Design issues and application of cable-based parallel manipulators for rehabilitation therapy

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In this study, cable-based manipulators are proposed for application in rehabilitation therapies. Cable-based manipulators show good features that are very useful when the system has to interact with humans. In particular, they can be used to aid motion or as monitoring/training systems in rehabilitation therapies. Modelling and simulation of both active and passive cable-based parallel manipulators are presented for an application to help older people, patients or disabled people in the sit-to-stand transfer and as a monitoring/training system. Experimental results are presented by using built prototypes.

Keywords: parallel robots; cable-based systems; rehabilitation therapy; experimental robotics

1. Introduction

Trends in robotics show how robots in the future will interact more and more closely with humans for many applications. In general, there are several tasks that can be performed by medical robots (Simaan 1999); the most important are surgical assistance, high-precision endoscopies, motion assistance of weak peoples and prosthesis. Rehabilitation represents a relatively new field of application for robotics.

Nowadays, several robot prototypes have been designed to explore the feasibility of robots aiding physiotherapists and medical personnel. A robotic system for a rehabilitation application should be able to interact with a patient in safe conditions; i.e., it must not damage people or surroundings, and it must be designed to guarantee high accuracy and low acceleration during the manipulative operation. Furthermore, it should not be too bulky and exert limited wrenches since a close interaction with people is needed. It is also advisable to have a portable system, which can be easily brought into the hospital environment. Cable-based manipulators possess all the above-mentioned characteristics.

Cable-driven robots are a type of parallel manipulator wherein the end effector is supported in parallel by \( n \) cables with \( n \) tensioning actuators. Indeed, the end effector is operated by actuators that can release or retract cables (Roberts et al. 1998; Verhoeven et al. 1998; Fattah and Agrawal 2002; Kossowski and Notash 2002; Oh and Agrawal 2003; Williams et al. 2003; Riechel and Ebert-Uphoff 2004; Hiller et al. 2005). Several cable-driven parallel manipulators have been studied as haptic devices (Katsura and Ohnishi 2004; Pocheville et al. 2004; Lee et al. 2005; Todd and Naghdy 2005). Haptic interfaces are those that allow both input and output interaction with a virtual environment and provide both realistic kinaesthetic sensations and tactile information from an artificial environment. They also allow the user to interact and modify the environment. There are several applications for such devices. For example, in tele-manipulation and virtual prototyping tasks (Pocheville et al. 2004), such interfaces may be used to provide reaction forces feedback to the users to help them interact with the environment, and in virtual training procedures (Katsura and Ohnishi 2004) for astronauts or surgeons, these interfaces provide a virtual environment when actual training is not possible or is difficult. Other examples of possible applications are in rehabilitation tasks (Lee et al. 2005) to help injured people to recover. Therefore, it is necessary for these applications to provide the user haptic and kinaesthetic feedback, i.e. to provide actual touch and position sense to the person who has lost a limb (Todd and Naghdy 2005). For such an application of cable-based architectures, it is of fundamental importance to be able to measure cables’ tensions during robot/human motion.

A class of measuring systems has also been based on the architectures of parallel manipulators with cables (Jeong et al. 1999; Ottaviano et al. 2002; Williams et al. 2004). In particular, cable-based tracking systems appear to be interesting since they show a good compromise between accuracy, resolution, cost, measurement range, portability and calibration procedure (Ottaviano et al. 2002). Cable-based tracking systems consist of a fixed base and a moving platform connected by at least six cables whose tension is maintained by pulleys and spiral springs on the base. They can be modelled as 6-df parallel manipulators because cables...
can be considered extensible legs connecting the platform and the base by means of spherical and universal joints, respectively (Thomas et al. 2005). To perform a measure, cable-based measuring systems must exert a wrench on the moving object under measure; that wrench should be bounded to prevent the quality of the measure.

