Interactive 7-DOF Motion Controller Of The Operator Arm (ExoArm 7-DOF)

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***Abstract*— The article focuses on designed construction of the exoskeleton, which significantly reproduces the kinematic structure and the range of joint movement of the human upper limb. The exoskeleton will able to control real objects i.e. loading crane, including force feedback. The designed device, composed of seven rotary joints, is equipped with the closed loop Bowden cable conduit system with linear DC actuators. This conduit system was applied in order to significantly reduce the mass of designed construction. The article describes the proposed kinematic structure, as well as the simple dynamic analysis of the ExoArm 7-DOF. The results of the device manipulability analysis are also included in this paper.**

Keywords— wearable robot, robotics, mechatronics, human robot interface

I. INTRODUCTION

In the near future, we will face a very rapid development of mobile robotics. Implementation of the achievements of robotics and industrial automation to a wider group of devices becomes more and more real. Providing increasing level of protection against dangerous and emergency situations necessitates the application of automated systems in an ever-larger group of devices. With the development of automated devices, there is a need to elaborate new methods of communicating with those devices. The modern methods of communication between the operator and the machine include voice control [1], vision systems [2], augmented reality [3], haptic systems [4], manual programing [5] and control systems with force feedback [6].

Utilization of intelligent human-machine interfaces has many advantages i.e. increases ergonomics and safety at work with machines, as well as increases the intuitiveness of machine operation by communicating with them through the voice, movement and power interaction, which are exactly natural ways of communication. Design and implementation of intelligent human-machine interfaces is an important field of applied research.

This study is part of the activities relating to the implementation Augmented Reality, Interactive Systems, and Operator's Speech Interface for Controlling Lifting Devices. The article focuses on exoskeleton of human upper limb. In particular, it describes the dynamic analysis of interactive 7-DOF motion controller of the operator arm (ExoArm 7-DOF). Exoskeleton within the biomechanical meaning is a device designed to:

- supporting human effort,
- assisting the rehabilitation,
- controlling virtual or real objects including force feedback.

The designed device, the ExoArm 7 DOF, is used for scanning the position of the operator arm and interacting with it by contact force.

The studies on exoskeleton of human upper limb are carried out by many research teams [6], [7], [8], [9]. The aim of the research is the use of exoskeletons to control virtual objects and teleoperation in space with regard to strength including force feedback. Exoskeletons have different kinematic structures, drive methods and functionalities. The solutions of wearable robots are focused on the problem of machine interaction with human tactile system. The control system of exoskeleton requires taking into account the intentions of the man during the operation with the machine. The wearable robots are mechatronic devices equipped with multiple sensors for measuring signals that allow for interpretation of the operator intentions. The interface between man and the exoskeleton is shown in Figure 1.

The signals of the operator force interaction with exoskeleton and the force or the torque generated by the actuators enable effective control based on the dynamic machine model.

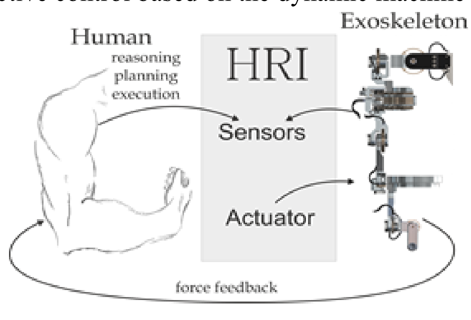

Fig. 1. Scheme of Human Robot Interface

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To the most advanced exoskeletons, we can include:

- X-ARM-2 EXOSKELETON - ESA Telerobotics & Haptics Laboratory [7]
- Upper-Limb Exoskeleton EXO-UL7 - University of California, Los Angeles, Bionics lab [8]
- ALEx - Wearable Robotics [9]

The mentioned devices substantially differ in possibilities of movement as well as the complexity of the structure. X-ARM-2 EXOSKELETON device is significantly different from the others as the fixed base of the device is disposed on the front of the chest, therefore, the realization of the upper limb exoskeleton movement requires the use of more degrees of freedom i.e. 14 joints, including linear joints [7]. This solution greatly reduces the mobility of the human upper limb. EXO-UL7 exoskeleton has 7 DOF and the structure corresponding to the kinematic structure of the human upper limb [8]. However, only part of the joints are driven by the wrapping-connectors which results in a greater weight of the exoskeleton and hence the need for greater power during movement of the device. The ALEx Exoskeleton does not provide full mobility of the human upper limb because it implements only 5 joints, of which only four are active [9]. In comparison to the above, ExoArm 7-DOF only slightly reduces the mobility of the human upper limb and enables the realization of high dynamic motion as achieved by mass reduction and removal the drives to the external stand..

