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Cable driven devices for telemanipulation

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1. Introduction

One of the most interesting developing fields in modern telemanipulation research is the use of a slave robot commanded by a kinematically different master. The interest in asymmetrical master-slave telemanipulators arises from the desire to design a master which will be as efficient as possible for the operator, whereas the symmetric arrangement would constrain the master design to the same strict requirements of the slave one.

The hand controllers (or joysticks) are among the most effective means for human operators to control the complex machines used in telemanipulation systems. From the point of view of the man-machine interface they can be seen as motion input devices, because the control system reads their sensors to elaborate the trajectories to be imposed to the remote manipulator.

An important characteristic of telemanipulators is the possibility to make the operators feel like they were at the remote site, actually performing the manipulation task. It is well known that not only position feedback, but also force feedback from the remote machine to the human operator is necessary to obtain good performance of telemanipulation in training simulators or in hazardous environment operations, providing the sense of balance and the feeling of touching real objects (McAfee & Fiorini, 1991; Conklin & Tosunoglu, 1996; Batsomboon et al., 2000), thus realising a *haptic* device (haptics is the science that deals with the sense of touch).

Force feedback hand controllers are actuated by motors, so that the control system can exert forces on the operator's hand; they can be seen as devices that output forces, therefore sometimes they are referred to as *force displays*.

Most of the existing devices have serial or parallel mechanical architectures. In a serial structure, the necessity to move most (or all) of the actuators tends to add weight and inertial forces to be controlled, conflicting with any force feedback received from the remote manipulator.

Even with the use of counterbalancing weights to equilibrate the mass effects of the structures, serial controllers still experience their intrinsic drawbacks. The advantages are greater than the disadvantages when a serial structure is used as a manipulator (large workspace, simple joint position control, etc.), but, when implemented as a manual master controller, their size often becomes too large, and their weight too heavy for practical use.

Moreover the play at joints and links and the errors at each joint variable measurement increase as one moves towards the payload, which implies bad precision at the end effector.

A parallel structure, on the other hand, usually allows placing all motors, brakes, and accessories at one centralized location. This eliminates the necessity to carry and move most of the actuators as happens in the serial case. Hence, input power is mostly used to support the payload, which is approximately equally distributed on all the links; the stress in the link is mostly traction-compression which is very suitable for linear actuators as well as for the rigidity, then excellent load/weight ratios may be obtained.

Parallel link mechanisms also present other interesting features: the position of the end effector of a parallel manipulator is much less sensitive to the error on the articulation sensors than for serial link robots. Furthermore, their high stiffness ensures that the deformations of the links will be minimal and this feature greatly contributes to the high positioning accuracy of the end effector.

A class among parallel devices, cable robots are parallel devices using cables as links. They have been proposed for the realization of high speed robot positioning systems needed in modern assembly operations (Kawamura et al., 1995).

Cable-actuated parallel devices represent an interesting perspective. They allow great manoeuvrability, thanks to a reduced mass, and also promise lower costs with respect to traditional actuators. Furthermore, the stroke length of each linear joint does not follow the same restrictions as with conventional structures (pantograph links, screw jacks, linear actuators), because cables can be extended to much higher lengths, for instance unwinding from a spool. This feature allows achieving the advantages typical of parallel mechanical structures without particular requirements on the positioning of motors, brakes, sensors and other accessories, giving the possibility to optimise the ratio between the device workspace volume and its total size.

On the other side, this type of actuation is totally irreversible (cables can only be pulled by the motors and they obviously cannot push). Therefore, to get a six degree of freedom device, it is necessary to have at least seven forces acting on the end effector. On Earth, gravity on the moving part exerts a constant force which may be considered in the force closure calculation. Therefore, six cables are sufficient for specific applications where no acceleration higher than g is required, at least downwards. Several examples exist of this kind of device, e.g. cranes (Bostelman et al., 1996). However, normally, higher accelerations are needed; therefore, most applications need at least seven cables with the corresponding actuators.

Cable-driven devices can be also employed as force feedback hand controllers, fixing on a handle several cables stretched by motors and leaning over pulleys, to effect force reflection; the measurement of the cable lengths allows obtaining position and orientation of the handle, determining the kinematical variables to be sent to the control system of the slave arm. Moreover, composing the traction forces of the cables, a six-dimensional wrench can be exerted on the operator's hand, representing the reactions acting on the slave robot.

On the other hand, the use of lightweight cables might induce undesired vibrations which could disturb the operator, overlapping the force feedback; therefore the necessary actuator redundancy may also be exploited to increase the device stiffness, producing suitable internal forces, contributing to a higher positioning accuracy of the manipulator as well.

Furthermore, cable redundancy is also useful to overcome another disadvantage typical of parallel mechanisms: the forward kinematics problem is not simple and, generally, many solutions for every actuator configuration are obtained, among which it is not always possible to distinguish the correct one actually reached by the end effector: in this case the

redundancy will help in the exclusion of solutions which may appear mathematically possible but do not correspond to reality. Finally, the number of cables greatly influences shape and size of the workspace and the overall device dexterity.

This chapter deals with the main peculiar aspects that must be considered when developing a cable-driven haptic device, with particular regard to the algorithms for geometric, kinematical and static analysis, to the control system and to the mechanical aspects typical of this kind of application.

2. Geometry

As pointed out in Section 1, designing a cable driven device with n degrees of freedom requires at least $n+1$ cables in a convenient layout. Apart from particular cases, it is often interesting to be able to control six degrees of freedom ($n = 6$); therefore, in the following structures with at least seven cables will be considered.

The conceptual scheme of a cable driven device is shown in figure 1.

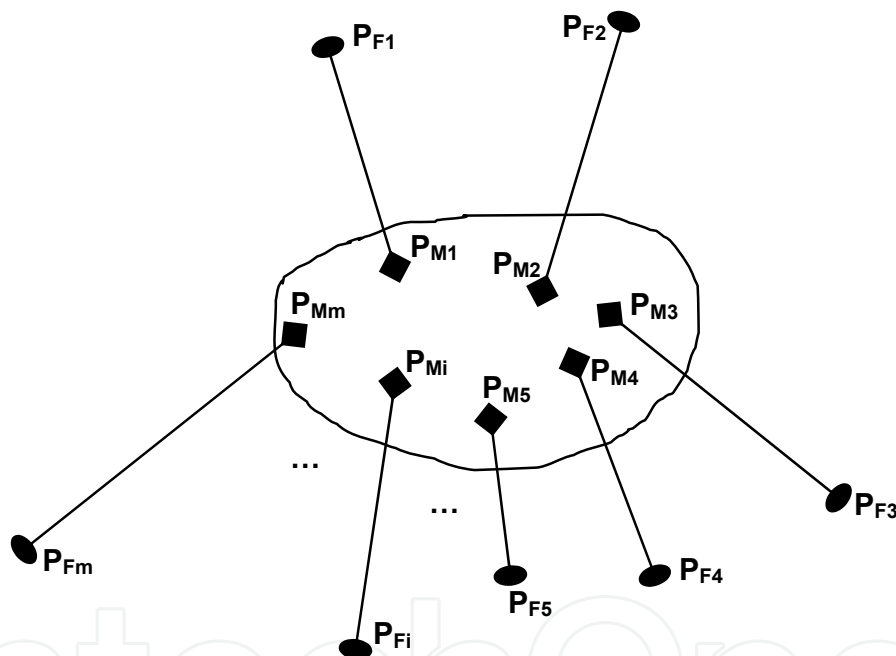


Fig. 1. Generic scheme of a cable driven device.

The moving part is a solid body of any shape, carrying the end effector or the handle for the user to operate. A total number of m cables are attached by one end to it. The point in which the i -th cable is attached to the moving part is called P_{Mi} . Towards the other end, each cable passes through a guide such as a bored support or a pulley, which conveys it to a spool, linear motor or whatever mechanism allows its motion.