Several robotic systems have been designed specifically for medical applications. PAMM (Personal Aid for Mobility and Monitoring) is a cane-based configuration with a skid-steer (non-holonomic) drive (Dubowsky et al. 2000). It is equipped with a six-axis force-torque sensor mounted under the user’s handle to capture the user’s intent. MariBot (MARisa robot) is a cable robot based on the NeReBot (NEuroREhabilitation roBOT), a former 3-df cable-driven system that was used for the treatment of patients with stroke-related paralysed or paretic upper limb during acute phase (Rosati et al. 2007). MACARM (Multi-Axis Cartesian-based Arm Rehabilitation Machine) is a cable-driven robot for upper limb rehabilitation (Mayhem et al. 2005). The prototype configuration is composed of an array of eight motors which are mounted on the vertices of a cubic support frame that provides 6 df to a symmetrically located end effector. A 6-df load sensor is mounted on the end effector to provide force measurements. ARMin is a robot for arm therapy applicable to the training of activities of daily living in clinics (Nef and Riener 2005). It has a semi-exoskeleton structure with 6 df and is equipped with position and force sensors.

In this study, design issues and operation are presented for both active and passive cable-based parallel manipulators for applications as motion aiding and monitoring/training systems in rehabilitation therapies.

2. Design of cable-based manipulators for rehabilitation purposes

Cable-based parallel architectures can be classified as active (cable-driven parallel robots) or passive (cable-based measuring systems). A schematic representation of a cable-based architecture is shown in Figure 1. Cable-based parallel manipulators are cable actuated. Cables are connected to the end effector and fixed frame through external connectors (Hiller et al. 2005). A cable-based manipulator can operate the end effector by changing the length of cables while preventing any cables from becoming slack. Therefore, feasible tasks are limited due to the main static (or dynamic) characteristics of the cables because they can only pull the end effector but do not push it (Roberts et al. 1998). Furthermore, the cables’ tension must be bounded to avoid excessive forces, which may cause stress deformation or failure in the cables (Verhoeven et al. 1998; Riechel and Ebert-Uphoff 2004). The main difference between cable-driven parallel manipulators and the classical serial or parallel ones is that the end effector is operated in parallel by \( n \) cables, which are connected to it. They can be actuated by several types of motors with different geometrical arrangements. The main advantages of cable-driven manipulators are as follows: a large workspace, if compared to the one of classical parallel manipulators; good inertial properties; high payloads; high repeatability and accuracy in positioning; good transportability and economical constructions (Kossowski and Notash 2002; Williams et al. 2003). The main drawback is related to the mechanical characteristic of the cables. In fact, they can work only in tension, and this fact limits the reachable workspace. Therefore, it is necessary to verify that for each configuration the cables’ forces are always positive.

A classification of cable-driven parallel manipulators is given for cables’ manipulation as ‘fully-constrained’ and ‘under-constrained’ (Hiller et al. 2005). They belong to the first class if the pose of the end effector can be completely determined by the cables’ configuration. For the second class of cable-driven manipulators, the position and orientation of the end effector cannot be completely defined by the cables’ configuration, and the gravity effect can be considered as an additional cable, which connects the end effector to the ground.

Cable-based measuring systems can be classified as passive parallel manipulators because the cables are not actuated. Cable-based tracking systems can be conveniently used for motion tracking and monitoring of large displacements.

In order to be used in medical or rehabilitation applications and fulfill the requirements of safety and reliability, cable-based parallel architectures have to face the problem of exerting or sensing forces and torques. Indeed, kinematic analysis is important, but also controllability is a fundamental issue. In particular, in passive cable-based manipulators, wrenches must be bounded to limit the influence on the system under measure. In active cable-based manipulators, wrenches must be bounded also to prevent stress deformation or failure in the cables. The robotic system has to be...
used within a close interaction with people with motion disabilities. In particular, a wrench/motion capture system can be designed as a passive cable-based parallel architecture, and active cable-based parallel manipulator can be used in the sit-to-stand transfer operation during rehabilitation therapy.

