2023 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)
June 28-30, 2023. Seattle, Washington, USA

ExSLeR: Development of a Robotic Arm for Human Skill Learning

Deokjin Lee[1], Kiyoung Choi[1], Junyoung Kim[1], Wonbum Yun[1], Taehoon Kim[1], Kanghyun Nam[2], and Sehoon Oh[1]

***Abstract*—The trend in robotics has shifted from collaboration with humans to learning and reproducing human skills, reflecting a growing social demand. In response, it is imperative to consider both hardware and software aspects in the design of robots. On the hardware side, the robot should be equipped with adequate sensors for mimicking human motion and force, and its design should meet necessary requirements such as workspace, degree of freedom, payload capacity, and weight, all of which are contingent upon the intended use of the robot. On the software side, the robot should be equipped with a real-time system and stable control algorithms to ensure safe operation. This paper presents the ExSLeR arm which meets the requirements for human skill learning. The performance of the ExSLeR arm is validated by a set of experiments through motion tracking with heavy payload and compliant interaction control tasks.**

I. INTRODUCTION

The phenomenon of the interruption in the transmission of cultural heritage and expert knowledge has become a matter of concern in contemporary society [1], [2]. The potential of robots to acquire and reproduce the advanced skills of experts is seen as a means of mitigating these social challenges. In response to these social demands, robots have undergone a transformation from serving as cooperative aids to humans to becoming autonomous entities capable of imitating human skills [3]–[5].

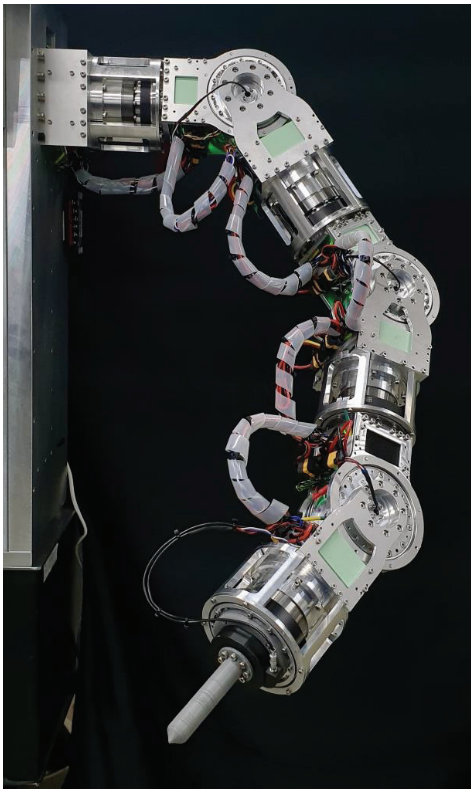


Fig. 1. The ExsLeR arm system

For a robot to effectively imitate the advanced skills of experts, it is necessary to consider the hardware and software requirements of the robot. From a hardware perspective, various sensors are necessary to accurately measure the position and force of the human arm. The UR [6] and the Rainbow RB series [7] are widely used as collaborative robots since they can measure the joint position. However, they have difficulty recognizing joint forces of the human arm due to the lack of joint torque sensors. Additionally, the use of motor-side position sensors may result in measurement errors in joint position due to deformation or uncertainty in the transmission between the motor and the link [8]. To address this issue, link position sensors are also required. There have been efforts to develop robots equipped with these necessary sensors, such as the IIT-INAIL arm [9] and the Anypulator [10]. However, these robots still face challenges in accurately replicating human arm movements as they have fewer degrees of freedom, resulting in an incomplete representation of the human arm joints. As the human arm joints can be represented with at least seven degrees of freedom, it is necessary for robots to possess a minimum of seven degrees of freedom to effectively mimic human arm movements [11]. Robots that possess redundant sensors and a sufficient number of degrees of freedom to imitate human arm joints include the Blue [12], the Kinova [13], and the Panda [14]. These robots are well-suited for interaction with their lightweight design and joint torque control capabilities. However, their payload capacity may be limited when it comes to replicating advanced expert skills that may require significant strength. To effectively replicate such skills, a robot should have a high payload capacity. The Kuka LBR iiwa [15] has a high payload capacity and a relatively light weight, making it a strong advantage in terms of safety and ease of use when interacting with human operators.