II. Degrees Of Freedom

The structure of ExoArm 7-DOF is anthropomorphic and includes all the degrees of freedom of the human upper limb in order to ensure maximum operator safety and minimize the risk of machine - operator collision. In addition, the device has only rotational degrees of freedom. The movements of subsequent exoskeleton joints do not directly correspond to the movements of the human joints, but the exoskeleton elements in contact with the man, i.e. arm, forearm and hand, are in line with the movements of corresponding man parts. In the ExoArm 7-DOF, we can distinguish equivalents of human joints:

a) shoulder joint 3 DOF

b) elbow joint 1 DOF

c) wrist joint 3 DOF

3 DOF joints are designed in such a way that the three axes of rotation pass through one point and realize the movement like the ball joint. During the kinematic analysis, the appropriate configuration of joints was developed in order to maximize the mobility of the machine and avoid the kinematic singularities in exoskeleton workspace. This configuration of joints assumes that the consecutive rotation axes of the exoskeleton are orthogonal to each other. Diagram of obtained kinematic structure manipulability is shown in Fig 2. The manipulability index of ExoArm 7-DOF was determined from the equation:

$$\mathbb{M} = \sqrt{|J(\varphi)^{\dagger}|} = \sqrt{|J(\varphi) * J(\varphi)^{t}|}$$

Where J(φ) is exoskeleton Jacobian with dimensions 7x6.

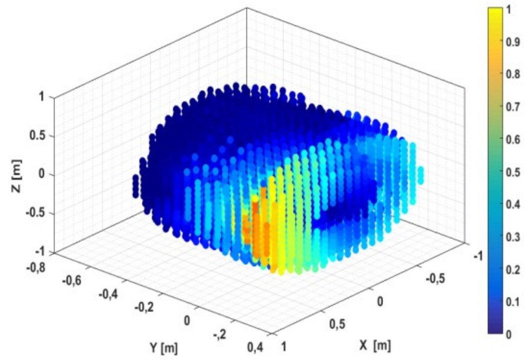

Fig. 2. Noramlized manipulabilty index of Exoarm 7-DOF

The results were obtained for the joints mobility corresponding to angular ranges of human joints presented in International Standard Orthopedic Measurements (ISOM) and in [10]. The designed kinematic structure has the greatest possibility of movement in the front of the operator, what can be considered as its advantage. The shoulder joints of ExoArm 7-DOF have 3 DOF and realize consecutively shoulder: adduction/abduction movements (1^{st} axis), flexion/extension movements (2^{nd} axis) and interior/exterior rotation movements (3^{rd} axis). The figure 3 shows the rotation axes of components corresponding to the 3 DOF shoulder joint. The elbow joint of ExoArm 7-DOF realize human elbow movement, i.e. flexion and extension. The Figure 4 shows the rotation axes of components corresponding to the 1 DOF elbow joint (4^{th} axis). The rotational movement of the forearm has been moved to the wrist. The wrist joints of the ExoArm 7-DOF are composed of 3 rotary axes corresponding respectively to rotational movement of the arm: elbow supination/pronation (5^{th} axis), wrist ulnar/radial deviation (6^{th} axis) and wrist flexion/extension (7^{th} axis). Figure 5 shows the rotational axes of the wrist joints. The arm and forearm of exoskeleton include interchangeable spacers, which allow adjusting the parts of device to the operator.

