Positioning Control of a One Mass Rotary System with CM-NCTF Controller

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***Abstract*—In this paper, a Continuous Motion Nominal Characteristic Trajectory Following (CM-NCTF) controller is proposed as a practical control approach on a DC driven one mass rotary system. A CM-NCTF controller has simple controller structure and easy design procedures, and it does not require the exact plant model parameters. The CM-NCTF controller is made up of two major parts: a Nominal Characteristic Trajectory (NCT) and a Proportional-Integral (PI) compensator. The NCT is constructed on a phase plane with open loop information of the mechanism, while PI compensator is designed to ensure the mechanism follows the NCT and stops at the origin of the phase plane. The positioning performance of the CM-NCTF controller are evaluated and compared with a PID controller in point-to-point and tracking motion experimentally. The proposed controller achieved at least 36.8 % smaller steady state error than the PID controller, with no presence of overshoot in point-to-point motion. In tracking motion, the maximum tracking error produced by the CM-NCTF controller is 3 times lower than the PID controller in 1 rad amplitude. Overall, the experimental results demonstrated that the CM-NCTF controller has greater positioning and tracking performances than the PID controller.**

***Index Terms*—Practical Control; Positioning Control; One Mass Rotary System.**

I. INTRODUCTION

In manufacturing and automated industries, precision motion systems are highly demanded as they are capable of giving high productivity and high quality goods. Yet, alterations to the machineries to achieve high positioning performance are relatively expensive and burdensome. Thus, practical controllers are designed and implemented to utilize the mechanisms' features for high motion control performances.

As per stated by Dorato [1], a practical controller presents various characteristics, including simple design procedures, fixed control structure, satisfies multiple performance specifications and achieves robust closed-loop stability. Despite the abundance of advance controllers designed to meet these characteristics, the conventional PID controller retains its popularity in the industries for being a practical and simple-to-design controller. PID controllers provide agreeable performance given that the parameters are properly tuned. However, the positioning performance of the PID controller is limited should the requirements of positioning performances and robustness are raised. Hence, it is important to propose a controller that fulfill these requirements, while having a noncomplex structure and a set of easy design procedures.

Up to date, different types of controllers such as Disturbance Observer (DOB) [2-4], sliding mode control [5-6] and time optimal control [7] have proven their effectiveness in producing promising positioning performance. In spite of that, one may find that the design procedures of these controllers require a relatively high degree of control knowledge. Besides, majority of these controllers require the determination of exact plant model parameters, which is a laborious and time consuming procedure.

In recent years, a Nominal Characteristic Trajectory Following (NCTF) controller is gradually gaining attention from the industries. Various studies have shown that NCTF controller has straightforward design procedures and simple structure, as well as its capability in achieving high positioning performance. On top of that, the design of NCTF controller does not require any model parameters of the system. In [8], the effectiveness of NCTF controller in an AC driven two mass rotary system with the presence of actuator saturation was shown. On the other hand, Maeda and Sato proposed a NCTF controller to achieve ultra-precision positioning in a ball screw mechanism driven by DC motor [9]. Despite its achievement in point-to-point motion, Sato and Maeda have pointed out that NCTF controller has to be improved for tracking and contouring motions [10]. While keeping the simple design procedures, the improved the NCTF controller, Continuous Motion NCTF (CM-NCTF) controller has demonstrated far superior tracking as well as positioning performances than the conventional NCTF and PI-D controller. Two years later, Chong and Sato implemented the CM-NCTF controller on a 1DOF air slide mechanism [11]. The study indicates that the design procedures of the controller is straightforward and independent of friction characteristics. Findings of the literature also show that the CM-NCTF controller has higher positioning and tracking performances than a PID controller.

While the CM-NCTF controllers are applied in different mechanisms, the implementation of the controller in a DC driven system has yet to be done. Thus in this work, a CM-NCTF controller is proposed as a practical control approach to perform positioning control of a DC driven one mass rotary system. This paper is organized as follow: Section II presents the modelling of the experimental setup, whereas Section III describes the control concept of CM-NCTF controller. In Section IV, the positioning performance of the CM-NCTF controller is discussed and compared with PID controller. Conclusions are drawn in Section 5.

