Design, Development, and Experimental Validation of a 2 dof Electro-Hydraulic Robot Arm Test System

Sule Taskingollu[1], Erman Selim[1], Enver Tatlicioglu[1]

***Abstract*— While electro-hydraulic actuation offers high force density, durability, and suitability for demanding industrial robotic applications, experimentally accessible multi-dof (degree of freedom) platforms that realistically represent robotic operating conditions are still limited. This paper presents the design, development, and experimental validation of a two dof electro-hydraulic robot arm established as a dedicated testbed for multi-axis robotic research. Unlike simplified single axis laboratory setups, the proposed system features a mechanically coupled serial manipulator structure, enabling the study of multi-joint robot dynamics and task space motion behavior in a more representative manner. The platform is built around a custom-developed electro-hydraulic architecture, including specially designed valve control blocks and embedded real time firmware, providing a flexible and instrumented environment for experimental implementation. To demonstrate its practical capability, the developed robot is evaluated in a material transfer task between two conveyor lines positioned at different heights. Experimental results confirm that the system can successfully execute coordinated task space motion and provides a realistic experimental platform between simplified academic setups and more complex industrial hydraulic manipulators.**

I. Introduction

Hydraulic actuation remains a compelling solution for applications that require large force output within compact mechanical structures. With their high power density and rapid force generation capability, hydraulic systems continue to be widely used in demanding engineering applications [1]. Accordingly, a broad body of literature has addressed the analysis and control of electro-hydraulic systems through simulation based studies [2], [3], including various nonlinear control designs and motion control applications [4], [5], [6]. For this reason, a considerable portion of the relevant literature has focused on one degree of freedom (dof) electro-hydraulic test benches, which offer controlled experimental environments for analyzing actuator dynamics and validating nonlinear control algorithms [7], [8], [9], [10], [11].

Although 1 dof experimental platforms are highly valuable for controller validation and system identification, practical industrial systems rarely operate as isolated actuators. In our previous work, a 1 dof electro-hydraulic experimental platform was designed and validated [12]. Despite its usefulness for actuator-level analysis, that setup was inherently limited in representing the inter-axis dynamic coupling effects encountered in practical multi-axis hydraulic applications. In systems such as robotic manipulators [13], construction machinery [14], and heavy-duty automation equipment, multiple hydraulic joints are mechanically coupled and organized in serial kinematic chains. Under such conditions, the motion of one joint directly influences the dynamic behavior of the others through inertial coupling, load redistribution, and pressure-flow interactions. These cross-coupling effects substantially increase the nonlinear complexity of the overall system and cannot be adequately captured by independent single-axis setups.

Although some multi-dof electro-hydraulic experimental platforms have been developed, such as the 2 dof hydraulic robotic arm presented in [15], the realization of systems dimensioned toward industrially relevant operation remains limited. The development of such representative multi-axis systems is still constrained by cost, integration complexity, and safety considerations.

Motivated by these limitations, this work extends a previously developed single-axis electro-hydraulic platform to a 2 dof serial robotic system. The proposed architecture is deliberately designed to preserve modularity and cost efficiency while enabling experimental investigation of nonlinear inter-axis coupling phenomena inherent in multi-joint hydraulic manipulators. By integrating two electro-hydraulic actuators within a mechanically coupled serial structure, the platform allows realistic evaluation of multi-axis coordination, load interaction, and pressure–flow coupling dynamics.

The main contributions of this paper are summarized as follows:

- Design and implementation of a 2 dof electro-hydraulic robotic arm testbed with a mechanically coupled serial manipulator configuration.
- Development of a modular and cost-effective electro-hydraulic platform designed to more realistically represent industrial operating conditions.
- Experimental validation of the platform through a conveyor-to-conveyor task space motion study, enabling the investigation of coupled multi-joint behavior and representative robot dynamics.

The remainder of this paper is organized as follows. Section II provides the system description, covering the mechanical structure of the robot arm, the electro-hydraulic actuation system, and the generation of Cartesian reference trajectories. In addition, physics-based simulation results are presented in this section. The experimental results are given in Section III. Finally, Section IV concludes the paper.

