Design and impedance control of a hydraulic robot for paralyzed people

Alireza Abbasimoshaei[1] Tobias Stein[1] Tom Rothe[1] Thorsten A. Kern[1*]
Hamburg University of Technology, Eissendorferstr. 38, 21073 Hamburg, Germany
al.abbasimoshaei@tuhh.de
tobias.stein@tuhh.de
tom.rothe@tuhh.de
t.a.kern@tuhh.de
https://www.tuhh.de/imek

***Abstract*— One of the most restricting conditions for any living being is the loss of mobility. For humans, quadriplegia is the most extreme form. Different causes like spinal cord or brain injuries resulting in various degrees of paralysis of all four limbs. In the most serious cases even the ability to feel is gone below the injury resulting in an absolute dependency on others. Technical devices are already able to help those affected in many ways. To regain some of their independence, a robot actuating their body and giving them their mobility back could be one approach. Since their conditions affect the ability to interact with a device the choices for an interface controlling device are limited.**

In this paper, a design for a one degree of freedom device for paralyzed patients is presented. This device is focusing on the wrist extension and flexion. It is considered as a demonstration platform for a new actuation and comfort approaches for assistive devices. Since moving the human body for manipulation of objects will require high output forces, using a hydraulic system is a good option for actuating the device. Thus, after designing the device, a suitable actuator has to be chosen. One of the problems in using hydraulic systems is their hard controlling task. For controlling this hydraulic actuator, an impedance controller is proposed. For evaluating the controlling system, two different experiments are designed and their results are explored.

I. Introduction

According to a 2013 World Health Organization (WHO) report, 250,000 to 500,000 people worldwide suffer spinal cord injuries (SCI) every year. They can have disastrous consequences for the persons affected. The mortality rate for those people is two to five times higher than for those without an SCI. Twenty to thirty percent develop depression and many of them are severely restricted in their daily life [1]. In addition to the injuries, environmental conditions can also restrict a person. To overcome these hurdles, assisting devices can solve the problem. There are a lot of rehabilitation devices available for different kinds of impairments, such as SCI-related problems, strokes, or similar conditions that limit motor skills. Some of them focus on the lower limbs and help to regain the ability to walk (assisted) [1][2]. Others support smaller joints like as wrist [3][4][5][6] or the elbow [7]. In general, these mobile approaches do not consider to be implemented in a larger system. They aim for an independent, lightweight device.

* Corresponding Author: `t.a.kern@tuhh.de`

Considering the lack of muscles in the limbs of paralyzed people, the exoskeleton has to be able to transmit all occurring forces around the operator and no load must be transferred to their body. Tacking into account that a machine able to move a human being has to be substantially larger and heavier so systems supporting an existing movement with a good power-to-weight ratio should be used. Hydraulic systems are superior to electric motors in this respect [8].

The objective of this paper is to the development and control a machine that is able to actuate the wrist of a paralyzed person. Its primary function is not rehabilitation, but to overcome missing motor skills. It could be argued, that a full robotic approach without moving the body is more valuable and technically less complex. However, rehabilitation success is strongly dependant on the activation -even passively moved- of proprioceptive sensors and limbs. The proposed device, therefore, supports rehabilitation while giving immediate help for everyday tasks. Moreover, it uses the bones structure instead of another base, and psychologically, it provides a better sense for patients by feeling that they are using their body. The final system resembles a robot that can be opened to secure the operator in it and is controlled by impedance.

Since the safety of the paralyzed person and its surroundings is most important, a simple position control of the exoskeleton is not sufficient. Therefore, the use of a controller that not only controls the position but also the force is important. In this paper, the concept of the exoskeleton and its impedance control is modeled in Simulink. To test the system, two different experiments show the advantages and disadvantages of the controller. In general, the controller is able to control the force and position of the exoskeleton sufficiently and is able to deal with system uncertainties. As these tests are just done in simulation, the actual behavior of the controllers has to be verified on the real exoskeletons in further works.

