

Design and Development of a Powered Upper Limb Exoskeleton with High Payload Capacity for Industrial Operations

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Abstract—This study presents the hardware development and low level controller structure of an upper-body exoskeleton that is equipped with high torque-to-weight ratio actuators. It is intended to be used in industrial applications. The exoskeleton can be adjusted for various arm sizes and can ideally be used by an operator that has a height within the range of 160 cm and 200 cm. The robot structure was comprised of 4 degrees of freedom, 3 of which are powered via custom-built series elastic actuators with high power-to-weight ratio and real-time torque control capability. The 4th joint, a prismatic joint, was added to accommodate for glenohumeral head elevation, enabling the system to attain a workspace that is suitable for industrial tasks. The exoskeleton is equipped with a two-piece end effector (E1 and E2) to enable the power augmentation tasks. In order to check torque controllability, initial experiments of the system were conducted on a joint level. As a result, 20 Hz of control bandwidth was achieved when the peak-to-peak torque inputs were 20 Nm.

I. INTRODUCTION

The general purpose of upper body exoskeletons in industrial use can be generalized into two: i) to enhance the productivity in industrial applications, ii) to mitigate musculoskeletal disorders of workers. To achieve either one of these objectives, various types of exoskeletons were introduced. To name a few, Umetani et al. developed "Skill Mate", an exoskeletal structure that aims to assist construction workers [1]. Deng et. al. offered a concept for augmenting human capabilities in lifting tasks using hydraulic actuators [2]. Abdoli-E et al. offered a passive personal device to assist the spinal cord during lifting tasks [3]. A novel suit that is actuated pneumatically to reduce manual labor was introduced in [4]. The Stuttgart Exo-Jacket [5] was developed to help the workers during assembly processes.

Looking at the general view of upper body exoskeletons, one can see various types of mechanical structures and actuator selections. In the microscopic level, it is observed that each upper body exoskeleton is designed to meet certain task-dependent criteria. In the light of this fact, we specified the following design criteria as we targeted heavy object lifting tasks in industry: i) torque controllability, ii) high payload capacity, iii) no requirement for pressurized air/liquid, iv) ability to cope with shoulder glenohumeral head elevation. By meeting these criteria, we aim to develop a state-of-the-art upper limb exoskeleton which can potentially enable users to manipulate heavy objects in industrial operations.

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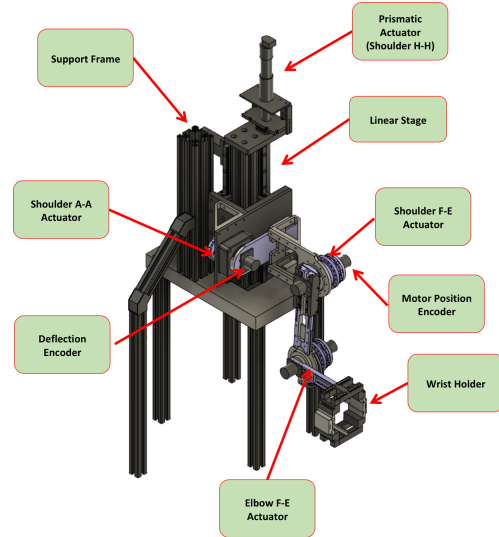


Fig. 1. CAD model of the proposed exoskeleton. F-E: Flexion-Extension, A-A: Abduction-Adduction, H-H: Humeral Head

The remainder of the paper is organized as follows. Section II describes the hardware development procedures in detail, with particular emphasis on the mechanical design of the exoskeleton and the design of the end effectors. Section III provides preliminary experimental results concerning the torque-control capability of the system. The paper is concluded in section IV.

II. HARDWARE DESIGN

A. Stabilizing Agents and Kinematical Structure

The current version of the exoskeleton was mounted on a frame that can be used by an operand with a body height between 160 cm and 200 cm. The frame covers a rectangular area of 68cm x 48 cm, which was kept small to transport the system easier as well as making it easy to work within confined spaces. The frame also includes counterweights to prevent the tipping of the exoskeleton under quasi-state equilibrium within its operational conditions. To make the exoskeleton more viable, the system can be mobilized. The connection of a user to the exoskeleton was achieved via orthotic pads and an end-effector that has housing for a user's wrist. The orthotic pads were made out of polypropylene and can be adjusted for various arm thicknesses. The C-shaped pads can be fastened easily via straps. These pads were plated with neoprene fabric to increase the stability and ergonomics of the connection and fixed on to the exoskeleton via bolts to correspond on the upper and the forearm of the user [6].