Additionally, the system must ensure safe operation in shared operational spaces with humans, through the satisfaction of real-time constraints in its software. This is of utmost importance, as unreliable periodic computation can

---

*This work was supported by the DGIST R&D Program of the Ministry of Science and ICT (23-PCOE-02).

[1]Department of Robotics and Mechatronics Engineering, DGIST, Daegu, 42988, Korea `[djlee, kychoi, kjyida, dnjsqjadbs, sean9595, and sehoon]@dgist.ac.kr`

[2]Department of Mechanical Engineering, Yeungnam University, Gyeongsan, 38541, Korea `khnam@yu.ac.kr`

978-1-6654-7633-1/23/$31.00 ©2023 IEEE

cause physical accidents to the user in the event of high latency occurrences or deadline expiration [16].

This paper presents the ExSLeR (Expertise Skill Learning Robot) arm capable of learning expertise skills, taking into account both hardware and software requirements. The key features of the ExSLeR arm are outlined as follows:

- The robot is designed based on the desired specifications such as the kinematics, workspace and payload capacity to enable human skill learning.
- To learn the expert's motion and force-based skills, the robot is equipped with various sensors such as joint dual position encoders, joint torque sensors, and a Force/Torque (FT) sensor.
- The control software integrates a motion/force controller for the robot and a task controller for replicating artisanal skills, with fast and reliable real-time computation.

The structure of this paper is as follows. Section 2 introduces the mission and requirements of the ExSLeR arm. Section 3 outlines the hardware development, which is designed to meet the requirements of the mission. The software development is described in Section 4. Section 5 provides experimental validation of the ExSLeR arm ability in terms of replicating expert skills. Finally, the conclusions are presented in Section 6.

II. MISSION AND REQUIREMENTS

Prior to the development of the robot, it is essential to establish a clear definition of the mission and requirements for the robot. The determination of the requirements for the mission plays a crucial role in specifying the desired specifications of the robot.

A. Acquisition of Artisanal Skills

The loss of specialized skills and knowledge, including intangible cultural heritage and artisanal skills such as carving, sculpting, and soldering, is a significant concern in contemporary society. The potential of robots to learn and preserve these skills through behavior storage offers a promising solution to mitigate this issue and secure their transmission to future generations. Thus, the development of robots capable of learning and storing human actions and artisanal skills is considered imperative.

B. Requirements

The following conditions are necessary for the robot to learn and reproduce human actions or artisanal skills.

- Anthropomorphic design: The robot arm should be designed to mimic the joint motion of a human arm.
- Range of motion: The robot should have a range of motion comparable to or greater than a human to effectively mimic expertise skills.
- Payload: The robot should be capable of handling a payload that is appropriate for tasks such as painting, welding, and sculpting that require expertise.

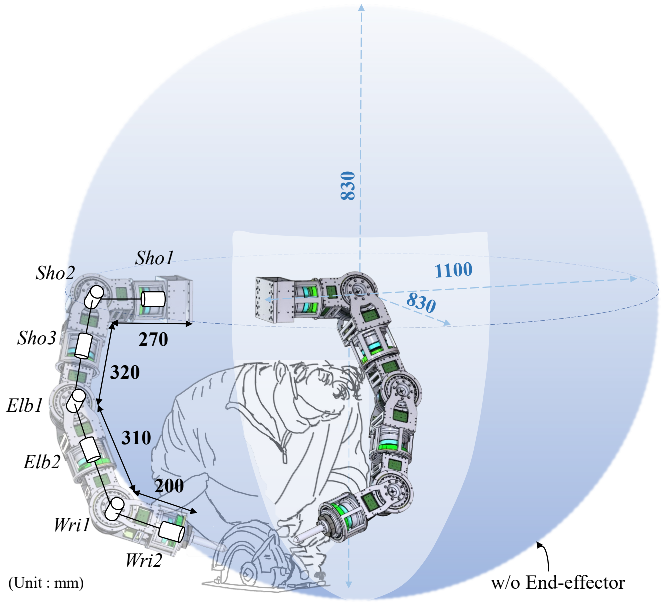


Fig. 2. Kinematics (left arm) and workspace(right arm) of the ExSLeR arm for human skill learning

