Mechanical Design and Motion Control of a Hand Exoskeleton for Rehabilitation

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Abstract **– Hand injuries are a frequent problem. The great amount of hand injuries is not only a problem for the affected people but economic consequences follow because rehabilitation takes a long time. To improve therapy results and reduce cost of rehabilitation a hand exoskeleton was developed. For research on control algorithms and rehabilitation programs a prototype supporting all four degrees of freedom of one finger was build (s. Fig. 1). In view of the fact that a lot of hand injuries affect only one finger, this prototype could already be functional in physical therapy. A robust sliding mode controller was proposed for motion control of the hand exoskeleton. The performance of the controller was evaluated for step response. In a second experiment varied forces where applied during the sensor was set to hold a constant position. Finally the controller was set to follow a complete trajectory.**

Index Terms – hand exoskeleton, rehabilitation, human-machine interaction, sliding mode control

I. INTRODUCTION

Hand injuries are a common result of accidents. Permanent impairments are regular consequences of these injuries. After hand operations it is essential to perform rehabilitation to regain previous dexterity. Social and economic consequences are severe if the result of rehabilitation is not optimal. As an example rehabilitation is necessary to treat flexor tendon injuries or to avoid scarring and adhesion after surgery. Another problem during the rehabilitation process is lack of reproducible measurements. These are needed to identify limitations in the dexterity of the hand and to evaluate the progress of rehabilitation.

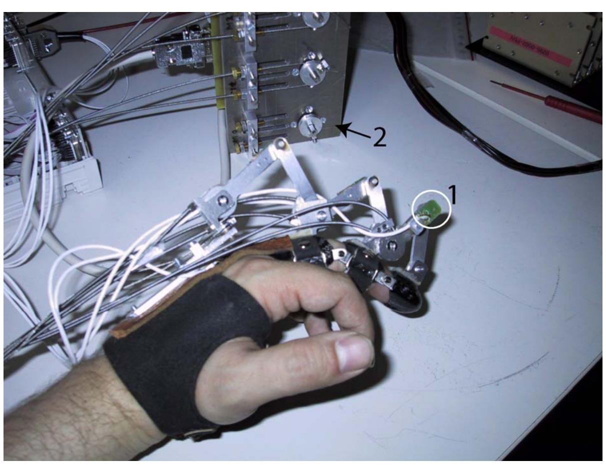

Figure 1 Prototype of the exoskeleton for one finger attached to the author's hand. Four degrees of freedom are actuated bidirectional by the use of two Bowden cables and levers for each finger joint. On each lever a Hall sensor (1) is attached to measure the angle of the finger joints accurately. Actuator unit is shown in the background (2).

Currently most rehabilitation is performed manually by physiotherapists. High personnel costs and lack of motivation to perform exercises at home present a problem. Some devices support physiotherapists by applying a continuous passive motion to the patient's hand, e.g. [1]. These devices are limited in the number of independently actuated degrees of freedom, and do not integrate sensors for diagnostics. The evaluation of progress is therefore done manually by the therapist. More flexible robotic support in rehabilitation of hand injuries is not common.

Research on hand exoskeletons is still going on but the majority of these devices were not developed with focus on rehabilitation. Other applications are haptic interaction with a virtual reality or remote manipulations with robot arms. Some hand exoskeletons restrict motions of the joints and do not exert them actively. An exoskeleton that uses ultrasonic clutches was presented in [2]. The commercially available CyberGrasp from Immersion restricts motion by pull cables with brakes on their distant end. Other devices can only exert forces in one direction. An example for this type of devices was presented in [3, 4]. For virtual reality these devices are suitable but for rehabilitation purposes a bidirectional active motion is desired. At the Robotics Center-Ecole des Mines de Paris a hand exoskeleton was developed that supports bidirectional movement for two fingers [5]. It supports up to four degrees of freedom per finger but controls only one of them at the same time through a pull cable. The LRP Hand Master is similar to the exoskeleton presented in this paper, but was not used for rehabilitation purposes yet [6]. It supports 14 bidirectional actuated degrees of freedom.