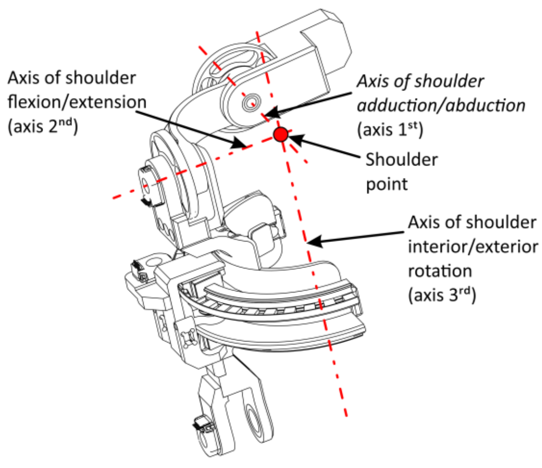

Fig. 3. 3 DOF Shoulder joint of ExoArm 7-DOF

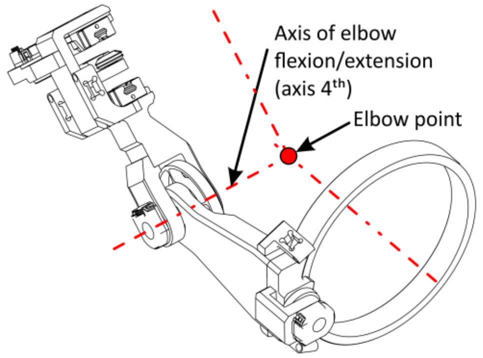

Fig. 4. 1 DOF Elbow joint of ExoArm 7-DOF

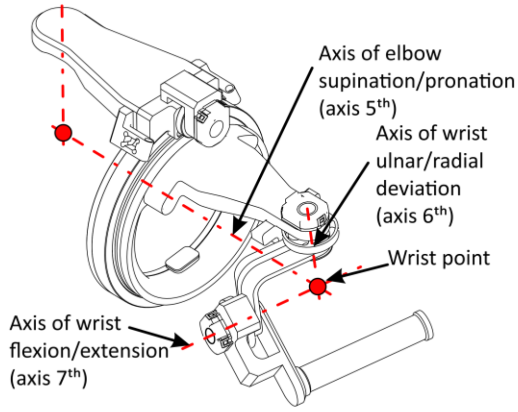

Fig. 5. 3 DOF Wrist joint of ExoArm 7-DOF

III. Device Drive System

The ExoArm 7-DOF has seven rotary joints, each of which is equipped with a drive with sufficiently large power. The criterion for selection of power, velocity and range of motion of drives was to achieve the dynamics of manipulation in the workspace in accordance with the dynamics of the human upper limb. The drives power largely depend on mass of the moving exoskeleton parts. To minimize demand for the drive torque required to generate motion, it was necessary to minimize the weight of ExoArm 7-DOF components, especially the mass of the forearm and wrist elements. In order to significantly reduce the exoskeleton weight, the closed loop Bowden cable conduit system was applied. The mechanical scheme of the closed loop Bowden cable conduit system is shown in Figure 6. This conduit system converts the linear motion of the DC actuator to the rotational joint movement of the exoskeleton. This enabled transfer the drives into a fixed stand. The Bowden cables was prestressed in order to minimize backlash of conduit system. The conduit system has a strain gauge measurement system for torque measurement and absolute encoder for angular position measurement.

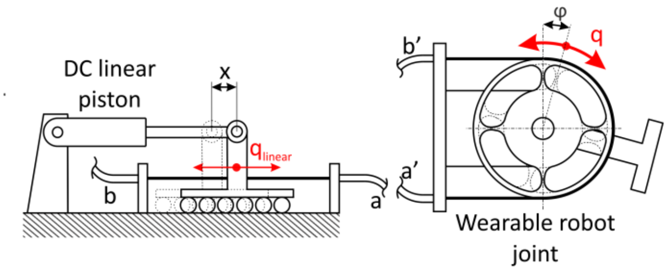

Fig. 6. Mechanical scheme of closed loop cable conduit system

The measurement systems are located on exoskeleton joints in order to reduce the impact of cable pull transmission faults on the joint position control system. The scheme of the joint position control system is shown in figure 7. It is worth to notice that using closed loop conduit system, we can obtain the linear driving torque dependence of the force generated by the actuator.

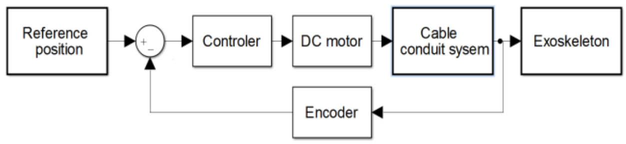

Fig. 7. Position control loop of Exoarm 7-DOF

IV. The Results Of Dynamic Analysis Of 7-DOF Exoskeleton

In order to determine the force and velocity to be generated by the drives, we performed simulations of device motion. These parameters, i.e. force and velocity of drives, are determined from the dynamic model of ExoArm 7-DOF and model of the closed loop Bowden cable conduit system. Due to taking into account the forces of contact at different points in the exoskeleton structure (see Figure 8) and the large number degrees of freedom, the dynamic model of ExoArm 7 DOF was built using the Newton-Euler approach [11].