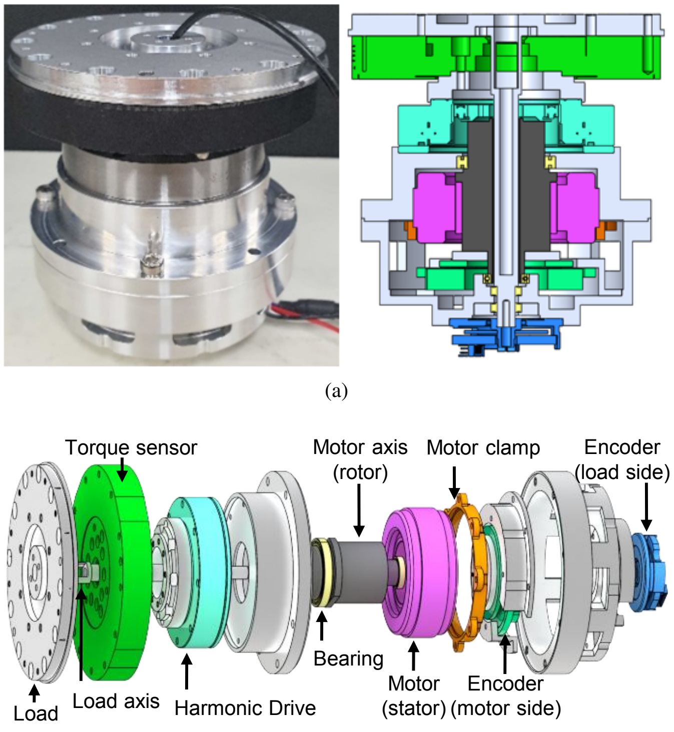
- Sensing: Accurate measurement of joint torque, joint position, and force at the end-effector is essential for the robot to effectively learn and reproduce expertise skills.
- Compliance: The robot should be designed with compliance and back-drivability in order to be sensitive to human interaction and respond immediately.
- Control: The robot should be equipped with various controls, including robot motion control, human-robot interaction control, and safety control, in order to effectively learn and reproduce human skills. In addition, an integrated real-time system that can freely integrate and convert these various control is necessary.

III. MECHANICAL DESIGN

For the mechanical design, it is essential to conduct an analysis of the desired robot specifications that meet the requirements in II-B. This analysis involves determining the maximum torque requirements of the robot joints for various tasks, and selecting the actuator specifications accordingly. Subsequently, the hardware and electronics of the robot are then designed based on the selected specifications.

A. Desired Robot Specification

The robot for the acquisition of expertise skills needs at least 7-DOF to mimic a movement of the human arm joint while learning the expertise skills [11]. In response, the ExLeR is designed as a 7-DOF anthropomorphic humanoid arm with three intersected axes in the shoulder (*Shol1*, *Shol2*, *Shol3*), two intersected axes in the elbow (*Elb1*, *Elb2*) and the remaining two intersected axes in the wrist (*Wri1*, *Wri2*). The kinematics and workspace are determined based on factors such as the payload and end-effector speed. The payload is set at 5 kg, taking into account tasks that require manual dexterity,



(a)

(b)

Fig. 3. General design of actuators (a) the developed actuator and section view of the actuator (b) Exploded view of the actuator

such as carving and sculpting. The workspace is designed to be slightly larger than that of the human arm to avoid restricting the range of motion when learning artisanal skills. The end-effector speed is set at 4 m/s, consistent with the maximum speed of the human arm [17].

In order to determine the maximum joint torques which are an important factor to design the robot, both static and dynamic analyses were conducted under worst-case scenarios. The static analysis accounted for the effects of gravity on various robot postures and the dynamic analysis considered the maximum speed of the end-effector during dynamic tasks. The results of the analyses indicate that the required maximum joint torques are *Sho1*=*Sho2*=100 Nm, *Sho3*=*Elb1*=35 Nm, *Elb2*=*Wri1*=20 Nm, and *Wri2*=5 Nm. It is found that when the robot's base is designed to resemble a human arm, the joint torques for *Sho1* and *Sho2* are equal due to the link connecting them being unaffected by gravity as illustrated in Fig. 1. The joint torques of *Sho3* and *Elb2* are derived following a similar methodology.