[1]Sule Taskingollu, Erman Selim, Enver Tatlicioglu are with the Department of Electrical and Electronics Engineering, Ege University, Izmir, Türkiye 91250000430@ogrenci.ege.edu.tr, erman.selim@ege.edu.tr, enver.tatlicioglu@ege.edu.tr

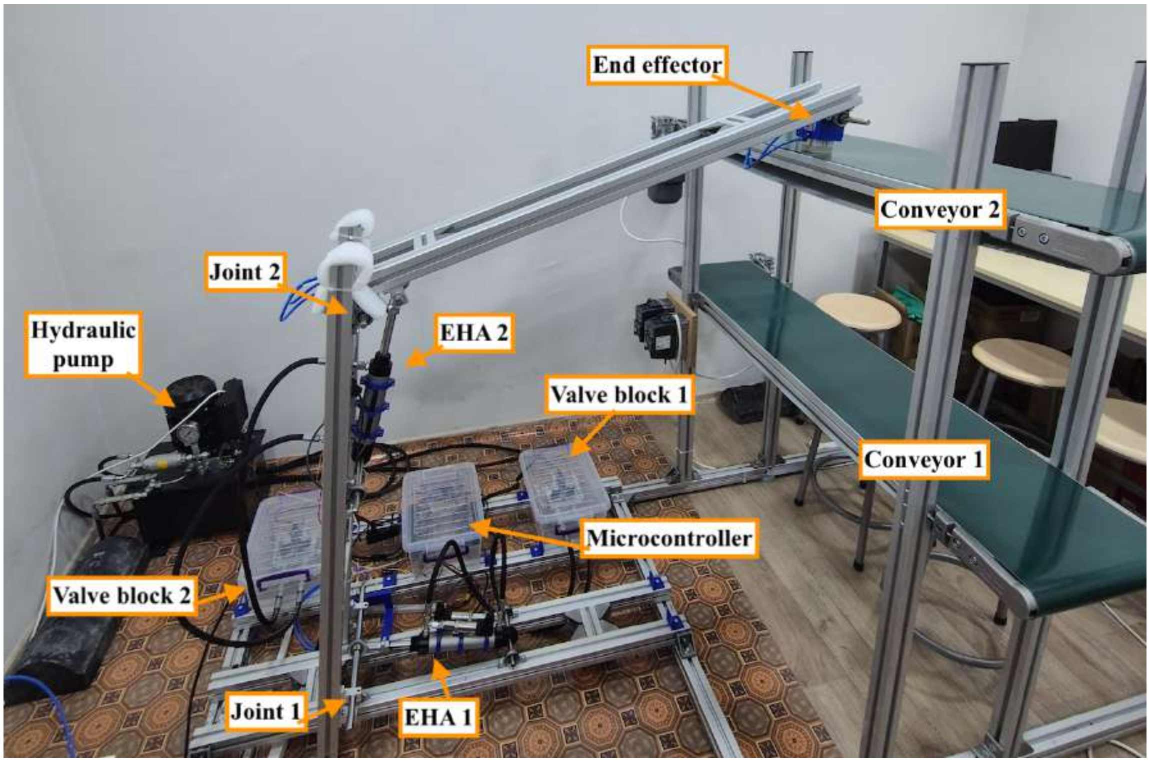


Fig. 1: 2 dof electro-hydraulic manipulator

II. System Description

A. Mechanical Structure of the Robot Arm

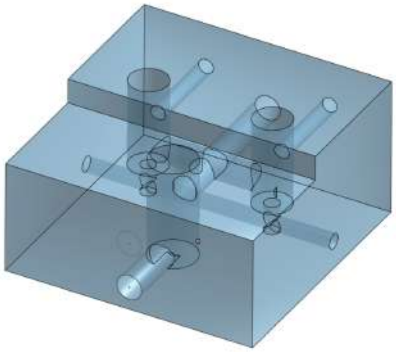
Within the scope of this study, a two degree of freedom electro-hydraulic robot arm was designed and manufactured as an experimental platform. To ensure sufficient load carrying capability while maintaining modularity and ease of modification, the mechanical structure was constructed using aluminum sigma profiles, providing adequate stiffness and flexibility for experimental investigations. The fabricated robot arm is shown in Fig. 1.