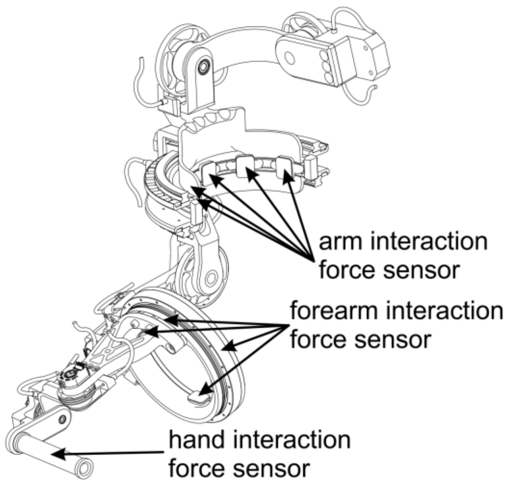

Fig. 8. Placement of reference systems of ExoArm 7-DOF

In the dynamics model, parts of ExoArm 7-DOF were treated as rigid body therefore we considered only the movements of kinematic pairs. Simulation test was carried out using movements recorded during the study described in [12]. As a result of the simulation of ExoArm 7-DOF movements, we received the maximum values of driving torque required to move through the closed loop Bowden cable conduit system.

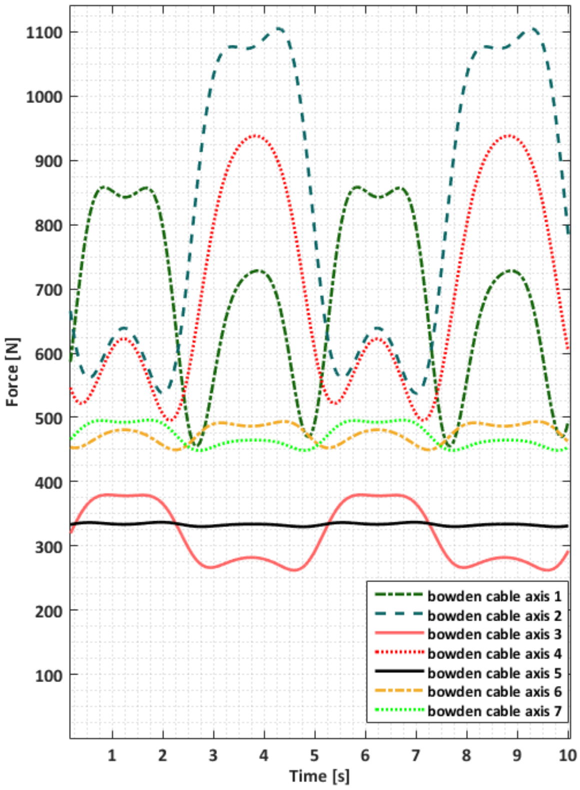

Fig. 9. Load of closed loop cable conduit system

Based on the results, we also determined the greatest possible forces recorded on drives of wearable robot. The values of forces were determined based on the driving torque required to generate the motion and the pretension of closed loop conduit system. The greatest values of velocity and force recorded during the simulations was considered as nominal values for projected drives. Figure 9 shows the maximum forces that have to be transferred by the Bowden cables during ExoArm 7-DOF operation.

V. Conclusion and Future Work

The aim of the research was to design the kinematics ExoArm 7-DOF corresponding to the kinematics of the human upper limb and most of all characterized by the dynamics identical with the dynamics of the operator movements. The design that meets these criteria will be applied to control real devices in a master-slave system. Reproduction of the human upper limb motion was made possible through the use of seven joint divded in 3 groups, which realize the movement of shoulder, elbow and wrist joints. The movement ranges of exoskeleton joints have been adapted in order to achieve the greatest possible movement range of the operator joints. Due to the very complex kinematic structure of exoskeleton, the next step of the project will be to develop an algorithm that will aim to prevent the collision between the operator and device. In some ExoArm 7-DOF configurations will be necessary to modify the motion range of specific joints.

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