II. Experimental Setup

The experimental setup used in this paper is shown in Figure 1, whereas the one mass rotary mechanism driven by DC motor is presented in Figure 2. The displacement of the one mass rotary mechanism is measured with a rotary encoder of 2000 counts per revolution. An amplifier with a saturation of ±10 V is used to drive the DC motor. The controller is implemented in the mechanism at a sampling frequency of 500 Hz. The model parameters of the one mass rotary system are presented in Table 1.

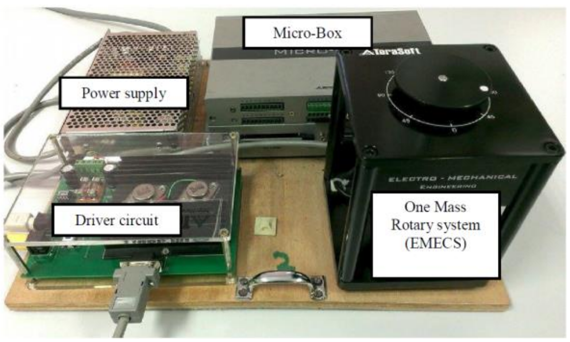
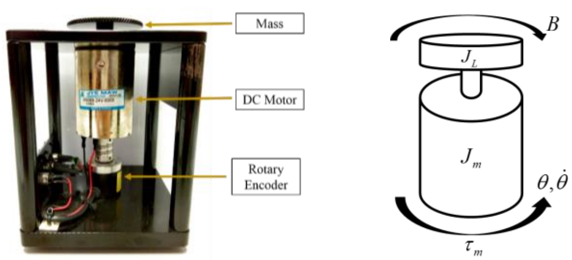


Figure 1: Experimental setup



(a) One mass rotary system (b) Dynamic model

Figure 2: A one mass rotary system and its dynamic

Table 1
Model Parameters of the One Mass Rotary System

Symbol	Description, unit	Value
J_m	Motor Inertia, kg·m^2	7.20×10^{-5}
B	Viscous Friction Coefficient, N·m·s/rad	9.14×10^{-5}
K_t	Torque Constant, N·m/A	1.83×10^{-2}
R_a	Armature Resistance, Ω	2.5604
L_a	Armature Inductance, H	4.69×10^{-3}
K_b	Motor Back EMF constant, V·s/rad	1.83×10^{-3}
J_L	Load Inertia, kg·m^2	2.12×10^{-4}
τ_m	Motor Torque, N·m	-

Since the stiffness of the shaft connecting the load and motor is very small and negligible, the equation of motion for the system is presented as:

$$\tau_m = J\ddot{\theta} + B\dot{\theta} \tag{1}$$

$$\tau_m = K_t u \tag{2}$$

where J is the equivalent inertia of motor, J_m and load, J_L, while u represents the input to the DC motor.

III. CM-NCTF Controller Concept

A. Controller Structure

Figure 3 shows the structure of the CM-NCTF controller. The controller comprises two portions: a Nominal Characteristic Trajectory (NCT) and a Proportional-Integral (PI) compensator. The NCT is constructed based on the open loop response that includes the characteristics of the mechanism. It represents the deceleration motion of the mechanism where the motion stops at the origin. A NCT comes with a reaching phase and following phase, as shown in Figure 4. At the reaching phase, the PI compensator controls the mechanism motion such that it reach the trajectory, i.e. by reducing up, where up is the difference between the actual error rate of the system, and the error rate of the NCT, N(e).

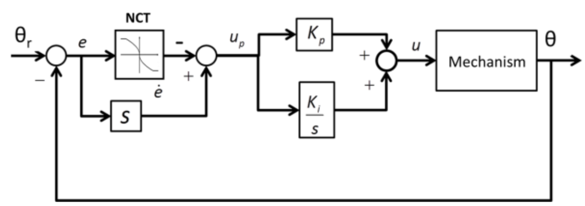


Figure 3: Structure of CM-NCTF controller

Once the mechanism motion reaches the following phase, the PI compensator controls the mechanism motion such that it moves according to the trajectory and ends at the origin, which denotes the stopping of the mechanism.