In particular, for the rehabilitation of an articulation, the mobility and force/torque measure can be used both as a preliminary stage and during the rehabilitation procedure to get a measure of the improving capability of the human subject.

The technology and design of joint implant systems and human rehabilitation have evolved considerably, with a variety of new systems available on the market. Common tools that can be used are the following (Adrian and Cooper 1995): optical devices, such as single-image photography, stroboscopy, cinematography, videography and magnetic resonance imaging. Goniometry and electro-goniometry give joint kinematic data for both static and dynamic action. Electromyography gives muscle action potentials. Dynamography and accelerometers give direct or indirect force measures. Computer-aided simulation gives an overall prediction of the kinematic and kinetic performances of the patient movement. A six-axis force/torque sensor can be used to get information about wrenches, and a six-axis position/orientation sensor (mini-bird) can be used to measure the displacement of the patient.

Economical obligations and needs for an easy implementation in medical environment stimulate the demand for alternative measuring systems or proper adaptation and redesign of existing devices.

Passive cable-based systems (measuring systems) can be used for a determination of the articulation motion and walking capabilities of the patient. Therefore, they can be used in a preliminary stage of rehabilitation therapy to get information about the motion capabilities of the patient.

The task of motion aiding in the sit-to-stand transfer is usually performed by one or more physiotherapists and medical personnel, who have to lift up or down and help to move the patient in a hospital environment. Another possibility is that the patient makes use of his or her arms to lift up or sit down, if possible.

The use of the proposed system may help the patient to be able to perform the above-mentioned operations without the use of his or her arms. After a clinical evaluation, the biomechanic problems related to walking, standing and sitting movements must be studied. In the walking problem, it must be ensured that the centre of gravity always falls in the area that is bounded by the person’s feet.

For the stand-and-sit transfer, the problem is different because the person could have front or rear rotations (Médéric et al. 2004), which are, respectively, called antepulsion and retropulsion, as shown in Figure 2.

Through the aid of a cable-driven system, antepulsion and retropulsion can be controlled. This solution can prevent the patient’s fall during the rehabilitation therapy. Therefore, it could be of great interest to use a cable-based parallel manipulator to aid and facilitate this kind of operation.

A cable-based system can be of great help because it can aid the stand or sit transfer when weakness does not allow the patient to use his or her legs or arms in the above-mentioned operation.

2.1. A model for wrench characterisation

All cable-based parallel architectures with translational and rotational capabilities may suffer from cable interference and reduced reachable workspace/working area. Therefore, a static analysis is required. For a static equilibrium, the sum of external forces and torques exerted on the end effector by the cables must equal the resultant external wrench that is exerted on the environment (Ceccarelli 2004). Alternatively, the wrench that is exerted by a serial-wrist mechanism acting on the environment must be balanced on the end effector.

Figure 3 shows a scheme for a general cable-based architecture with \( n \) cables, whose length is denoted by \( \hat{l} \). Two reference frames are defined; namely, a fixed frame \( OXYZ \) is attached to the base, and a moving frame \( OX’Y’Z’ \) is attached to the end effector or the moving platform.

Figure 4 shows a scheme of the free-body diagram for static analysis of a cable-based parallel manipulator. The static equilibrium of a cable-based parallel manipulator can be formulated as