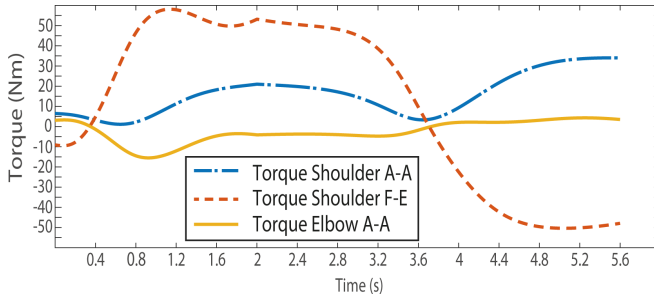


Fig. 2. The Torque Requirement of a Pick and Place Task

The exoskeleton has 4 degrees of freedom (DOF) as can be seen in Fig. 1, which could be sufficient to enable the user to conduct the majority of the tasks that are required in an industrial plant; e.g. assembly, positioning a tool to the desired location and picking-placing tasks [7]. The first three joints are rotational and the remaining one is a prismatic joint. The rotational joints are actuated via Series Elastic Actuators (SEA). Two of those are located on the shoulder, enabling the shoulder to perform abduction-adduction (A-A) and flexion-extension (F-E) motions. The remaining rotational joint is on the elbow for providing the flexion-extension for the forearm. The prismatic joint is situated at the top and provides a prismatic motion along the longitudinal axis for shoulder humeral head elevation [8].

B. Actuator Units

In each SEA module, a custom-designed torsional spring was embedded. Besides the spring, the module included a frameless and brushless motor (Kollmorgen TBM-7631 for the shoulder A-A joint and Kollmorgen TBM-7615 for the shoulder and elbow F-E joints) and a harmonic drive (Harmonic Drive CSG-25 with a conversion ratio of 1:100) [9]. The prismatic actuation unit was integrated with an IMU to control the required humeral head elevation (H-H) for a given configuration based on the data acquired in [8].

To understand the torque requirement, a pick and place simulation was conducted, in which a dynamic model of the exoskeleton was utilized. The study was conducted in MATLAB environment that was run with a computer having an Intel Core TM i7 8550 CPU 1.8 GHz processor and 16 GB RAM. For this task, a payload of 20 kg was displaced 0.7 meters within the duration of 5.6 seconds; picking up is completed in 2 seconds and placing is completed in 3.6 seconds. The trajectory was generated using a quintic polynomial set. The torque requirement for the given task can be seen in Fig. 2, in which the axes of Flexion and Abduction motions are indicated as the positive direction.

C. Mechanical Design

1) *Mechanical Design of the End Effectors*: For industrial operations, a two-piece end effector was designed. The first piece (E1) was used for properly securing the wrist of the user. This structure helps to transfer the torque load that the human wrist experiences to the exoskeleton properly while lifting an object. This was realized via securing the wrist to

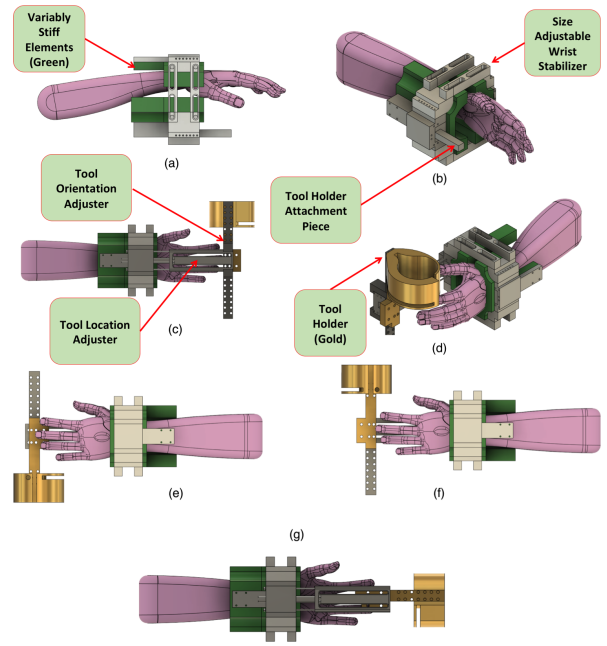


Fig. 3. (a)-(d) End-Effector Design: A possible use-case scenario; (e) Lower handle configuration, (f) Upper handle configuration, (g) Lateral handle configuration (Tool orientation adjuster is removed in this configuration)

the exoskeleton by a stiff and cushioned holder and a placing element that has variable stiffness to the lateral surfaces of the hand as to act as an ergonomic suspension element. For E1 a hybrid design methodology with two different materials was utilized. The material for the section where the back of the wrist is placed, as well as the size adjustable modules, are the same type of aluminum as we use exoskeleton structure. The adjacent section, which corresponds to the inner side of the wrist was made out of Aluminum 7075-T651, to be able to dissipate the stress of the carried load easily. Both of the aforementioned sections were coated with a variably stiff element to strengthen the grip of the user [10]. The structure was intended to be used to carry a load up to 20 kg.

