A new design for wire-driven parallel robot

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***Abstract*— Wire-driven parallel robots offers potential advantages for various applications such as medical rehabilitation, entertainment, virtual reality. However as any parallel robot their performances is greatly varying with their geometry and no fixed geometry allows to fulfill all requirements for all possible applications. Hence it is interesting to consider a *modular* parallel robot, whose geometry may be adapted to the task at hand. We describe the original mechanical hardware of our modular wire-driven robot *Marionet* and give some prospective on the algorithms that will allow to determine which geometry is the most appropriate for a given task, taking into account the unavoidable uncertainties in the manufacturing.**

I. Introduction

Wire-driven parallel robot have attracted the interest of researchers since the very beginning of the study of parallel robots [14], [18] with crane as a first possible application [8], [1]. This type of robot has the advantage of having a light mobile mass, simple linear actuators with possibly relatively large stroke and less risk of interference between the legs. On the other hand their major drawback is that wire actuator can only pull and not push. This imply that any property that was only kinematic for robot with rigid links has now to be examined in view of this static behavior [6], [16], [24], [27], [28]. For example for rigid robot the workspace limitation are due only to the limited stroke and range of motion of the passive joints, while for wire-driven robot we must also ensure that the tension in the wires remains positive.

The potential interest of wire-driven robot has led to the development of a large number of prototypes: the high-speed *Falcon* [17] (figure 1), the *Segesta* [15] (figure 2), the *Cablev* [13], haptic interface [2], sport training [22], planar robot [11], metrology device [23], telescope [25] and portable crane [26].

To the best of the authors knowledge all wire-driven robots developed so far share the same mechanical architecture for the actuators. A rotary motor is used to turn a drum on which the wire is coiled. The rotation of the drum is used to measure the change in the wire lengths, which is necessary for controlling the robot. If a relatively high positioning accuracy is required, this imposes that the wire is coiled along a specific guide on the drum so that a given rotation of the drum corresponds to a fixed change in the wire length. Such mechanical structure allows for high speed and for easy control with an inexpensive motor and controller. But the drum and the guiding mechanism of the wire are relatively difficult to design and are expensive. Furthermore such system does not allow for very large change of the wire length and for modularity in the possible stroke

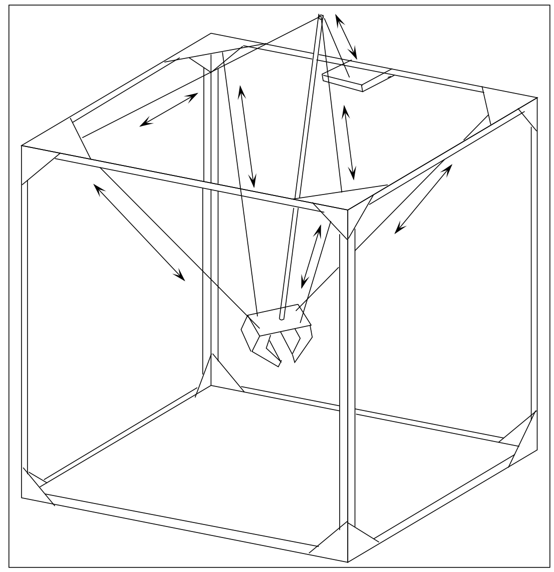

Fig. 1. The Falcon wire-driven high-speed robot by Kawamura [17]

Fig. 2. The Segesta wire-driven robot of Duisburg University [15]

as the radius of the drum is limited by the minimal radius of curvature of the wire for small drum and by the inertia for large one.

Our purpose is propose both a mechanical architecture that allows for a larger modularity and to develop the algorithmmic tools that are necessary to fully use the modularity of the mechanism for adapting the robot to the task at hand.

II. An original mechanical architecture

Our purpose is to design a mechanical system that allows fast change in the geometry of the robot, together with enabling a wide range for the possible change in the wire lengths. Indeed we propose to investigate extreme tasks such as surgeon training or haptic device for virtual reality. In the first case the required workspace is small but the positioning accuracy should be high together with a high force resolution. In the later case the required workspace may be very large while the quality of the positioning accuracy and force restitution may be relatively rough. Typically wire length change may range from ten centimeters to over two meters and such different strokes cannot be obtained with a rotary drum.

Our design is based on the fast and accurate linear actuator *ThrustTube 2504* module provided by *Copley Motion* that has a stroke 40cm, a positioning accuracy of 1 μm, a maximal force of 51 N and a maximal speed of 10m/s. The wire is attached to the mobile part of the linear actuator and moves along a pulley system, using *Harken* pulleys with low friction bearings, that is similar to the one used in light dinghy (figure 3). Such