Linear motion generated by the electro-hydraulic cylinders is converted into rotational joint motion through revolute connections at both robot joints. Actuation is provided by SMC CHMC-series hydraulic cylinders with a bore diameter of $40\ \mathrm{mm}$ and a stroke length of $100\ \mathrm{mm}$. The cylinder rod ends are equipped with $12\ \mathrm{mm}$-diameter spherical joints, accordingly, all rotational shafts were selected with a diameter of $12\ \mathrm{mm}$. At each joint, the shaft is rigidly fixed to the child link, such that the joint angle directly corresponds to the shaft rotation. The effective angular range of each joint is determined by the geometric relationship between the cylinder attachment points and the joint axis. The target joint motion range was specified between 45° and 135°, corresponding to cylinder stroke lengths of approximately $5\ \mathrm{mm}$ and $95\ \mathrm{mm}$, respectively. The cylinder body length and rod-end dimensions are $182\ \mathrm{mm}$ and $143\ \mathrm{mm}$. Assuming variable attachment distances, the relationship between cylinder length L and joint angle θ can be expressed as $L^2 = d_1^2 + d_2^2 - 2d_1 d_2 \cos(\theta)$, where d_1 and d_2 denote the distances from the joint axis to the cylinder attachment points. By numerically evaluating this relationship under both extreme angle conditions, the optimal attachment distances were determined as $d_1 = 376\ \mathrm{mm}$ and $d_2 = 72\ \mathrm{mm}$. These values were applied to both joints.

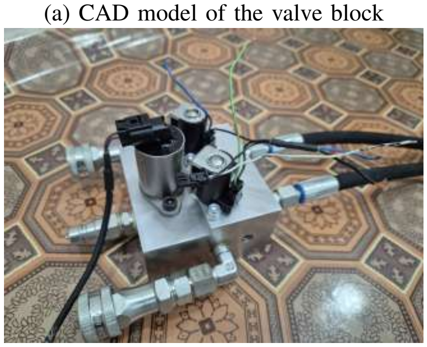
To enable payload manipulation, a magnetic gripper was integrated at the end-effector. Unlike conventional electromagnets, the gripper employs a permanent magnet whose position is actuated pneumatically. As a result, energy is consumed only during state transitions between grasping and release, significantly reducing power consumption. Since the robot does not provide active end-effector orientation control, a passive joint was designed at the wrist. Owing to gravity, this passive joint ensures that the gripper consistently remains oriented toward the conveyor surface.

B. Electro-Hydraulic Actuation System

The robot arm is actuated by an electro-hydraulic system developed as a modular experimental platform equipped with comprehensive sensing and measurement capabilities. All experiments were performed with a constant supply pressure of $30\ \mathrm{bar}$. This pressure level was selected to ensure safe and reliable operation of the sensing components while providing sufficient actuation performance for the intended manipulation tasks. For each hydraulic cylinder, a dedicated control block was custom designed and manufactured. The block integrates two $3/2$ directional control valves, a logical OR valve, and a proportional flow control valve within a single housing. The control block was machined from aluminum using CNC manufacturing techniques, and the fabricated unit is shown in Fig. 2. This compact integration simplifies hydraulic routing and enables independent control of each joint actuator.



