`MARIONET`, a family of modular wire-driven parallel robots

J.-P. Merlet

INRIA Sophia Antipolis - Méditerranée, Sophia Antipolis, France,
e-mail: jean-pierre.merlet@sophia.inria.fr

Abstract. We present several prototypes of wire-driven parallel robots that we have recently designed and which use two different actuation schemes. Two of them have been completed and submitted to extensive tests. These tests have allowed to determine interesting open problems related to kinematics that are presented.

Key words: kinematics,wire-driven parallel robots

1 Introduction

Major drawbacks of parallel robots are the limited workspace and a certain lack of flexibility that does not allows one to easily modify their geometry to adapt the robot to the tasks at hand. Using wires instead of rigid legs is a natural solution to the workspace problem. Indeed major limitations for the workspace of parallel robots are due to the limited stroke of linear actuators and to the limited range of motion allowed by the passive joints that are used. For a wire system the amount of possible leg length change may be very large while passive joints may be avoided or an appropriate mechanical design may push their influence much farther than classical mechanical joints.

After the pioneering work of Landsberger [11] wire-driven parallel robots have been extensively studied with various applications in mind. Without claiming to be extensive we may mention: crane [1, 8], motion tracking [2, 6] and metrology [19], haptic interface [3, 5], surgery [7, 18], rehabilitation [9, 13, 14] and sport training [12, 17], telescope [15] and rescue robotics [16, 4].

However they are still various unsolved issues regarding wire-driven robots:

- *accuracy*: wire elasticity and sag, unmodeled wire deformation of the wires at the platform anchor points and measurement errors in the wire length induce inaccuracy in the platform location
- *kinematics and statics:* although it is sometimes claimed that parallel robot may be fully constrained, provided that they have at least $n+1$ wires for controlling n d.o.f. of the platform, this is true only if all wires are in tension. But being given the wire lengths a fully constrained robot may perfectly end up in a pose in which not all of its wires are under tension. Conversely although a solution of the inverse kinematics with positive tension may have been computed there is no guarantee that the platform will reach the desired pose when applying this

solution to the robot. Hence direct kinematics remains to be investigated first by determining all possible poses satisfying the mechanical equilibrium condition that can be reached with 1 to *n* wire under tension, and then determining the current pose which is among all the solutions

- *modularity management*: wire-driven robot may be designed so that changing their geometry (i.e. the location of the anchor points of the wires) is an easy task. But determining the possible location of the anchor points so that the robot will fulfill a set of requirements is still an open problem.

To investigate these issues both theoretically and experimental we have decided to design and build a whole family of parallel wire-driven robots, based on two different actuation schemes.

2 Actuation scheme

Classically wire-driven robots use drums that are actuated by a rotary motors. The wires coil on the drum and the measurements of the motors rotations allows theoretically to determine the wire lengths. Although implementing this actuation scheme is easy (and is used in some of our robots) it has various drawbacks, especially regarding the determination of the wire lengths. We may indeed calculate this length from the motor rotation under the following assumptions: the wires coil on the drum always in the same manner so that we can exactly determine the number of layers and the wire diameter is constant. In practice both assumptions have to be verified or a better measurement method has to be designed. This actuation scheme will be denoted Drum/Rotary Motor (DRM).

In order to improve the wire length measurement we have investigated another approach that is based on the use of a linear actuator and a pulleys system. One extremity of the wire is fixed to the ground and from this extremity the wire goes alternatively to a pulley on the mobile part of the actuator and then to a pulley on the fixed part of the actuator. The last pulley is fixed and the wire get out of the system through a hole whose location is also fixed with respect to the ground. The pulleys system is designed in such way that all wire strands in the system are parallel. The pulleys system allows to produce a length change of the wire that is a multiple of the stroke of the actuator: a system with *m* pulleys has a multiplication factor of *m*. Such actuation scheme will be called Linear Actuator/Pulleys System (LAPS). The LAPS principle has several advantages compared to DRM:

- the measurement of the motion of the linear actuators allows to measure the wire length with an error that is at most *m* time the error on the actuator measurement.
- the velocity of the wire is *m* times the velocity of the actuator
- the system may be designed in such way that the number of pulleys may be changed, hence allowing to adapt the multiplication factor. This offers an additional flexibility

LAPS has however some drawbacks: the maximal tension available in the wire is equal to the maximal force of the actuator divided by *m* and consequently there is a limit on the maximal number of pulleys as each additional pulley add a small amount of friction that decreases the available tension in the wire. Hence LAPS allows only limited length changes compared to the virtually unlimited range provided by DRM (however we will see that the motion range of LAPS is still large). Consequently LPAS should be used for fast and accurate robots with limited load and relatively limited workspace while DRM should be preferred for large load and workspace and for tasks for which accuracy is not a major issue.

