A 4-4 Cable-Based Parallel Manipulator for an Application in Hospital Environment

E. Ottaviano*, M. Ceccarelli and M. De Ciantis
LARM: Laboratory of Robotics and Mechatronics, University Cassino, Cassino, Italy

Abstract—In this paper a 4-4 cable-based architecture is presented for an application in hospital environment. For robots in medical applications, safety and reliability are the most important requirements. Cable-based robots can accomplish those requirements because of their main characteristics in terms of good kinematics and dynamics properties and transportability. In this paper a 4-4 cable-based robot is presented to be used in hospital environment. Its task is to move injured or disabled people in a hospital room. The feasibility of the proposed lay-out is presented through an analysis and design of the system, and experimental simulations in laboratory tests. A low-cost easy-operation system for tension monitoring is proposed for experimental validation of the prototype operation.

I. INTRODUCTION

Last trends in Robotics show how future robots will interact more and more deeply with humans for many tasks. Robotics for medical applications is a field of growing interest in the last decades.

In particular, introducing a robot as a part of a surgical tool array provides several advantages to a surgeon, such as a reduction of the number of assistants in the operating room and introduction of a useful tool for training surgeons, [1]. Robots can be also used for tasks such as carrying loads and helping disabled people in any environment or rehabilitation therapies [2].

Robots interacting with humans in hospital should firstly fulfill requirements of safety, i.e. they must not damage people or surroundings; they should not be too bulky and they should exert limited wrenches since a close interaction with people. Cable-based robotic structures can fulfill all those requirements because of their main characteristics.

Cable-based parallel manipulators are robotic systems, which are cable actuated. Cables are connected to the end-effector and are attached at a fixed frame through external connectors. A cable-based manipulator can move by changing the cables’ lengths while preventing any cable from becoming slack. Therefore, feasible tasks are limited due to main characteristic of the cables; they can only pull the end-effector but do not push it. Furthermore, in cable-based parallel manipulators cables’ tension must be bounded to avoid excessive forces, which may cause stress deformation or failures in cables. A scheme for a cable-driven manipulator is shown in Figure 1.

There are several advantages of cable-based parallel manipulators over conventional serial or parallel robots. Namely, such mechanisms have a relatively large workspace area for their size and are generally lighter and easier to transport than serial manipulators, [3-5]. Moreover, they have few moving parts, which give good inertial properties, high payload-weight ratio, transportability, and economical construction [6-11]. These are important features for applications requiring a manipulator to be brought to a work site.

Cable-based robots can be used for applications in construction that normally require cranes and scaffolding, which are labor intensive and expensive. Furthermore, cable-based manipulators are in general more controllable and safer to operate than conventional cranes. The operation of an overhead crane can cause severe swinging of the load, especially by inexperienced operators. This is obviously dangerous and it can significantly increase the time that is required to move loads. An example of the combination of robotics and cranes is the ROBOCRANE, [12]. Another example of a cable-based system is CHARLOTTETM, which is a robotic device developed for space travel, [13]. Other possible applications include spray painting, window cleaning, and visual inspections. Several cable-based parallel manipulators have been studied as haptic devices [14-19]. A class of measuring systems has been also based on the architectures of parallel manipulators with cables, [20-22].

In this paper a 4-4 cable-based architecture has been designed for an application in hospital environment, which consists in carrying injured or disabled people with

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*E-mail: ottaviano@unicas.it
reduced mobility that need to be moved from one location to another in a hospital room. CALOWI (Cassino Low-Cost Easy Operation Wire Robot) prototype is available at LARM in Cassino, has been used for experimental validation of the proposed application.

II. CALOWI: A 4-4 CABLE-BASED PARALLEL MANIPULATOR

At LARM: Laboratory of Robotics and Mechatronics in Cassino we have approached the problem by looking at practical applications with robust easy-operation devices [23].

Figure 2 shows a prototype of CALOWI, a 4-4 cable-based parallel manipulator, which has been designed and built at LARM for planar and spatial operations [24-26]. The actuation system of the proposed manipulator is composed by four DC motors, which can extend or retract cables, as shown in Fig. 3a). In order to operate the cable-based parallel manipulator for either planar or spatial tasks a transmission system with pulleys has been considered, as shown in Fig. 3b).

III. A MODEL FOR WRENCH CHARACTERIZATION

All cable-based parallel architectures with translational and rotational capabilities may suffer conditions for cable interference and reduced reachable working area. Therefore, Static and Kinematic analyses are required.

A static equilibrium, the sum of external forces and moments exerted on the end-effector by the cables must equal the resultant external wrench that is exerted on the environment.