For geometric purposes, it is convenient that the guide through which the cable passes is made in such a way that it is possible to identify a single, fixed point called P_{Fi} where the cable passes in all of its configurations. This way, the remaining part of the cable holds no

interest and, simplifying, each cable can be treated as an actuator of variable length attached to the fixed frame in the point P_{Fi} and to the moving part in the point P_{Mi} . Apart from particular cases, it is convenient to design a well-organized layout of fixed and moving points to simplify geometry, kinematics and most of all control of the device. For instance, having the points lay on planes or making two or more cables converge to a single point can lead to significant simplifications, as will be pointed out later in this Section. As examples, consider the two structures in figure 2. Note the presence of a fixed frame, referred to as *base*, while the moving part, connected to one end of each cable, is called *platform*.

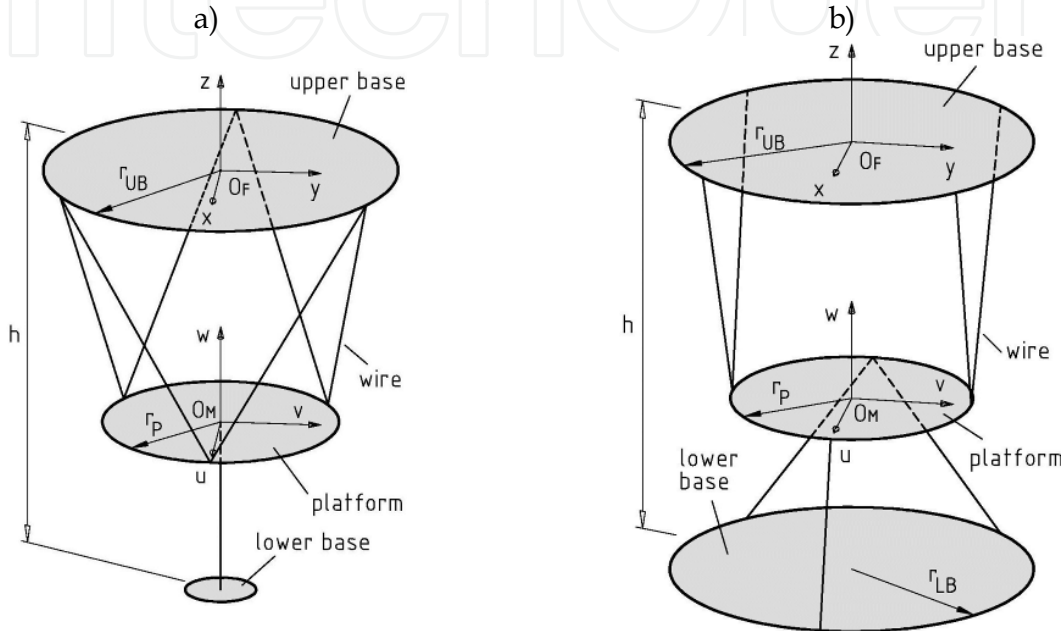


Fig. 2. Two examples of seven-cable parallel structures: a) WiRo-6.1; b) WiRo-4.3.

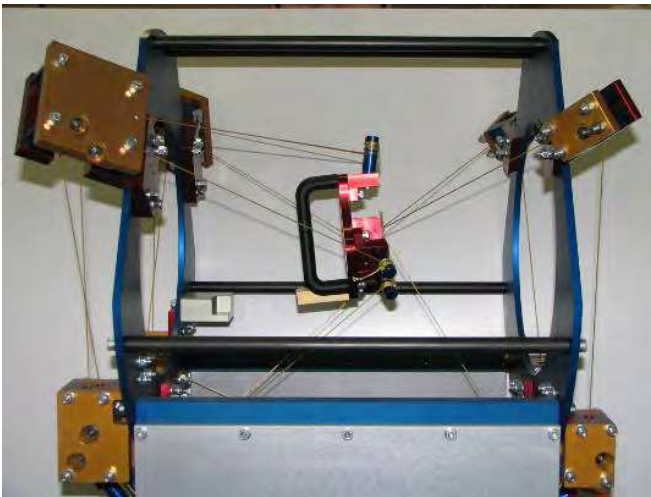
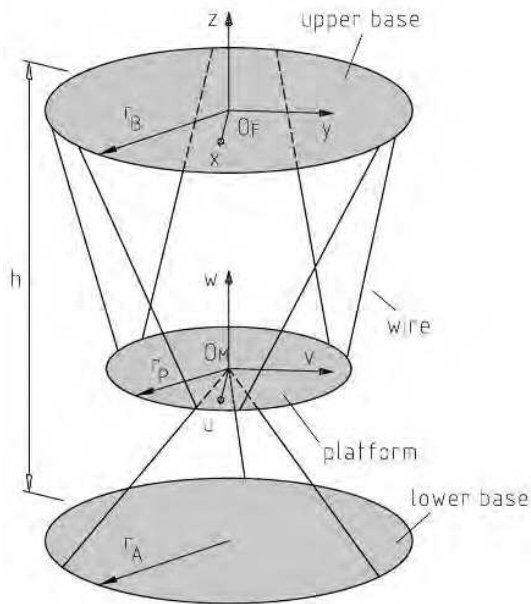


Fig. 3. A nine-cable parallel structure with polar symmetry and a prototype based on the same scheme: the WiRo-6.3.

Each of the structures is characterized by two coordinate systems, one integral with the fixed frame, with centre O_F and axes x, y, z , and the other moving with the platform, with centre O_M and axes u, v, w . The same notations apply to the nine-cable structure presented in figure 3, which has led to the realisation of the prototype shown beside. This device presents a similar layout to the one shown in figure 2a, with the single lower cable substituted by three cables converging to a single point on the platform. From the contraction of *Wire Robot* and from the layout of the cables (in number of p on the upper base, q on the lower one) the structures presented have been nicknamed WiRo- $p.q$ (Ferraresi et al., 2004).

The inverse kinematics study, providing the length of each actuator starting from the pose of the platform, is always simple for purely parallel structures. The following procedure does not only apply to the three structures shown as examples, but to any cable-driven robot and to any parallel device in general. It can be described through the simple geometric chain shown in figure 4, constituted by the fixed passing point P_{Fi} , the moving attachment point P_{Mi} and the cable linking them.

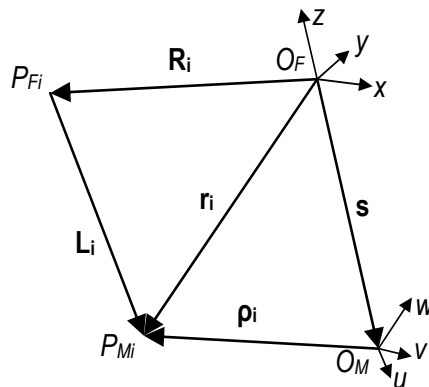


Fig. 4. Single kinematical chain of a parallel device.

Knowing the coordinates of P_{Fi} and P_{Mi} in their respective coordinate systems, the position vector representing the i -th mobile attachment point with respect to the fixed coordinate system is:

$$\mathbf{r}_i = [x_i \quad y_i \quad z_i]^T = \mathbf{A} \cdot \boldsymbol{\rho}_i + \mathbf{s} \quad (1)$$

where $\boldsymbol{\rho}_i = [u_i \quad v_i \quad w_i]^T$ is the position vector of the i -th attachment point with respect to the mobile coordinate system, \mathbf{A} is the 3x3 orientation matrix of the platform and \mathbf{s} is the position vector of the origin O_M . Naming $\mathbf{R}_i = [X_i \quad Y_i \quad Z_i]^T$ the position vector of the passing point P_{Fi} with respect to the fixed frame, simple geometrical considerations lead to the vector representing the i -th cable:

$$\mathbf{L}_i = \mathbf{r}_i - \mathbf{R}_i \quad (2)$$

The modulus of \mathbf{L}_i is the length of the i -th cable.