B. Design Procedure

In general, the design of the CM-NCTF controller is similar with a conventional NCTF controller as presented in [8-11], where it can be structured into three fundamental steps:

1. Drive the mechanism with a suitable input in open-loop configuration.
   In this paper, a step-wise input is used to drive the one-mass rotary system. The amplitude of the input is carefully selected such that it does exceed the saturation limit of the amplifier. The open loop displacement and velocity curve is obtained as shown in Figure 5.
2. Construct the NCT on phase plane with open loop response.
   The NCT is constructed on a phase plane with the displacement and velocity curve of the mechanism during deceleration motion. The inclination near origin, β which denotes the maximum velocity of the mechanism, is obtained as β = -m = 439 s^{-1}. The constructed NCT is presented in Figure 6.

3. Design the PI compensator with open loop response and NCT information.
   In the design procedure of PI compensator, it is crucial to ensure stability and positioning performance of the system. To do so, a practical stability limit is established by first driving the mechanism with CM-NCTF controller using only proportional element. The gain is increased until the mechanism sustains periodic oscillations. This gain, also known as ultimate proportional gain, K_u indicates the margin of stability of the system. Thus, the derived practical stability limit, ζ_p as presented in [12] is given as in (3):

$$\zeta_p = \frac{K_u m h}{2\omega_n u_r} \tag{3}$$

The compensator gain, K_p and K_i is calculated based on the value of ζ and ω_n selected from the practical stability limit plotted in Figure 7. The calculations are done based on (4) and (5):

$$K_p = \frac{2\zeta\omega_n u_r}{mh} \tag{4}$$

$$K_i = \frac{\omega_n^2 u_r}{mh} \tag{5}$$

Overall, it can be seen that the CM-NCTF controller has straightforward design procedures and does not require any exact plant model parameters. Tuning of the controller does not require one to have very deep understanding of control knowledge as well.

