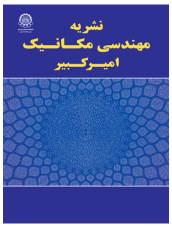

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Clutch Position Control for an Automated Manual Transmission Using Electromechanical Actuators

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ABSTRACT: In this paper, an adaptive sliding mode controller with variable gains to cope with uncertainties is proposed for an electromechanical clutch position control system to apply in the automated manual transmission. Transmission systems undergo changes in parameters with respect to the wide range of driving conditions, such as changes in friction coefficient of clutch disc and stiffness of diaphragm spring, hence, an adaptive robust control method is required to overcome the uncertainties and disturbances. As the majority of transmission dynamics variables cannot be measured in a cost-efficient way, a non-linear estimator based on an unscented Kalman filter is designed to estimate the state valuables of the system. Also, a non-linear dynamic model of the electromechanical actuator is presented for the automated clutch system. The model is validated with experimental test results. A numerical simulation of a reference input for clutch bearing displacement is performed to evaluate the performance of the designed controller and estimator. To evaluate the performance of the proposed control system the root mean square value of the position tracking error has been used. The results of the analysis indicate higher efficiency of the adaptive controller designed to improve the position tracking error compared to the conventional sliding mode controller.

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1- Introduction

Nowadays, the two types of most widely utilized transmission systems are Manual Transmission (MT) and Automatic Transmission (AT), each with its advantages and disadvantages. With the development of electronics and intelligent systems and their application in mechatronic systems of vehicles, the idea of automating the MT using actuators and intelligent controllers was introduced as an Automated Manual Transmission (AMT). Clutch actuation is one of the most complex parts of the AMT. The automated clutch can be disengaged and engaged automatically and should be designed to satisfy different and conflicting objectives, such as small friction losses, minimum time required for the engagement, and driver comfort during the engaging and disengaging process [1].

Position tracking control was implemented for the motor-driven gear-shift actuating mechanism of the electro-mechanical AMT system. To realize rapid and precise gear-shift control, an optimal discrete-time preview position control scheme was introduced. The proposed control method included the state-feedback control, discrete integrator, and feed-forward control [2]. A new hybrid optimization algorithm for the DC motor of electro-mechanical AMT was designed. It included a non-linear time-optimal controller and optimal linear quadratic regulator [3].

A Sliding Mode Controller (SMC) was proposed to design the combined electromechanical and electrohydraulic actuators. The main focus of this study was on pressure control in an electrohydraulic actuator with time-varying parameters without using the observer of state variables and the clutch spring was modeled nonlinearly [4]. In another paper, the researchers proposed a combination of a proportional-integral-derivative controller and an SMC to design an electromechanical actuator control system. However, the effect of parametric uncertainties on the controller performance was not investigated and the state variables used in the design of the control system were measurable. As a result, the estimator was not adopted in the control algorithm [5].

Due to the hard non-linearity of the spring stiffness of the actuator and clutch, a nonlinear estimator is needed to estimate the system states. To achieve this, many approaches have been suggested such as recursive least-square, sliding mode observer, Extended Kalman Filter (EKF), and Unscented Kalman Filter (UKF). However, the EKF has been rarely investigated in the previous AMT studies. When an EKF is applied to a complex non-linear system, a few problems may arise. One of them is the computation of the state transition matrix which requires the calculation of the Jacobian matrix. Moreover, the linearization can make large

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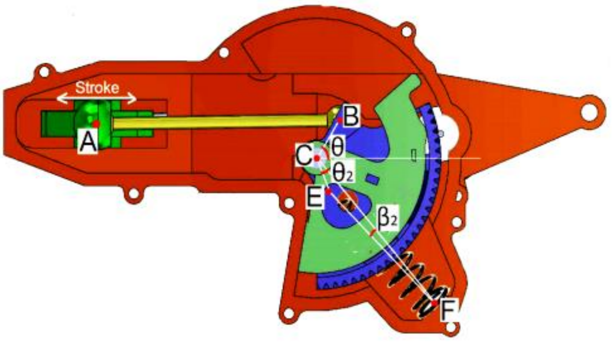