(a) CAD model of the valve block



(b) Fabricated valve block

Fig. 2: CAD model and fabricated prototype of the valve block

The directional control valves determine the extension and retraction of the hydraulic cylinder, whereas the proportional valve regulates the actuator velocity by adjusting the supplied flow rate. The proportional valve is driven by a current-controlled input signal, allowing continuous modulation of the flow. To support detailed analysis of the electro-hydraulic behavior, a dedicated sensing architecture was implemented. Pressure measurements were obtained at both the inlet and outlet of each control block using industrial pressure sensors (BSP B050-EV009-P00S2B-S4), which provide analog output signals in the 0–10 V ranges. These measurements enable direct observation of pressure variations across the actuator during operation. Accurate joint angle measurement is critical for experimental evaluation. Therefore, a 14-bit resolution magnetic encoder is mounted directly on each joint shaft. All sensors integrated into the system provide either 0–10 V analog outputs or digital signals via SPI communication, whereas the proportional valves are driven by 4–20 mA analog current commands. Analog signal acquisition and command generation were performed using an NI PCIe-6351 data acquisition (DAQ) card. Digital sensor data were handled by an STM32F746ZG microcontroller, which communicates with the host computer through a USB interface with data rates up to 12 $\mathrm{Mbit/s}$. This architecture enabled stable bidirectional data exchange between MATLAB and the embedded system at a sampling frequency of 1 kHz. Accordingly, all hardware components were selected to ensure full compatibility with the Simulink Desktop Real-Time framework.

C. Cartesian Reference Trajectory Generation

To validate the proposed setup under a realistic manipulation task, a payload transfer between two vertically separated conveyor lines is considered. This representative pick-and-place scenario permits defining the reference motion in Cartesian coordinates and assessing the resulting end-effector behavior in the task space.

The task was formulated in Cartesian coordinates based on the physical layout of the experimental setup. The inlet positions of the two conveyors, the task start and end locations, and the required approach points were measured in the workspace prior to experimentation. The start and end points were selected to represent typical grasping and releasing locations, while additional approach offsets were introduced near the conveyor inlets to ensure safe and repeatable interaction between the robot end-effector and the conveyor surfaces. Based on these spatial definitions, several waypoint sequences were generated to represent different operational scenarios, including transfers from the start position to either conveyor and direct motion toward the final drop-off location. These waypoint sequences define the desired Cartesian reference paths to be followed by the robot end-effector. When a trajectory is generated to pass through discrete waypoints using high-order polynomial interpolation without an explicit velocity reference, the robot tends to decelerate to (near) zero velocity at each waypoint. This induces an undesired stop-and-go motion, which is particularly unfavorable for electro-hydraulic systems due to increased pressure fluctuations and reduced motion smoothness. To mitigate this effect, an optimization-based trajectory generation procedure with velocity constraints is employed. The end-effector waypoints are specified in Cartesian space on the (x, y) plane, and the motion between consecutive waypoints is parameterized by the corresponding transition times. The end-effector motion is initiated at the *Home* location $[0.50,\ 1.00]\,\mathrm{m}$ and returns to the same point at the end of the cycle. A *Transition* waypoint at $[0.65,\ 1.20]\,\mathrm{m}$, positioned approximately between the two conveyor stations, is included to provide a smooth passage between task regions. The two task waypoints correspond to the conveyor locations: *Conveyor 1* at $[0.85,\ 1.00]\,\mathrm{m}$ and *Conveyor 2* at $[0.85,\ 1.50]\,\mathrm{m}$. Accordingly, the waypoint sequence is

- `home`
- `transition`
- `conveyor 1`
- `transition`
- `conveyor 2`
- `transition`
- `home`

This ordering makes the arm repeatedly visit each conveyor station with a brief approach segment, while intermittently returning to the home and rest locations to ensure smooth and well-structured motion between the task regions. These transition times are selected to minimize the overall traversal time while ensuring that the speed demand for each segment remains below a prescribed maximum value. In the experiments, the allowable upper bound on the end-effector speed was set to $0.07\ \mathrm{m/s}$. Enforcing this constraint independently on each segment prevents excessive speed requests, improves motion continuity across waypoints, and yields a smoother trajectory that better matches the physical limitations of the electro-hydraulic actuation system.

