A Cable-Driven Robot for Upper Limb Rehabilitation Inspired by the Mirror Therapy

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Abstract. The paper presents the development of a mechatronic system composed by a cable-driven robot and a vision system to be used for upper limb rehabilitation. It is inspired by the mirror therapy that is a valuable method for enhancing motor recovery in post stroke hemiparesis making use of the mirror-illusion created by the movement of a sound limb that is perceived as the paretic limb. In particular, a software has been developed and it is able to acquire images of a target, i.e. the hand of an individual, and after image processing, reproduces the target movement by a cable-driven manipulator. More specifically, the end-effector of the manipulator can be fixed to the paralyzed hand of the individual. The development of a planar 4-2 cable-driven parallel robot by low-cost mechanical design and easy control can be effective for the home-care of individuals for continuous training and recovering. First experimental tests are provided to show the feasibility of the system.

Key words: Cable-Driven Parallel Robot, Rehabilitation, Mechatronics.

1 Introduction

Stroke is the leading cause of disability among adults in developed coun-tries and leaves a significant number of individuals with motor, cognitive, or language deficits. The paralysis of the upper limb is the most frequent conse-quence of brain injury, and very often the rehabilitation procedures deal with repetitive passive movements, with the aim to restore if possible the damaged functions, or alternatively to teach how to handle differently those functions.

Although for long time it was assumed that after a brain injury, a patient has 3 to 6 months for maximizing the effects of recovery, recent studies show that a long-term stroke rehabilitation has very positive benefits to individuals in the chronic stage of stroke [15]. Intensive stroke rehabilitation is associated with enhanced and faster improvements, in particular, the intensity of exercise therapy has great effect on daily-life, gait, and dexterity in patients with stroke [9]. In addition daily practice sessions can significantly improve complex motor tasks [6, 7].

Modern rehabilitation therapy is in the most cases supported by technical systems. The Mirror Therapy (MT) induces a visual illusion that appears to mimic the movement of the paretic part [13, 4] in which the perception, more than being a simple feedback mechanism, enhance motor recovery of the impaired part [1, 2].

In recent years, Robotics has been applied to rehabilitation [11] and assistive tasks, as in [8, 12]. In the end-effector devices, the hand or the whole human forearm is fixed on an end-effector of a robot, either made of rigid links as in [5], or operated by cables [11]. The exoskeletal devices encloses the shoulder, the elbow and the hand and allows a better guidance of all articulations of the upper limb [10]. Another classification deals with the use of both upper limbs (bimanual) or the use of the affected part only (unilateral). In this paper we present the design and operation of a cable-driven robot, which has been inspired by the MT, for long-term stroke rehabilitation to be performed daily at home having bimanual characteristics. In particular, the motion of the unaffected upper limb is followed by a camera and reproduced by a cable robot that drives the affected upper limb. The paper is organized as follows: in Section 2, the design of a cable-driven robot is described with the motion capture system, Section 3 reports experimental set-up and tests, finally conclusions are outlined.

2 The Design of a Cable-Driven Robot RehaBot

The system proposed is a cable driven robot that acts in a plane, so that it can be used for a planar mirror therapy. The robot Fig.1 consists of a frame, which is of rectangular shape, four stepper motors connected to the rectangular end effector board via four cables. The motion of the non-paralyzed limb should be transferred to the paralyzed limb. Therefore, the robot guides the paralyzed arm on a trajectory, which is the mirrored trajectory of the non-paralyzed limb. A motion capturing system is used to observe the motion of the non-paralyzed arm. This robot can be classified as a proximal, bimanual end-effector robot.

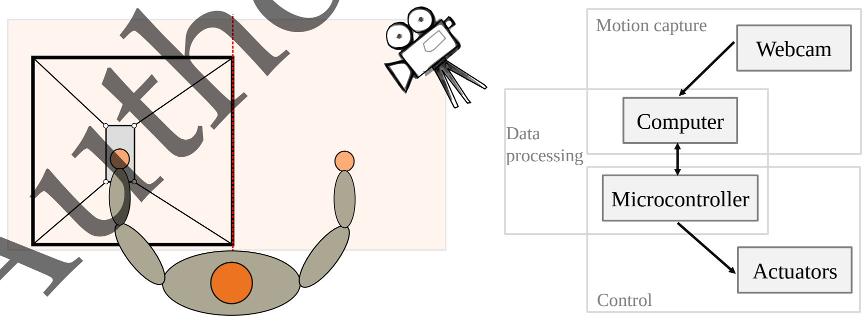


Fig. 1 Basic principle of the cable-driven robot for rehabilitation tasks: a) lay-out; b) scheme.