II. Designing the model

A. Mechanical structure

The mechanism has to hold the hydraulic cylinder and convert its translating movement into rotation around the wrist. This system is controlled by the volume flow set through the control unit, actuates the operator, and feedbacks its position

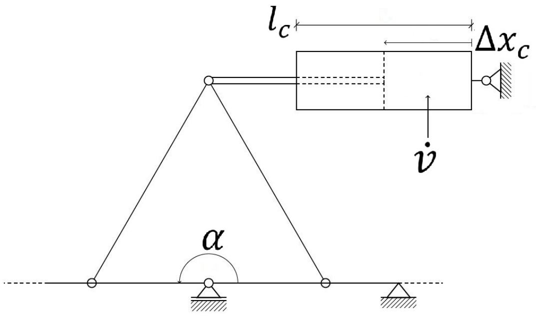

Fig. 1. Schematic sketch of the device

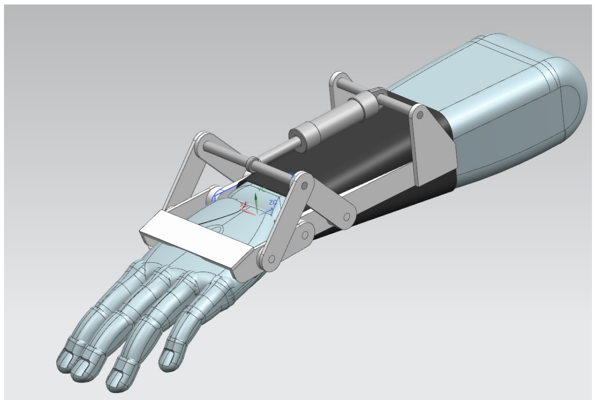

Fig. 2. Exoskeleton for wrist actuation

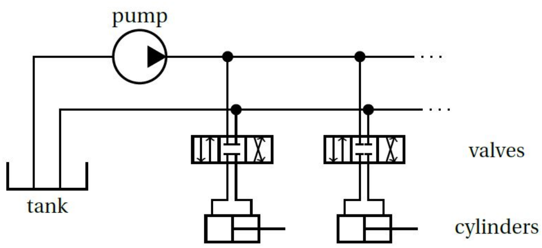

Fig. 3. Hydraulic example circuit

to the control unit. Considering the complete exoskeleton, every part has to be fully self-supporting. The design of the prototype is kept simple to be easy to manufacture in a workshop by hand. Small adjustments can be done without having to redesign and rebuild everything. That is also the reason for the usage of bolts and nuts, as there are plenty other ways to assemble the proposed system if advanced tools can be used and all dimensions proved to be correct. A schematic and measurements of the working parts are given in Fig. 1. The forearm sits in the device and the patient grabs the forward link which rotates by the hydraulic cylinder rotation. The cylinder itself is also attached to the above links. The linear displacement of the piston is converted to the rotational movement around the wrist and provides the rotation. The construction to support the mechanism consists of a tubular aluminum cage for the forearm and can be opened with two hinges on the backside. The hand-piece is hinged to the sides of the cage and can be fastened with velcro to the hand of the operator. A forearm splint is used as a height-adjustable sleeve. On the proximal side, a triangular mounting for the hydraulic cylinder is installed. The piston of the cylinder is attached to the two longer links of the linkage. The smaller links are parts of the cage and the hand piece. In this way, the small movement of the actuator results in double the range of motion of the hand-piece. The joints are lined with a brass tube as a plain bearing. On the joint of the wrist, between cage and hand-piece, an attachment for a potentiometer is placed to implement position control. The mechanical design allows 140° of movement, therefore, suitable limits have to be chosen to avoid injury to the operator. Also, some mechanical stops can be added for safety. The final design is shown in Fig. 2. Back driveability, which is the ability to have a movement when the system is off, could be an issue with hydraulic systems. When the corresponding valve is closed no oil can enter or leave to the actuator so it stucks in its position. To circumvent this, a pressure feedback mechanism can be added to the servo valve [9] .