Contrary to the inverse kinematics, the forward kinematics – determining the pose of the platform from a given set of actuator lengths – is often quite complicated for parallel structures. In particular, it is not always possible to obtain a closed-form solution, obliging to work it out through numerical analysis. When designing the control software, this can become a huge issue since cycle times are critical in real-time applications. However, particular cases exist for which a closed-form solution can be found, depending on a convenient layout of the fixed and moving points.

For example, the nine-cable structure WiRo-6.3 presents a closed-form solution of the forward kinematics, thanks to the planarity of all moving attachment points and to the fact that three of them merge into one. This allows the three translation degrees of freedom of the platform to be decoupled from the orientation ones.

In the following a closed-form solution for the forward kinematics of the WiRo-6.3 is described (Ferraresi et al., 2004). The following approach does not require the polar symmetry of the robot; therefore, it can be used for any nine-actuator robot (not just cable robots) with six actuators connected to the same mobile platform plane and three actuators converging to a single point on the same plane.

As said above, the position of the centre of the platform O_M can be determined with ease. In fact, for each of the three lower cables it is $\mathbf{p}_i = [0 \ 0 \ 0]^T$ (see figures 3 and 4). The equations that must be solved in order to obtain the vector $\mathbf{s} = [s_x \ s_y \ s_z]^T$ linking O_F to O_M are:

$$(\mathbf{s} - \mathbf{R}_i)^2 = \mathbf{s}^2 + \mathbf{R}_i^2 - 2\mathbf{R}_i \cdot \mathbf{s} = L_i^2 \quad (3)$$

For each of the three lower cables, the values of L_i and \mathbf{R}_i are different (but known), leading to a system of three equations in the form (3) with the three components of \mathbf{s} as unknown quantities. Its solution is trivial and will not be exposed here for the sake of brevity.

To obtain the orientation matrix equations (1) and (2) are combined:

$$\mathbf{L}_i = \mathbf{r}_i - \mathbf{R}_i = \mathbf{A} \cdot \mathbf{p}_i + \mathbf{s} - \mathbf{R}_i = [L_{ix} \ L_{iy} \ L_{iz}]^T \quad (4)$$

Considering each component separately:

$$\begin{aligned} L_{ix} &= A_{11} u_i + A_{12} v_i + A_{13} w_i + s_x - X_i \\ L_{iy} &= A_{21} u_i + A_{22} v_i + A_{23} w_i + s_y - Y_i \\ L_{iz} &= A_{31} u_i + A_{32} v_i + A_{33} w_i + s_z - Z_i \end{aligned} \quad (5)$$

The length of the i -th cable is defined by the 2-norm of vector \mathbf{L}_i . Squaring it:

$$\begin{aligned} L_i^2 &= (\mathbf{L}_i)^T \cdot (\mathbf{L}_i) = L_{ix}^2 + L_{iy}^2 + L_{iz}^2 = \\ &= s_x^2 + s_y^2 + s_z^2 - 2(s_x X_i + s_y Y_i + s_z Z_i) + r_p^2 + r_B^2 + 2(A_{11} u_i + A_{12} v_i + A_{13} w_i)(s_x - X_i) + \\ &\quad + 2(A_{21} u_i + A_{22} v_i + A_{23} w_i)(s_y - Y_i) + 2(A_{31} u_i + A_{32} v_i + A_{33} w_i)(s_z - Z_i) \end{aligned} \quad (6)$$

This formulation leads to a system of six equations, corresponding to each of the upper cables, in which the unknown quantities are the nine terms A_{ij} . In fact, all other quantities are known, and the three lower cables have already been used to find \mathbf{s} . However, three of

the terms A_{ij} (A_{13} , A_{23} , A_{33}) disappear when considering the fact that $w_i = 0$ for every i , thanks to the planarity of the attachment points on the platform. A solution of the 6x6 system can now easily be found.

3. Workspaces

When designing a robot, particular care should be devoted to verify its operative capabilities, in particular its workspace and dexterity. In fact, a device that can work just in a very small portion of space, or with limited angles, is of little practical use. Furthermore, analysing cable-driven structures, it is not sufficient to consider the usual definition of workspace as *the evaluation of the position and orientation capabilities of the mobile platform with knowledge of the dimensional parameters, the range of actuated variables and the mechanical constraints*. In fact, a further limitation lays in the condition that cables can only exert traction forces. Thus the workspace of a cable-actuated device may be defined as the set of points in which the static equilibrium of the platform is guaranteed with positive tension in all cables (or tension greater than a minimum positive value), for any possible combination of external forces and torques.

At first, it can be supposed that cable tensions and external forces and torques can virtually reach unlimited values. Under that condition, the set of positions and orientations that the platform is able to reach can be called *theoretical workspace*.

To verify the possibility to generate any wrench with positive tensions in the cables, it is necessary to write the equations relating the six-dimensional wrench vector to the m -dimensional cable tension vector (with m : number of cables). The ability of any given device to provide a stable equilibrium to the end effector is called *force closure*. The force closure of a parallel structure in a particular configuration is calculated through the equation of statics:

$$-\mathbf{W} = \mathbf{f} = \tilde{\mathbf{J}} \cdot \boldsymbol{\tau} \quad (7)$$

where, in the case of a redundant parallel robot with m actuators, \mathbf{W} is the six-component wrench acting on the platform, \mathbf{f} is the wrench provided by the robot, $\tilde{\mathbf{J}}$ is the $6 \times m$ structure matrix calculated for any particular configuration and $\boldsymbol{\tau}$ is the m -component vector containing the forces of the actuators or, in the case of a cable-driven robot, the cable tensions.

The condition to check if a given pose of the platform belongs to the theoretical workspace can be expressed imposing that for any \mathbf{f} the tensions of the cables can all be made positive (or greater than a prefixed positive value):

$$\boldsymbol{\tau} > 0 \quad (8)$$

while checking at the same time that $\tilde{\mathbf{J}}$ has full rank, equal to six (if not, the structure lays in a singular pose). Since $\tilde{\mathbf{J}}$ is not square, equation (7) allows an infinite number of solutions for any given \mathbf{f} . By inverting equation (7), the minimum-norm solution can be obtained:

$$\boldsymbol{\tau}_{\min} = \tilde{\mathbf{J}}^+ \cdot \mathbf{f} \quad (9)$$

where $\tilde{\mathbf{J}}^+$ is the pseudoinverse of $\tilde{\mathbf{J}}$.

The generic solution of equation (7) is given by:

$$\boldsymbol{\tau} = \boldsymbol{\tau}_{\min} + \boldsymbol{\tau}^* \quad (10)$$

where $\boldsymbol{\tau}^*$ must belong to the kernel, or null space of $\tilde{\mathbf{J}}$, defined through the expression:

$$\tilde{\mathbf{J}} \cdot \boldsymbol{\tau}^* = 0 \quad (11)$$

If $\tilde{\mathbf{J}}$ is not square, like in this case, the number of solutions of (7) is ∞^{m-6} . This means that the infinite possible values of $\boldsymbol{\tau}$ can be found by adding to $\boldsymbol{\tau}_{\min}$ a vector $\boldsymbol{\tau}^*$ that does not affect the resulting wrench, but can conveniently change the actuator forces.

Condition (8) may be met for a particular six-dimensional point of the workspace if at least one strictly positive $\boldsymbol{\tau}^*$ exists. In this way, knowing that all the multiples of that $\boldsymbol{\tau}^*$ must also belong to the null space of $\tilde{\mathbf{J}}$, it is possible to find an appropriate positive multiplier c able to compensate any negative component of $\boldsymbol{\tau}_{\min}$:

$$\mathbf{f} = \tilde{\mathbf{J}} \cdot (\boldsymbol{\tau}_{\min} + c \cdot \boldsymbol{\tau}^*) \quad (12)$$

where, as said above:

$$c \cdot \boldsymbol{\tau}^* \in \text{Null}(\tilde{\mathbf{J}}); \quad \boldsymbol{\tau}_{\min} + c \cdot \boldsymbol{\tau}^* > 0 \quad (13)$$

Having defined a convenient procedure to evaluate if a particular six-dimensional point belongs to the theoretical workspace, it is now possible to apply it to a discretised volume. It is not trivial to find out whether at least one strictly positive $\boldsymbol{\tau}^*$ exists, especially for highly redundant structures; a possible method has been developed by the authors (Ferraresi et al., 2007) but its description is beyond the scopes of this Chapter and will not be presented here. Moreover, several strategies may be adopted to minimise calculation times and to deal with displacements and orientations of the platform. In fact, since workspaces are six-dimensional sets it is not simple to represent them graphically. In order to obtain a convenient graphical representation, a possible choice is to consider separately the orientation and position degrees of freedom by distinguishing the *positional workspace* from the *α -orientation workspace*.