Fig. 1. Schematic diagram of the clutch actuating mechanism

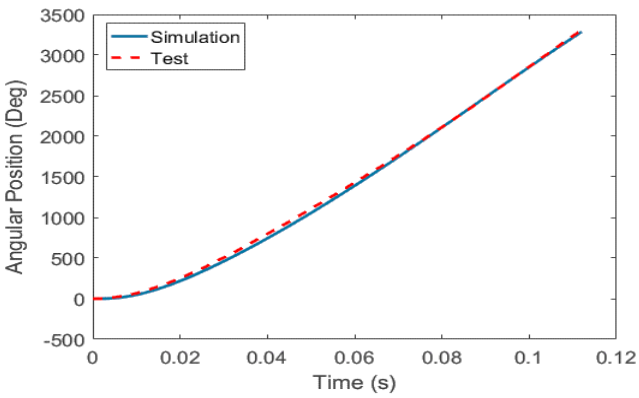

Fig. 2. The angular position of the electromotor shaft

errors and even cause divergence of the filter. To overcome this limitation, the UKF is utilized and developed currently. The UKF algorithm has many advantages over the EKF, especially in the case of high non-linearity. The UKF directly uses nonlinear equations of the system and does not require linearization [6]. According to the review of the presented studies, the contributions of this paper can be described as follows:

The first contribution of this paper is to build a validated and accurate model for the electromechanical clutch actuator without an available dynamic model and known parameters according to test results for the electromechanical clutch actuator. This model is applied to design the Adaptive Sliding Mode Controller (ASMC) and verified based on comparison with the simulation results of a created model in ADAMS/View software.

The second is a combined use of ASMC and UKF estimator to improve the clutch position control performance for the AMT system. The designed ASMC, which is insensitive to system uncertainties, offers adaptive sliding gains to eliminate the bounds of uncertainties. The rotational speed and acceleration of the clutch actuator are estimated in real-time utilizing the UKF.

2- Electromechanical Clutch Actuator Model

The electromechanical clutch actuator model uses an electric motor to engage and disengage the clutch. In the clutch actuator, the rotary movement of the electric motor is transferred via a toothed gear segment into a linear movement, which is then used to open the clutch with the help of the release lever and release bearing. A schematic diagram of the clutch actuating mechanism is shown in Fig. 1. As shown in the figure, the system mainly consists of three components: a gear, a coil spring, and a slider-crank mechanism. Thus, the system model is obtained by a set of kinematics and kinetics equations that describes the dynamics of the electromechanical actuator. The slider-crank includes links of BC and AB and revolute joints A, B, and C. The points of C and F are fixed and point A has translation motion. The input gear link is a compound member with a circular segment. There are teeth around this link that engage the electromotor pinion. The angular velocity of the gear is ω. According to the geometry of mechanism, trigonometric relations, also the relative motion analysis, the derivative of the spring length is obtained as follows:

$$\dot{\overline{EF}} = \frac{\overline{CE}.\overline{CF}.\omega.sin\theta_2}{\overline{EF}} = \frac{17.665\times10^{-4}\,\omega.sin\theta_2}{\overline{EF}} \qquad (1)$$

So, the spring force and its torque around point E is determined if angle β is known. This angle is found as follows:

$$\dot{\beta}_2 = \frac{-\overline{CE}.\omega.\cos\left(\theta_2+\beta_2\right)}{\overline{EF}} = \frac{-0.025\omega.\cos\left(\theta_2+\beta_2\right)}{\overline{EF}} \qquad (2)$$

After actuator modeling, several tests run to investigate the performance of the clutch actuator is driven by the DC electromotor with the $u_a=14$ V rated voltages. Then the simulation results were compared with the measurements on the test stand which has been done in the laboratory as shown in Fig. 2. Some necessary modifications have been made in the model parameters, to get good agreements with the test results.

3- Design of the System Controller

The controller design based on ASMC for the automated clutch is presented in this section. First, the conventional SMC is introduced, and then the ASMC with adaptive gains is proposed. For the SMC, the error functions are defined by the following expression:

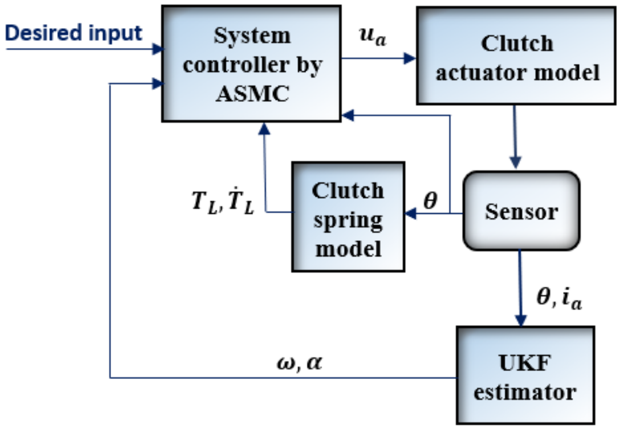

Fig. 3. The overall structure of the proposed controller scheme

Table 1. Comparison between the RMS of tracking error for different control systems