D. Physics-Based Simulation Results

Simscape is a physics-based modeling environment that enables hydraulic and mechanical subsystems to be represented as a unified multi-domain physical network by interconnecting energy-domain components. In this work, the electro-hydraulic actuation units and the planar two-link mechanism were modeled by coupling hydraulic, translational mechanical, and rotational mechanical blocks. This formulation captures fluid flow and pressure dynamics together with force transmission and rigid-body motion in a consistent energy-based framework, allowing the simulation to reflect the dominant nonlinearities of the overall system. A physics-based Simscape model of the 2 dof electro-hydraulic manipulator is shown in Fig. 3.

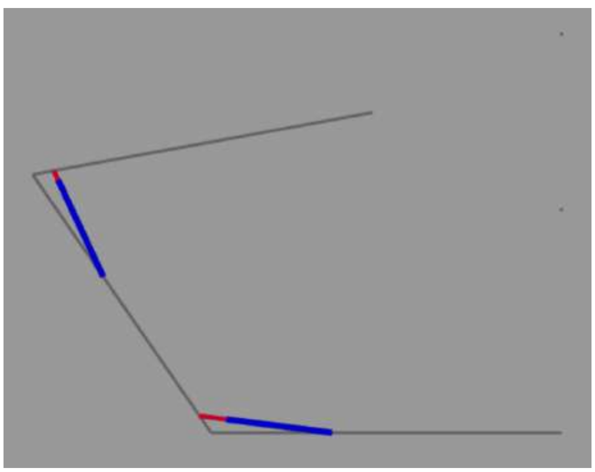


Fig. 3: Physics-based simulation model of the 2 dof electro-hydraulic manipulator

The simulation was executed using a fixed-step discretization with a sampling period of $1\,\mathrm{ms}$, which is compatible with real-time implementation constraints. The model parameters were selected according to the physical properties of the actuator and linkage system. The mechanical parameters were taken as $m = 1\,\mathrm{kg}$, $b = 10\,\mathrm{N\,s/m}$, and $k = 50\,\mathrm{N/m}$. The hydraulic parameters were chosen as $A_p = 40 \times 10^{-3}\,\mathrm{m}^2$, $\beta_e = 7000\,\mathrm{bar}$, $V_t = 8.74 \times 10^{-5}\,\mathrm{m}^3$, $C_{tl} = 2.5 \times 10^{-11}\,\mathrm{m}^3/(\mathrm{s\,bar})$, $C_d = 0.62$, $\omega = 0.024\,\mathrm{m}$, $\rho = 850\,\mathrm{kg/m}^3$, and $p_s = 30\,\mathrm{bar}$. At the joint level, each axis was regulated by a PID controller with gains selected as $K_p = 2500$, $K_i = 1500$, and $K_d = 15$. Identical PID gains were used for both joints without fine tuning in order to demonstrate the feasibility and functional operation of the developed system.

The simulation results are presented in Figures 4–6. Figure 4 illustrates the desired reference trajectory together with the actual piston displacement responses for both joints. The tracking performance is further quantified in Figure 5, where the position tracking errors are depicted. The control input voltages applied to the electro-hydraulic actuators are depicted in Figure 6.