The positional workspace is the set of platform positions belonging to the workspace with the platform parallel to the bases. The α -orientation workspace is the set of platform positions that belong to the workspace for each of the possible platform rotations of an angle $\pm\alpha$ around each of its three reference axes. With those definitions, both the positional and the α -orientation workspaces are three-dimensional sets.

As an example, figure 5 shows the positional workspace of the structures presented in figures 2a, 2b and 3, with their projections on the coordinate planes for visual convenience. Figure 6 shows their α -orientation workspaces for a few different values of α .

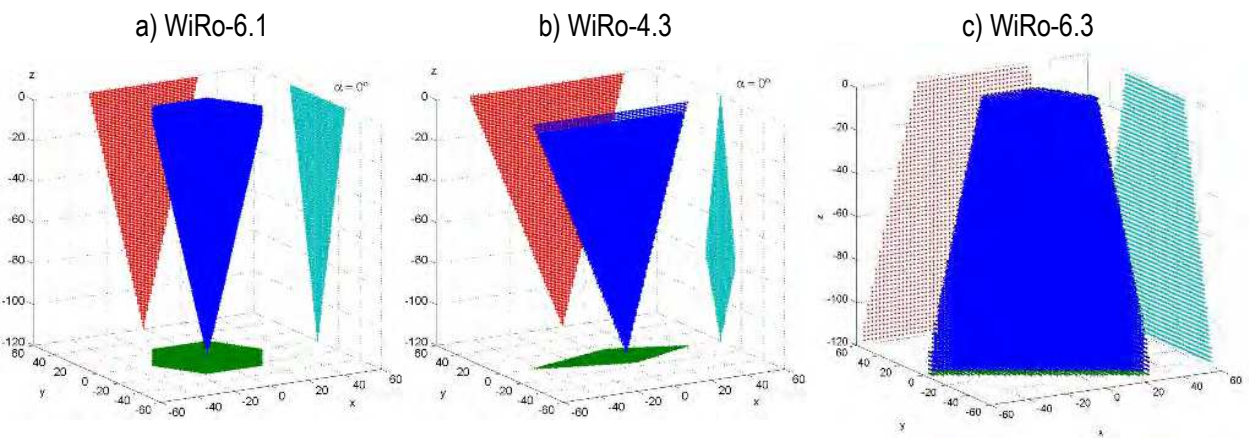


Fig. 5. Positional workspace of the three structures considered.

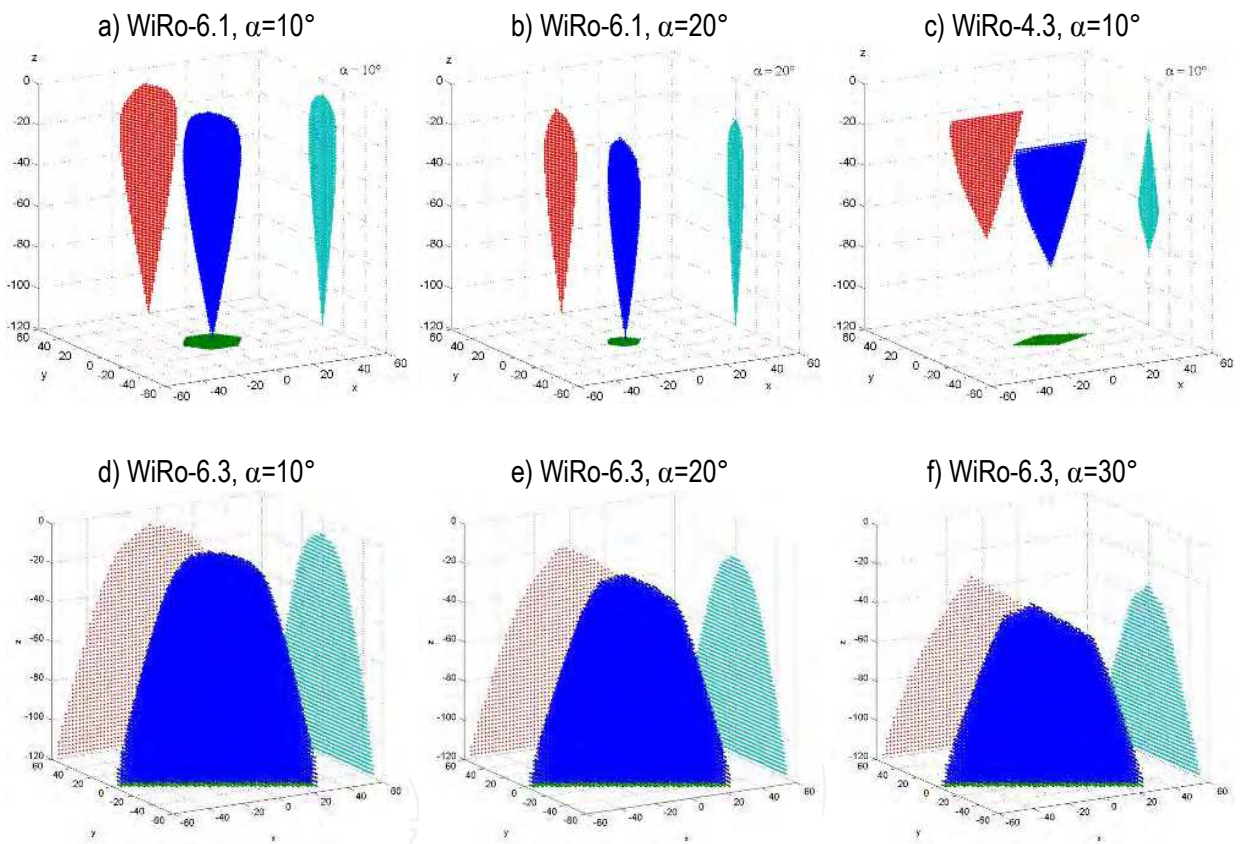


Fig. 6. α -orientation workspaces of the three structures for different values of α .

The geometric dimensions of the three structures have been set using arbitrary units, making them scalable. Obviously though, a rigorous method to compare the results is needed and it must be independent from the size and proportions of the structures. Three dimensionless indexes have been proposed (Ferraresi et al., 2001) in order to analyse the results in a quantitative and objective way. They are the index of volume, the index of compactness and the index of anisotropy. The index of volume I_v evaluates the volume of the workspace relatively to the overall dimension of the robotic structure. The index of compactness I_c is the ratio of the workspace volume to the volume of the parallelepiped circumscribed to it. The index of anisotropy I_a evaluates the distortion of the workspace with

respect to the cube with edge equal to the average of the edges of the parallelepiped. The mathematical expressions for those indexes are:

$$I_v = \frac{p\Delta x\Delta y\Delta z}{\pi h_{cc}D_{cc}^2/4} \qquad I_c = \frac{p\Delta x\Delta y\Delta z}{abc} \qquad I_a = \frac{|m-a|+|m-b|+|m-c|}{m}$$

(14)

where p is the quantity of discrete points contained into the workspace, Δx , Δy , Δz are the discretisation steps used along their respective axes, D_{cc} and h_{cc} are the base diameter and height of the smallest cylinder containing the whole structure, a , b , c are the edges of the parallelepiped circumscribed to the workspace, and m is the average of a , b and c . An optimal workspace should have large indexes of volume and compactness, and an index of anisotropy as close as possible to zero. As an example, these three indexes can be used to compare the workspaces of the three devices considered above, shown in figures 5 and 6.