Parameter uncertainties	10%		20%	
Control system	SMC	ASMC	SMC	ASMC
RMS of error (mm)	0.251	0.216	0.282	0.225
The relative improvement of ASMC	14%		20%	

$$e_1 = x_c - x_d \ , \ e_2 = v_c - v_d \ , \ e_3 = a_c - a_d \qquad (3)$$

The sliding surface S consists of an integral component expressed as:

$$S = e_3 + k_1 e_2 + k_2 e_1 + k_3 \int_0^t e_1 dt \qquad (4)$$

where k_1 and k_2 are the strictly positive design scalars, x_d, v_d, and a_d are desired trajectory, velocity, and acceleration. v_c and a_c are the values of clutch bearing velocity and acceleration. The SMC control law can be described as Eq. (5) in which, T_L is the load torque considered as a disturbance, k_t is the electromechanical coupling coefficient, k_e is the back electromotive force constant, R_a is the armature resistance, and L_a is the armature inductance. The gear ratio between the input gear link and electromotor pinion is N_m=40.5. The moment of inertia of the entire system, I_a is equal to 0.02 kg.m^2, k_ω=0.32, and $\lambda=R_a/L_a$.

$$\begin{aligned} u_a = \frac{L_a}{k_t N_m}\Bigg[& (\frac{I_a}{c_1}).(\dot{a}_d - k_1 e_3 - k_2 e_2 - k_3 e_1 - \eta \, sign(S))... \\ & + \left(k_\omega + \frac{R_a I_a}{L_a}\right)\alpha + \left(\frac{R_a k_\omega + k_t N_m^2 k_e}{L_a}\right)\omega ... \\ & -\hat{\lambda} T_L - \hat{\phi}\dot{T}_L \Bigg] \quad , (\eta, c_1 > 0) \end{aligned} \qquad (5)$$

$$T_L = -0.906\theta^3 - 4.94\theta^2 + 28.68\theta - 25.03 \qquad (6)$$

The SMC gains k_1, k_2, k_3, and η depending on the upper bounds of uncertainties in the actuator clutch controller such as the load torque of the actuator and its derivative. These gains should be tuned by a trial-and-error method in practical applications. To overcome this disadvantage, the sliding mode control with adaptive gains has been presented. The overall structure of the proposed controller scheme for the clutch actuator is shown in Fig. 3.

4- Simulation Results

The accuracy of the proposed SMC combined with the UKF estimator is evaluated without any torque disturbance for the model with nominal parameters. The objective is to control the clutch to move from the initial position to the end. Hence, the position control of the clutch is analyzed in this investigation by adopting the SMC controller. The designed SMC combined with the UKF estimator is efficient to track precisely the desired trajectories for the clutch displacement. However, the proposed SMC system cannot perform with high accuracy in the presence of parameter uncertainties and external disturbances. Since the transmission systems undergo changes in parameters with respect to the wide range of driving conditions, such as changes in friction coefficient of clutch disc and stiffness of diaphragm spring, and the longer-time wear and tear during the running period, an ASMC method is required to guarantee good tracking performance and cope the uncertainties and disturbances. To achieve this, in the following, the simulations are conducted under two different conditions of parameter uncertainties in modeling for load torque of clutch spring. Let us assume that the parameters of the Eq. (6) have been decreased by 10% firstly, then 20%. In order to assess the performance of the proposed adaptive controller, the results of the ASMC are compared with the SMC.

An important index for the better quantitative evaluation of proposed control systems is the Root Mean Square (RMS) value of the tracking error of clutch position. The RMS values of tracking error for the control systems are computed, as given in Table 1.

5- Conclusions

This paper proposed an ASMC combined with the UKF estimator for the automated clutch system. The stability of the controller was approved by using the Lyapunov theorem and the robustness of the designed ASMC was investigated by performing some simulations in the MATLAB environment based on a validated non-linear model for the clutch actuator. The analyses are conducted under two different conditions of parameter uncertainties. It was presumed that the parameters of the clutch spring model were decreased by 10% and 20%. A precise tracking response of position control can be observed by employing the proposed ASMC in the presence of parameter uncertainties against the traditional SMC. Also, the UKF was applied to estimate precisely the full states of the system without a significant error. The contributions of this study are the following:

The first contribution of this paper is to build a validated model for the electromechanical clutch actuator without available dynamic model and known parameters. By comparison with the test results and simulation analyses, the actuator model was verified. The second is that a nonlinear estimator was proposed through UKF to estimate the variables that cannot be measured in a cost-efficient way such as rotational speed and angular acceleration. The third one is presenting the high effectiveness of the ASMC against the conventional SMC to track exactly the reference trajectories and control the dynamic systems accompanied by uncertainties and disturbances.

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