Recent research on the usage of exoskeletons in physical therapy was done by scientists of the University of Salford [7]. For their experiments they used a tendon driven exoskeleton which controls flexion of two degrees of freedom per finger. The Rutgers Master II actuates the fingers by four pneumatic pistons inside the palm [8]. The device was employed in a study for the rehabilitation of stroke patients

[9]. Another example for an exoskeleton used in rehabilitation showed the possibility to improve rehabilitation progress as well [10].

II. Mechanical Construction of the Exoskeleton and Integrated Sensors

Existing exoskeleton devices do not satisfy all needs of rehabilitation. The device should be modular, lightweight, and easy to attach even to deformed or scarred hands. Furthermore the palm should be free of any mechanical elements to allow interaction with the environment. Bidirectional movement in all degrees of freedom is desired. Each finger has four degrees of freedom: Flexion and extension in metacarpophalangeal (MCP) joint, proximal interphalangeal (PIP) joint, and distal interphalangeal (DIP) joint; and abduction/adduction in MCP joint.

The developed construction fulfils these requirements and supports bidirectional motion in all joints. It moves fingers by a construction of levers which are connected to the hand by orthopaedic attachments. Link lengths were designed to allow nearly full range of motion. Each lever ends in a pulley where two ends of a Bowden cable are fixed. The Bowden cables are connected to actuating motors with transmission gears. Flexible Bowden sheaths allow some movement of the hand in relation to the actuator unit. Movement of the cables within the sheaths leads to a rotation of the pulleys which results in a rotation of finger joints. Each pair of the Bowden sheaths are attached to a mount at the phalanxes. On the other end they are attached to a tension device to keep cables under tension reducing slackness.

On one joint of each lever a Hall sensor is integrated. The corresponding finger joints angles can be calculated with help of trigonometric equations and known link lengths. The positions of motor axes are measured by optical encoders. These values are also used to calculate joint angles of the fingers. As a result of strain and slackness both values for joint angles deviate.

Force sensing resistors attached on top and on bottom of each phalanx measure the applied forces during flexion and extension. The resulting forces are inaccurate because not all forces are exchanged through the sensors. The contact area is maximized by applying distance pieces to assure that most of the force is passed through the force sensors. The values are accurate enough to measure dynamic changes in the applied forces. The actual currents of the motors can deviate from the values set by the control system. These currents and therefore the torques at the motor axes are measured as well. Together with transmission ratio of gears and leverage they can be used to estimate the force exerted to the phalanges. The friction of the Bowden cables has to be considered as a source of error.

Upon request of physicians the activity for selected muscles can be measured simultaneously with the other data. Surface electromyography (sEMG) sensors are used to acquire these data. These sEMG data are currently only arranged to be used for diagnostic support and medical research.

III. Control System

The control system (see Fig. 2) consists of three parts: a real-time controller, the host computer running the interface for the instructor, and the client interface giving visual feedback to the user. The user and the instructor interface can run on separate computer if desired. The different parts of the system are connected through network interfaces.

The real-time controller from *National Instruments* is running the real-time operation system *Pharlap* and samples all sensor data (Hall sensors, quadrature encoders, motor currents, and force sensors) through data acquisition cards. All control loops are executed on this controller as well. The motors are driven through analog output channels which are connected to PWM-controllers using a torque control mode. The system is designed for the control of the complete hand exoskeleton with 20 axes.

The host computer running the interface for the instructor allows the setting of desired motion and displays all sensor data. The system allows recording the motion of all joints. The motion can be filtered and replayed later at a customised speed. Remote assistance is possible as the application can run on any computer connected to the internet. This possibility of telerehabilitation is especially useful for people living in remote areas and for injuries where only few specialists are available. A lot of travelling could be avoided.

