ICRA2026 Late Breaking Results Poster presented at
2026 IEEE International Conference on Robotics and Automation (ICRA 2026)
June 1-5, 2026. Vienna, Austria

Friction-Aware Actuator Modeling for Accurate Torque Estimation Using External Sensors

Jiman Park[1,2], Hyunyong Lee[1,2], Hansol Kang[1], Seongwon Nam[1], Yeongwoo Son[1],
Bumsu Yi[1], Jaeyoung Oh[1] and Hyouk Ryeol Choi[1,2*], *Fellow, IEEE,*
[1]*School of Mechanical Engineering*, *Sungkyunkwan University (SKKU)*, Suwon, South Korea
[2]AIDIN ROBOTICS Inc., Anyang, South Korea
E-mail: pjm753@skku.edu, choihyoukryeol@gmail.com

***Abstract*—Modern robotic controllers are typically designed in simulation and subsequently deployed on real robots. However, discrepancies between simulated and actual actuator torque often lead to sim-to-real (sim2real) problems. Various actuator approaches have been proposed to address this problem, but when external torque sensors are used, it is difficult to measure the intrinsic actuator output torque due to disturbances from external load systems. This paper proposes an actuator modeling method that minimizes the influence of external systems. The friction torque of the actuator is first identified under no-load conditions, and the measured torque under loaded conditions is compensated accordingly to estimate the pure output torque. Experimental results across various actuators and load conditions demonstrate that the proposed model closely matches the measured torque, even in actuators with large friction. The proposed approach overcomes the modeling limitation using external sensors and provides an effective solution for reducing sim2real problems in diverse actuator systems.**

***Index Terms*—Dynamics, Software-Hardware Integration for Robot Systems, Calibration and Identification.**

I. INTRODUCTION

Recent robotic control methods can be categorized into optimization-based [1] and learning-based methods [2]. Both methods are typically designed in simulation and then deployed on actual robot systems. However, the simulated and actual actuator torque differ and additional tuning is required. To address this sim-to-real(sim2real) issue, several actuator modeling methods have been proposed: Quasi-Direct Drive(QDD) [3], friction modeling [4] and Actuator-Net [5]. QDD approach achieves high transparency using low gear ratios, but it heavily depends on high-torque motors and it is difficult to manufacture. Friction modeling approach compensates for actuator dynamics by linearizing friction parameters. However, its accuracy may degrade in regions with strong nonlinearities. Actuator-Net approach deploys a learned model of actuator behavior into simulation. It enables accurate representation of nonlinear actuator behavior, but it requires extensive training time and large-scale experimental data. When applying these approaches to estimate torque across various actuators, external torque sensors are required. However, measurements are affected by external load systems, making it difficult to obtain the pure output torque of actuator. Therefore, this paper proposes an actuator torque modeling method using external torque sensors by analyzing and eliminating the effects of external systems.

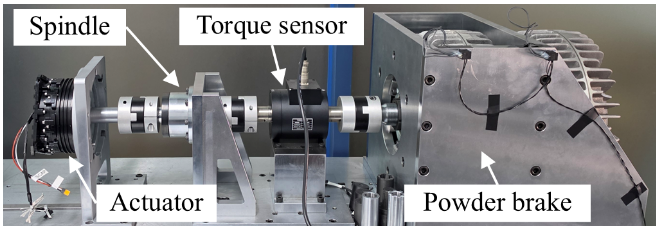


Fig. 1: Measurement setup

II. MODELING METHODS

The actuator torque can be measured by a external torque sensor. However, the measurements are distorted by the external systems. To address this issue, it is necessary to eliminate the effect of external system. For this purpose, the friction torque is modeled under both no-load and loaded conditions.

A. Friction modeling

Under no-load conditions, the actuator generates zero output torque during constant velocity motion but it still consumes a small amount of current. This indicates the presence of friction torque. The friction torque τ_{fric} can be converted into a friction current I_{fric} using the motor torque constant K_t. I_{fric} can be modeled as a function of the output angular velocity ν, following a Stribeck friction curve as follows [6]:

$$I_{fric} = \frac{\tau_{fric}}{K_t} = \sum_{i=1}^{N} \alpha_i \cdot \tanh(\beta_i \cdot \nu) + \gamma \cdot \nu^3. \qquad (1)$$

where α_i, β_i and γ are coefficients of friction Stribeck curve. From 1, the average friction current is measured as a function of ν, as shown in Fig. 2, enabling quantitative estimation of the actuator's friction characteristics.

When measured using an external torque sensor, the actuator output torque τ_o is affected by load system's friction torque τ_{fric}^{load}, leading to inaccuracies in the pure actuator

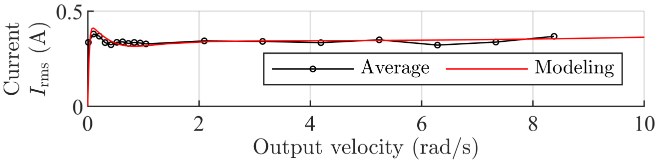
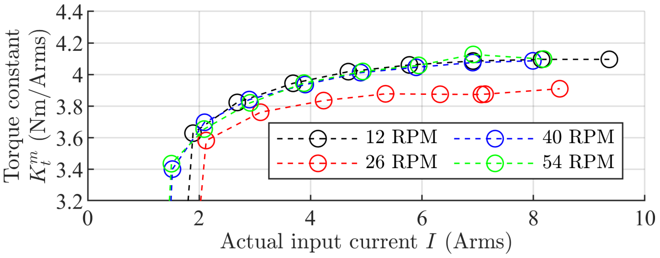
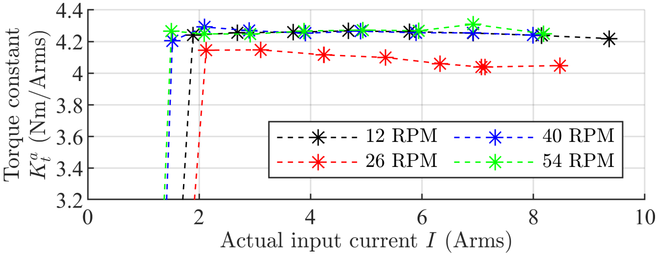