2.1 A Model for the Cable-Driven Robot

Let us consider a cable-driven manipulator with m cables and n DOFs in Fig.2), and denote with $OXYZ$ a global reference frame attached to the fixed base, and a reference frame is attached to the moving platform at point K.

A commonly used model for the kinematic analysis is based on the assumption of mass less inextensible cables, with the hypothesis that they are always in tension and can thus be treated as line segments representing bilateral constraints.

Inverse kinematics consists in computing the vector connecting each cable attachment point $\mathbf{A}_i$, to the ending point of the cable attached to the mobile platform $\mathbf{B}_i$. Vectors $\mathbf{B}_i$ are given in the K reference frame and $\mathbf{A}_i$ are given in the O coordinate frame. ${}^{O}\mathbf{R}_K$ is the rotation matrix between the two frames.

The vectors representing the cable lengths can be evaluated in the form

$$ {}^{O}\mathbf{l}_i = {}^{O}\mathbf{A}_i - \left({}^{O}\mathbf{R}_K {}^{K}\mathbf{B}_i + {}^{O}\mathbf{r}\right) \tag{1} $$

The Jacobian matrix associated to the Inverse Kinematics can be written as

$$ \mathbf{J} = \begin{pmatrix} \hat{\mathbf{l}}_1^T & -\left(\hat{\mathbf{l}}_1^T \times \mathbf{R}_K {}^{K}\mathbf{B}_1\right)^T \\ \hat{\mathbf{l}}_2^T & -\left(\hat{\mathbf{l}}_2^T \times \mathbf{R}_K {}^{K}\mathbf{B}_2\right)^T \\ \vdots & \vdots \\ \hat{\mathbf{l}}_m^T & -\left(\hat{\mathbf{l}}_m^T \times \mathbf{R}_K {}^{K}\mathbf{B}_m\right)^T \end{pmatrix} \tag{2} $$

$\hat{\mathbf{l}}_i^T$ being the transpose of the unity vector in cable directions.

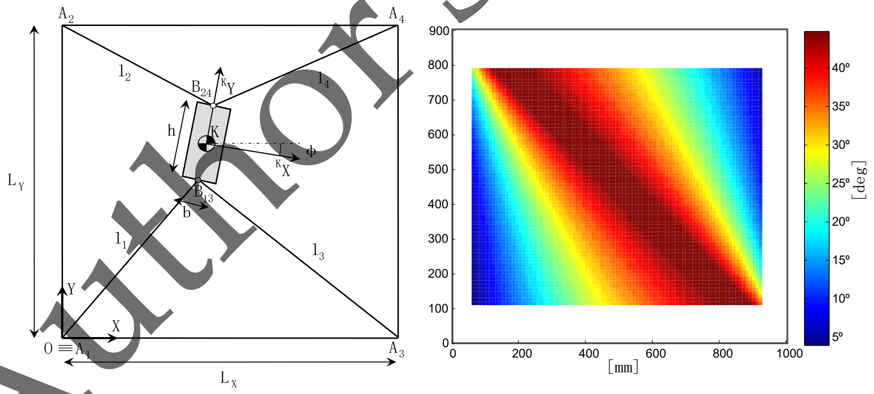


Fig. 2 A scheme for the kinetostatic analysis and workspace of the 4-2 planar cable-driven robot.

The Jacobian is a linear mapping between the rotation and translation velocity of the end effector and the joint velocities, The transpose of $\mathbf{J}$ in Eq.2 maps the cable forces $\mathbf{t}$ to the external forces $\mathbf{F}$ and torques $\mathbf{M}$ and it is used to check the cables forces distribution, and the static equilibrium for each pose, i.e. all tensions must be strictly positive [3]. The resulting robot work-space is shown in Fig.2 (right).

$$\mathbf{J}^T = \begin{pmatrix} t_1 \\ t_2 \\ \vdots \\ t_m \end{pmatrix} = \begin{pmatrix} \mathbf{F} \\ \mathbf{M} \end{pmatrix} \tag{3}$$

2.2 Motion Capture System

The motion capture system is based on a single camera and an optical marker. The camera stream is analyzed to find the optical marker. The result is filtered by Kalman, which has been implemented for this application. Then, the motion is computed by solving a back-projection problem using homography, which is fundamental for the motion capturing system of the robot [14]. It is a planar cable-driven robot, and for the motion capturing, a single camera is used. Therefore, the constraints of the homography are satisfied without the knowledge of the intrinsic and the extrinsic parameters. Detailed description is reported in [14].