Structure	α	I_v	I_c	I_a
WiRo-6.1	0°	0.07	0.26	1.1
	10°	0.02	0.35	2
	20°	0.006	0.34	2.5
	30°	0.0004	0.28	3.2
WiRo-4.3	0°	0.04	0.18	1.3
	10°	0.007	0.23	1
	20°	0	0	NaN
WiRo-6.3	0°	0.31	0.4	0.17
	10°	0.24	0.34	0.24
	20°	0.18	0.3	0.36
	30°	0.06	0.3	0.85

Table 1. Application of volume, compactness and anisotropy indexes to the three structures.

Comparing figures 5 and 6, the different performance of the structures in terms of workspaces is evident. Table 1, thanks to the three indexes, provides a more rigorous support for the comparative evaluation of different devices.

4. Force reflection

Any cable-driven structure of the kind presented in Section 2 may be used as an active robot, installing an end effector on the platform and controlling its pose through the imposition of cable lengths. However, on the contrary, it may also work as a master device for teleoperation: for this, a handle or similar object must be integrated on the platform to allow command by an operator. In this case the user determines the pose of the platform which in turn constrains the theoretical cable lengths. To avoid any cable to be loose, all of them must be continuously provided with a pulling force greater than zero; moreover, it is not enough to provide a constant tensioning force to

each cable because, due to their different orientations, the resulting wrench on the platform might greatly disturb the user's operation.

So, apart from peculiar cases of little interest here, every cable must be actuated by winding it to a spool integral to a rotary motor shaft, or directly attached to a linear motor or any other convenient actuation source.

Since the aim is controlling the resultant wrench on the platform, each actuator pulling a cable must be force- or torque-controlled (opposed to the case of an active robot, where the control imposes positions and velocities and forces and torques come as a consequence). Through a convenient set of cable tensions it is possible to impose any desired wrench on the platform and, finally, on the user's hand. The first, intuitive choice could be setting to zero all forces and torques acting on the platform, to permit the user an unhampered freedom of movement. However, it is more interesting to provide the device with force reflection capabilities.

The presence of force reflection in a teleoperation device gives the operator a direct feeling (possibly scaled) of the task being performed by the slave device. In this way, effectiveness of operation improves greatly, because the operator can react more promptly to the stimuli received through the sense of touch than if he had only visual information, even if plentiful (direct eye contact, displays, led indicators, alarms, etc.). For example, it is not immediate to perceive the excessive weight of a remotely manipulated object, or a contact force unexpectedly high, using only indirect information; when the alarm buzzes, or the display starts flashing, it might already be too late. On the contrary, if forces and torques are directly reflected to the operator, he might act before reaching critical situations. The same applies for small-scale teleoperation, e.g. remote surgery: excessive forces may have terrible consequences.

Equations (12) and (13) guarantee that it is theoretically possible to give the platform any desired wrench, if its current pose belongs to the theoretical workspace.

Statics relates the cable forces to the six-dimensional wrench on the platform, according to equation (7). For a nine-cable structure it can be interpreted as follows: given a vector $\mathbf{f} \in R^6$ that is desired to act on the platform as a force reflection, it is necessary to find a vector of cable forces $\boldsymbol{\tau} \in R^9$ fulfilling equation (7). Due to the redundancy of the structure, if $\tilde{\mathbf{J}} \in R^{6 \times 9}$ has a full rank equal to 6, the set of vector fulfilling equation (7) is a three-dimensional hypersurface in a nine-dimensional Euclidean space, meaning that the number of solutions is ∞^3 .

Among all possible solutions, the one reckoned optimal may be chosen through the following considerations. Once a minimum admissible cable tension τ_{adm} has been set, every component of $\boldsymbol{\tau}$ must be greater than or equal to that value, while at the same time keeping them as low as possible and still fulfilling equation (7).

Therefore the following target may be written:

$$\text{minimize } G = \sum_{i=1}^9 \tau_i \quad (15)$$

under the conditions:

$$\begin{cases} \tilde{\mathbf{J}} \cdot \boldsymbol{\tau} = \mathbf{f} \\ \tau_i \geq \tau_{adm} \quad i = 1 \dots 9 \end{cases} \quad (16)$$

That is a linear programming problem that may be solved, for instance, by using the simplex method. The solution to the problem (15), (16) leads to an optimised and internally connected $\boldsymbol{\tau}$, i.e. it can be demonstrated that if \mathbf{f} and $\tilde{\mathbf{J}}$ vary continuously, then also the solution $\boldsymbol{\tau}$ calculated instant by instant presents a continuous run against time.

The procedure to identify the theoretical workspace does not take into account the interaction of the structure with the environment, in terms of maximum forces and torques acting on the platform, and the maximum tension each cable can exert. Therefore a further, different definition of workspace is necessary, involving those considerations. The portion of theoretical workspace where the structure can provide the desired wrench with acceptable cable tensions is called *effective workspace*.

In detail, to find that out, the following parameters must be set: maximum force on the operator's hand in any direction, maximum torque around any axis, minimum and maximum admissible values of cable tension. Then, for every pose in the theoretical workspace, maximum forces and torques must be applied in different directions. For every pose, the cable tensions must be calculated according to the problem (15), (16), recording the largest value of cable tension. In this way, every pose of the platform is characterised by a maximum cable tension resulting from the application of the maximum wrench. This value can be compared to the maximum admissible one, determining whether or not that particular pose belongs to the effective workspace.

As an example, figure 7 shows in graphical form a few results created applying that procedure to the WiRo-6.3, for a given set of parameters (maximum force on the operator's hand in any direction: 10N, maximum torque around any axis: 1Nm, minimum admissible value of cable tension: 5N, maximum value of cable tension: 150N). For the sake of graphical representation, the workspace has been cross sectioned at various values of z ; the base plane represents the platform centre position on that cross section, while the dimension on the third axis and the colour intensity represent the cable tension magnitude.

After a complete scan of the workspace, the result is – in this particular case – that the effective workspace is a wide subset of the theoretical one, making it possible to construct a structure with the physical characteristics that have been chosen as parameters. On the other hand, it must be noted that towards the borders of the workspace the maximum tensions increase dramatically, resulting one or even two orders of magnitude greater than in the central portion. Therefore, possible misuse of the structure taking the platform in one of those conditions must be carefully avoided; otherwise cable tensions and forces on the operator's hand can literally become uncontrollable. Obviously, the same should be done for orientations which, in the examples considered here, must be limited to $\pm 30^\circ$ around any axis (a greater angle would dramatically reduce the available orientation workspace shown in figure 6). A possible strategy can be generating a strong opposing force (or torque) when the operator tries to move (or rotate) the platform across the border of the effective workspace, thus limiting its freedom of movement “virtually”, i.e. without the use of physical end-of-run stop devices.