B. Actuator

In the design of the actuators, it is important to consider both the desired robot specifications and the power-to-weight ratio for optimal efficiency. It is imperative to ensure that the actuators are capable of providing the required maximum joint torques as determined through static and dynamic analyses, while also maintaining an appropriate power-to-weight ratio to maintain overall efficiency.

TABLE I
ACTUATOR SPECIFICATIONS

	Actuator1	Actuator2	Actuator3
Joint	*Sho1-2*	*Sho3*	*Elb1-2, Wri1-2*
Gear ratio	100	50	50
Weight [kg]	2.2	2.2	1.8
Power [W]	258	258	114
Rated speed [rad/s]	4.1	8.2	8.4
Torque [Nm] (rated/peak)	94/304	47/152	28/70
Torque sensor resolution [Nm]	0.1	0.1	0.1
Motor Encoder resolution [bit]	19	19	19
Load Encoder resolution [bit]	19	19	19

The development of three types of actuators, Actuator1, Actuator2, and Actuator3, is carried out to ensure the desired specifications for the robot. Actuator1 is designed with a nominal torque of 98 Nm to serve *Sho1* and *Sho2* joint of the shoulder, Actuator2 is designed with a nominal torque of 47 Nm to serve *Sho3* joint of the shoulder, and Actuator3 is designed with a nominal torque of 28 Nm to serve *Elb1* and *Elb2* of the elbow and *Wri1* and *Wri2* of the wrist. To account for potential safety concerns, the torque of the actuators is set higher than the derived joint torques from the previous analysis (as discussed in Section III-A), considering factors such as the potential increase in weight during development and unexpected dynamic tasks.

The actuators are comprised of several components, including a Kollmorgen brushless DC motor, a Harmonic gear, a torque sensor, and both motor-side and load-side 19-bit absolute rotary encoders as shown in Fig. 3. The torque sensor is employed not only to accurately measure human joint force but also to control the output torque of the actuators. The motor-side encoder is imperative for the control of the motor and the load-side encoder is necessary for measuring the precise position of the actuator output, in order to prevent errors from arising in the transmission placed between the motor and the load output.

In the design and assembly of the actuators, it is crucial to ensure the concentricity of the motor and load shafts and to decouple any undesired axial forces. This can be achieved by incorporating two ball bearings for each shaft, as cumulative machining errors and assembly processes may potentially result in distortions of the concentricity. The specifications of the actuators can be found in Table I.

C. Robot Arm

The structure of the ExSLeR arm is designed as a 7-DOF anthropomorphic arm, consisting of three intersected axes at the shoulder, one axis at the elbow, and three intersected axes at the wrist. The exoskeleton structure of the robot links facilitates the integration of actuators and drive electronics, thereby simplifying the design and maintenance process. The links are machined from aluminum alloy 6061, which has a good combination of low weight and high strength. The stress and strain of the links are validated through finite element method (FEM) analyses taking into consideration the worst-case scenarios in both static and dynamics situations as shown

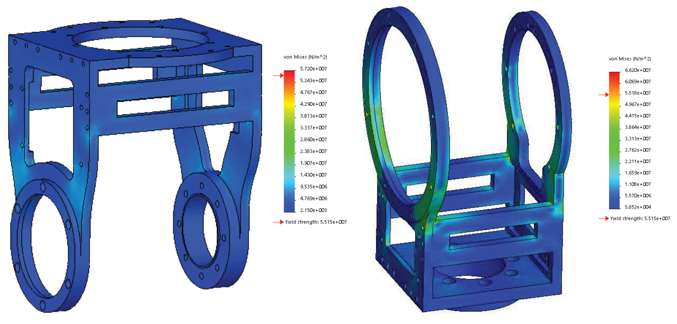


Fig. 4. FEA result for load capacity and stiffness

in Fig. 4. The link lengths are 270 mm (from the base to *Sho2*), 320 mm (from *Sho2* to *Elb1*), 310 mm (from *Elb1* to *Wri1*), and 200 mm (from *Wri1* to *Wri2*). A maximum reach is 1100 mm and a workspace is shown in Fig. 2. The total weight of the robot is 17 kg, and its nominal payload capacity is 5 kg. A cross-roller bearing is implemented on the output of the actuator to minimize the effect of non-axial moments. The specifications of the ExSLeR arm are presented in Table. II.