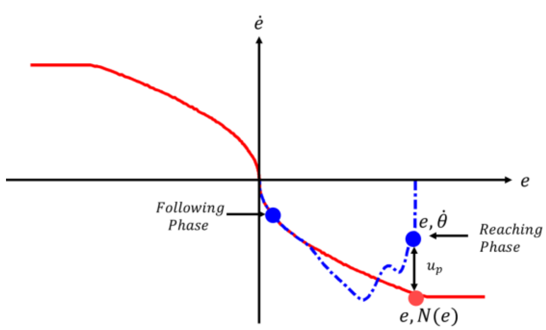


Figure 4: Phases on NCT

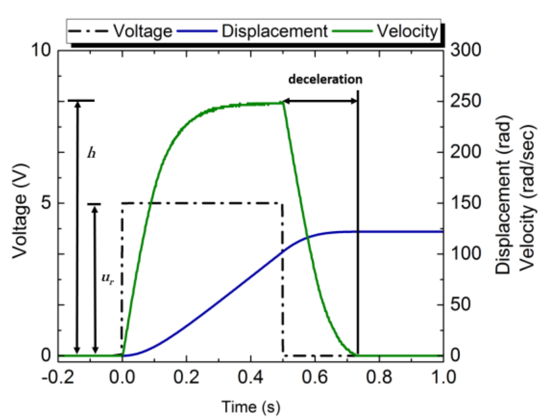


Figure 5: Open loop response with step-wise input

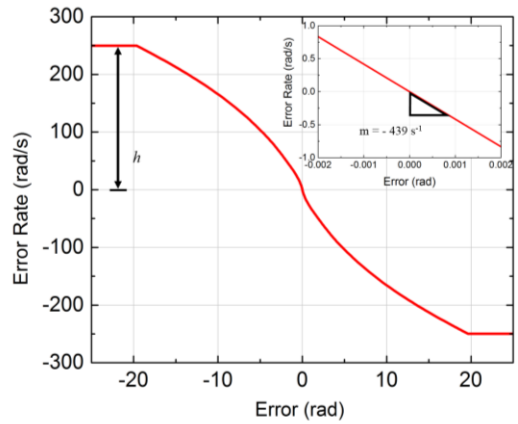


Figure 6: Constructed NCT

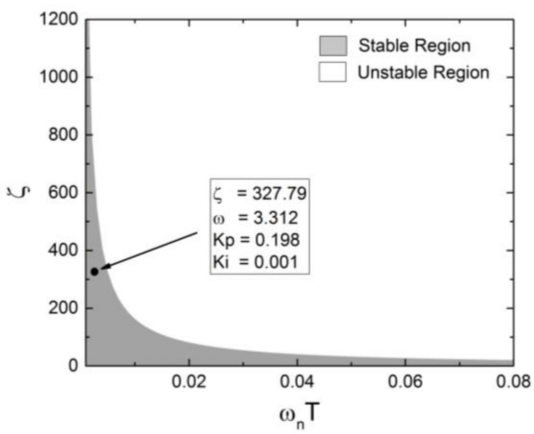


Figure 7: Practical stability limit of the system

IV. Performance Evaluation

In order to evaluate the effectiveness of the CM-NCTF controller, the positioning and tracking performances of the controller are examined experimentally. To perform comparative analysis, a PID controller was designed such that it has the same bandwidth as the CM-NCTF controller, as shown in Figure 8. The parameters of the PID controller are presented in Table 2.

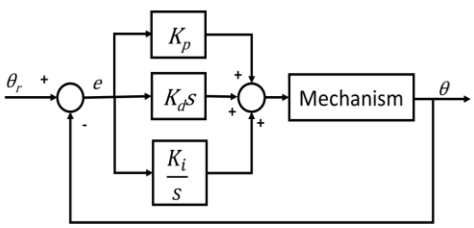
Figure 9 and Figure 10 present the experimental results of the two controllers to step heights of 1 rad and 4 rad. The quantitative results comprising of rise time, t_r, overshoot, *%OS* settling time, t_s, and steady state error, *e* is summarized in Table 3.

Despite having shorter rise time, the PID controller produces relatively large overshoot than CM-NCTF controller. The quantitative results presented in Table 3 shows that when the mechanism moves in a larger displacement (4 rad), the overshoot produced by the PID controller is 41% larger than the CM-NCTF controller. The CM-NCTF controller, on the other hand, does not produce any overshoot despite the increment of displacement. It can be seen that although the CM-NCTF controller has longer rise time, the settling time of the two controllers are similar, while CM-NCTF controller settles faster than PID when the reference input is increased to 4 rad. Overall, it can be concluded that CM-NCTF controller has shorter settling time than the PID controller.

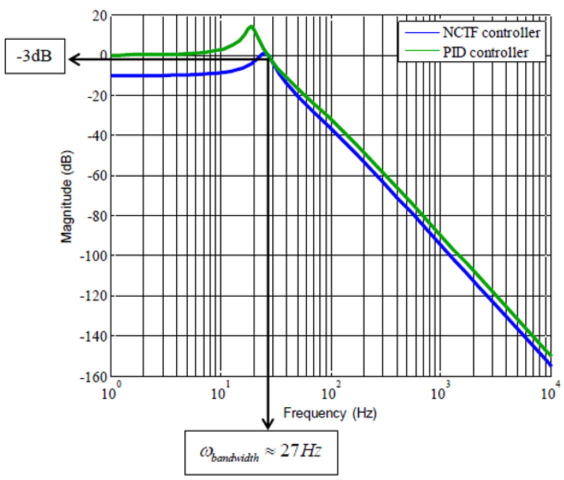
Based on Table 3, it can be observed that the CM-NCTF controller has lower positioning error than the PID controller. At the step height of 1 rad, the steady-state error of the PID controller is 36.8% higher than CM-NCTF controller. When the step height is increased, the positioning performance of the PID controller deteriorates significantly. The steady-state error of the PID controller has increased 65.4% when the step height is set as 4 rad.

Table 2
Parameters of CM-NCTF and PID Controller

Controller	β	K_p	K_i	K_d
CM-NCTF	439	1.98×10^{-1}	1.00×10^{-3}	-
PID	-	1.20×10^{1}	5.00×10^{-1}	1.50×10^{-1}