The control loops run independently for each controlled joint. The controlled variable for each control loop is the measured angle at the optical encoders of the motors. The measured angles from the Hall sensors are not yet used inside the control loop. The redundant angle sensor data are currently only used to detect mechanical failures. The control loop used for position control is described in the next section. Experiments were performed to evaluate the performance of the controller.

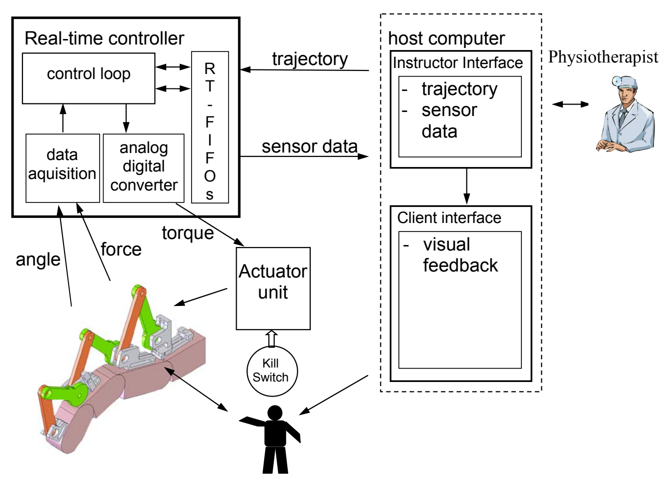

Fig. 2: Diagram of the system. The Real-Time controller samples the sensors data and controls the movement through the actuation unit of the hand exoskeleton worn by the patient. The physiotherapist can supervise the exercises through the instructor interface. The kill switch can abort the movement at any time.

III. Control Algorithm

The precise motion control of the proposed exoskeleton is complicated because of the two following facts: the parameters of the mechanical system are changing by each trail due to the deflection of Bowden cables; the load of the actuators caused by the resistance of the hand changes. Therefore, the standard controllers which can be well tuned only for some small operation area provide a bad performance when the load or parameters of the system are changed.

The proposed solution for motion control is based on application of the sliding mode control (SMC). One advantage of the SMC is the insensitivity to parameter variations and rejection of disturbances [11]. As it was shown, see e.g. [12], a system, linear in the input

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x},t) + \mathbf{B}(\mathbf{x},t)u \tag{1}$$

can be forced to move in the state subspace, called sliding manifold or sliding surface, given by s(**x**)=0, where s(**x**) is a scalar function. To achieve the motion on the sliding manifold, discontinuous control is used:

$$u = \begin{cases} u_+(\mathbf{x}), & \text{for } s(\mathbf{x}) > 0 \\ u_-(\mathbf{x}), & \text{for } s(\mathbf{x}) < 0 \end{cases} \tag{2}$$

The control (2) works as follows: if the system state does not lie on the sliding manifold, the control u takes one of its values u_+or u_- and steers the system state toward the sliding manifold. After reaching the sliding manifold the control performs infinite fast switching between u_+ and u_- and the system state remains in the sliding manifold forever. If u_+ and can be made independent of system parameters, only the definition of the sliding surface determines motion of the system, and control (2) makes the system totally insensitive to parameter variations and disturbances.

In spite of its advantages, SMC is seldom used for control of robot motion. The main difficulty in connection with application of the SMC is practical realization of infinite fast switching in the control (2) which leads to the so called chattering (high frequency oscillation).

