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Development of a Testbed and Quantitative Evaluation Framework for Characterization of Robot Actuator Dynamics

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Abstract— **The performance of robot actuators is still primarily evaluated using manufacturer-provided static specifications such as maximum torque and rated speed. However, these metrics are insufficient for assessing dynamic behaviors that are essential for physical interaction, including backdrivability, transparency, and disturbance response. This paper presents HYPERDYNE, a novel proof of concept test platform and evaluation framework for dynamic characterization and quantitative benchmarking of robot actuators. The reconfigurable testbed is developed, enabling three test configurations of no-load, fixed-load, and interaction scenarios within a single hardware setup. In addition, an evaluation protocol is proposed that includes system identification, control performance, load robustness, and disturbance rejection. Experimental validation on a QDD actuator demonstrates that the proposed framework enables the extraction of key dynamic parameters such as backlash, friction, inertia, and frequency response characteristics, while also providing performance indices for objective comparison. The results show that actuator performance can be quantitatively assessed beyond conventional static specifications, supporting the development of robots with improved physical interaction capabilities.**

I. Introduction

Robots are increasingly required to operate in environments that involve direct physical interaction with humans and unstructured surroundings. Applications such as humanoid robotics, service systems, and mobile manipulation demand actuators that can not only deliver high torque but also respond effectively to external disturbances while enabling precise force control. In such settings, actuator behavior is governed not only by nominal output capability but also by dynamic characteristics such as backdrivability, friction, and interaction compliance, which directly affect safety, stability, and performance [1].

Despite this, actuator evaluation in practice still relies on manufacturer-provided static specifications, such as maximum torque and rated speed [2]. These metrics do not account for dynamic properties that are significant for interaction, including nonlinear friction, drive transparency, and disturbance response. As a result, actuator selection and comparison remain largely empirical, with limited ability to predict real-world performance. To the best of our knowledge, a technique that addresses this problem has not yet been established. Therefore, this work presents HYPERDYNE, a proof of concept test platform and evaluation framework for dynamic characterization and quantitative benchmarking of robot actuators. The proposed system integrates a reconfigurable hardware testbed, an evaluation protocol, and a set of quantitative performance metrics.

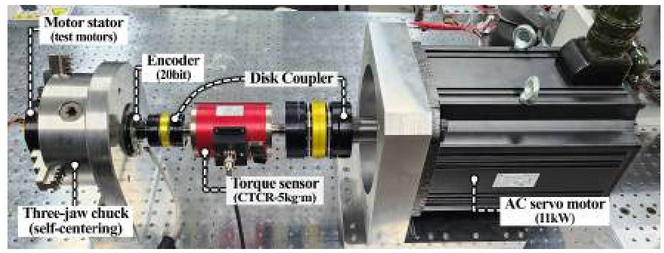

Fig. 1. HYPERDYNE testbed for dynamic characteristic analysis.

II. Proposed HYPERDYNE Test Platform

HYPERDYNE, a test platform based on the principle of a dynamometer is developed to enable repeatable and high-fidelity actuator testing. The proposed setup is presented in Fig. 1. The system consists of a three-jaw self-centering chuck that holds the motor stator, a high-resolution encoder, a torque sensor, and a high-power AC servo motor. A key design contribution is a reconfigurable mechanical interface, which allows multiple test configurations without disassembly. The three-jaw chuck ensures consistent concentric alignment and reduces experimental variability. Three test modes are supported: (1) no-load configuration for intrinsic actuator behavior, (2) fixed-load configuration for controlled loading, and (3) dynamic interaction configuration for external disturbance and impedance testing. This setup enables all experiments to be conducted without hardware reconfiguration, improving repeatability and efficiency.

III. Dynamic Characterization Protocol

A four-stage evaluation protocol is proposed to systematically characterize actuator dynamics across position (P), velocity (V), and force (F) control domains. The protocol proceeds in the following order.

A. System Identification

In this stage, intrinsic mechanical parameters that define the physical limits of actuator performance are identified. These include backlash and static friction τ_s, measured

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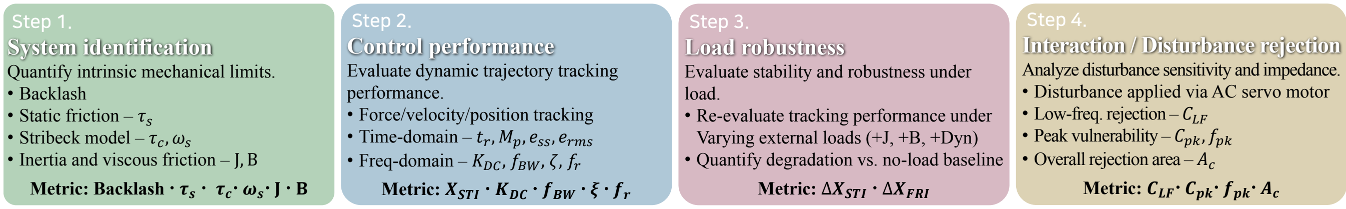

Fig. 2. Overview of the four-stage dynamic characterization protocol and associated evaluation metrics.

under quasi-static rotation, and nonlinear friction characteristics obtained by fitting the stribeck model from constant-acceleration ramp inputs to extract coulomb friction τ_c and critical velocity ω_s. Inertia J_m and viscous friction B_m are separately identified through frequency response function (FRF)-based methods. Such parameters are typically unavailable from manufacturer data.