(a) Structure of PID



(b) Frequency response of CM-NCTF and PID

Figure 8: Design criteria of PID controller

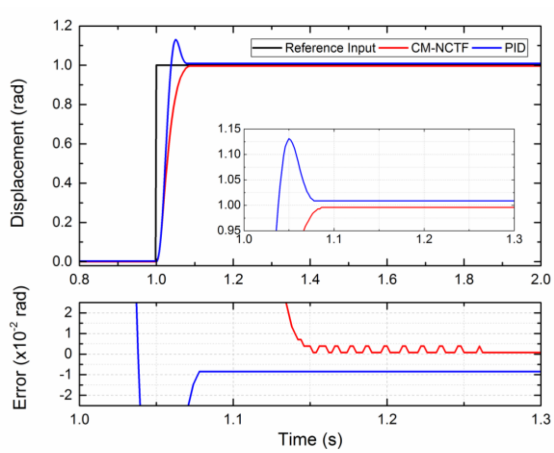


Figure 9: Point-to-point response to 1 rad

To examine the tracking motion of the controller, a sinusoidal reference of 1 Hz with amplitude of 1 rad and 4 rad are applied to the one mass rotary system. The maximum tracking error, e_{max} and root-mean-square error, e_{rms} of the controllers are evaluated and presented in Table 4. As compared to PID controller, the CM-NCTF controller shows far lower tracking error in the two amplitudes (refer Figure 11 and Figure 12). In the sinusoidal reference of 1 rad amplitude, the e_{max} of CM-NCTF controller is 3 times lower than PID controller, and 1.8 times lesser in 4 rad amplitude. Besides that, the lower e_{rms} also demonstrate that CM-NCTF controller has a higher tracking accuracy than PID controller.

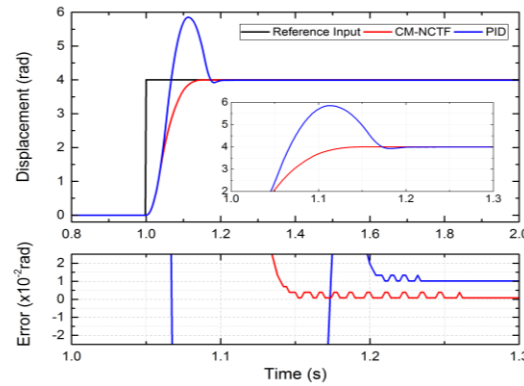


Figure 10: Point-to-point response to 4 *rad*

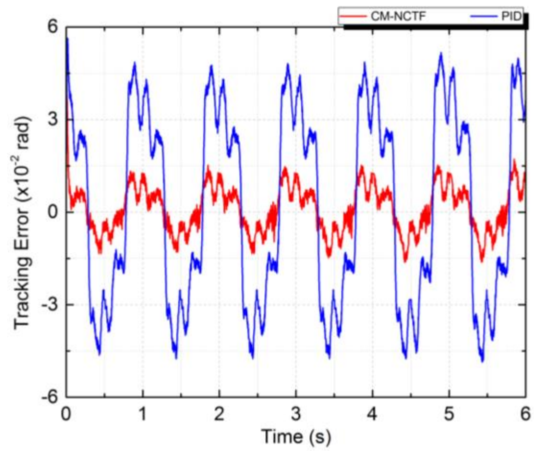


Figure 11: Tracking response to sinusoidal input of 1 Hz, 1 rad

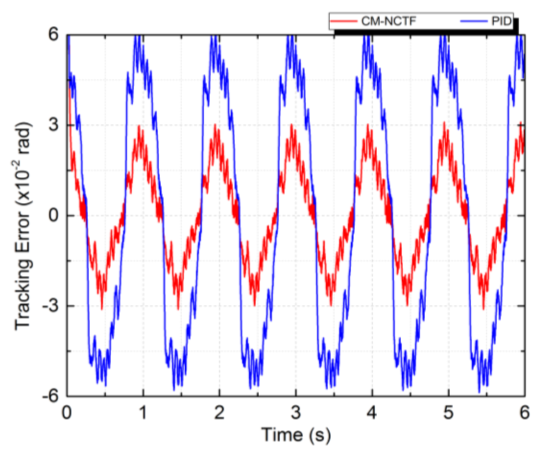


Figure 12: Tracking response to sinusoidal input of 1 Hz, 4 rad

Table 3
Positioning Performance of 10 Times Experiments

Step Height	Performance Index		CM-NCTF	PID
1 rad	t_r, s	Average	4.56×10^{-2}	2.40×10^{-2}
		Standard deviation	3.00×10^{-4}	1.10×10^{-3}
	OS, %	Average	0.00	1.32×10^{1}
		Standard deviation	0.00	3.95×10^{-1}
	t_s, s	Average	1.07	1.07
		Standard deviation	5.00×10^{-4}	1.16
	e, rad	Average	3.80×10^{-3}	5.20×10^{-3}
		Standard deviation	9.00×10^{-4}	1.70×10^{-3}
4 rad	t_r, s	Average	7.38×10^{-2}	4.20×10^{-2}
		Standard deviation	5.00×10^{-4}	3.00×10^{-4}
	OS, %	Average	0.00	4.10×10^{1}
		Standard deviation	0.00	9.25×10^{-1}
	t_s, s	Average	1.12	1.16
		Standard deviation	6.00×10^{-4}	3.01×10^{-2}
	e, rad	Average	8.00×10^{-4}	8.60×10^{-3}
		Standard deviation	0.00	5.10×10^{-3}