2.3 Control and programming

Basic idea for the development of the control strategy is inspired by the principles of the mirror therapy, in particular using the master-slave principle. The trajectory is given by tracking a marker fixed on the unaffected body part (the hand) that acts as target. Then the end-effector of the cable-robot corresponds to the slave with the task of following the mirrored configuration of the master, as shown in Fig.3. When the master moves, then the slave forces the paralyzed hand fixed to it to follow the mirrored trajectory. Therefore, knowing the pose of the marker fixed to the non-paralyzed hand from the motion capturing system, through the actuation and control of the system, the end-effector is driven on the mirrored trajectory. The blue marker is the master with vector $\mathbf{r}_m$. A“virtual end-effector” is considered to evaluate cable lengths l_{mi} indicated by dashed lines in the Fig.3. The cable lengths of the slave are in an actual pose l_{si}. Knowing the real lengths of the cables of the end-effector, we know the lengths, which the end effector has in the position of the master. Therefore, the information is used to drive the motors to the target position, i.e. the mirrored position of the master.

The control of the system is performed using a master-slave principle. The position of the hand is tracked. This defines the position, which the end effector has to reach. Moving the hand causes an offset between the end effector and the master. This offset is used to calculate the steps that each stepper motor has to drive. A scheme of the rehabilitation robot operations is given in Fig.4. Figure5 shows a scheme for the robot connections. It has to be mentioned that the motion of the non-paralyzed hand should not interfere with the robot frame during the rehabilitation task. Therefore, the rehabilitation robot will be designed according to Fig.1 to avoid collisions, interference, and cables wrapping. In this paper we have used an available prototype, as it will be shown in Section 3.

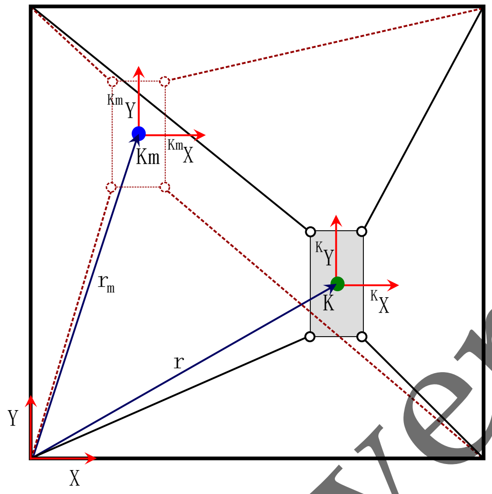


Fig. 3 Principle of control

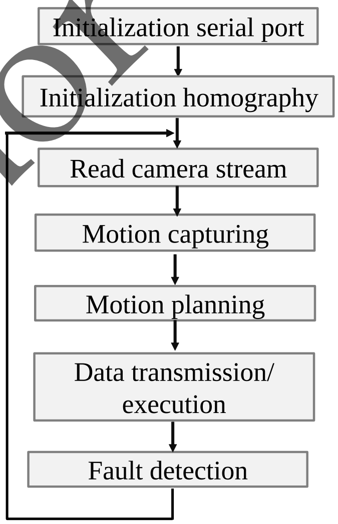


Fig. 4 A scheme of the operations of the rehabilitation cable-robot.

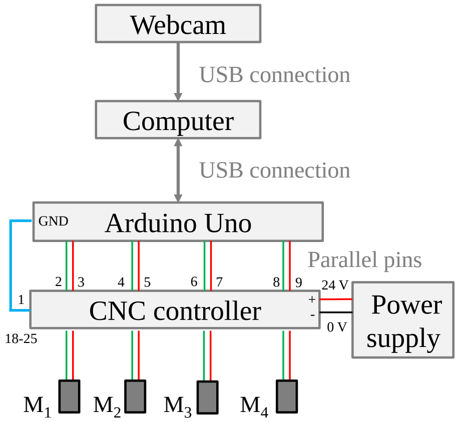
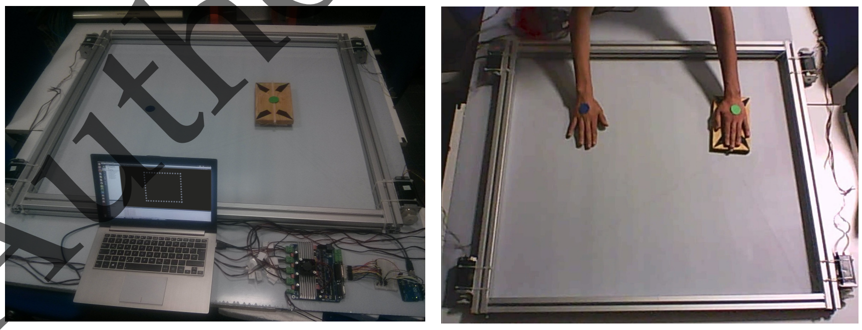


Fig. 5 A scheme of connections for the rehabilitation cable-robot.