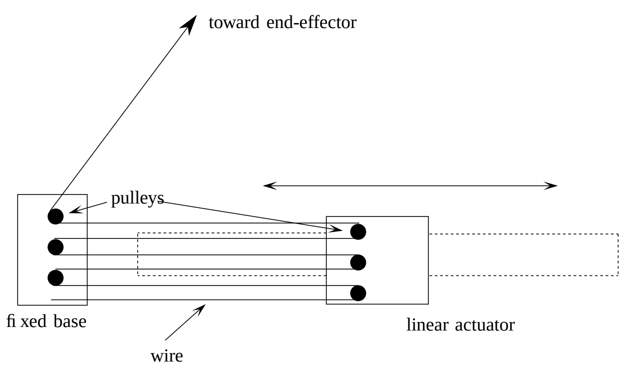

Fig. 3. The mechanical system used to provide changes in the wire length

system allows one to easily modify the amount of wire length changes by a simple modification of the number of used pulleys and thus offers a better modularity. Furthermore the pulley system allows at the same time to amplify the strokes of the linear actuators and the velocities of the wires. For example we intend to have a pulley system that produces an amplification factor of 10, leading to a 400 cm stroke for the wire. Additionally this amplification factor will lead to a wire velocity of 100 m/s and as the velocity of the platform along some direction is also amplified, we may end up (provided that the robot controller is able to sustain the necessary calculation in real time) with platform velocities in some direction larger than 300 m/s.

We may also revert the pulleys system in order to obtain very accurate motion of the platform over a reduced workspace. For example we may obtain a maximal wire change length of 20 cm by using 3 pulleys (note that the available tension in the wires will also be doubled).

Clearly the main drawback of our design is that the available tension in the wires (and hence the available wrench at the end-effector) will change according to the number of pulleys that are used. Furthermore the linear actuator and pulley system induces a larger friction than rotary motor, which may not be convenient for using the robot as an haptic device.

Our robot is constituted of seven such wire system that have to be put in a horizontal plane due to constraints on the linear actuators. The wire systems may be put in arbitrary position on a rigid frame of approximately 3m by 2m that surrounds the robot. Being able to change easily both the geometry and the stroke of the actuator will lead to a very flexible wire-driven robot. First trial in open-loop with 4 actuators have been conducted in December 2006 (figure 4). They have shown

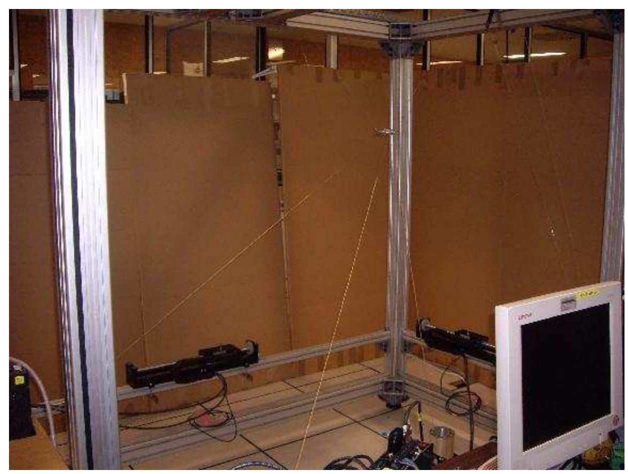

Fig. 4. The preliminary Marionet prototype with 4 actuators

smooth motion of the actuator, which may however difficult to control at high speed. On the long term we intend to have a controller implemented using Linux RTAI operating system directly interfaced with the actuators controllers.

III. Kinematics and Force measurements

Kinematics of parallel robot is now relatively a well know subject although not an easy one. Inverse kinematics (computing the lengths of the wire for a given pose of the platform) is straightforward but direct kinematics is difficult. For robot with 6 rigid links we have proposed a fast certified solving scheme based on interval analysis [19]. At the opposite of the more classically used Newton method, this scheme cannot provide a wrong solution. Indeed there may be up to 40 different solutions to the direct kinematics and the Newton method may converge to a pose different from the current one, even if its initial guess is very close to the desired solution.

For a wire-driven robot we have even an advantage as the seventh wire length measurement provide a redundant information. This information is difficult to introduce in the Newton scheme while it can easily be used in the interval analysis method and will speed up the calculation. We may also consider having measurements of the output direction of the system, i.e. direction of the wires, by using rotary sensors on two output pulleys. All these extra information may be used for solving the forward kinematics problem [3], [4], [5], [7], [12], [20] and for calibration purposes [9].

For measuring the force exerted on the platform we intend to use three different methods. The first one relies on the measurement of the force exerted by the linear actuator: the actuator controller allows for force control and measurements. However this is clearly a rough method because this force will include the friction in the pulleys system and may be influenced by the elasticity in the wire. A second method will be to incorporate sub-miniature strain gages in the wires, close to the platform: such approach allows a better measurement of the tension in the wires but requires some additional wiring. Finally our experience with force sensing in parallel robot is that it is difficult to ensure similar force sensitivity when having the force sensing elements in the legs (for example when the legs are oriented roughly along a vertical direction we get a very good sensitivity for forces directed along the horizontal directions and a low sensitivity for the vertical force). As a last resort we will use a 6D force sensor directly on the platform.

Note that having measurement of the tension in the wires may also be useful to improve the accuracy of the robot. Indeed we may have some linear elasticity in the wires and the force measurement may be used to determine the real wire lengths. Similarly when the wires will be extended on a long range we may use a deformation model to estimate the shape of the wire, thereby allowing a better estimation of the distance between the wire system and the end-effector.