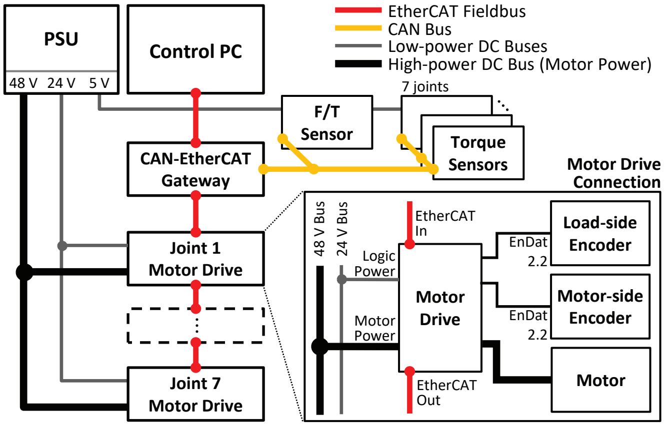


Fig. 5. Diagram for electrical systems connection of the robot

TABLE II
THE EXSLER ARM SPECIFICATIONS

Degree of Freedom	7
Payload	5kg
Weight	17kg
Maximum reach	1100mm
End-effector velocity	Up to 4m/s
Workspace	Fig.2.
Range of motion	(Sho1) ±170° (Sho2, Elb1, Wri1) ±110° (sho3, Elb2, Wri2) ±165°
Sensor	Motor encoder (each joint) Load encoder (each joint) Torque sensor (each joint) 6-DOF FT sensor (end-effector)
Power	48V, 24V, 5V
Communication	EtherCAT, CAN, EnDat 2.2

D. Electronic Integration

The electronics integration is crucial for ensuring reliability and maintenance efficiency in multi-joint manipulators, a complex system. The electronic structure comprises of power, communication (EtherCAT, CAN), motor drive, and sensor components, as illustrated in Fig. 5. A power supply unit (PSU) provides 48V for the motor power, 24V for the motor drive, and 5V for the sensors. The communication between components is facilitated through an EtherCAT-based interface. The torque sensors and the FT sensor communicate through the CAN network, which is then converted to EtherCAT via a CAN-to-EtherCAT conversion device. The motor-side and load-side encoders communicate with the motor drive via the EnDat2.0 interface. The daisy-chain connection of the power and communication components in each joint reduces wire weight and optimizes space, thereby simplifying maintenance. The electronic components are integrated into the internal space of the links, resulting in a compact and reliable wire integration.

IV. SOFTWARE DESIGN

In order to facilitate the safe and reliable execution of human skills by the robot, it is necessary to have a real-time operating system and a human skill-oriented robot controller in place. These elements play a crucial role in ensuring the effective learning and reproduction of human skills by the robot.

A. Real time robot system

The ExSLeR arm is operated using real-time Linux (version 5.4 kernel and Xenomai 3.2) [18]. The EtherCAT master, to acquire status and to control each joint, is established by open source EtherCAT master stack (SOEM 1.4.0 [19]). In the real-time computer, three core threads are employed to operate the tasks of the robot (Fig. 6): the graphical user interface thread (GUI), the online kinematics/dynamics calculation thread (CALC), and the high/low-level control threads (HCTR and LCTR). The GUI thread provides an interface to operate the tasks and observe the status and information of the robot. In order to secure the high control frequency of the entire system, the control-associated calculation is separately performed on the three real-time threads: the CALC thread calculates the robot kinematics and dynamics; the LCTR thread handles the robot motion and force control; and the HCTR thread handles trajectory generation for tasks. With the multi-real-time controller threads, the joint controllers in the LCTR run at up to 20 kHz for current control. The robot motion and force control in the LCTR generating control commands are executed over 1 kHz. The trajectory generation in the HCTR, which necessitates a significant computational cost, operates at a frequency of less than 1 kHz.