To avoid the chattering problem the control scheme shown in Fig. 3 was proposed. An imaginary input ζ of the system is introduced and the real input u will be considered as a part of the system state. The imaginary input ζ is integrated to form the real input u, which is then fed to the actuator. The integrator belongs to the controller and thus ideal switching for input ζ becomes possible. The resulting control rule for each actuator of the exoskeleton is therefore:

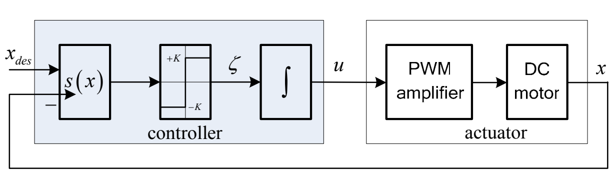

Fig. 3 The idea of the control schema

$$u = \int -K \,\mathrm{sign}\big(s(\mathbf{x})\big)\,dt \tag{3}$$

The sliding surface was defined as follows:

$$s(\mathbf{x}) = C_q e + C_{\dot{q}}\dot{e} + C_{\ddot{q}}\ddot{e} = 0 \tag{4}$$

Here e is the error in the coordinate and C_i are constants. It can be easily shown, see e.g. [12], that if the system moves on sliding surface (4), the error progression moves along function exp($-\lambda t$). For this case, the constants C_i should be chosen as follows: C_q is free, $C_{\dot{q}} = 2C_q/\lambda$,. $C_{\ddot{q}} = C_q/\lambda^2$ In [12] the stability of the proposed controller is proven for a large class of mechanical systems.

For time discrete implementation of the control law (3) the switching element should be approximated by means of linear function with a large slope. For given controller period the slope of this linear approximation and the constant K can be easily determined in an experiment. It can be shown [13] that the controller can also be approximated by a PID controller with high gains.

IV. Experimental Results

For system evaluation the SMC was implemented to control the joint angles of the hand exoskeleton. The maximum torque of each motor gear combination is about four Nm. But for safety reasons the torques of the motors were limited to 20% of their maximum torque so that the human wearing the exoskeleton is stronger. The constants for SMC were determined in experiments with no load. The control loop currently runs at 2.5 KHz.

In a first experiment the performance was evaluated on a step response from 0 to 90 degrees in the MCP joint. The control works for multiple joint simultaneously but all results are only shows for one joint. In that experiment the user was passive and not working with or against the motion. The parameters used in this experiment were $\lambda = 70$, K = 5700 and $u_{+/-} = \pm 10^5$. Fig. 4 shows the recorded step response for the implemented SMC. The SMC could be tuned for fast response

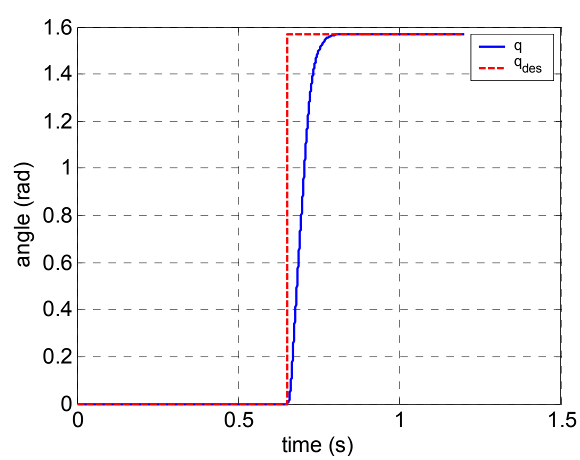

Fig. 4 Step response measured at the first finger joint (MCP) during flexion and extension using the sliding mode control algorithm.