3 The `MARIONET` family

The `MARIONET` family is a set of four wire-driven robots with different size, actuation scheme and applicative purposes:

- `MARIONET-REHAB` (MR): a 2.2m × 1.2m × 2m robot using LAPS that is intended to be used for rehabilitation tasks and fast pick-and place operation
- `MARIONET-CRANE` (MC): a 15m × 15m × 15m robot using DRM that is intended to be used for rescue operations and the manipulation of large load in a large workspace
- `MARIONET-ASSIST` (MA): a 3m × 5m × 3m robot using DRM whose main task will be to act as a at-home lifting crane for assistance robotics, especially for elderly and handicapped people
- `MARIONET-VR` (MV): a 6m × 5m × 3m robot using LAPS that will be used in a virtual reality environment as a motion provider and haptic device

Currently `MARIONET-REHAB` and `MARIONET-CRANE` have been built and are fully functional, while `MARIONET-ASSIST` and `MARIONET-VR` are at the design stage and will be available at the end of 2010.

3.1 `MARIONET-REHAB`

The development of this robot with 7 wires (figure 2) has started in 2004 and is the major test bed for the study of LAPS. It uses Copley Motion linear actuator with a stroke of 40cm, a maximum force of 48N, a positioning accuracy of $1\mu m$ and a maximal velocity of 10m/s. The LAPS may use up to 10 pulleys: with a maximal wire velocity of 100m/s the platform velocity may theoretically exceed the speed of sound at some poses of its workspace, although we have tested it only up to 8m/s. Our accuracy test have shown that this robot was very accurate with a positioning error less than 0.1 mm.

We have recently tested MR for a rehabilitation task. After a coronary stroke patient may suffer a loss of arm coordination. A classical protocol to correct this coordination problem is to ask the patient to extend his arm and to draw with his finger the straight line between the successive location of a colored mark that is moving on a computer screen. The pratician then evaluates visually the arm coordination. We have first used MR in a passive mode where the robot just records the patient motion, thereby allowing an objective assessment of the quality of the motion. (figure 1). It has then be observed that this protocol is very demanding for the patient as working with an extended arm leads quickly to arm fatigue. We have therefore used MR in a semi-active mode where the robot is still passive except in the vertical direction where it exerts a vertical force to relieve the patient from the weight of his arm (the apparent weight of the arm is reduced to approximately 15% of the real weight), allowing for longer rehabilitation session.

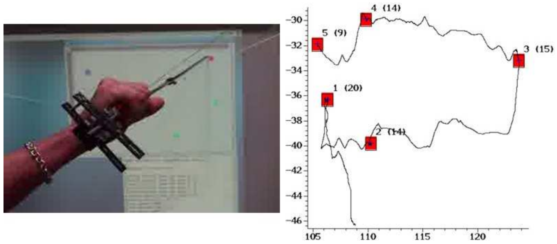

Fig. 1 Trajectory followed by a patient during a rehabilitation test: he should move in a straight line between the successive location of the square mark

We intend now to use MR to measure precisely human joint motion. For that purpose we will use the 7 wires of the robot, together with several 3D accelerometers (figure 2).

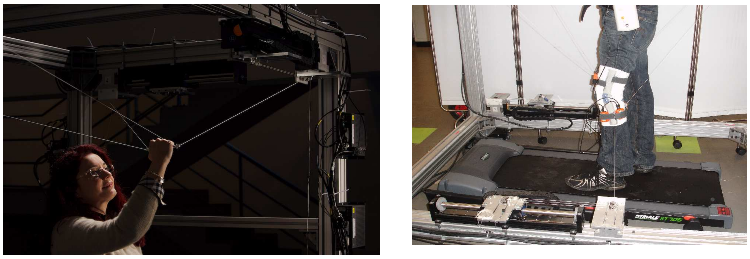

Fig. 2 `MARIONET-REHAB` used in rehabilitation tasks. The wires and the 3D accelerometers will be used to precisely measure human joint motion during a rehabilitation task.

3.2 `MARIONET-CRANE`

`MARIONET-CRANE` (MC) is a very large DRM 6 d.o.f. robot that is intended to be used for rescue operations. Our motivation to develop this robot may be illustrated by quoting Skynews after the 5/15/2008 earthquake in China: *Rescuers efforts have been hampered by landslides, buckled roads, collapsed bridges and wet weather. The Chinese government has made an emergency appeal for cranes and heavy lifting equipment amid warnings that time is running out for survivors of Monday's 7.9-magnitude quake.* Hence we have designed the robot as a portable, fully autonomous device. It has 6 wire system whose weight is about 10 kg with a drum capacity of between 50 and 100m. Each wire may sustain up to a 1.5 tons load, leading to a robot that may lift up to 2 tons in most of its workspace. Optional tripods may be used to increase the height of the wire systems. MC has been deployed outdoor during 3 months at the end of 2009. The 6 tripods have been installed on top of three buildings, surmounting a 20m × 20m × 12m work area (figure 3).