B. Hydraulics

To develop a robot actuating the complete body of a quadriplegic operator, many actuators are needed. Hydraulics have an up to ten times better weight-to-power ratio than electrodynamic actuators. Moreover, in comparison with a hydraulic actuator, to obtain the same force, a much larger pneumatic cylinder is needed. Therefore hydraulic system could be a good option for this device. The hydraulics translate the volumetric flow, given through the control unit into translating movement. This is done in this case with a double-acting hydraulic cylinder which can generate forces expanding as well as contracting to be able to move the hand of the operator in both directions. In addition to the cylinder, the hydraulic system consists of the tank, a pump with an attached motor, a valve, and hoses connecting everything (Fig. 3). The oil is kept in a tank. A pump is powering the system and each cylinder has its valve. The ones shown are 4/3-valves, which means they have four connectors and three possible positions. Depending on that position the valve is either completely closed (neutral), or either one side of the cylinders is supplied with fluid. The other side is connected to the reservoir and the oil is pushed back out. The required force for wrist movement is really small for hydraulic cylinders. Most industrial cylinders are manufactured for up to 200 bar and generate multiple kilonewton force. Keeping the dimensions of the design in mind, only very small cylinders are considered. The pumps for those cylinders are also rated for at least 200 bar which is too much for this application. An alternative to them is hydraulic systems used for remote-controlled (RC) models. These cylinders come in small sizes and are built for up to 20 bar of pressure delivering a few hundred newtons of force. The much smaller pumps are driven by high powered direct current (DC) motors normally used for RC aircraft and are independent of an external power supply through rechargeable batteries. The valves are

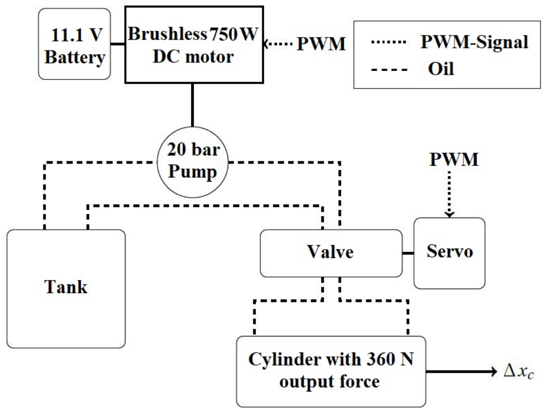

Fig. 4. Hydraulic system

controlled by servos, up to five of them can be mounted in series, and are cost-effective in comparison to their industrial counterparts. Moreover, the addition of further degrees of freedom would be very easy to implement and the much smaller system is better suited with regard to the cost and mobility. The system is shown in Fig. 4. A cylinder with a maximum output force of 360N is selected. The slightly lower force is sufficient as the range of motion will be less than the full 180° between full extension at 90° and full flexion with 270°. It is powered by a pump delivering 20 bar at around 133 Hz, which is driven by a brushless DC motor with a suitable controller. The motor is powered by a rechargeable battery pack with a voltage of 11.1 V and a 6500 mAh charge. Estimating how much current the motor will draw is difficult without testing the assembly, so the maximal load is used for the estimation of run time. The power of the motor is indicated with 750W.

III. Controller Design

A. Hydraulic actuation system simulation

The hydraulic actuation system consists of a 4/3 directional control valve, a pressure relief valve, a pump, an electric motor, a cylinder, and the hoses. The input of the hydraulic actuation system is the valve displacement, the wrist joint angle, and the wrist joint velocity. The output is the hydraulic force and the whole system is simulated as shown in Fig. 5 A.

B. Design the Impedance Controller

The main idea of impedance control is to substitute the mechanical behavior of the manipulator into a desired one. The key theory was invented by Hogan [10] and since then it is often used in different manipulators and tasks. Not only for hydraulic actuators [11][12] but also for other actuators and applications like a robotic hand [13]. A state of the art can be seen in [14].