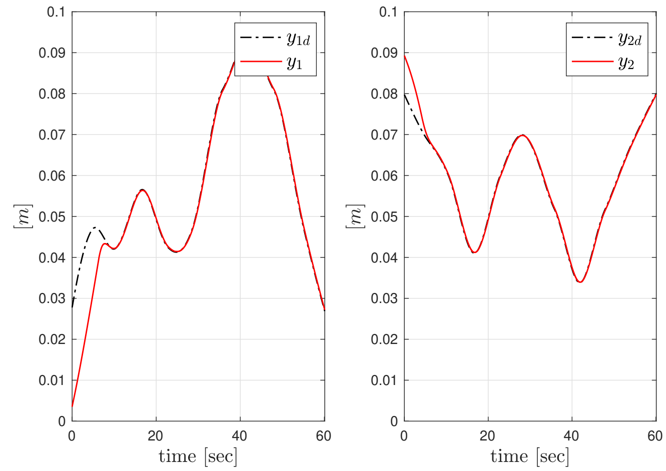


Fig. 4: [Simscape] Tracking performance

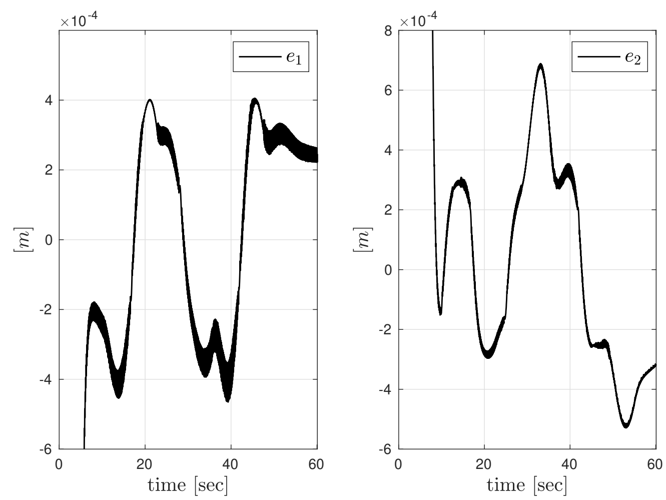


Fig. 5: [Simscape] Tracking errors

III. Experimental Results

Experimental studies were carried out to evaluate the performance of the proposed two degree of freedom electro-hydraulic robot arm under a representative material handling task.

The optimized Cartesian reference trajectories were transformed into joint-space commands using inverse kinematics and applied simultaneously to both electro-hydraulic actuators. At the joint level, each axis was regulated by a PID controller with gains selected as $K_p = 2000$, $K_i = 1000$,

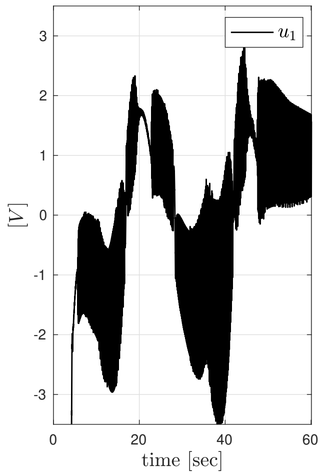


Fig. 6: [Simscape] Control input voltages

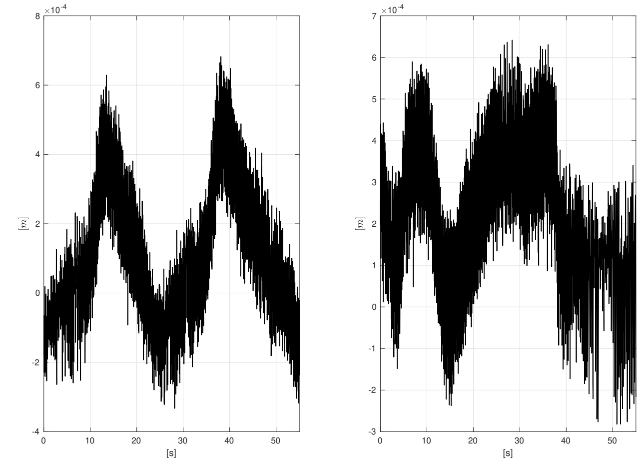


Fig. 8: [Experiment] Task space tracking errors

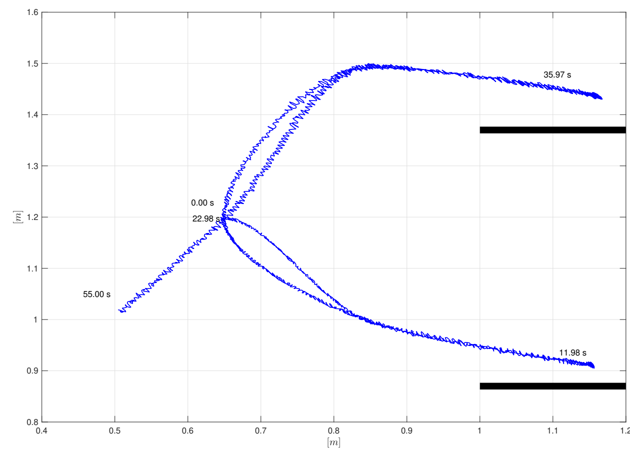


Fig. 9: [Experiment] End-effector trajectory of the electro-hydraulic robot arm in the (x, y) plane.

and $K_d = 5$. Compared to the simulation study, relatively lower controller gains were used in the experiments in order to avoid aggressive motions and to ensure safer system operation.