For one of the cases of study, since the 4-4 cable-based manipulator can be used both for planar and spatial applications, gravity action must be considered in the proposed model.

A. Kinetostatic Analysis

The CALOWI 4-4 cable-based parallel manipulator is schematically shown in Fig. 4. Two reference frames have been considered, namely OXYZ is the fixed reference frame and Guvw is the moving frame. Points Ai (for i = 1,…,4) lie on upper face, which has a square shape with dimension L, as shown in Fig. 4. According to the proposed scheme, the four cable lengths have been indicated with li (i = 1,…,4).

Cables are connected to the end-effector through four attachment points ai (i = 1,…,4) whose coordinates, with respect to the moving frame are described by vectors ai.

Therefore, the position vector of the i-th attachment point on the platform can be written in the fixed reference as

\[ \mathbf{r}_i = \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} \]

where R is the rotation matrix relating the orientation of the moving frame to the fixed frame. The location of point G must fulfill the following constraints: coordinates xG, yG and zG must be within the limits of the construction frame given by b<=xG<=L-b; b<=yG<=L-b; 0<=zG<=L.

Figure 5 shows a scheme of the free-body diagram for Static analysis of CALOWI cable-based parallel manipulator.

The static equilibrium of a cable-based parallel manipulator can be formulated as
Figure 5. A scheme for the static analysis of a cable-based manipulator.

\[ \sum_{i=1}^{n} F_i \mathbf{i}_i = \mathbf{P} ; \quad \sum_{i=1}^{n} \mathbf{i}_i = \sum_{i=1}^{n} \mathbf{i}_i \times \mathbf{Rb}_i = \mathbf{M} \quad (2) \]

In (2), \( F_i \) 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. Moreover, \( \mathbf{b}_i \) (for \( i = 1, \ldots, n \)) are the position vectors from \( O' \) to the \( i \)-th cable attachment points, as expressed in the \( O'X'Y'Z' \) frame; and \( \mathbf{P} \) and \( \mathbf{M} \) are the resultant vector force and moment (when considered together they give a wrench) 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 (2) yields to

\[ \mathbf{J}^T \mathbf{F} = \mathbf{W} \quad (3) \]

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; \( \mathbf{J} \) is the Jacobian matrix. It has been assumed for the cable-based parallel manipulator that there are no external wrenches on the robot other than gravity.

For example, the Jacobian matrix \( \mathbf{J} \) can be expressed for the 4-4 cable-based parallel manipulator in Fig. 2 as

\[ \mathbf{J} = \begin{bmatrix} \mathbf{i}_1 & \mathbf{i}_2 & \mathbf{i}_3 & \mathbf{i}_4 \\ \mathbf{i}_1 \times \mathbf{Rb}_a & \mathbf{i}_2 \times \mathbf{Rb}_a & \mathbf{i}_3 \times \mathbf{Rb}_b & \mathbf{i}_4 \times \mathbf{Rb}_b \end{bmatrix} \quad (4) \]

Equations (1) to (4) can be used to evaluate the cable tension for a given trajectory.

It is worth to note that for cable-driven parallel manipulators it is necessary to take into account the so-called controllable workspace [3-5], for which the tension in each cable must be positive, but also bounded.

CALOWI 4-4 cable-based manipulator is a cable-based robot; therefore it belongs to the class of under-constrained manipulators. Indeed, gravity plays an important role for the analysis of the controllable workspace. It is worth to note that not each force vector \( \mathbf{F} \) satisfying (3) is feasible. For the case understudy the condition that must be satisfied is that all the components of \( \mathbf{F} \) must be non-negative, [3].

If there are no external wrenches on the robot other than gravity, the condition in (3) can be rewritten as

\[ \mathbf{W}_g - \mathbf{J}^T \mathbf{F} = \mathbf{0} \quad (5) \]

where \( \mathbf{W}_g \) is the wrench applied to the robot due to gravity. If \( \mathbf{J} \) is augmented with the negative of the transpose of the wrench vector due to gravity, to give a new matrix \( \mathbf{J}^* \), then a static equilibrium at a given configuration is achieved if and only if there is a left null vector of \( \mathbf{J}^* \) with the properties that its components are all nonnegative and its last component is positive, [27]. Figure 6 shows a simulation for a given trajectory of the CALOWI manipulator in Fig. 2, whose scheme is shown in Fig. 4.

Figure 6. A numerical result for a simulation for a given trajectory among points A, B, C, and D of CALOWI prototype in Figs. 2 and 7.
IV. DESIGN REQUIREMENTS FOR AN APPLICATION IN HOSPITAL ENVIRONMENT

Robotics for medical application is a wide and relatively new field of research. End-users can make use of the great advantages of using robots, such as accuracy, motion steadiness, and repeatability.