The second piece (E2) is a replaceable part that aims to assist the user in operational tasks. To this end, the replaceable part was designed as a tool holder that stabilizes a given tool, e.g., a drill or a grinder, to increase the efficiency and the accuracy of the task as well as mitigating possible chronic injuries to the wrist. The holder can be adjusted into 3 different configurations depending on the nature of the tool; see Fig. 3. E2 was designed to lift and hold a tool in a stationary configuration considering payloads up to 15 kg with the longest arm and hand length in mind. To increase the stability of the carried tool during the operations, the section in which the tool is being carried was made out of Aluminum 7075, whereas the material for the section that the user places their wrist and adjusts the width thickness were selected as Aluminum 6061-T6.

To accommodate various hand sizes, the end effector was designed to be adjustable for different wrist (upper hand) sizes. The limits for the size-adjustable elements of the exoskeleton were designed in accordance with the values in

Table I. With the additional module that regulates the tool's distance from the palm, the system becomes configurable for different hand sizes as well.

TABLE I
LIMITS OF THE SIZE ADJUSTABLE PARTS

	<i>Longest Subject</i>	<i>Shortest Subject</i>
Upper Hand	105 mm	45 mm
Forearm	305mm	195 mm
Upper Arm	340 mm	245 mm
Shoulder	280 mm	210 mm

2) *Mechanical Design of the Exoskeleton Structure:* The exoskeleton can be adjusted for various arm sizes so that it can be used by different individuals. This adjustment is enabled by the structure of the limbs. Each limb consists of three parts, one male, and one female sub-parts for the limbs that are connected via slider-like structure, and the motor holder at the end of the male limb. The male part was directly attached to the motor's actuator cap that is carried by the motor holder of the previous limb and was fastened by bolts. The male part was fitted inside the slider rail depending on the desired limb length and then fixed to that location via bolts. The aforementioned slider's range was adjusted to cover all possible arm sizes between the longest and shortest possible in accordance with the dataset provided in [12]; see Table I. The motor holder that was used to actuate the next limb was then fastened to the other end of the female part.

For the mechanical design of the limb structure, a threefold system was utilized. In the first phase, the links and the motor holders were designed. The material selected for these parts is Aluminum 6061-T6. These initial parts were designed to be overly-safe and bulky but functional. Although this situation may seem desirable for the practical use of the exoskeleton, the over-safety notion of the system could mean that the limbs are heavier than they should ideally be. This directly reduces the capabilities of the exoskeleton since this extra weight reduces payload capability. Hence, for the system to be safe and efficient; a trade-off between the safety of the system and its payload capacity should be considered.

For the second phase, free-body diagrams for individual limb parts were derived. For this purpose, several factors were taken into account, e.g., the length of the limb, the mass, the center of mass, the amount and the distance of the bolt connections for the parts. The free-body diagrams were constructed from the final limb (male forearm) to the initial one (the female limb of Shoulder A-A joint).

To simulate the maximum possible stress that the system could undergo, the inspected limb's size was adjusted to the longest configuration (it was approximated to be 0.3 meters away from the end effector (E1) and a load that could match the corresponding joint's maximum continuous torque capacity to effectively stall it. To investigate the response of the system in this state, stress, safety, and displacement analyzes were conducted following the derivation of the free body diagrams for the parts in question.

After this process, free body diagrams for these cases were

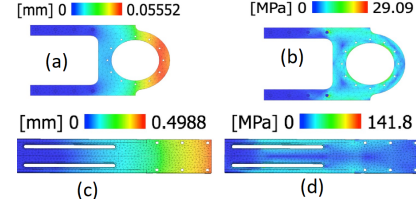


Fig. 4. Exemplary analyses for the given link (top) and holder (bottom). (a) Displacement analysis, (b) stress analysis, (c) re-designed part.

constructed. Although each free body diagram is unique, only two distinct types can be generated throughout the system. The initial one is the limb case. In this case, the distinction is that the effective moments around the supporting bolts are cumulative. This means that when calculating the moment around a supporting section, all the previous forces are needed to be taken into account. Therefore, the primary and the secondary shear forces at the supporting bolts also influence the effective moment. The second case is the motor holder case. All of the motor holders are circular and the load carried by them is supported via evenly distributed bolts. In this case, the moment of the previous forces are not cumulative; instead, they are effectively acting on the center of the circle of the motor holder. The moment was calculated through the distance of the center from the supporting section of the link. These forces were calculated based on (1).