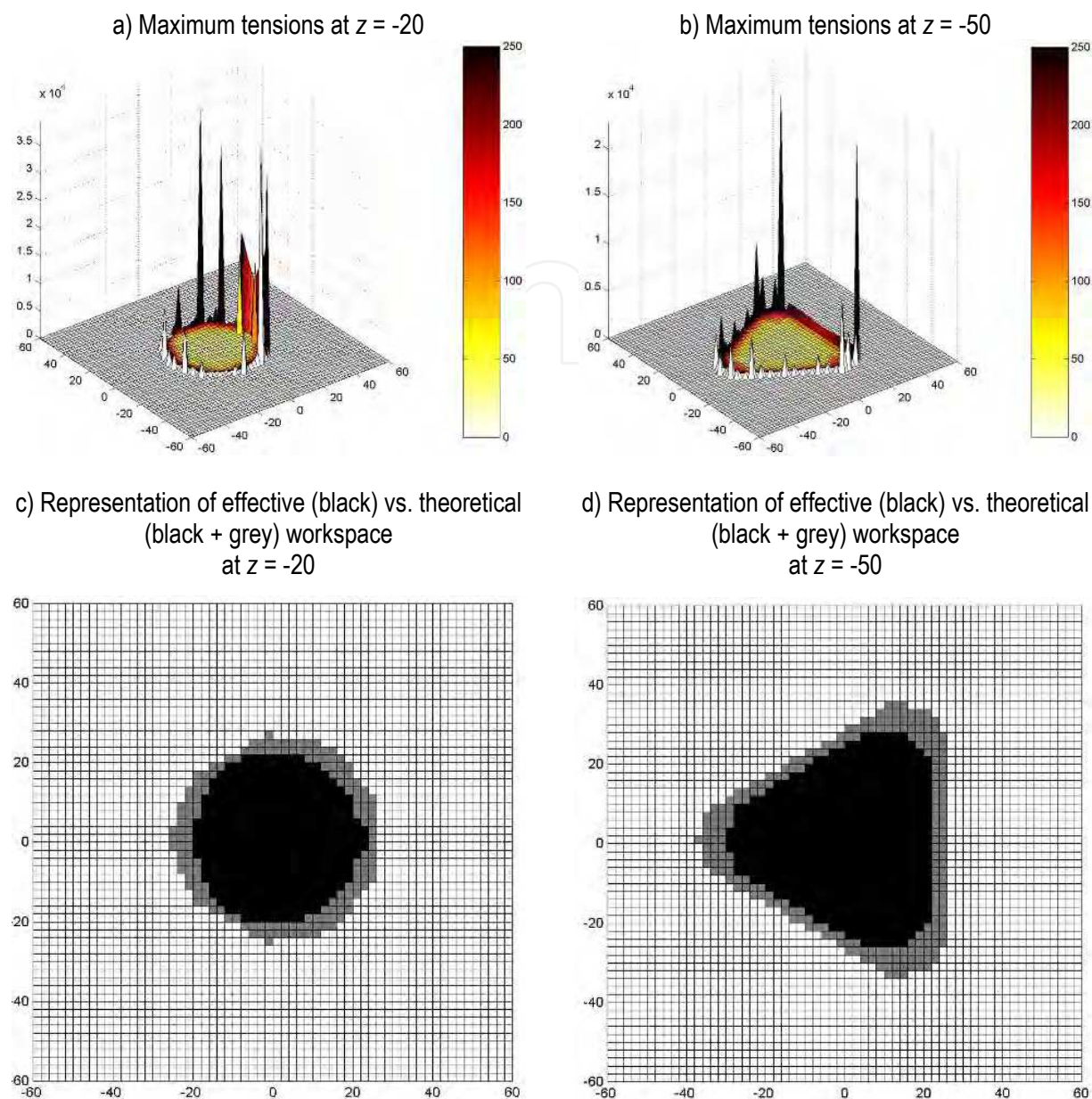


Fig. 7. a), b) Example cross sections of the workspace showing maximum cable tensions. c), d) The same cross sections shown to underline the distinction between theoretical and effective workspace.

5. Device control and cable actuation

The control logic is summarized in figure 8. The operator imposes position and velocity to a proper element, which may be a handle or some other device, suspended in space by the cables. Each cable is tensioned by a specific actuator and under the operator’s action it can vary its length between the fixed and moving points (indicated as P_{Fi} and P_{Mi} in figure 1). Measuring the length of each cable through transducers, the control system is able to evaluate position, orientation, linear and angular velocity of the handle by means of the forward kinematics algorithm. Those results are used as reference input to the control

system of the slave robot actuators: the slave unit is therefore driven to carry out a particular task.

As a consequence, interaction forces are exerted on the slave unit by the environment; such forces may be measured by convenient sensors and reproduced on the operator’s handle. The global environment forces are therefore used as reference input to the control system. The latter can calculate the exact force that each cable must exert on the handle by means of the inverse statics algorithm; this value is therefore used as reference input to each cable actuator.

The control system may apply a scale factor both to the movement of the slave unit and to the forces reflected to the operator.

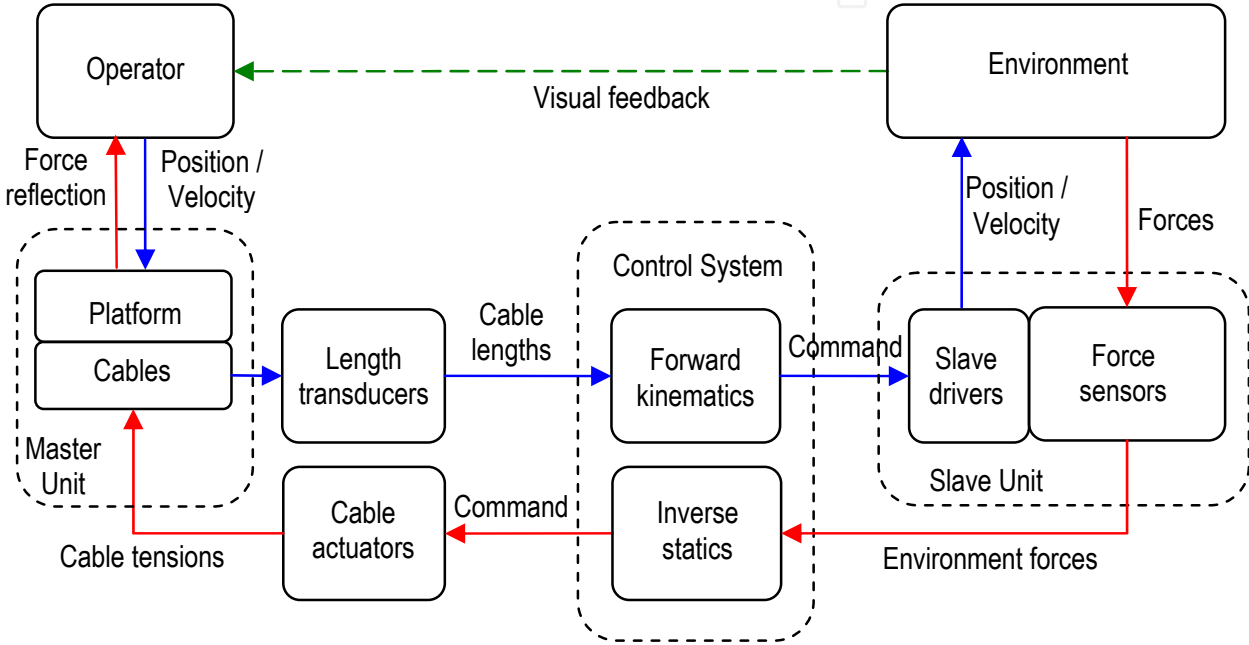


Fig. 8. The control logic of a telemanipulation system with a cable driven haptic master

- The control system must perform a double function:
- (a) on the basis of the cable lengths it must calculate the pose of the platform; since the master has a parallel structure (that may be also multi-redundant), this real-time calculation can be very demanding;
 - (b) a convenient sensorial system should read the wrench exerted by the environment on the remote slave unit; such six-degree-of-freedom information is used by the control system to calculate, by means of an inverse statics algorithm, the exact value of each cable tension; again, the single or multiple redundancy of the parallel cable structure makes real-time operation particularly demanding.

The accuracy of the control depends on the physical characteristics of the device, in particular the mechanical layout and how the control system interacts with the cables and their actuators.

The two main functions of the control system (master pose calculation and cable tension generation) may be affected by certain errors, which can compromise the effectiveness of the device.

In particular, the kinematical accuracy is strictly related with the characteristics of the cables and their path. The path of each cable can be described considering two different sections, starting from the mobile platform where one end is attached. The first is called the *free section* of the cable, since its direction and its length are determined by the platform motion. The cable passes through a given point on the structure corresponding theoretically to a fixed point. The variable lengths of the free section of each cable are used to calculate the platform pose. The second section of the cable goes from the cited fixed point to the actuation group and has an ideally constant length. The way to realize the passage through the fixed point is crucial for the geometric accuracy of the system.