IV. Managing the geometry

Having a modular mechanism structure is only the first necessary step for the full use of a modular robot. Indeed the second step is to design algorithms that allows one to determine which geometry(ies) are the most appropriate for performing a given task. Ideally such algorithms should take into account the unavoidable uncertainties of mechanical system.

We may assume that for the given task the end-user is able to define performance requirements such as workspace shape and volume, maximal positioning accuracy, maximal tension in the wires over the desired workspace and singularity avoidance. Note that these requirements are usually *imperative* i.e. they must all be satisfied simultaneously. Hence the classical optimal design approach cannot be used as it does not guarantee the satisfaction of all requirements. Furthermore this approach leads to a unique theoretical solution and cannot provide guarantee on the performance satisfaction of the *real* robot which will differ from its theoretical model due to manufacturing errors.

To solve this problem we have proposed an original design methodology [10], [21]. Let D be the design parameter space i.e. a n dimensional space where each axis corresponds to one of the n design variable (hence a point in D represents a unique robot geometry). We consider in turn each of the requirements and ideally we try to compute the region of D that corresponds to **all** robots satisfying the requirement. In practice however such exact calculation is not easy and instead we use a numerical method to find an approximation of the region. Our method of choice is interval analysis that allows one to obtain the approximation as a set of boxes in D. We get only an approximation as not all solutions will be obtained: indeed if we cannot determine that a ”small” box in D includes only solution we will neglect it. In the algorithm a ”small” box is defined as a box for which at least one dimension is lower than twice the manufacturing tolerance associated to the corresponding design variable. Neglecting such box is legitimate: indeed even if the box contains some theoretical solution we cannot use these solutions as nominal geometry for the robot as the manufacturing tolerances may lead to a point in D that is not included in the box and therefore a robot that will not satisfy the requirement. Hence our approximation excludes solutions that lie on the border of the region.

Being given the approximation we may choose **any point** in it to design a robot that will satisfy the requirement. Then we consider a second requirement and use the computed approximation as an initial guess for the region of D for which the second requirement will be satisfied. The result of this second run is a new approximation of **all** robot geometries that satisfy both the first and second requirements, whatever are the uncertainties on the design variables. We then process the remaining requirements in the same manner. Finally we get a region of D whose points define robot geometries for which all the requirements are satisfied. If this region is empty this means that the requirements are too strict and some of them must be relaxed. For that purpose we look at the variation of size of the approximation after each requirement and relax the requirement that lead to the largest decrease in the size of the approximation. The algorithms are then run again until a non empty region is obtained.

At this point we get an infinite number of design solutions. Clearly they cannot be all presented to the end-user. Hence we select a few representative solutions that offer various compromise between all interesting performances. It is then the responsibility of the end-user to choose the solution that is the most appropriate for the task.

This strategy may be used for our wire-driven robot. The design variables are the unit vectors of the actuator axis (that will be restricted to be close to the x, y axis of the reference frame), the location of the actuators along these directions (that are bounded by the physical dimension of the frame) and the amount of necessary change in the wire lengths together with the initial lengths of the wires. This amounts to 21 (7 unit vectors)+7 (location)+7 (stroke)+7 (initial lengths) variables, i.e. a total of 42 design variables. Note that the unit vectors are included to take into account errors when assembling the robot but that the corresponding ranges for these variables are small. As for the stroke remember that we will have only to consider as possible ranges $m \times [0, 40]$ centimeters, where m is an integer between 0 and 10.

V. Potential test applications

We intend to explore three main applications:

- *portable rescue crane*: as mentioned in [26] wire-driven robots may be used as a fast, deployable and autonomous intelligent crane after an earthquake. A rescue team may reach the catastrophe site and will deploy the robot using as attachment points for the wire system remaining walls, trees or deploy a specific support frame [29]. An automatic calibration procedure will be used to determine the geometry of the robot by using the extra sensory information. Hence after a few minutes the rescuers may use the crane to move debris and gain access to buried people
- *service robots*: many recent buildings present outside glass walls of various shape that have to be washed on a regular basis. Climbing robots have been used for that purpose but without much success: the joints between the glass panels are difficult obstacle and the washing process is slow. We believe that a wire-driven robot may be used with a better efficiency and at a lower cost. Here inexpensive winch may be used and directly integrated in the building
- *medical rehabilitation*: a collaboration between University Cassino, Monastir Engineer School and Oran University has been funded by INRIA in the *RoRas* project to explore how a force-controlled robot may be used for rehabilitation. The first goal is to objectively monitor the progress of the patient during the rehabilitation and a second goal is to impose pre-specified forces on the injured member. Here wire-driven robot have various interest with their low intrusivity and low cost together with the possibility of adapting the robot to the patient's morphology

VI. Conclusion

Wire-driven robots have a huge potential for applications but require still additional theoretical investigations. For that purpose we propose the use of a highly modular robot, having actuators that completely differ from the classical drum and which allow a much larger flexibility. We have also outlined the methodology that we plan to use for determining the most appropriate robot geometry for a given task, this methodology allowing us to take into account unavoidable uncertainties. Finally we have presented some possible applications of such robot that will be tested with our prototype.

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