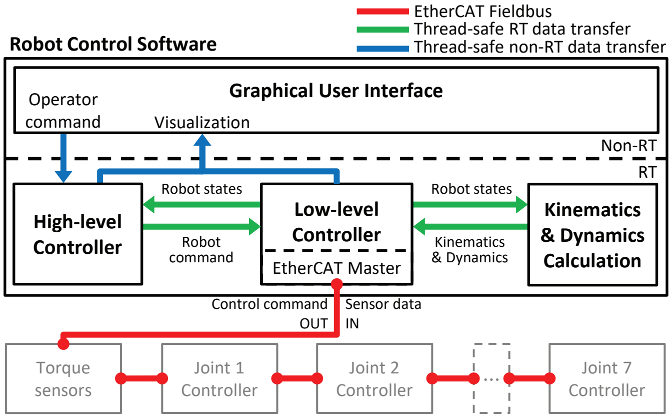


Fig. 6. Structure of real-time control software

B. *Control Algorithm*

The control algorithm of the ExSLeR arm consists of low-level and high-level control, as depicted in Fig. 6. The low-level control implements algorithms for the motion and force control, including a single-joint control and a multi-joint control. The single-joint control includes position, torque, and impedance control in joint space, and it can be implemented by designing controllers independently for each joint without considering the dynamics of the robot. The multi-joint control, on the other hand, implements position, torque, impedance, and gravity-compensated torque control based on the dynamics of the robot. In some cases, tasks-based hierarchical control such as singularity avoidance and collision avoidance algorithms are incorporated.

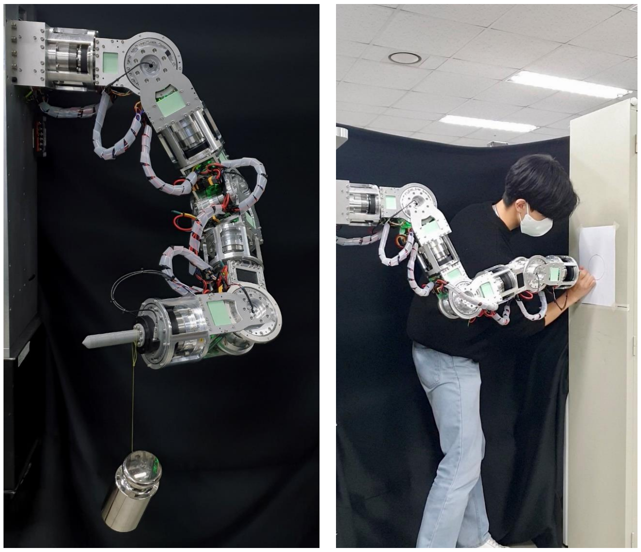
The high-level control of the robot system is responsible for the generation of trajectories necessary for task execution. The utilization of real-time threads is employed for tasks that demand human skill acquisition, which requires algorithms based on human dynamics. In contrast, tasks that involve learning and optimization can be efficiently managed by non-real-time threads.

V. EXPERIMENT

To validate the performance of the ExSLeR arm in replicating human skills, two experiments are conducted. The first experiment is motion tracking with a heavy payload which aimed to verify the consistency of motion reproduction. The second experiment is the zero impedance control (ZIC) [20], which aims to eliminate impedance in the interaction between the human and the robot. The experiments are conducted using a robot arm mounted on a robot body to resemble a human arm, and its control is executed by a real-time PC system with a frequency of 1 kHz based on EtherCAT communication.

A. *Motion Tracking with high payload*

The experiment is conducted to evaluate the motion tracking performance of the ExSLeR arm in replicating expertise skills. A 5 kg payload is utilized to evaluate both the motion tracking performance and the payload capacity. The robot is commanded to follow a cubic trajectory and is controlled by a Proportional-Derivative (PD) controller with gravity compensation. The results, depicted in Fig. 8, demonstrate that the ExSLeR arm is able to accurately follow the cubic reference trajectory with all joints while carrying the 5 kg payload.