3 Experimental Tests

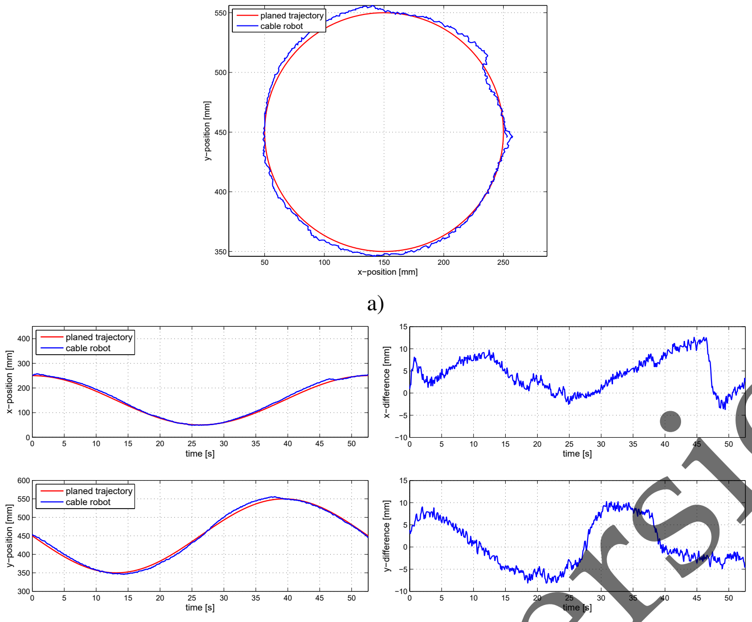
Experimental tests were carried out with an available laboratory prototype as shown in Fig.6. In particular, given trajectories were reproduced i. e. a circle and a square, as shown in Figs. 7 and 8. Nevertheless, a set of experiments have been performed also with natural trajectories and that the associated motion was followed precisely. In particular, during the experiments, the trajectories of the master in red, and the slave in blue, were recorded for further analysis.

Data processing allows evaluating differences in trajectories giving a measure of the repeated exercises for continuous training and verification of recovery.



a) b)

Fig. 6 Experimental tests: a) laboratory set-up; b) mirrored trajectory



a)

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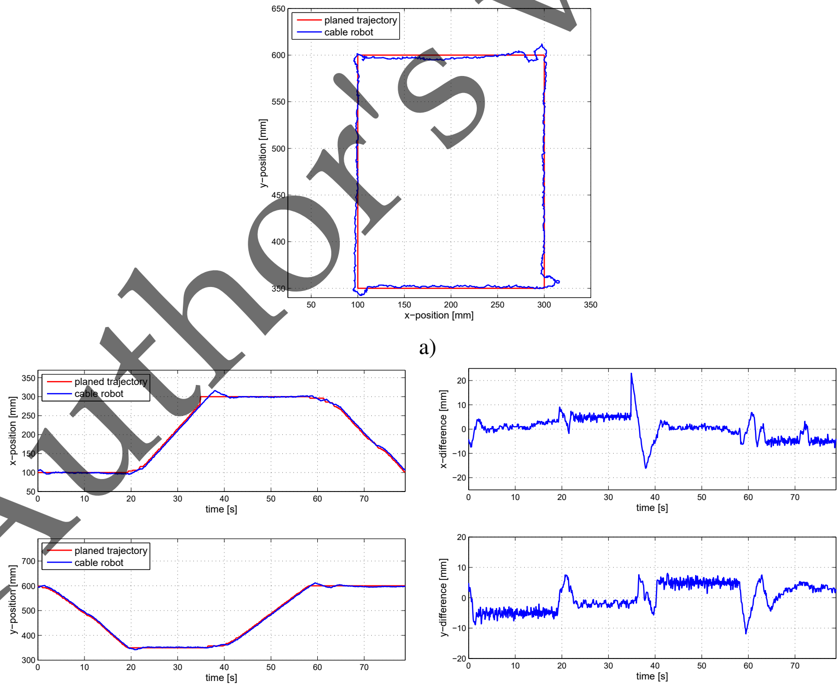
Fig. 7 Experimental tests: a) master (red) slave (blue) trajectories; b) x and y components; c) differences between master and slave.



a)

b) c)

Fig. 8 Experimental tests: a) master (red) slave (blue) trajectories; b) x and y components; c) differences between master and slave.

4 Conclusions

In this paper, we presented the mechatronic design and implementation of a rehabilitation system based on a cable-driven manipulator inspired by the mirror therapy. Experimental tests showed encouraging performance of the system developed for the home-care and continuous training during the upper limb rehabilitation.

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