Figure 9 shows a possible way to realize a fixed passing point of the cable. The cable is conveyed into a cylindrical nylon insert whose entrance hole represents the theoretical passing point and then it is diverted by the pulley towards the actuator.

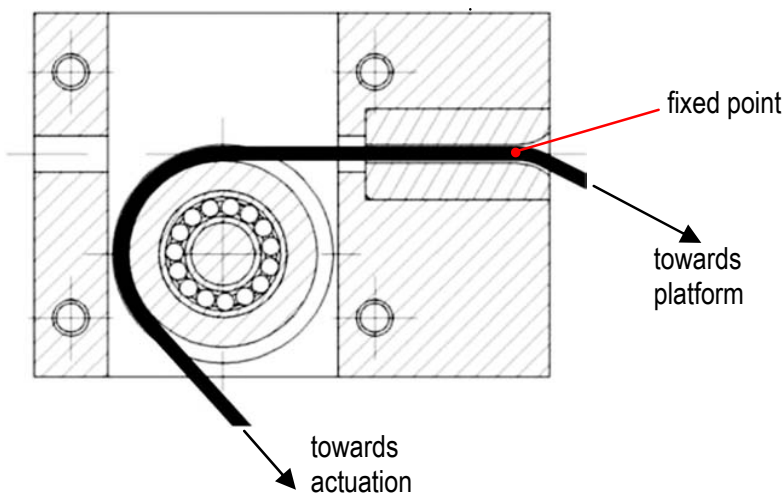


Fig. 9. Realization of a fixed passing point for the cable using a low-friction insert

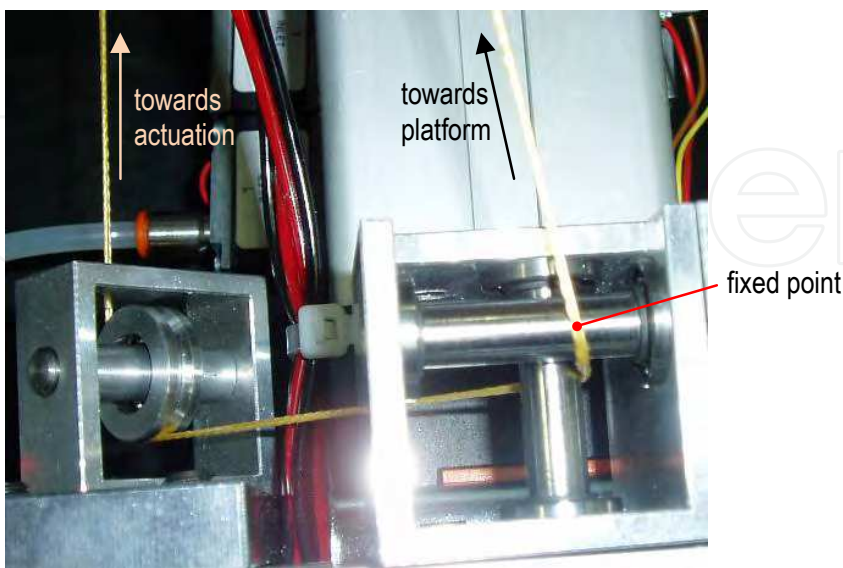


Fig. 10. Realisation of a fixed passing point for the cable using skew rollers.

Another possible solution is shown in figure 10. The cable coming from the platform is diverted by a pair of skew rollers mounted perpendicularly, and then follows the second part of the path defined by fixed pulleys.

Due to the physical characteristics of cables and diversion system, during the handle motion the end of the cable free section is not actually fixed, but moves in a given range, introducing an error in the calculation of the platform pose. For instance, the solution of figure 10 is less accurate than the former one but greatly reduces friction, producing a considerable advantage as will be explained later.

In an ideal situation, each cable should be inextensible and perfectly flexible; as a matter of fact, tensile load causes deformation and flexural stiffness makes sure that the theoretical passing point actually corresponds to a small area. To limit such drawbacks it is necessary to choose cables with convenient characteristics. In particular, a good choice may be adoption of synthetic fibre cables, such as Dyneema® (Hoppe, 1997). In comparison with steel wires of the same strength, those cables are much more flexible and just slightly more extensible, while presenting a similar cross section.

The greater flexibility reduces drastically the extension of the passing area, which can reasonably be approximated to a point.

Moreover, the longitudinal compliance of Dyneema cables is comparable with steel cables but, although non-linear, presents a much more regular run, thus allowing compensating the length variation with a convenient relation as a function of cable tension.

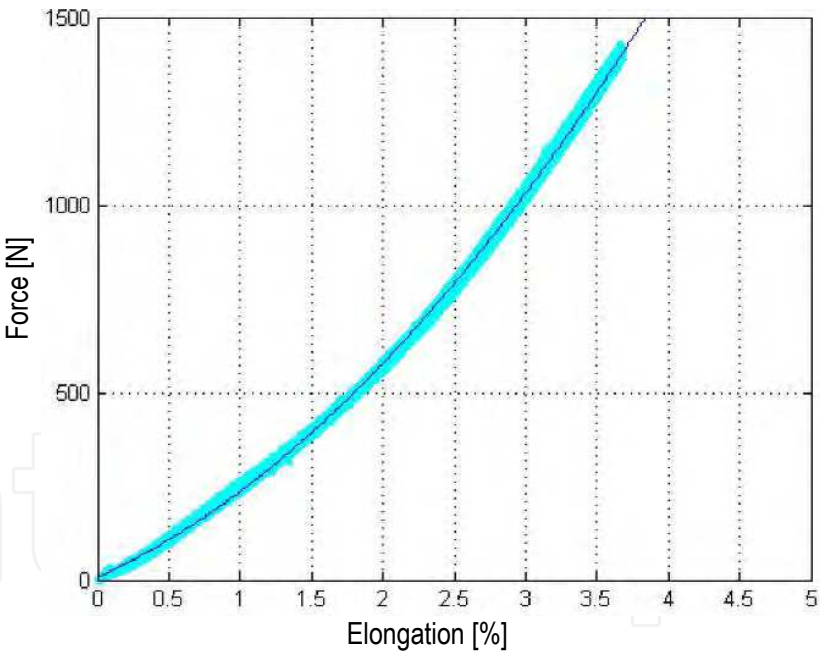


Fig. 11. Mechanical characteristic of a Dyneema-140 cable

As an example, figure 11 shows the mechanical characteristic of a Dyneema-140 cable. This characteristic allows calculating a simple function yielding the percentage elongation (E) as a function of the tensile force (F) expressed in N:

$$E = -1.53 + \sqrt{2.34 + 0.0177 \cdot F} \tag{17}$$

The non-linearity of the cable characteristic can also be exploited as an advantage. As can be seen in figure 11, such a stiffening run allows to make the whole structure more rigid by properly increasing the minimum tension τ_{adm} in the conditions (16), thus producing an advantage for the system controllability.

A further advantage of great cable flexibility is the simplicity of realising the attachment to the platform: this can be realized by a simple knot, practically reducing the attach area to a virtual point fixed to the handle.

As regards the fixed-length part of the cable, it covers a path from the fixed point to the actuator. It is important that the cable constraints are as rigid as possible; therefore the cable should preferably be guided by pulleys rather than a flexible sheath which may be longitudinally compliant.

Another peculiarity of haptic teleoperation systems is the fact that the accuracy of the master pose calculation is less important than that required for the force reflection on the operator's hand.

This is in analogy with actions effected directly by a human subject: the approach and positioning of the hand is controlled by the human proprioceptive (i.e. self-sensing, detecting the motion or position of the body or a limb) and visual system, relatively rough, while the completion of the operation, however accurate, is controlled by tactile forces.

The generation of the wrench on the operator's hand is therefore a very critical point, which requires great accuracy and must compensate various disturbances.