In (1), F' is the primary shear, V is the total shear force exerted on the system, N_{bolts} is the number of bolts that the limb is supported by, F'' is the secondary shear, M is the moment acting on the system, r_n is the distance of the bolt to the center of rotation and $\sum r_i^2$ is the sum of squares of the distance of the bolts to the center of rotation. F' is the same for all of the bolts and in the same direction as the resultant of the external forces. F'' is different for all of the bolts in magnitude, depending on the distance of the bolt to the center of rotation. It is in the same direction as the effecting moment.

$$F' = \frac{V}{N_{bolts}}, \quad F'' = \frac{Mr_n}{\sum r_i^2} \quad (1)$$

3) *Mechanical Analysis:* The exoskeleton limbs were analyzed concerning the stress, displacement, and the safety factor in terms of its material's yield strength concerning the two types of limb components and end effectors. The mechanical design at hand was re-evaluated to diminish the over-safe parts by machining these areas out; see Fig. 4. To ensure the validity of the optimization, the redesigned parts were analyzed again by considering the changes in the mass values, and the structural integrity was validated.

The end effector designs were analyzed as multi-body structures due to having a single, non-cumulative load case, under the upper boundary conditions. The resulting FEA (Finite Element Analysis) can be seen in Fig. 5.

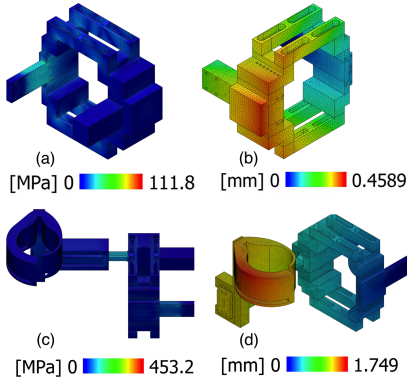


Fig. 5. (a) E1 stress, (b) E1 deflection, (c) E2 stress, (d) E2 deflection

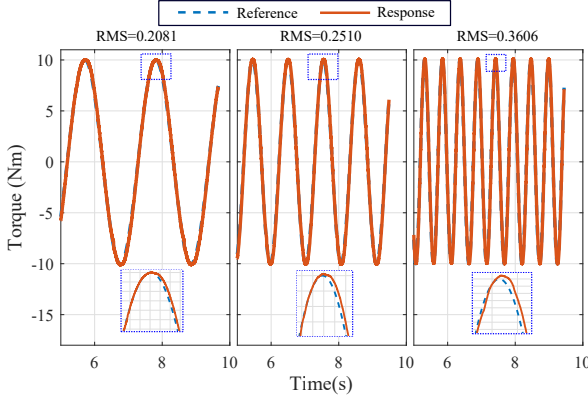


Fig. 6. Sine response of the SEA-powered joint under different input frequencies: 3 rad/s, 6 rad/s, and 12 rad/s, respectively from left to right.

D. Electronics and Communication Design

The low-level electronic circuit consists of an STM32F407 MCU (microcontroller unit), a DP83848 Ethernet module, a digital multiplexer integrated chip for reading multiple encoders and line drivers to convert differential signals of the SSI (Synchronous Serial Interface) into a singular signal. This configuration is capable of collecting data simultaneously from the system. The MCU runs FreeRTOS kernel to ensure real-time operations and the tasks that are handled by the MCU is collecting data from encoders and calculate the positional reading of each joint, as well as transmission of the data through the Ethernet port. The Ethernet speed was chosen as 100 Mbps for this application and the main loop for data collection was run in 1 kHz sampling frequency.

III. PRELIMINARY EXPERIMENTS: TORQUE CONTROL

Preliminary experiments were conducted at the joint level to show the tracking performances under sinusoidal references with different frequencies. As a controller, a sliding mode observer-based method was used [13]. For all the experiments, the joint level controller had a 1 kHz sampling rate. Peak-to-peak amplitudes of 20 Nm were chosen as the input magnitude. The results can be seen in Fig. 6 where solid red and dashed blue lines indicate measured and reference torque variations. As may be observed in this figure, torque tracking performance is favorable, since

the tracking is attained with a sufficiently large control bandwidth.

IV. CONCLUSION

In this paper, design, development and the preliminary experiment procedures for an upper-limb exoskeleton are presented. The exoskeleton was developed to be utilized in industrial applications to ensure the safety of its users and to increase the efficiency of the plant without restricting the working environment. To this end, the exoskeleton was designed to be used via orthotic pad structures that are easy to strap on and off and the whole system was aimed at possessing high payload capacity to respond well to the given industrial tasks. The kinematic structure and the hardware design of the exoskeleton system were explained in detail. The actuation of this system was enabled via SEA units, which are controlled by measuring the torque in terms of torsional deflection. The real-time communication of the actuators and the controllers are enabled via custom-developed electronic modules and run an RTOS with a 1 kHz sampling. Our next work will focus on validating the feasibility of the system in a real use-case scenario.

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