B. Control Performance Evaluation

Tracking performance is evaluated in both time and frequency domains. Time-domain step responses are used to assess response time t_r, overshoot M_p, steady-state error e_{ss}, and residual vibration e_{rms}. An index X_{STI} (Step Tracking Index), where $X \in \{P, V, F\}$ denotes position, velocity, and force, is introduced to combine these metrics into a single score. In addition, closed-loop FRF frequency-domain analysis is used to extract bandwidth f_{BW}, damping ratio ζ, resonance frequency f_r, and DC gain K_{DC}.

C. Load Robustness Evaluation

The tracking performance obtained in the previous stage is re-evaluated under varying external loads. Using the AC servo motor in impedance control mode, virtual inertia J_v, damping B_v, and their combinations are applied to the test actuator. Performance degradation is quantified by ΔX_{STI} and ΔX_{FRI} with respect to the minimum load condition, evaluating changes in step tracking and frequency-domain retention metrics such as gain and bandwidth.

D. Disturbance Rejection and Interaction

External disturbances are applied to the test actuator through the AC servo motor while the actuator maintains regulation. The disturbance sensitivity function $C(j\omega)$ is analyzed to extract low-frequency rejection level C_{LF}, peak sensitivity C_{pk} at frequency f_{pk}, and integrated disturbance response area A_c. These metrics directly relate to interaction stability and compliance of the actuator.

IV. Experimental Validation - Initial Results

The proposed framework is validated using a QDD actuator (CubeMars AK70-9). The system identification stage extracts key mechanical parameters, including backlash of approximately 18 arcmin and Stribeck friction parameters: static friction $\tau_s = 0.793$ Nm, Coulomb friction $\tau_c = 0.2$ Nm, critical velocity $\omega_s = 0.5$ rad/s, and viscous friction $B = 0.0189$ Nm/(rad/s).

Time-domain results show consistent position tracking performance with an average X_{STI} score of approximately 0.30. In contrast, force control exhibits higher variability due

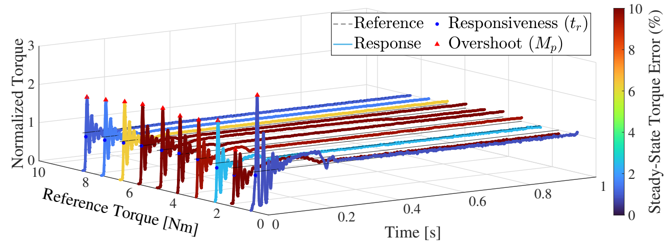

Fig. 3. Force tracking performance of the actuator.

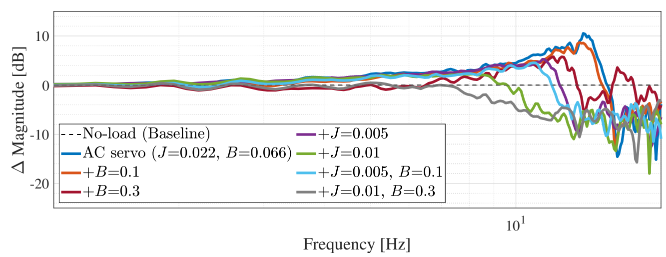

Fig. 4. Velocity FRF under varying virtual inertia and damping.

to nonlinear friction effects, with an average $F_{\mathrm{STI}} = 3.956$, $t_r = 12$ ms, and $M_p = 107\%$, as shown in Fig. 3.

Load robustness is evaluated under varying virtual inertia and damping conditions, as shown in Fig. 4. The frequency response deviation is computed relative to the no-load baseline, and the average ΔX_{FRI} is 0.0906.

Disturbance rejection analysis shows that the actuator maintains stable regulation under varying disturbance magnitudes, with average peak frequency $f_{\mathrm{pk}} = 14.28$ Hz and integrated rejection area $A_c = 1.3903$ relative to the minimum disturbance condition.

V. Conclusion

This paper presented HYPERDYNE, a proof of concept test platform and evaluation framework for dynamic characterization of robot actuators. The proposed system enables objective comparison of actuators using the selected metrics, separation of mechanical and control effects, and quantitative evaluation of interaction performance beyond conventional static specifications. Future work will extend validation to a broader range of actuators and apply the identified parameters to nonlinear control design.

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