The system impedance controller is designed according to [15] and fitted to the system to receive its goal values from an eye-tracking system in the future work. This model can be divided into two parts: The impedance filter and the full dynamic model. Firstly, the impedance filter calculates the desired trajectory through the following formula. Since the degree of freedom equals to one, the matrices are the size of 1x1.

$$M_d * (\ddot{\alpha}_c - \ddot{\alpha}_d) + B_d * (\dot{\alpha}_c - \dot{\alpha}_d) + K_d * (\alpha_c - \alpha_d) = T_H$$

In which α_c is the wrist joint position and α_d is the wrist joint goal position. As the impedance filter models the desired behaviour of the hand movement, T_H is the torque applied on the hand and is 0.06 $*F_H$ in which F_H is the force on the hand. The computed $\dot{\alpha}_c$ is converted into the computed piston velocity ($\dot{x}_{p,c}$) according to the following equation.

$$\dot{x}_{p,c} = \dot{\alpha}_c * \frac{60 * 10^{-3} m}{\pi}$$

Later, the full dynamic model converts the calculated piston velocity and the measured force into the displacement of the valve. The Simulink block of the full dynamic model is shown in Fig. 5 B. It is designed and consists of the inverse dynamics of the four-bar linkage, hydraulic cylinder, and the hydraulic valve. It follows the following formula.

$$u_{imp} = \sqrt{\frac{A_{cyl}^3 * 2 * \dot{x}_{p,c} * |\dot{x}_{p,c}|}{A_{cyl} * (p_{pump} - p_{tank}) - F_{cyl,inv}}} * \frac{1}{K_v * \alpha_v * \sqrt{\frac{2}{\rho}}}$$

In which u_{imp} is the impedance controller output, K_v and α_v are the valve gain and flow discharge coefficient respectively. $F_{cyl,inv}$ which is the calculated hydraulic force changes according to the measured force (F_H) and the other parameters for this simulation are ascertained with the trial and error method and have the following values.

$$M_d = 7kgm^2, B_d = 40\frac{Nm * s}{rad}, K_d = 60\frac{Nm}{rad}$$

When more degrees of freedom are required, the controller can be changed according to [15]. The connection of the force and the movement in hydraulic actuators has to be determined and put into a second-order system.

IV. Experiments and Results

In order to evaluate the controller, two different tasks are executed. The idea is to compare the position and force accuracy of the system. The tasks are selected in the way that they consist daily tasks for paralyzed patients. The step input could be used in order to move or grab objects and the sinusoidal input can be used for therapeutic purposes like rehabilitation. For equality reasons, the automatic variable step size solver chosen by Simulink is used. The relative tolerance is set to 10^{-3}.

A. Experiments description

In the first experiment, the step response is tested with a position step input of $\Delta\alpha = -80° = -\frac{4}{9} * \pi$ while starting at maximum flexion $\alpha_{start} = 220° = \frac{11}{9} * \pi$. In this system,