\[
\sum_{i=1}^{n} F_i = - \sum_{i=1}^{n} F_i \hat{l}_i = P; \quad \sum_{i=1}^{n} \hat{l}_i = \sum_{i=1}^{n} \hat{l}_i \times Rb_i = M. \tag{1}
\]
In Equation (1), \( F_i \) is the cable tension that is applied to the \( i \)-th cable in the negative cable length unit direction of \( l_i \) because \( F_i \) must be in tension; \( R \) is the rotation matrix relating the orientation of the moving frame \( O'X'Y'Z' \) to the fixed frame \( OXYZ \). Moreover, \( b_i \) (for \( i = 1, \ldots, n \)) are the position vectors from \( O' \) to the \( i \)-th cable attachment point, as expressed in \( O'X'Y'Z' \) frame, and \( \mathbf{P} \) and \( \mathbf{M} \) are the resultant vector force and torque (when considered together, they give a wrench \( \mathbf{W} \)) that are exerted on or by the environment, in accordance with the active or passive nature of the cable-based system. Substituting the above-mentioned terms into (1) yields to

\[
J^T F = W,
\]

(2)
in which \( \mathbf{F} = [F_1 \ldots F_n]^T \) represents the vector of scalar \( n \) cable forces, \( \mathbf{W} \) is the resultant external end-effector wrench vector expressed in the fixed frame and \( J \) is the Jacobian matrix. It has been assumed for the cable-driven parallel manipulator that there are no external wrenches on the robot other than gravity.

The Jacobian matrix \( J \) can be expressed for a cable-driven parallel manipulator as

\[
J = \begin{bmatrix} \hat{l}_i \\ \hat{l}_i \times \mathbf{R} \mathbf{b}_i \end{bmatrix}
\]

(3)

where \( i = 1, \ldots, n \), in which \( n \) represents the number of cables. Equations (1) to (3) can be used to evaluate the cable tension for a given trajectory, together with the kinematics.

It is worth noting that for cable-driven parallel manipulators it is necessary to take into account the so-called controllable workspace (Hiller et al. 2005), for which the tension in each cable must be not only positive but also bounded. For a cable-suspended robot, which belongs to the class of under-constrained manipulators, gravity plays an important role for the analysis of the controllable workspace. It is worth noting that not every force vector \( \mathbf{F} \) satisfying (2) is feasible. For the case of under-constrained cable robots, the condition that must be satisfied is that all the components of \( \mathbf{F} \) must be non-negative (Ottaviano 2008).

2.2. Mechanical design of the systems for an experimental characterisation

At LARM (Laboratory of Robotics and Mechatronics) in Cassino, Italy, robust and easy-operation devices have been designed and built. In particular, several prototypes of parallel and active and passive cable-based architectures have been studied.

Figure 5 shows a prototype of a CALOWI (Cassino low-cost wire robot) 4-cable-driven parallel manipulator, which has been designed and built at LARM to be applied for planar and spatial operations (Ottaviano 2008). The actuation system of the proposed manipulator is composed of four DC motors, which can extend or retract cables.

CATRASYS (Cassino Tracking System) is a cable-based measuring system. It has been conceived to identify the pose of a rigid body during its motion through an online computation of the kinematics of the designed 3-2-1 cable-based architecture, as shown in Figure 6. Details of CATRASYS and its evolution are reported in the study by Ottaviano et al. (2002). It is composed of a mechanical part, an electronics–informatics interface unit, and a software package. The mechanical part consists of a fixed base and a moving platform, which has been named as an end effector for CATRASYS, as shown in Figure 6. The two platforms are connected by six wires, whose tension is maintained by pulleys and spiral springs that are fixed on the base.

The end effector for CATRASYS operates as a coupling device; it connects the wires of the six transducers to the extremity of a moving system. Signals from wire transducers are fed through an amplified connector to the electronic...
interface unit, which consists of a personal computer for data analysis.

The above-mentioned cable systems have been equipped with a low-cost easy-operation system to monitor the cables’ tensions, which has been designed and settled up at LARM to be used for both passive and active cable-based architectures (Ottaviano et al. 2002). For both classes, the identification of applied/exerted wrenches is of fundamental importance for the use and feasible operation of the system. A suitable model and low-cost easy-operation system for tension monitoring are proposed for experimental validation for both classes as a unified type of system.