In general, in order to be used for medical applications robots must fulfill the basic requirement that is safety, i.e. the robot does not injure people or damage the environment. Therefore, the following points should be addressed:

1. position and force-feedback control of the tool/end-effector;
2. reliability, that this fail safe features during its operation, especially in configurations close to singularities;
3. easy-operation, in order to be used by operators without high level skills in Robotics;
4. no influence by magnetic fields, which may arise in an operating room.

Other desired features are lightness, transportability or compactness. Those features make the robot to be easily located in site and moved elsewhere. Therefore, cable-based robots are well-suited for those requirements, since cables have negligible mass and in general cannot damage people.

The application understudy for hospitals consists of designing a cable-based parallel manipulator to be used as a system to aid disabled people to move from one bed to another or from a bed to a wheelchair. Usually, this kind of task is performed by one or more persons, who have to lift and move the patient from one location to another in a hospital room. Therefore, it could be of great interest to be able to use an external device to aid and facilitate this kind of operation.

A scheme for the proposed application is shown in Fig. 7 in which CALOWI manipulator can be used. A cable-based robot has been selected because its intrinsic characteristic: it relies on gravity action, it is extensively used in construction and for many other applications. It may suffer of the disadvantage of load swinging because of its underconstrained nature. Therefore, it will be assumed that for security reasons, low velocity and accelerations will be considered for this kind of applications.

Task requirements that are considered for a mechanical design, whose main elements are schematically reported in Fig. 7, can be outlined as follows:
- hospital room size: 10 m x 10 m;
- load to carry: 350 kg
- maximum velocity for each cable: 0.80 rad/s;
- maximum tension in each cable: 2,000 N.

By considering the above-mentioned requirements mechanical components of a 4-4 cable system can be designed or chosen. In particular, the attachment system for each cable to a portable bed must have a diameter of 7 mm, the cable diameter must be of 5 mm, and the actuation torque must be of about 250 Nm.

The mechanical design and choice of commercial components are reported in detail in [28]. A simulation of the operation of the CALOWI system for the proposed application is shown in Figs. 8 and 9, which refers to the scheme in Fig. 7. In particular, the patient is lifted from location A to B and then moved toward the bed (locations C and D). The scheme in Fig. 7 refers to the initial configuration.

V. LABORATORY SET-UP AND EXPERIMENTAL RESULTS

A low-cost easy-operation system to monitor the cables’ tensions has been designed and settled up at LARM in Cassino with the aim to be used both for passive and active cable-based architectures. A prototype for tension monitoring has been built and applied to the existing CALOWI prototype in Fig. 2.

Experimental tests have been carried out to verify the engineering significance and operation of the system. The experimental set-up is shown in Figs. 8 and 9. In particular, CALOWI prototype has been equipped with 4 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, we have chosen a commercial force sensor, which is capable to measure the force on its extremity. The experimental set-up of Fig. 8 includes three pulleys according to the system of Fig. 8b).

Therefore, the resulting tension as measured by each force sensor $S_i$ can be evaluated as a function of the i-th cable tension $F_i$ in the following form

$$S_i = F_i(1 + \mu \mu)$$

in which $\mu$ coefficient takes into account friction effects and transmission capabilities of the pulleys. $\mu$ can be estimated to be 1.05 by preliminary laboratory tests.
The sensored prototype has been used for experimental evaluation of the positive cables’ tensions occurring during a spatial motion of the end-effector, which is reported in Fig. 10.

In particular, Fig. 10 shows numerical and experimental results that have been obtained with CALOWI manipulator in Figs. 2 and 9 when the end-effector mass is of 3 kg. The end-effector trajectory is obtained by considering the cables’ lengths in Fig. 6. It is worth noting that the measured forces $F_i$ (i=1,...,4) show differences with respect to those obtained by the numerical simulation, which nevertheless give satisfactory results from numerical simulation. Discrepancies between numerical and experimental results are mainly due to friction forces and vibratory effects, which can be significant for cable-based parallel manipulators.

VI. CONCLUSION

In this paper a cable-driven parallel manipulator has been presented for an application in hospital environment. In particular, CALOWI a 4-4 cable based robot has been modeled to be used to aid disabled persons or people with
reduced mobility. A simulation for a large scale system is proposed and an experimental validation of the system has been carried out with CALOWI prototype, which is available at LARM in Cassino. A tension monitoring system has been used to measure the cables’ tension during the experiments. Future work concerns with the development of a 6 cable-based manipulator for application in hospital environment to increase safety and reliability of the system.

REFERENCES