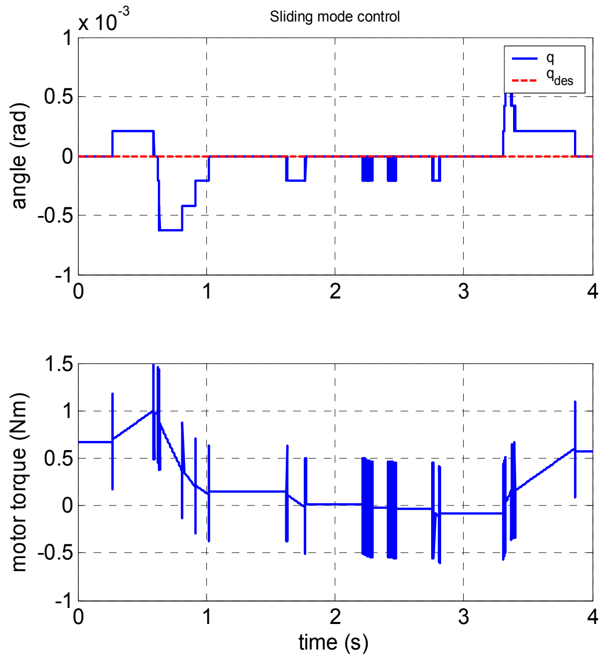

Fig. 5 Error during varying forces holding constant position. Lower Graph shows the varying controller output as a response of the varying forces.

maintaining the stability. Higher λ and therefore even faster response would have been possible but would have led to unpleasant high velocities. The trajectory is very smooth while approaching the desired value. The greatest deviation after reaching the desired position was within one step of the optical encoders.

In a second experiment the controllers were set to hold a constant position. The parameters used were the same as the ones used in the experiment before. The human wearing the hand exoskeleton varied the applied force. The sliding mode controller performed good even with varying load applied to the exoskeleton (Fig. 5). The greatest deviation in the position was within three encoder steps. The motor torques changing

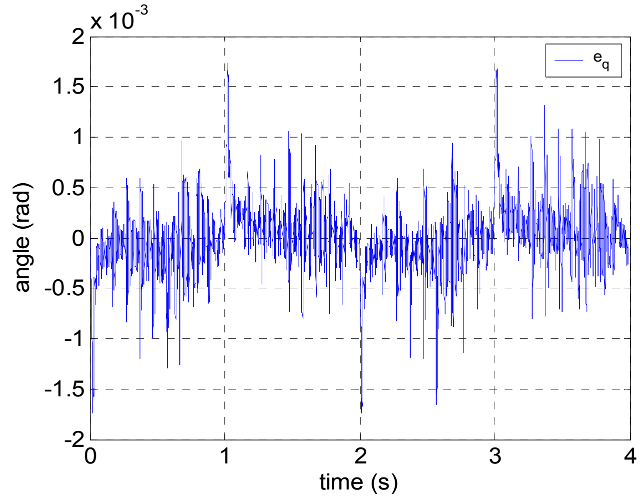

Fig. 7 Position error occurring during execution of desired trajectory (see Fig. 6). The maximum error occur when the direction of the movements is reversed.

with high frequency occurred due to deflections in the Bowden cable. However these rapid changes did not result in undesired vibrations at the finger joints.

In the last experiment the SMC was set to follow a predefined trajectory. For evaluation purposes a sine wave with a frequency of 0.5 Hz was used, but every two times differentiable trajectory is allowed. The amplitude of the sine wave was π/4 rad so that the finger moved the full range of motion of π/2 rad. The parameter used where different as in the previous experiments because now a greater λ is feasible. The parameters used in this experiment were $\lambda = 250$, $K = 2.3*10^4$ and $u_{+/-} = \pm 10^5$. The trajectory was generated and used to set the desired position for every time step. The desired velocity and the desired acceleration derived from the trajectory were not set because this did not improve the results.

The desired and the resulting trajectory are shown in Fig. 6. The trajectory is followed very well; in Fig. 7 the

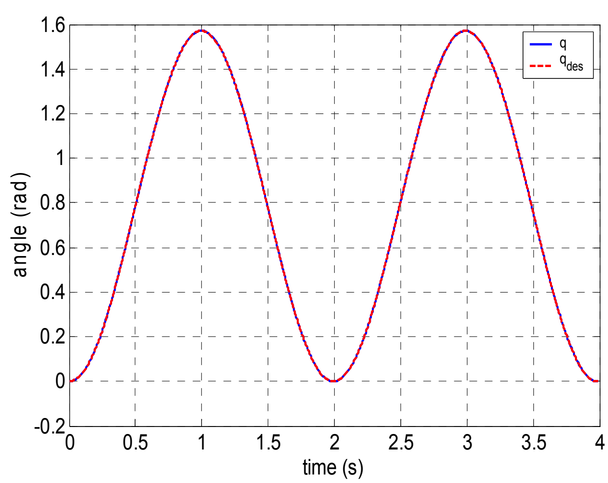

Fig. 6 Desired trajectory (sine wave with a frequency of 0.5 Hz frequency and an amplitude of π/2 rad) and actual trajectory for the flexion resp. extension of the MCP.

