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„Reha-Maus: A Novel Robot for Upper Limb Rehabilitation“

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Reha-Maus: A Novel Robot for Upper Limb Rehabilitation

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Abstract

This paper presents a novel robot-aided rehabilitation system for upper limbs. The overall concept, the robotic system, and the position control strategy are described. An initial indication of its performance is provided.

Introduction

A number of robotic devices have been developed to assist, enhance, evaluate, and document neurological and orthopaedic rehabilitation of movement, including *MIT-Manus* [4], *GENTLE/s* [5], and *ARMin* [6]. These devices have been proven to reduce motor impairment in the hemiparetic upper limbs of stroke patients. However, their development for an exclusively clinical use entails a lack of mobility, high acquisition costs and limited patient training times. To address some of these issues, concepts that allow stroke patients with upper limbs impairments to continue rehabilitation therapy at home have been suggested [3]. An existing attempt is given by "*Arm-Skate*" [7], a semi-passive tabletop device that is lightweight and easy to set up. However, its potential is limited by its lack of active patient support.

The *Reha-Maus* poses the first concept of a portable rehabilitation robot that actively provides different levels of patient assistance. Its compact design and reduced complexity facilitate user friendly home training as well as clinical use. Furthermore, its estimated low price allows for group therapy with several robots in use. Prospective training applications include assisted or perturbed motion of shoulder and elbow induced by controlled robot motion. Moreover, the utilised sensors and the use of computer control allow for advanced training programs and continuous patient assessment and monitoring.

Robot Set-up

Figure 1 shows a prospective application scenario of the *Reha-Maus*. The lower right arm of a patient is pivoted on the moving robotic platform. Human-device interaction forces are measured by a force sensor underneath the arm support.

Arbitrary motion, i.e. planar robot translation and rotation, on the application surface is facilitated by three assembled omni-wheels. Their design allows for low-friction rolling perpendicular to the attached motor shaft. Each omni-wheel is driven by a DC motor with gear and encoder. Furthermore, separate external power electronics provide analogue current controllers for each motor. A compact, yet powerful device design is achieved by mounting the high-performance drives along the edges of an equilateral triangle. The configuration is capable of producing a predetermined range of force (0–55 N) and velocity (translational 0–0.6 m/s, rotational 0–9 rad/s). The robot weighs 2.8 kg and has a diameter of 300 mm.

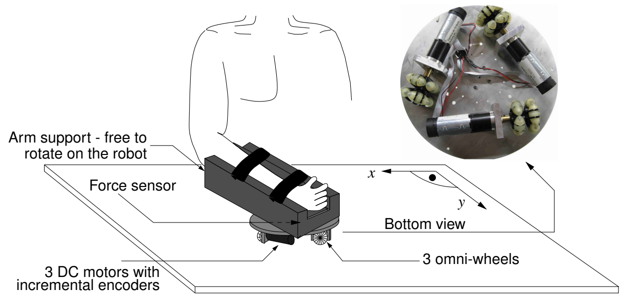

Figure 1: *Reha-Maus.*

At this stage of development, absolute position information is gathered by an infrared camera.

A real time Linux-based computer interface allows for the use of advanced control algorithms that have been implemented using Scilab/Scicos[1] and the HART toolbox[2].

Position Control Scheme

Several prospective *Reha-Maus* applications rely on the following control system for the generalised position $q = (x, y, \theta)'$, i.e. planar coordinates x and y, and θ, the robot orientation with respect to a fixed coordinate frame.

Fast and accurate estimates of q are provided by a sensor fusion scheme. The utilised Kalman filter combines an optical absolute position measurement q_m with wheel speed information, processed by a kinematic model

$$q[k] = q[k-1] + t_s \Gamma[k-1] \omega[k-1] \qquad (1)$$

where t_s is the sampling time, ω is a vector of wheel velocities, and Γ is a time-varying transformation that nonlinearly depends on θ. Furthermore, the algorithm accounts for a non-negligible transmission delay in the optical positioning system.