(a) (b)

Fig. 7. Experimental Scenario: (a) the ExSLeR arm was instructed to follow a cubic trajectory while carrying a payload of 5 kg. (b) The operator drew a circle on a piece of paper grasping the end-effector.

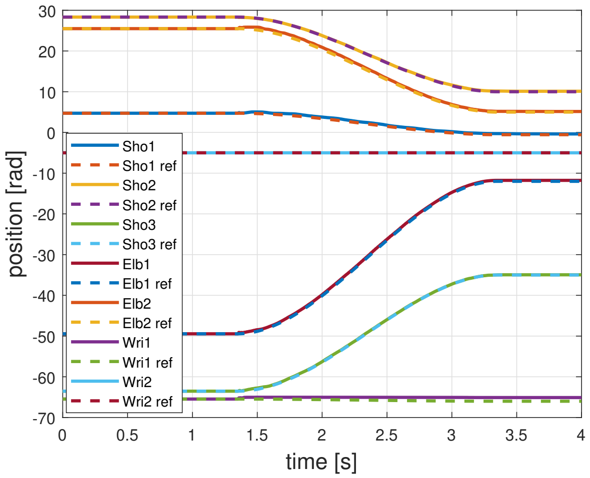
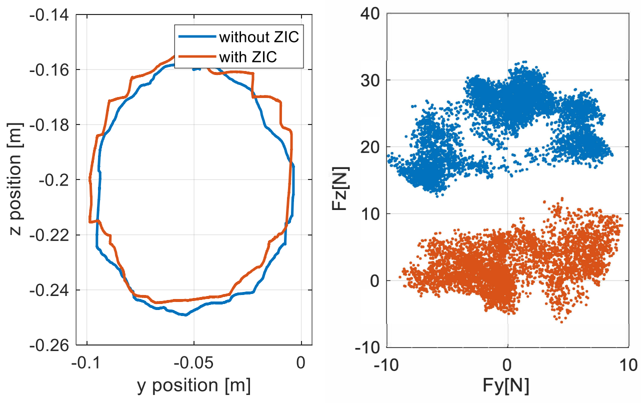


Fig. 8. Motion tracking control in all joints while carrying a 5 kg payload

B. *Compliant Interaction Control*

In this experiment, the ZIC performance is evaluated to ensure the suitability of the ExSLeR arm for skill learning. The ZIC is implemented through the use of joint torque sensors where the operator holds the end-effector and draws a circle on the y-z plane in Cartesian coordinate, as shown in Fig. 7(b). A



(a) (b)

Fig. 9. Zero impedance control experiment: time history of end-effector position (a) and force applied at end-effector (b) in Cartesian Y-Z coordinate while human draws a circle manipulating the ExSLeR arm

PD controller with gravity compensation is used for the ZIC control at each joint. The force applied by the robot to the operator in the cartesian space is measured by the FT sensor attached to the end-effector.

Fig. 9(a) shows the end-effector position on the y-z plane, and Fig. 9(b) shows the force applied at the end-effector during the task of the operator drawing the circle. The blue and orange color indicates the experiment results without the ZIC, and with the ZIC, respectively. As shown in Fig. 9(b), forces in the z-direction with the ZIC remain close to zero, while the forces without the ZIC have a significant offset. The results indicate that manipulation of the ExSLeR arm with the ZIC requires less force compared to manipulation without the ZIC.

VI. CONCLUSION AND FUTURE WORK

In this paper, the ExSLeR arm preserving intangible cultural heritage and artisanal skills is presented. Design requirements of the ExSLeR arm for replicating expertise skills were determined, leading to the selection of desired robot specifications. The actuator and the links were designed to meet the desired specifications. The robustness of the actuator and the links was verified through finite element method analysis for rough tasks.

A real-time system was implemented to integrate individual systems of the actuators, and control algorithms for robot operation and task execution were established through a control framework based on 1 kHz EtherCAT communication. The performance of the ExSLeR arm was experimentally evaluated in terms of motion tracking and compliant interaction control, demonstrating the feasibility of the proposed approach.

Future work includes the development of a hardware cover to protect electronics and enhance maintenance and reliability, as well as the implementation of a robot hand to expand the robot's dexterity and facilitate diverse skill learning and reproduction.

