PExCon: Design and Development of Passive Exoskeleton for Construction

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Abstract –

The concept of teleoperation is crucial in modern and future construction workplaces, as it can be used in remote or challenging/hazardous environments such as workspace in a desert, close to a nuclear reactor, or underwater, among others. The success of teleoperation hinges on its interface, where passive exoskeleton with ergonomics considerations has shown great promise. In the literature, however, the ergonomic design of the passive exoskeleton and the 3-D environment for precise visual feedback is lacking. To address that, the authors target to design and develop an ergonomic inclined and light-weighted passive exoskeleton to support construction teleoperation activities.

Keywords –

Tele-operation; Manipulator; Construction Technology; Passive Exoskeleton; Sensors; Construction Education.

1 Introduction

With the workforce shortage prevalent in the construction industry, companies are picking up interest again in construction automation with robotics. While new robot design tailored for construction has been looked into, an alternative and potentially more cost-effective approach is to adapt industrial robots to the construction work context. One challenge faced in this approach is the more dynamic and uncertain environment of the construction sector compared to those in the manufacturing industry. Given that, the concept of teleoperation is crucial in modern and future construction workplaces, as it can be used in remote or challenging/hazardous environments such as workspace in a desert, close to a nuclear reactor, or underwater, among others.

The success of teleoperation hinges on its interface, where a passive exoskeleton with ergonomics considerations has shown great promise. In the literature, however, the ergonomic design of the passive exoskeleton and the 3-D environment for precise visual feedback is lacking. To address that, the authors target to design and develop an ergonomic inclined and light-weighted passive exoskeleton to support construction teleoperation activities. By using a passive exoskeleton as a master unit in a teleoperation system, an operator can control a robotic arm that would otherwise be difficult to access, enabling smooth remote manipulation of the arm [1]. In this paper, we proposed a novel design of a passive exoskeleton for remote construction operations. A human operator will wear the passive exoskeleton to support the teleoperation activity useful in construction operations, such as in transferring heavy payload, screwing, etc., [2-6], which is to be carried out by an industrial arm manipulator. To ensure proper operation, the motion of the exoskeleton (master unit) is replicated in the arm manipulator (slave unit), with the power amplified according to the user's preferences. "Position-based teleoperation" is used, which refers to this particular mode of control where the developed exoskeleton's end-effector is mapped to the manipulator's end-effector. One challenge in this mapping is matching the movements at all degrees of freedom (DOF). As per the anatomy, a human arm has seven degrees of freedom, while the anthropometric exoskeleton only has six.

On the other hand, the arm manipulator adopted (KUKA) only has six DOFs. Specifically, there are three DOFs at the shoulder joint, two at the wrist joint, and two at the elbow joint. The exoskeleton has sensors mounted in seven distinct locations across its surface to detect the various joint angles. Potentiometers are utilized for the elbow joint's rotation and the shoulder joint's pronation and supination. The angle of rotation of adduction - abduction (outside - inside) and extension - flexion (backwards - forward) motions can be measured with the help of rotary potentiometers. The performance evaluation of sensor coupling and human motion tracking will be used. In addition, smooth control of the slave robot (KUKA) using the exoskeleton (PExCon) as a master device will be pursued.

2 Methodology

2.1 Design and Development Steps

The design steps that are going to be incorporated are as follows:

(a). Literature review of state of the art reported in design, control interfaces, power, actuation, communication networks, and 3-D immersive environments.

(b). Biomechanics and ergonomic study based on the design optimisation.

(c). Mechanical design of the proposed PExCon exoskeleton.

(d). Kinematics analysis and workspace analysis.

(e). Instrumentation process that includes fabrication of the sensor, noise-removing filters, Kalman estimation algorithms, and switching circuits.

(f). Setting up of communication protocols, including Inter-Integrated Circuit (I2C), Transmission Control Protocol/Internet Protocol (TCP/IP) and User Datagram Protocol (UDP).

(g).The design process involves analysing and fabricating the filtering circuits, such as Butterworth order five, median, and Kalman filters, to deal with the noise incorporated in the sensors while taking the reading.

(h). Development of a 3-D immersive environment to enable teleoperations when looking at the 3-D rendering of the live-streamed scene and its integration with the PExCon exoskeleton.