Fig. 2: Friction current I_{fric} of actuator



(a) Before compensation (K_t^m)



(b) After compensation (K_t^a)

Fig. 3: Actuator torque constant with friction compensation.

torque constant K_t^a. To account for this effect, the measured torque τ_m is modeled as follows:

$$K_t^m = \frac{\tau_m}{I} = K_t^a - \frac{\tau_{fric}^{load}}{I}. \tag{2}$$

The calculated actuator torque constant K_t^m, measured using the load system in Fig. 1, varies with respect to the input current I, as shown in Fig. 3a. This current-dependent behavior is consistent with (2), indicating that the measurement model (2) appropriately reflects the effect of the load system.

B. Actuator modeling

Since motor torque is proportional to I, additional current at a constant velocity is converted into an increase in output torque. From Chap. II-A, the estimated friction current represents the baseline under zero torque; therefore, any additional current beyond baseline is converted into τ_o and the actuator torque model is defined as follows:

$$\tau_o = K_t^a \cdot (I - I_{fric}). \tag{3}$$

From (3), K_t^m can be converted to K_t^a. In Fig. 3b, K_t^a is close to constant value, indicating that the proposed model accurately reflect actuator behavior.

TABLE I: Actuator model estimation results of actuators

Act No.	Unit	1	2	3	4
GR	-	42.35	42.35	35.42	36.67
K_t^a	Nm/Arms	4.197	4.236	4.094	4.349
RMSE	Nm [%]	2.01[1.4]	2.80[1.9]	2.74[2.8]	2.56[2.6]

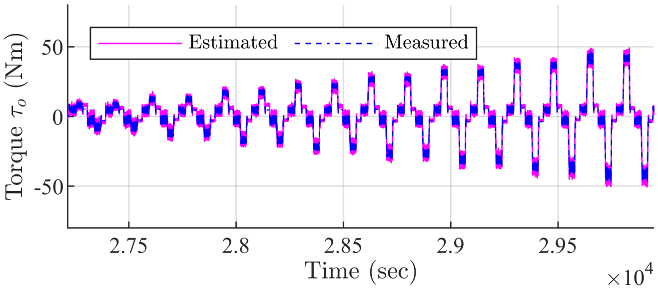


Fig. 4: Actuator output torque estimation at ν = 12 RPM

III. EXPERIMENTS AND RESULTS

Based on (3), torque constants were identified for several actuators with different gear ratios GR, as shown in Tab. I. The estimated torque with the proposed model closely matches the measured values across most regions (Fig. 4), with an RMSE within 3.0 % of the rated torque. High accuracy is maintained even in two actuators (3rd & 4th) with increased friction due to sealing O-rings.

IV. CONCLUSION

Conventional low-transparency actuators suffer from sim-to-real discrepancies due to torque mismatch. While torque is measured or modeled to minimize discrepancies, external sensors are affected by external system disturbances. To overcome this limitation, we propose a friction-aware actuator modeling method that enables accurate torque estimation across various actuators, effectively reducing sim-to-real gaps. Future work will extend this approach to system-level actuator modeling, rather than individual actuators.

REFERENCES

[1] J. Di Carlo, P. M. Wensing, B. Katz, G. Bledt and S. Kim, ”Dynamic Locomotion in the MIT Cheetah 3 Through Convex Model-Predictive Control,” in *Proc. IEEE/RSJ Int. Conf. Intell. Robot. Syst.*, Madrid, Spain, Oct. 2018, pp. 1-9.

[2] F. Bjelonic et al., ”Learning-Based Design and Control for Quadrupedal Robots With Parallel-Elastic Actuators,” in IEEE Robotics and Automation Letters, vol. 8, no. 3, March 2023, pp. 1611-1618.

[3] B. Katz, J. D. Carlo and S. Kim, ”Mini Cheetah: A Platform for Pushing the Limits of Dynamic Quadruped Control,” 2019 International Conference on Robotics and Automation (ICRA), Montreal, QC, Canada, May 2019, pp. 6295-6301.

[4] P. M. Wensing, S. Kim and J. -J. E. Slotine, ”Linear Matrix Inequalities for Physically Consistent Inertial Parameter Identification: A Statistical Perspective on the Mass Distribution,” in IEEE Robotics and Automation Letters, vol. 3, no. 1, Jan. 2018, pp. 60-67.

[5] Jemin Hwangbo et al., ”Learning agile and dynamic motor skills for legged robots,” Sci. Robot, vol. 4, no. 26, Jan 2019, eaau5872.

[6] Phillips JR., ”An Integrated Stribeck Friction Model: analysis, simulation, and comparison with Dahl and LuGre,” SIMULATION., vol. 101, no. 4, Jan 2025, pp. 477-491.