Fig. 3 The outdoor implementation of `MARIONET-CRANE`.

One of the role of MC is to free victims from the rumbles: this may require the use of all d.o.f. of the robot. To identify the necessary freeing motion we use a small mobile robot with a web cam so that thes wire may be attached to the most appropriate anchor points (figure 4).

Fig. 4 `MARIONET-CRANE` used from freeing a victim from rumbles

Then the victim may be lifted toward the surface (figure 3). An originality of this experiment is that the mobile robot is lifted with the victim so that the medical team on the surface may get physiological information during the transfer. Furthermore a small smart communicating object allows to get other measurements such as temperature and heart rate.

3.3 `MARIONET-ASSIST` *and* `MARIONET-VR`

`MARIONET-ASSIST` (MA) is a reduced version of MC that is intended to be used in a flat as a low-cost lifting crane and walking aid for elderly and handicapped people. At rest it lies on the ceiling of the room and is almost invisible. It is deployed on request and is designed to provide a lifting capacity of 150 kg. `MARIONET-VR` (MV) is a LAPS robot using linear drives with toothed belt whose stroke is 2m and a pulleys system. It will be deployed in front of a 5m immersive wall for rehabilitation, motion training and entertainment.

4 Lessons learned

4.1 Improving the DRM

A major issue with large parallel robot is the determination of the ground anchor points of the wire system. We have successfully solved this problem by using a laser distance meter that measure the distances between a mark close to the anchor points and 1) the origin of the reference frame and 2) two points located on the x,y axis of the reference frame. A simple triangulation method allows then to determine quite accurately the location of the anchor points. We have then measured the accuracy of the robot when performing a vertical motion by using a plumb-line that allows one to determine the deviation of the robot center along the x,y axis. For a vertical motion of 8m the maximum deviation on these axis was less than 2cm, which is quite acceptable.

But the extensive tests of MC have shown that a major problem for DRM is the inaccuracy of the wire length measurement. Although MC has a guiding system for coiling the wires we have observed changes in the coiling process after several hours of use, leading to an error in the wire lengths that may exceed 50 cm. Hence on a regular basis it was necessary (especially for steel wire) to completely uncoil the wires and then coil them in a controlled manner. To overcome this drawback we will test a method that will allow to measure from time to time the wire lengths almost exactly. We are currently being investigating two methods based on the same principle but using different sensors:

- *magnetic*: small strips of magnetic tape are glued at known distance on the wire. A Hall sensor in the wire system is able to detect the presence of one strip, allowing to determine the current wire length
- *optical*: we will use small colored marks that may be detected by an IR optical sensor

Between two marks we may interpolate the measurement using the drum rotation. Preliminary tests have shown that both type of marks are detectable. The magnetic method seems to offer a better resolution but is more difficult to implement and may disturb the coiling process.

4.2 Kinematics

Tests of both MC and MR have shown that kinematics is the most important issue for an efficient control of wire-driven parallel robot. Although all of our robots are so-called fully constrained we have noticed discrepancies between our solution of both the direct and inverse kinematics and the observed robot pose. For the 6-wires MC the direct kinematics is equivalent to solving the one of a classical parallel robot and to retain the solution(s) that satisfies the mechanical equilibrium condition with positive tension in the wires. To the best of the author knowledge there is no known bound on the maximum number of such solution. But even if such a solution exists the current robot pose may be different. Indeed let us consider the set of robots derived from the MC by suppressing from one up to five wires and compute their forward kinematic solutions. For a robot with m wires we have m constraint equations that relate the wire lengths to the pose parameters and 6 equilibrium equations for $6+m$ unknowns (6 pose parameters and m tensions in the wires). Among all these solutions we retain only the one such that the length(s) of the disconnected wire(s) is at least equal to the distance(s) between their anchor points. After this process we get a set of possible solutions, one of them being the current pose of the platform. But nothing guarantee that the current pose will be the solution of the fully-constrained robot. Hence even for a fully-constrained robot we have to investigate the forward kinematics of under-constrained robots. A similar study has to be performed for the inverse kinematics. These studies will be even more complex if elasticity and sagging of the wires [10] are taken into account.

4.3 Singularity

Singularity is related in depth to the static analysis of wire robot. Indeed the mechanical equilibrium constraint is equivalent to having the lines associated to the wires and the vertical line going through the platform center spanning a linear complex. As linear complexes may be characterized geometrically such formulation allows one to write the equilibrium constraint without involving the wire tensions.