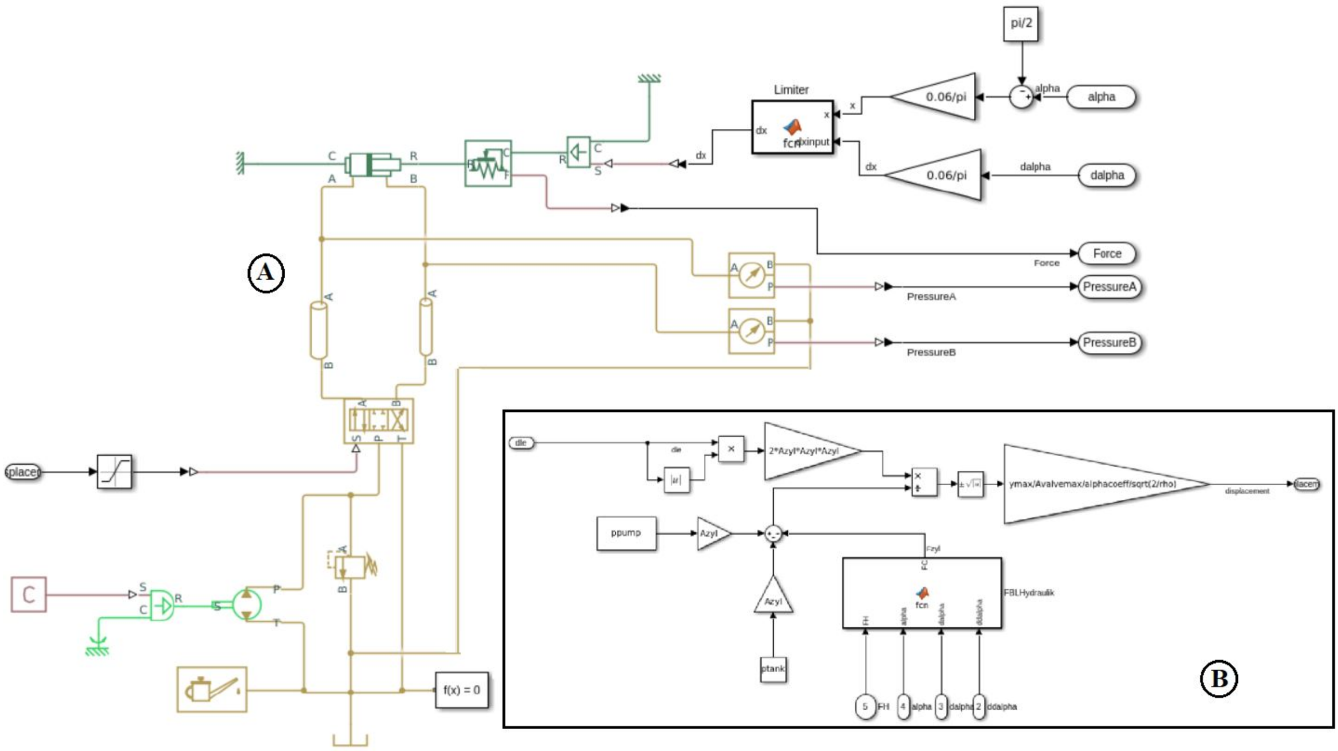

Fig. 5. A) hydraulic system simulation B) full dynamic model of the hydraulic system

the performance parameters are the rising time, the settling time, and maximum of force and velocity of the human hand. Of course, the steady state error also plays a big role and should be lower than 0.5% . Behaviors like as big overshoot, undershoot and excessive chattering are unacceptable.

The rising time is defined as the time that passes when the output is within 10% to 90% of the step size. The settling time is defined as the time in which deviation from its steady state value of the output remains less than 1% expressed with the following formula.

$$\left|\frac{\alpha(t_s) - \alpha_d}{\alpha_d}\right| \leq 0.01$$

So in this test, the time is measured until

$$\alpha(t_s) \leq 2.468$$

In addition to getting reliable values, the input signal is given after one second after starting the simulation. This is done in order to give equal initial conditions and to compare the behavior of the controller when it is initialized.

In the second test, the task is to follow a sinusoidal position trajectory with the associated velocity and acceleration. The input starts at $\alpha = 180°$ with an amplitude of $40°$ and a frequency of $f = 1Hz$ and a full flexion extension movement is fulfilled. Here the difference in amplitude and the phase shift time are crucial. The difference in amplitude is calculated as the difference of the wrist joint angle to the desired wrist joint angle at the positive beginning of the second period. The phase shift time is measured as the difference of time when the second period starts and the wrist joint angles crosses the value π and is calculated as

$$\Delta t = t(\alpha_d = \pi) - t(\alpha = \pi)$$

TABLE I

RESULTS OF THE FIRST TEST FOR IMPEDANCE CONTROL

Rising Time	Settling Time	Maximum velocity	Maximum force	Steady state error
2.169 s	1.128 s	1.5 rad/s	11.99 N	0.012 rad

TABLE II

RESULTS OF THE SECOND TEST FOR IMPEDANCE CONTROL

Controller	Difference in amplitude	Phase shift time
Impedance Control	0.06 rad	-0.006 s

B. Results

The results of the first test are shown in Table I and Fig. 6. All of the plots start with a chattering at the beginning of the simulation. The impedance controller reduces the chattering quickly. It has a relatively fast-rising and settling time while not overstepping the maximum velocity. Additionally, the peak of the wrist joint acceleration is pretty low. The controller gains a steady state error lesser than 0.5%.

In the second test, the impedance controller follows the desired wrist joint angle pretty accurately. There is a small error at the beginning of the simulation and after 1.5 seconds the wrist joint angle follows the desired path. The results are shown in Table II and Fig. 7.