(i). Verification and validation of the PExCon exoskeleton. To assess the operation of remotely human-controlled systems, several techniques will be employed:

1. Simulation-based testing (and training).
2. Physical testing.
3. User validation — interview operators about effectiveness, ease of use, and their preferences of the system.
4. Formal verification, for example, as part of corroborative verification [7].

(j). Deployment and repeatability test.

2.2 Arm Kinematics

The human arm, or upper limb, extends from the shoulder to the fingertips. It consists of three segments: the forearm, the arm (the region between the shoulder and elbow in anatomy), and the hand, which are connected by three joints: the elbow, the shoulder, and the wrist. According to Figure 1, the upper limb is composed of the clavicle (which is attached to the trunk), the humerus in the arm, the scapula, the radius and ulna in the forearm, and the carpal bones, metacarpals, and phalanges of the hand and wrist [8].

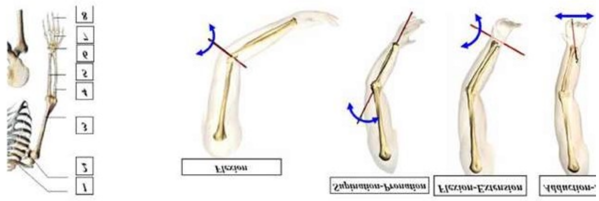

Figure 1. Human upper limb prominent bones, elbow, and wrist joints

2.3 System Architecture based on UDP Protocol

UDP is used to communicate between the manipulator's KRC2 controller and the computer connected through which the robot is controlled using Robot Sensor Interface (RSI), as illustrated in Figure 2. For PExCon and KUKA manipulator integration, UDP transmits data between two computers, as both are connected to the KUKA KRC2 controller [9].

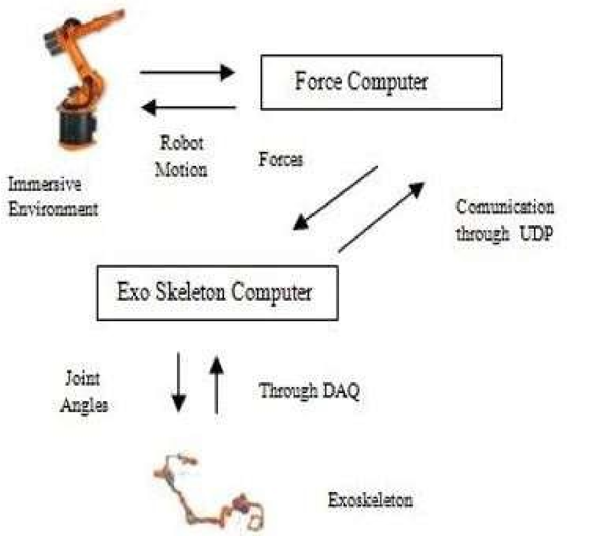

Figure 2. Communication between the KUKA manipulator and exoskeleton [10]

2.4 System Architecture Based on UDP Protocol

User Datagram Protocol (UDP) is the elementary Transport Layer protocol available within the Transmission Control Protocol/Internet Protocol (TCP/IP) protocol suite. There are few communication mechanisms involved [10]. Some consider UDP an unreliable protocol, but it employs IP services that provide a best-effort delivery mechanism, as illustrated in Figure 2. In UDP, the receiver does not send a packet acknowledgement, and the sender does not wait for a packet acknowledgement.

2.5 Ergonomic Design Reported in the PExCon

An aesthetic design of the exoskeleton will be implemented with the following features incorporated:

1. Modular fitment for sensors and accompanying electronics.
2. Jacket model for the stable base of the PExCon base.
3. Joystick design for the hand.