Friction must be avoided or limited as much as possible. Effective software compensation by means of an algorithm that considers the sliding direction and velocity of seven or more cables is practically impossible due to irregular behaviour and most of all to the discontinuity around zero velocity. That is a further reason in favour of realising the cable path along the fixed-length part using pulleys and low friction bearings rather than a flexible sheath.

Friction may be present not only in the cable path, but also inside the actuators. Therefore their choice is a very strategic point. Generally, two main options are available: (a) electric motors; (b) pneumatic actuators.

The most common solution in this kind of application is the adoption of electric motors, but this choice is somehow disputable: the actuators must operate around the stall condition, so they may have difficulties in controlling accurately the torque value.

A typical drawback arises when using brushless motors, characterized by a more or less evident *cogging torque*, i.e. a variation in torque depending on the rotor angular position. In some cases such variation can amount to 10% of the total torque.

Moreover, a rotating motor requires a given device to transform its motion into linear, for example a spool on the shaft. On the other hand, an electric motor presents a very high dynamics, thus allowing an effective control of the cable tension during the handle motion.

An effective alternative is represented by pneumatic actuators. This technology may give interesting advantages, but several aspects need to be accurately considered and evaluated (Ferraresi et al., 2006)

Force control is apparently simpler, since this is obtained by controlling the air pressure in the chambers of a cylinder. Such operation is relatively easy in static condition, but could be difficult during motion, because of the low dynamics of the overall pneumatic system (actuator, valves, piping).

Pneumatic actuators present noticeable friction, due to the seals and also to the fluidic resistance of the air through the various orifices; even the adoption of a membrane pneumatic actuator cannot completely eliminate friction.

The motion of pneumatic actuators is already linear, but may be too limited with respect to the requirements; in this case the actuator stroke can be multiplied by means of a pulley device of the kind shown in figure 12. In this device, the actuator 1 exerts his action on a group of mobile pulleys 2; the cable 3 leans on mobile pulleys 2 and fixed pulleys 4-5; a rotating potentiometer 6, connected to the fixed pulley 5, measures the cable motion. In this example the actuator stroke is multiplied by 6, and its force is divided by the same factor. Such a device allows limiting the size of the actuator, but on the other side it introduces further friction in the system. Of course the stroke multiplier may also be used when adopting linear electric motors, in order to limit their size.

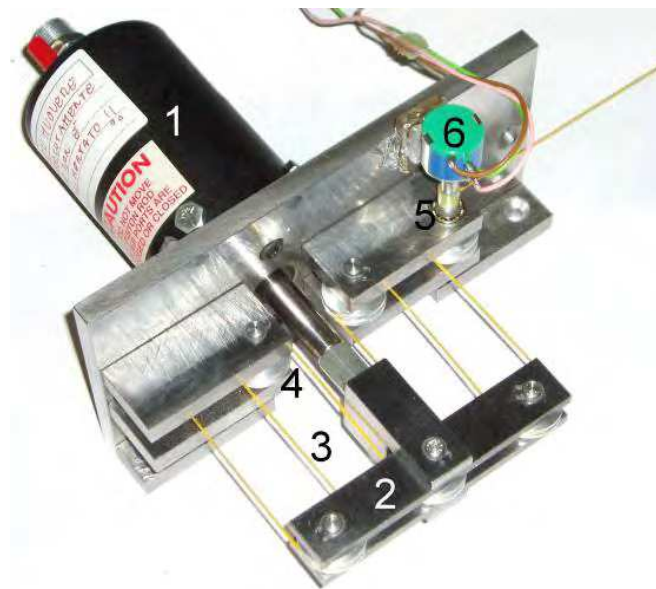


Fig. 12. Device for stroke multiplication of a linear actuator.

In case of pneumatic actuation of the cables, particular attention is required for the control of the supply pressure of the actuator. A simple and economic way is to use on-off valves controlled by PWM logic, but it is necessary to achieve a good compromise, considering the following points:

- (a) the PWM signal introduces vibrations in the pressure value, generating the force reflection; such vibrations may be reduced by a proper dimensioning of the pneumatic system, creating a low-pass pneumatic filter that, on the other side, may penalize the system dynamics;
- (b) the overall dynamics also depends on the valve size; in particular the discharge valves should be properly dimensioned.

As regards the control of cable tensions, it is possible to choose two different strategies:

- (a) Open loop control. In this case the tension value calculated by the control system is used as reference for the motor torque (in case of electrical actuation of cables) or the cylinder pressure (in case of pneumatic actuation). The actual cable tension will be therefore affected by errors due to the friction along the transmission line and various disturbances such as cogging torque, PWM control, etc.

- (b) Closed loop control. The reference value is compared to a direct measure of the cable tension, through a convenient sensor. The control is in general more accurate, but instabilities may arise, due to the non-linearities present in the system, such as friction, cogging torque of electric motors, static and dynamic characteristics of pneumatic valves.

Among all the possible options presented in the previous paragraphs, a choice must be made according to the project specifications, desired performances and, of course, budget limitations.

6. Conclusion

Cable driven robotic devices present peculiar aspects, requiring the solution of very specific problems.

As regards the determination of the main operational characteristics, like the workspace, it is necessary to consider that such devices are often parallel and redundant structures. Moreover, cables can only exert traction forces. As a consequence, the development of such structures requires coping with two main aspects:

- (a) the solution of forward kinematics and inverse statics, necessary for the remote control of the slave device and the force reflection on the operator, are usually very complicated and often a closed form does not exist;
- (b) it is useful to find a convenient layout of the attach points on the mobile platform, in order to obtain closed-form solutions or optimal numerical solutions for the kinematical and static equations.

The workspace characteristics also depend on the number of cables and the layout of their passing points on the fixed structure, but it is difficult to foresee those performances in the design phase and to evaluate them in an objective way. Therefore it is necessary to develop methods aimed at finding out the shape of the six-dimensional workspace, expressing it in a graphical form and evaluating its characteristics by means of objective numerical parameters.

The actuation by cables needs particular attention as regards both the generation and the transmission of cable tensions. This has required a wide research activity concerning the kind of actuators to be used and the mechanical aspects of the transmission lines.

As regards the actuators, it must be noticed that their action must be generated at very low velocities, often near the stall condition. Therefore, particular care must be devoted to the choice of technology (electrical or pneumatic), to the kind of actuator and to the way of controlling the force or torque.

The physical characteristics of the cable and its path have direct influence on the control accuracy. The cables connect the operator with the motors and with the device sensors; the accuracy of the device is affected by the friction acting on the cable and by characteristics like longitudinal compliance and flexural stiffness; those phenomena may only be partially compensated by the control system, therefore the choice of the cable is a very delicate point.

The research described here has faced all the aspects above mentioned. Several original solutions reported have been described in detail in previous works.

Future work will be devoted to improve the way of controlling the reflection forces, which has been spotted as the most delicate aspect for the accuracy of this kind of devices.

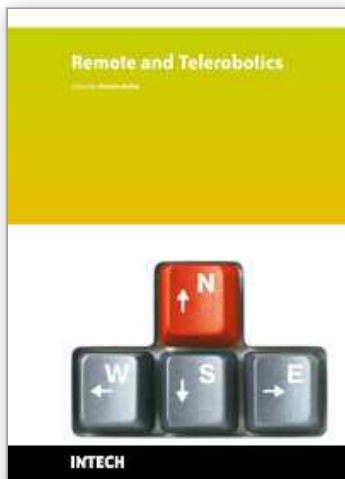
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Any book which presents works about controlling distant robotics entities, namely the field of telerobotics, will propose advanced technics concerning time delay compensation, error handling, autonomous systems, secured and complex distant manipulations, etc. So does this new book, Remote and Telerobotics, which presents such state-of-the-art advanced solutions, allowing for instance to develop an open low-cost Robotics platform or to use very efficient prediction models to compensate latency. This edition is organized around eleven high-level chapters, presenting international research works coming from Japan, Korea, France, Italy, Spain, Greece and Netherlands.

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