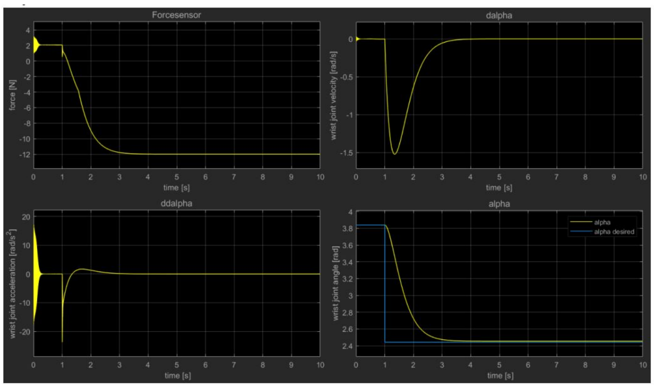

Fig. 6. Impedance controller results of the first test

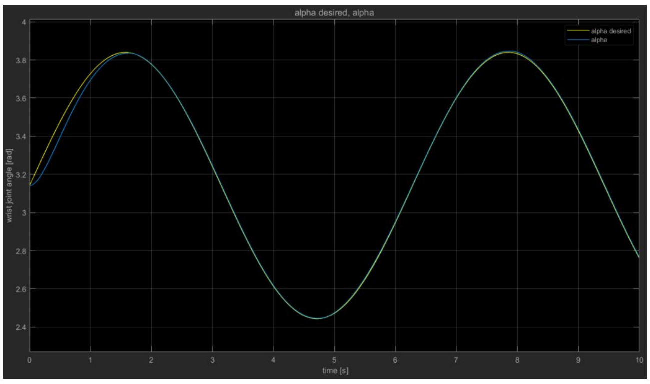

Fig. 7. Impedance controller results of the second test

V. Conclusion and Further research

In this paper, a concept to help paralyzed people to regain some of their independence is developed and a mechanism to translate the input of the actuating system into rotation was designed. Then, a proper hydraulics system was selected and combined with a wrist device. The control unit for the hydraulics was simulated in Simulink. The device is designed to be easy to build in a common workshop as a prototype and for easy adjustments. In the kinematic evaluation for controlling the system, one of the reasons for discrepancies between the simulation and the real device are the unknown parameters of the hydraulic system. There are subjects to future tests after full assembly.

In order to guarantee the safety of the operator and the surroundings, the controller should be able to control not only the position of the exoskeleton but also the force. Therefore, an impedance controller has been designed in theory and was implemented. With two different tests, the controller is evaluated. Just with the results of these tests, the impedance controller is shown that it could satisfy the expectations. However, as this is just a simulation, the results have to be verified by implementing the controller in the actual exoskeleton. The problem with an impedance controller is that it is not possible to exactly describe the dynamics of the manipulator and the hydraulic actuator, as uncertainties, coulomb friction, numerical inaccuracies, and not modeled dynamics which are always present. But one of the advantages of the impedance controller is that for the usage of an eye-tracking input, the impedance controller is a good option and it follows the desired trajectory very well. If the patient would like to increase the desired force, he can increase the stiffness value or the desired position. In order to improve the controller, an algorithm could be implemented to increase the damping value if the stiffness value increases. In this way, it could be verified that by adjusting the ratio of the stiffness and damping parameters no overshoot will happen. In general, it is shown that the controller is safe enough to be used for a hydraulic exoskeleton.

Before going any further, the next step will be to build and implement the device. Moreover, combining the controlling system with the eye-tracking for sending the goal controlling signal would be another work. Together with these, paralyzed people will be included during further development. The goal remains to have a robot to actuate the whole body of a paralyzed person. Moreover, feedbacks from the affected or caregivers who work with paralyzed people can ensure that the system will actually be an aid for those in need. Regarding the construction, two degrees of freedom are missing to allow full mobility of the hand. Taking into account the collected feedback, those degrees of freedom or additional joints can be added until the full exoskeleton is completed. Furthermore, the properties of the hydraulic actuators have to be taken into account. Pronation and supination could be added, for example, by fixing the exoskeleton wrist proximally in a cuff so that it can be rotated and turned via two cylinders which run in diagonally mounted rails on the wrist. Also, an elbow joint would be easier to add, two cylinders could be placed parallel to biceps and triceps. The only difficulty here would be the construction of a feasible opening mechanism.

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