In particular, each prototype has been equipped with $n$ force sensors for experimental determination of the tension...
acting on each cable. Among several set-ups that can be considered to measure the cable's tension, a commercial force sensor has been chosen which is capable of measuring the force on its extremity. The experimental set-up shown in Figure 7 includes two or three pulleys according to the system under study. Advantages of the proposed tension-monitoring system are low cost, which is related to the use of commercial force sensors, and flexibility, which is due to the possibility of being used for both classes of cable-based architectures. Furthermore, since the force sensor is installed on a fixed frame, it does not influence the measure and the end-effector movement.

According to the scheme in Figure 7, the resulting tension measured by each force sensor can be evaluated as a function of the \( t \)-th cable tension \( F_t \) and a coefficient, which takes into account friction effects on the pulleys. Sensored prototypes have been used for experimental evaluation of the positive cables' tensions occurring during a general spatial motion of the end effector.

The tension-monitoring system has been installed on both active and passive systems, as shown in Figure 8, and it has been used during the experimental tests.

3. Rehabilitation issues

Rehabilitation therapy deals with the study and reactivation of movement patterns of an injured person, a disabled person or both through strategies that are based on the integration of activity by doctors, physiotherapists and medical personnel. Biomechanics can help rehabilitation therapies by analysing movement patterns, predicting forces acting on the joints and muscles, designing assistive devices, optimising performance and reassessing performance after rehabilitative training (Adrian and Cooper 1995).

Rehabilitation involves three main areas, namely, exercise, rehabilitative locomotion and normal daily living activities analyses. The goals of rehabilitation can be summarised as follows (Adrian and Cooper 1995):

1. Define or analyse the biomechanical characteristics of a patient, and then compare the movement patterns and posture of the patient to normal patterns.
2. Determine whether normalcy of the function is a realistic goal, if not, determine the compensatory pattern to be used.
3. Evaluate exercises, substitution devices or both to be used.
4. Evaluate the environment and conduct experimental tests.

This paper deals with Tasks 1, 3 and 4, which involve the use of novel robotic systems for motion capture and aiding motion. The motion capture system should be used at the first stage not only to determine the actual situation of the patient but also to evaluate mobility-strength improvement in the fourth phase. The aiding motion system should be used in the third phase.

To design the robotic system and its operation, the clinic history of patients must be studied first. Patients may be of different ages from young to elderly people and they may also have different clinical problems, for example as regarding the equilibrium posture while they are walking or during the stand (or sit) transfer and injury to the lower limbs.

All types of patients need rehabilitation therapy, but it may vary from one patient to another because of the above-mentioned problems as well as their weight. Obviously, a robotic system can be used for all types of patients, because of its characteristics of flexibility and versatility. In particular, exercises in rehabilitation therapies should be carried out by considering slow movements of the body part to reduce inertia effects and allow the muscles
to contract throughout the range of motion (Adrian and Cooper 1995). Furthermore, the movements of the body parts should be carried out by always maintaining a certain alignment of the parts to avoid extra wrenches in muscles, tendons and ligaments. The balance of antagonistic muscle groups should also be maintained. Finally, the development of a set of exercises will prevent the patient from being bored and provide versatility for home or travel environments.

Desired features of a robotic system for medical application and, in particular, for rehabilitation therapies should be the following:

1. General consumer products should be design oriented, therefore the system must be easily accessible or usable by the operator with no high-level robotics skills.
2. Considering safety requirements, the system must not inconvenience people or damage surroundings; it should not be too bulky, and it should exert limited wrenches since a close interaction with people is needed.
3. Low-cost, lightness, transportability, and compactness, to be accessible and usable by a general consumer. Furthermore, these features allow the robot to be easily located in site and moved elsewhere. In general, in order to fulfill the basic requirements such as safety, the following points for a rational design should be addressed:

- Position and force-feedback control of the end effector;
- Reliability, that this fail safe features during its operation, especially in configurations close to singularities;
- No influence by magnetic fields, which may arise in an operating room.