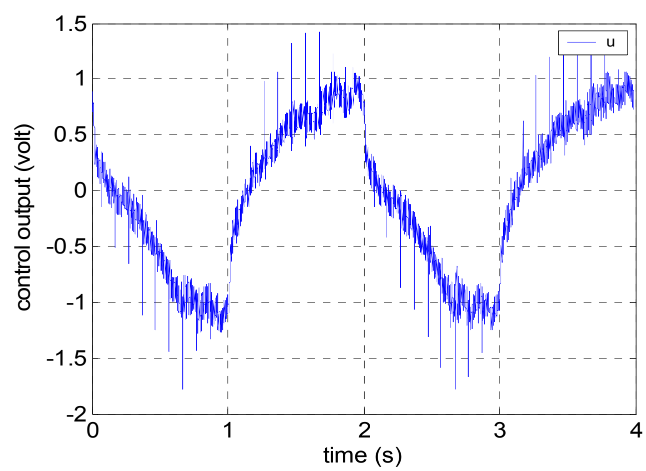

Fig. 8 The control output during execution of the desired trajectory (see Fig. 6). Maximum output voltage was limited to 2 V. The peaks in the control output do not lead to undesired vibrations at the hand exoskeleton.

position error is shown. The greatest deviation from the desired trajectory is less than $2*10^{-3}$ rad. The deviation is usually much smaller, only at the points where the direction of the movement is reversed the position error reaches these values. The standard deviation is smaller than $3*10^{-4}$ rad. The performance is not as good as the results for approaching a static position; but still better than needed for the desired application. Due to the flexible attachment to the skin the angles of the mechanical construction and the real angles of the finger joints differ. Therefore the position accuracy reached is better than the mechanical construction can reproduce.

Fig. 8 shows the control output during the execution of the trajectory. Due to the integrator the control outputs are relatively smooth. The few peaks that occur are most probably due to deflection in the Bowden cables. Even more important is that no undesired vibrations are felt inside the hand exoskeleton.

V. Conclusions and Future Work

The presented work is a basis for future research and clinical studies. The hand exoskeleton was developed under consideration of the special needs of the rehabilitation. The previously used standard PID controller gave satisfying result [14]. But the sliding mode control is more robust to changes in the applied load. It was shown that trajectories can be followed with good accuracy. The sliding mode control allows a fast and stable position control. The integrated sensors allow measurements for new methods in rehabilitation and diagnostic of hand injuries. Automatic adaptation to the progress of the rehabilitation for individual patients becomes possible (e.g. by measuring their resistance to the applied motion).

Next steps will include the assembly of the hand exoskeleton to support all four fingers and the thumb. Calibrated force sensors will allow a better force measurement. The integration of an automatic calibration of the finger joint angles could simplify the usage of the exoskeleton as well [15].

The position accuracy of the control loop could be further improved by integrating the measured angles from the Hall sensors. By that measure, the tolerance introduced by the flexibility of the Bowden cables could be reduced. Further control modes incorporating the measured force will allow more flexible training programs. As an example the speed of the trajectory could be varied according to the resistance of the patient against the movement which is measured by the force sensors. This would allow the system to synchronize with the patient and avoid forcing the timing of the exercises onto the patient. The comfort of the rehabilitation program and possibly the success could be improved by this way.

Another desired control mode is a force control mode where the user is solely defining the motion by his or her movements; friction introduced by the exoskeleton will be suppressed. In this mode measurements are possible without interference of the hand exoskeleton with the patient's movements.

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