The experiment results are presented in Figures 7–9. The resulting end-effector motion in Cartesian coordinates and the corresponding time evolution of the reference trajectories are illustrated in Figure 7. In Figure 8, the task space position tracking errors are depicted. End-effector trajectory of the electro-hydraulic robot arm in the (x, y) plane is shown in Figure 9. From Figures 7, 8 and 9, it is evident that the robot successfully executed the conveyor-to-conveyor transfer tasks while closely following the prescribed reference trajectories in the task space. The control input voltages applied to the electro-hydraulic actuators are depicted in Figure 10.

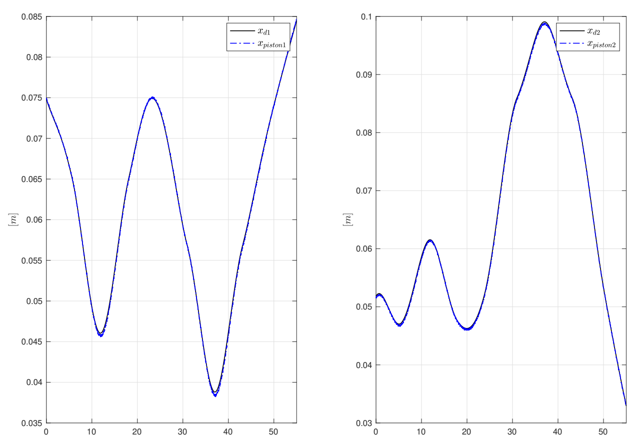


Fig. 7: [Experiment] Tracking performance

IV. Conclusions

This paper presented the development of a 2 dof electro-hydraulic robot arm as a realistic experimental testbed for multi-axis robotic studies. Unlike simplified single-axis hydraulic setups, the proposed system was constructed as a serial robot manipulator, allowing the investigation of coupled robot dynamics under more representative operating conditions. The platform was supported by a custom developed electro-hydraulic infrastructure, including dedicated valve hardware and embedded real time firmware, and was specifically organized to enable task space robotic experiments rather than only joint level actuator tests.

Experimental studies verified that the developed system can successfully execute a task space material transfer motion between two conveyor lines. The results showed that the electro-hydraulic actuation system was capable of tracking the prescribed motion with millimeter level positional accuracy, demonstrating that hydraulic cylinder driven robotic structures can be used effectively in coordinated task space applications. Overall, the study established that the proposed platform is not only a laboratory demonstrator, but also a representative intermediate scale robotic testbed bridging basic academic setups and more realistic industrial electro-hydraulic manipulation systems. Future work will focus on advanced control methods, improved motion planning, and further analysis of multi-axis coupling effects.

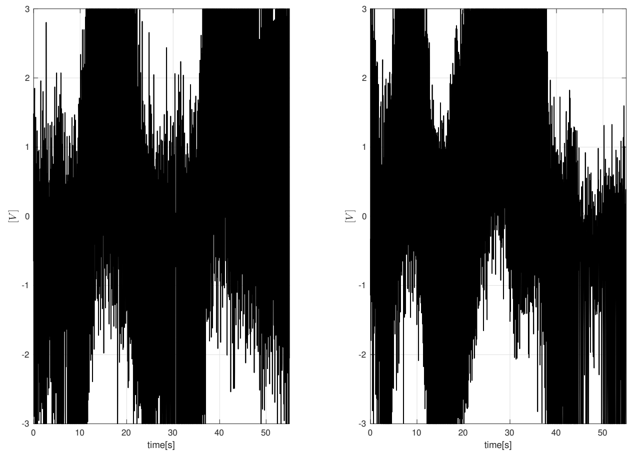


Fig. 10: [Experiment] Control input voltages

ACKNOWLEDGMENT

This study was supported by the Scientific and Technological Research Council of Türkiye (TÜBİTAK) under grant number 123E023. The authors gratefully acknowledge TÜBİTAK for their supports.