Cable-based parallel systems are therefore well-suited for these requirements, since they can fulfil the above-mentioned requirements. End users can make use of the great advantages of using robots, such as accuracy, motion steadiness and repeatability.

4. Experimental tests

The proposed application deals with the use of a cable-driven parallel manipulator as a robotic system in a rehabilitation application. Therefore, the system has been designed to be portable and assembled in hospitals or medical centres.

Characteristic dimension of the frame can be chosen as $D = 2300$ mm. The maximum payload for the application can be chosen as $P = 2000$ N. These two values and other design considerations are used to size and choose the most important manipulator’s components, namely the sling system and the cables, the attachment system, the pulleys and the actuator system. The cable-driven manipulator is the CALOWI prototype, but with suitable dimensions, as shown in the layout of Figure 9.
The patient can sit on a chair located on a tapis-roulant, which can also be used for aiding people in walking. These two components are located on the base floor and inside the workspace too. Preliminary results for the proposed application are reported in the study by Cannella et al. (2008).

Numerical simulations, as based on the proposed formulation and experimental tests, have been carried out for the stand transfer operation, as shown in Figure 9. Results for experimental and numerical forces in the cables are shown in Figure 10. The plots show a good qualitative and quantitative correspondence between numerical and

![Figure 9](image1.png)  ![Figure 10](image2.png)

Figure 9. Layout for the proposed application: (a) a scheme for the simulation and (b) experimental tests at LARM with CALOWI manipulator.

Figure 10. Comparison between experimental and numerical results for the stand transfer operation in Figure 9 (black curve is for numerical simulation, and grey curve is for experimental results).
Experimental results. Discrepancies are due to the under-constrained nature of the manipulator, which gives some vibratory effects. The choice of this type of cable-based manipulator, for which the end effector is not fully controllable, can give the possibility not to completely restrain the human body movement during the movement.

The passive cable-based system CATRASYS has been used as a monitoring and training system for patients. Experimental tests and numerical simulation have been carried out for a given trajectory, which corresponds to a movement of an upper human limb, as shown in Figure 11. Therefore, the system CATRASYS can be used as a pose- and wrenches-monitoring system, and also to verify the strength and improvement of the patient during rehabilitation therapy. Preliminary results for the proposed application are reported in the study by Palmucci et al. (2008).
Figure 12 shows numerical and experimental results of CATRASYS for the resulting wrenches, which are exerted on the end effector for CATRASYS during a generic movement. Discrepancies between numerical and experimental results are mainly due to friction forces and vibratory effects, which can be significant in the case of cable-suspended parallel manipulators.

The proposed kinetostatic model can be used to identify different regions of the workspace as function of the force applied by/on the end effector. It can also be used to predict the force sensed by the user in a rehabilitation application. In particular, once the clinical history of a patient is known, it will be possible to identify the most appropriate workspace region to perform the motion.

5. Conclusion

In this paper, design issues and operation are presented for cable-based parallel architectures to be used in rehabilitation applications. According to the requirements, it has been discussed how cable-based parallel systems can be well-suited, thanks to their favourable characteristics. For the above-mentioned application, force sensing can be important for rehabilitation purposes, when it is advisable to monitor improvements and recovering in terms of both mobility and force capability. In particular, in this paper, an active system CALOWI and a passive system CATRASYS have been proposed for application as aiding motion systems for people with motion disabilities. A CALOWI manipulator has been proposed as an aiding or monitoring/training system for the sit-to-stand transfer, and a CATRASYS manipulator has been proposed for application as an aiding or monitoring/training system for the sit-to-stand transfer, and a CATRASYS system has been used to determine the location and exerted forces/torques of the human limb extremity during its movement. A tension-monitoring system has also been used to determine the forces and torques acting on/by the end user. A laboratory set-up and experimental tests are reported in the study.

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