Using wires also allows the robot to move from one *aspect* to another one more easily than for parallel robots with rigid legs, because of the flexibility of the wires. We have been fortunate to observe and record such phenomena. Going through a singularity with a wire driven robot is also an interesting open problem.

5 Conclusion

Experimental tests allow to discover new theoretical open problems. Our large experimental effort with the development of 4 new wire-driven robots have shown that the kinematics of such robot is still an open issue. They have especially shown that for fully constrained robots the kinematics cannot be restricted to the case where all wires are under tension as the kinematics of all under-constrained systems have also to be solved.

References

1. Albus J., Bostelman R., and Dagalakis N. The NIST SPIDER, a robot crane. *Journal of research of the National Institute of Standards and Technology*, 97(3):373–385, May 1992.
2. Andrade-Cetto J. and Thomas F. Wire-based tracking using mutual information. In *ARK*, pages 3–14, Ljubljana, June, 26-29, 2006.
3. Arcara P. and others . Perception of depth information by means of a wire-actuated haptic interface. In *IEEE Int. Conf. on Robotics and Automation*, pages 3443–3348, San Francisco, April, 24-28, 2000.
4. Ceccarelli M., Ottaviano E., and Tavolieri C. Experimental activity on cable-based parallel manipulators: issues and results at LARM in Cassino. In *2nd Int. Congress, Design and Modelling of mechanical systems*, Monastir, March, 19-21, 2007.
5. Dominjon L., Perret J., and Lécuyer A. Novel devices and interaction techniques for human-scale haptics. *Visual Computer*, 23(4):257–266, April 2007.
6. Geng Z. and Haynes L.S. A 3-2-1 kinematic configuration of a Stewart platform and its application to six degree of freedom pose measurements. *Robotics and Computer-Integrated Manufacturing*, 11(1):23–34, March 1994.
7. Hamid S.A. and Simaan N. Design and synthesis of wire-actuated universal-joint wrists for surgical applications. In *IEEE Int. Conf. on Robotics and Automation*, pages 1807–1813, Kobe, May, 14-16, 2009.
8. Higuchi T., Ming A., and Jiang-Yu J. Application of multi-dimensional wire crane in construction. In *5th Int. Symp. on Robotics in Construction*, pages 661–668, Tokyo, June, 6-8, 1988.
9. Homma K. and Arai T. Upper limb motion assist system with parallel mechanisms. In *2nd Japan-France Congress on Mechatronics*, pages 388–391, Takamatsu, November, 1-3, 1994.
10. Kozak K. and others . Static analysis of cable-driven manipulators with non-negligible cable mass. *IEEE Trans. on Robotics*, 22(3):425–433, June 2006.
11. Landsberger S.E. and Sheridan T.B. A new design for parallel link manipulator. In *Proc. Systems, Man and Cybernetics Conf.*, pages 812–814, Tucson, 1985.
12. Morizono T., Kurahashi K., and Kawamura S. Realization of a virtual sports training system with parallel wire mechanism. In *IEEE Int. Conf. on Robotics and Automation*, pages 3025–3030, Albuquerque, April, 21-28, 1997.
13. Ottaviano E., Ceccarelli M., and Palmucci F. Experimental identification of kinematic parameters and joint mobility of human limbs. In *2nd Int. Congress, Design and Modelling of mechanical systems*, Monastir, March, 19-21, 2007.
14. Rosati G., Gallina P., and Masiero S. Design, implementation and clinical test of a wire-based robot for neurorehabilitation. *IEEE Trans. on Neural Systems and Rehabilitation Engineering*, 15(4):560–569, December 2007.
15. Su Y.X. and others . Development of a large parallel-cable manipulator for the feed-supporting system of a next-generation large radio telescope. *J. of Robotic Systems*, 18(11):633–643, 2001.
16. Tadokoro S. and others . A portable parallel manipulator for search and rescue at large-scale urban earthquakes and an identification algorithm for the installation in unstructured environments. In *IEEE Int. Conf. on Intelligent Robots and Systems (IROS)*, pages 1222–1227, Kyongju, October, 17-21, 1999.
17. V. Zitzewitz J. and others . A versatile wire robot concept as a haptic interface for sport simulation. In *IEEE Int. Conf. on Robotics and Automation*, pages 313–318, Kobe, May, 14-16, 2009.
18. Wendlandt J.M. and Sastry S.S. Design and control of a simplified Stewart platform for endoscopy. In *33nd Conf. on Decision and Control*, pages 357–362, Lake Buena Vista, December, 14-16, 1994.
19. Williams II R.L., Albus J., and Bostelman R. 3D cable-based cartesian metrology system. *J. of Robotic Systems*, 21(5):237–257, 2004.