REFERENCES

[1] H. E. Merrit, *Hydraulic control system*. Wiley & Sons, 1967.

[2] S. Taskingollu, E. Selim, A. Bayrak, E. Tatlicioglu, and E. Zergeroglu, "Robust control of electro-hydraulic systems subject to input constraints," in *International Conference on Control, Decision and Information Technologies*, pp. 912–917, 2025.

[3] H. Guner, S. Ertugrul, and G. T. Tayyar, "Fault simulation and identification of an electrohydraulic system by using fault emulation," in *International Conference on Control, Decision and Information Technologies*, pp. 229–235, 2024.

[4] D. Enciu, I. Ursu, and G. Tecuceanu, "Dealing with input delay and switching in electrohydraulic servomechanism mathematical model," in *International Conference on Control, Decision and Information Technologies*, pp. 713–718, 2018.

[5] S. Taskingollu, A. Bayrak, E. Selim, E. Tatlicioglu, and E. Zergeroglu, "Nonlinear robust position tracking control of electro-hydraulic systems without velocity measurements," in *American Control Conference*, pp. 4339–4344, 2025.

[6] S. Taskingollu, B. M. Yilmaz, E. Selim, A. Bayrak, E. Tatlicioglu, and E. Zergeroglu, "Adaptive fuzzy logic based control of electro-hydraulic systems," *IFAC-PapersOnLine*, vol. 59, no. 19, pp. 126–131, 2025.

[7] W. Kim, D. Won, D. Shin, and C. C. Chung, "Output feedback nonlinear control for electro-hydraulic systems," *Mechatronics*, vol. 22, no. 6, pp. 766–777, 2012.

[8] M. Y. Coskun and M. İtik, "Intelligent pid control of an industrial electro-hydraulic system," *ISA Transactions*, vol. 139, pp. 484–498, 2023.

[9] B. Helian, Z. Chen, and B. Yao, "Constrained motion control of an electro-hydraulic actuator under multiple time-varying constraints," *IEEE Transactions on Industrial Informatics*, vol. 19, no. 12, pp. 11 878–11 888, 2023.

[10] D. P. Van, H. S. Phuong, and A. K. Kwan, "Disturbance attenuation-based global integral sliding mode control of an electro-hydraulic system with prescribed performance," *IEEE Access*, vol. 12, pp. 105 108–105 118, 2024.

[11] J. Ma, Z. Yao, and J. Yao, "Fixed-time sliding mode control of electro-hydrostatic actuators with adaptive neural network compensation," *Control Engineering Practice*, vol. 165, p. 106616, 2025.

[12] S. Taskingollu, E. Selim, and E. Tatlicioglu, "Development of a digital twin-based simulation model for a one degree-of-freedom electro-hydraulic experimental setup," in *Innovations in Intelligent Systems and Applications Conference*, pp. 1–5, 2025.

[13] H. Song and D. Lim, "Application of the water-based electro-hydraulic actuator (eha) to the heavy-duty collaborative robot," *Actuators*, vol. 13, no. 11, 2024.

[14] Y. Hao, L. Quan, S. Qiao, L. Ge, Z. Li, and B. Zhao, "Energy and operation characteristics of electric excavator with innovative hydraulic-electric dual power drive boom system," *IEEE Access*, vol. 11, pp. 107 265–107 275, 2023.

[15] Q. Guo, "Optimal robust control of electro-hydraulic system based on hamilton–jacobi–bellman solution with backstepping iteration," *IEEE Transactions on Control Systems Technology*, vol. 31, no. 1, pp. 459–466, 2023.