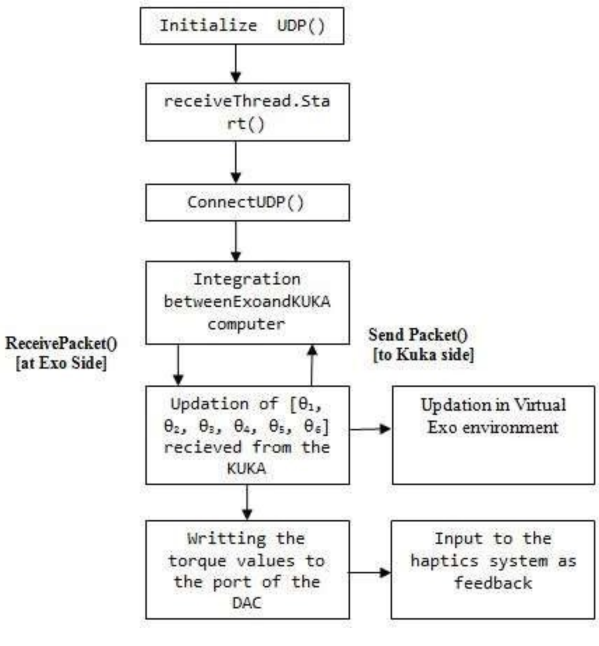

Figure 3. System architecture based on UDP protocol [3]

Table 1 Components of the PExCon

Implementation Modules	Description
Goniometry	7 joints
Kinematics	DH-parameters
Interface	PExCon -KUKA-3D immersive environment
Electronic components	Noise removing algorithms
Haptics	Yes
Communication protocols	TCP/IP + UDP

2.6 Design and Deployment Phases

The passive exoskeleton reported in [10] has limitations such as in weight, sensor alignment, sensor placement, and noise. We will target to resolve these concerned issues in the steps followed to achieve the design and deployment phases:

1.Design of low-weight framework for the PExCon.

2. Development of a simulation-based environment (integrating the KUKA robot with PExCon).

3. FEA-based analysis of the PExCon.

4. Development of a UDP-based communication channel for data sharing and updating.

5. Interfacing the developed PExCon with the KUKA robot in the real-time scenario.

6. Verification and validation of the developed environment.

7. Deployment of the PExCon in construction context and register the feedback (user-based, vision-based, and data log).

2.7 Construction Testbed

The PExCon will be implemented at the new construction lab located in the Dudley and Lambertus Hall (i.e., The Gateway Building) at Purdue University for testing in a real construction environment. The construction lab is a high-bay space with more than 430 square meters of floor area and an overhead gantry crane to help mobilize equipment and materials across the area (Figure 4) [10]. The construction lab can host multiple timber/steel construction projects in parallel.

In previous research at the Automation and Intelligent Construction (AutoIC) Lab at Purdue University, a workflow has been established that integrates building information modelling (BIM) and robotic simulation to investigate the feasibility of selected robotic systems in construction operations [11]. This workflow will be adapted to examine the feasibility of using the PExCon and KUKA robots (Figure 5) in helping with the operations of timber and steel construction in the construction lab, prior to the physical test. This represents a closed-loop testbed that integrates modelling, simulation, and physical hardware testing. Furthermore, the successful testing of the PExCon will help tremendously in the accessibility of the construction lab to both residential and online learners by providing remote access to construction operations.

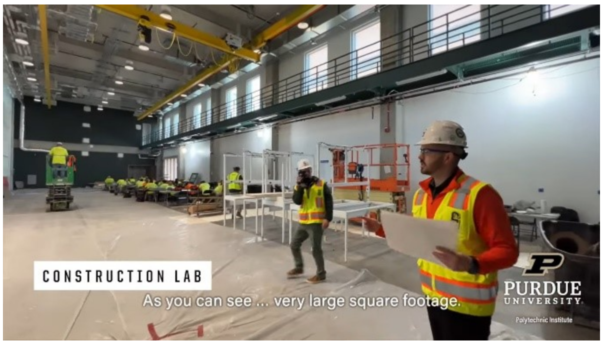

Figure 4. The new construction lab at Purdue University opened in 2023 [12]

Figure 5. The KUKA robot to be installed at the construction lab

3 Conclusion

This short paper gave a detailed overview of the development of the PExCon passive exoskeleton-based remote construction robotic operation system, where an arm exoskeleton was deployed for the teleoperation of the KUKA manipulator and preliminarily tested. The teleoperation will be carried out in our further test in a real construction environment to perform construction operations, such as carrying a heavy payload, unbolting, etc., to support closed-loop testing of construction operations and remote accessibility of the construction lab by both residential and online learners.

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