Turning to control action, separate anti-windup wheel velocity control loops [2] have been implemented which allow for operating the system at maximum actuator capacities and provide, to some extent, a decoupling of ω. Consequently, the relation between reference vector ω_r and actual

[1]http://www.scilab.org/
[2]http://hart.sourceforge.net/

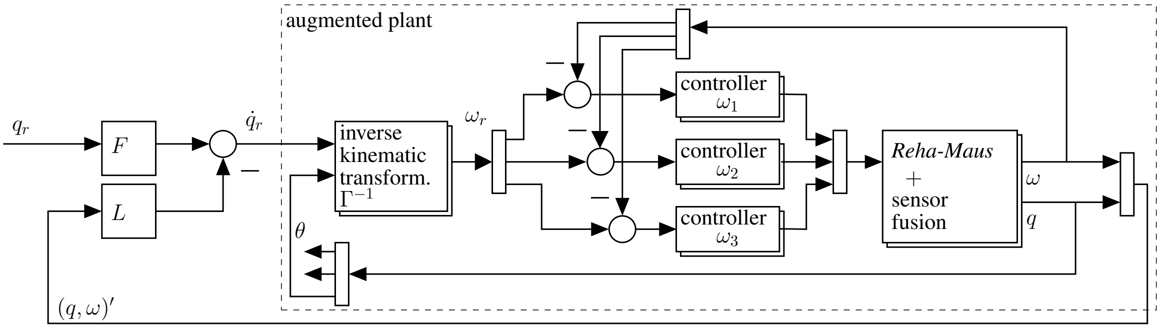

Figure 2: Control scheme.

wheel velocity ω can be approximated by a discrete-time first-order system. Moreover, by augmenting the system with an inverse kinematic transformation Γ^{-1}, the orientation dependency is approximately eliminated. Let I and O be 3×3-identity and zero matrix, respectively, and a the parameter that determines the rise time of a discrete-time first order system. Then, a simplified state-space description of the augmented plant is given by

$$\begin{pmatrix} q[k] \\ \omega[k] \end{pmatrix} = \begin{pmatrix} I & t_s\Gamma[k-1] \\ O & aI \end{pmatrix} \begin{pmatrix} q[k-1] \\ \omega[k-1] \end{pmatrix} + \begin{pmatrix} O \\ (1-a)\overline{\Gamma}[k-1]^{-1} \end{pmatrix} \dot{q}_r[k-1] \qquad (2)$$

where $\dot{q}_r$ is a generalised reference velocity, the new plant input. As a result of the dynamic inversion, a static state-feedback control design can be applied for arbitrary reference orientations. Figure 2 illustrates the control scheme with system state $(q, \omega)'$, feedback matrix L and static reference filter F. Here, L is a linear-quadratic regulator [1], and F has been designed for achieving unity DC gain.

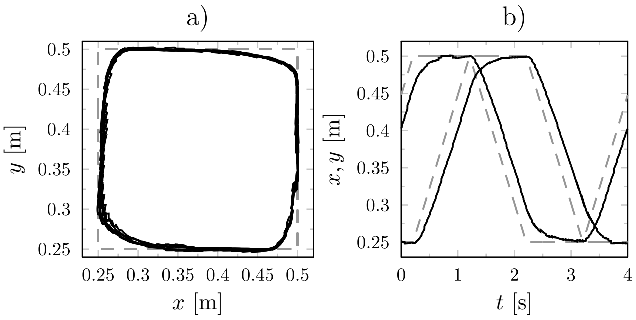

Figure 3: Square trajectory.

Figure 3 shows the control performance for tracking a rectangular path q_r. An external load, the arm of a subject, has been imposed during the trials. More precisely, the subject was instructed to be passively guided by the system. Although the resulting position (solid) shows small deviations from its target (dashed), the signals remain their characteristic shape for several cycles (x-y-plot, Figure 3a). Figure 3b discloses a phase shift between individual components x and y, and their references. Obviously, the controller is not capable of tracking linearly increasing reference trajectories in the present form. As a consequence, the desired corners appear smoothed in the x-y-plot. Not illustrated is a minor parasitic deviation in θ (RMSE 3.1 deg).

Conclusion

A prototype rehabilitation robot has been developed and presented. The utilised position control scheme has been shown to function for the conducted trials. The imposed load and reference trajectory concur with prospective conditions in a rehabilitation scenario.

Further work includes design of a proper arm support and replacement of the infrared camera with a robot-mounted absolute position estimation scheme.

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