Table 4
Tracking Performance of CM-NCTF and PID

Reference Input	Performance Index	CM-NCTF	PID
1 rad, 1 Hz	e_{max}, rad	1.50×10^{-2}	4.83×10^{-2}
	e_{rms}, rad	7.65×10^{-3}	3.19×10^{-2}
4 rad, 1 Hz	e_{max}, rad	3.79×10^{-2}	6.82×10^{-2}
	e_{rms}, rad	2.26×10^{-2}	4.73×10^{-2}

V. Conclusion

In this paper, the CM-NCTF controller is proposed as a practical approach to perform positioning control on a DC driven one mass rotary system. The design procedures of the CM-NCTF controller are presented. The positioning and tracking performance of the CM-NCTF controller are validated and compared to a PID controller experimentally. While having a straightforward and simple design process, comparative analysis shows that the CM-NCTF controller is capable of suppressing the occurrence of overshoot, while maintaining fast transient response in point to point motion. In tracking motion, the CM-NCTF controller has higher motion accuracy than the PID controller, thus generating lower tracking error in the process. Therefore, it can be concluded that CM-NCTF controller has higher positioning and tracking performance than the PID controller.

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References

[1] P. Dorato, "Quantified multivariable polynomial inequalities: the mathematics of practical control design problems," *IEEE Control Magazines*, vol. 20,no. 5, pp.48-58, 2000.

[2] K. Kim, K. Rew, and S. Kim, "Disturbance observer for estimating higher order disturbances in time series expansion," *IEEE Trans. on Automat. Control*, vol. 50, no. 8, pp. 1905-1911, 2010.

[3] Y. X. Su, C. H. Zheng, and B. Y. Duan, "Automatic disturbances rejection controller for precise motion control of permanent-magnet synchronous motors," *IEEE Trans. of Ind. Electron.*, vol.52, no. 3, pp. 814-823, 2005.

[4] Q. W. Jia, "Disturbance rejection through disturbance observer with adaptive frequency estimation," *IEEE Trans. of Magnetics*, vol. 45, no. 6, pp. 2675-2678, 2005.

[5] Y.F. Li and J. Wikander, "Model reference discrete-time sliding mode control of linear motor precision servo systems," *Mechatronics*, vol. 14, no. 7, pp. 835-851, 2009.

[6] H. M. Chen, Z. Y. Chen, and M. C. Chung, "Implementation of an integral sliding mode controller for a pneumatic cylinder position servo control system," in *Int. Conf. Innovative Computing, Information and Control*, Kaohsiung, Taiwan, 2009, pp. 552-555.

[7] R. Shieh and Y. Lu, "Jerk-constrained time-optimal control of a positioning servo," in *Int. Conf. Control Automation and Systems*, Gyeonggi-do, Korea, 2010, pp. 1473-1476. 2010.

[8] Wahyudi, K. Sato, and A. Shimokohbe, "Characteristics of practical control for point-to-point (PTP) positioning systems effect of design parameters and actuator saturation on positioning performance," *Precision Engineering*, vol. 27, no. 2, pp. 157-169, 2003.

[9] G. J. Maeda and K. Sato, "Practical control method for ultra-precision positioning using a ballscrew mechanism," *Precision Engineering*, vol. 32, no. 4, pp. 309-318, 2008.

[10] K. Sato and G. J. Maeda, "A practical control method for precision motion-Improvement of NCTF control method for continuous motion control," *Precision Engineering*, vol. 33, no. 2, pp. 175-186, 2008.

[11] S. H. Chong and K. Sato, "Practical controller design for precision positioning, independent of friction characteristic," *Precision Engineering*, vol. 34, no. 2, pp. 286-300, 2010.

[12] R. Mohd Nor, Practical positioning control of a one mass rotary system, M. S. Thesis, Dept. Elect. Eng., Universiti Teknikal Malaysia Melaka, Malacca, 2014.