturbance compensation performance was observed for the quasi-sliding mode controller than other proposed controllers. It is also shown that the evaluation of estimated disturbance magnitude and magnitude of error by fuzzy logic can result in a supervisory control scheme which improves close loop control performance.

AUTHOR CONTRIBUTIONS

Gökmen Atakan Türkmen and Levent Çetin conceived of the presented idea. Gökmen Atakan Türkmen developed the theory and caried out the experiments. Aysun Baltacı, Barış Oguz Gürses, Mert şener, Özge Akbülbül devised the study, the main conceptual ideas. All authors discussed the results and contributed to the final manuscript.

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