REFERENCES

[1] M. Alivizatou-Barakou, A. Kitsikidis, F. Tsalakanidou, K. Dimitropoulos, C. Giannis, S. Nikolopoulos, S. A. Kork, B. Denby, L. Buchman, M. Adda-Decker, *et al.*, "Intangible cultural heritage and new technologies: challenges and opportunities for cultural preservation and development," *Mixed reality and gamification for cultural heritage*, pp. 129–158, 2017.

[2] M. F. Brown, "Heritage trouble: recent work on the protection of intangible cultural property," *International Journal of Cultural Property*, vol. 12, no. 1, pp. 40–61, 2005.

[3] A. Ajoudani, A. M. Zanchettin, S. Ivaldi, A. Albu-Schäffer, K. Kosuge, and O. Khatib, "Progress and prospects of the human–robot collaboration," *Autonomous Robots*, vol. 42, no. 5, pp. 957–975, 2018.

[4] A. Albu-Schäffer, S. Haddadin, C. Ott, A. Stemmer, T. Wimböck, and G. Hirzinger, "The dlr lightweight robot: design and control concepts for robots in human environments," *Industrial Robot: an international journal*, 2007.

[5] M. Zinn, O. Khatib, B. Roth, and J. K. Salisbury, "Playing it safe [human-friendly robots]," *IEEE Robotics & Automation Magazine*, vol. 11, no. 2, pp. 12–21, 2004.

[6] "Universal robots." https://www.universal-robots.com. Accessed: 18-01-2023.

[7] "Rainbow robotics, rb series." http://www.rainbow-robotics.com/. Accessed: 18-01-2023.

[8] P. Tomei, "A simple pd controller for robots with elastic joints," *IEEE Transactions on automatic control*, vol. 36, no. 10, pp. 1208–1213, 1991.

[9] E. Barrett, E. M. Hoffman, L. Baccelliere, and N. G. Tsagarakis, "Mechatronic design and control of a light weight manipulator arm for mobile platforms," in *2021 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, pp. 1255–1261, IEEE, 2021.

[10] K. Bodie, C. D. Bellicoso, and M. Hutter, "Anypulator: Design and control of a safe robotic arm," in *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 1119–1125, IEEE, 2016.

[11] J. Rosen, J. C. Perry, N. Manning, S. Burns, and B. Hannaford, "The human arm kinematics and dynamics during daily activities-toward a 7 dof upper limb powered exoskeleton," in *ICAR'05. Proceedings., 12th International Conference on Advanced Robotics, 2005.*, pp. 532–539, IEEE, 2005.

[12] D. V. Gealy, S. McKinley, B. Yi, P. Wu, P. R. Downey, G. Balke, A. Zhao, M. Guo, R. Thomasson, A. Sinclair, *et al.*, "Quasi-direct drive for low-cost compliant robotic manipulation," in *2019 International Conference on Robotics and Automation (ICRA)*, pp. 437–443, IEEE, 2019.

[13] "Kinova, gen series." https://www.kinovarobotics.com/. Accessed: 18-01-2023.

[14] "Franka emika, panda." https://www.franka.de. Accessed: 18-01-2023.

[15] S. Shepherd and A. Buchstab, "Kuka robots on-site," in *Robotic Fabrication in Architecture, Art and Design 2014*, pp. 373–380, Springer, 2014.

[16] J. Park, R. Delgado, and B. W. Choi, "Real-time characteristics of ros 2.0 in multiagent robot systems: An empirical study," *IEEE Access*, vol. 8, pp. 154637–154651, 2020.

[17] H. Nagasaki, "Asymmetric velocity and acceleration profiles of human arm movements," *Experimental brain research*, vol. 74, no. 2, pp. 319–326, 1989.

[18] "Xenomai." [Online] Available: https://www.xenomai.org.

[19] "SOEM (Simple Open EtherCAT Master)." [Online] Available: http://openethercatsociety.github.io/.

[20] S. Oh and K. Kong, "High-precision robust force control of a series elastic actuator," *IEEE/ASME Transactions on mechatronics*, vol. 22, no. 1, pp. 71–80, 2016.