Wire-driven parallel robot: open issues

Jean-Pierre Merlet*
INRIA Sophia-Antipolis

Abstract Wire-driven parallel robot (WDPR) is a special class of parallel robot in which the rigid legs are replaced by wires, with potential advantages in terms of intrusivity and workspace. Although the study of WDPR seems to be a well-addressed subject, we will show that there are still numerous challenging open issues in this field.

1 Wire-driven parallel robots

Wire-driven parallel robot (WDPR) is a special class of parallel robot in which the rigid legs are replaced by wires. As for classical parallel robot, motion of the platform may be obtained either by changing the lengths of the wires (*type 1*) or having fixed wires lengths and modifying the location of the attachment point A of the wires on the base (*type 2*). In the first case wire lengths may be modified by using either a coiling winch or by using a linear actuator with a pulleys system (Merlet, 2010). We may also distinguish *completely restrained* robot where the wires fully constrained the n d.o.f. of the platform (in which case the number of wire must be at least $n+1$ (Ming et al., 1994)) and *cable suspended* robot with at least n wires, gravity playing the role of a virtual downward pulling wire.

WDPR have been introduced in the 80's (Landsberger and Sheridan, 1985),(Miura and Furuya, 1984) as an alternate to parallel robot with rigid links. The foreseen advantages was less intrusive legs, a simpler mechanical structure (passive joints are eliminated) and potentially larger workspace for the type 1, as the amount of leg lengths variation may be much larger than with rigid legs. WDPR shares with classical parallel robots the ability to manipulate large load and to be energy efficient. But the major difference is that wires can be pulled but not pushed, which imposes an unilateral constraint: that must be checked. We will see that this constraint greatly complexifies the analysis of WDPR.

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Several prototypes have been built in the 90's, among them the famous ROBOCRANE (Albus et al., 1993), the FALCON robot (Kawamura et al., 1995) and the rescue robot of Tadokoro (Tadokoro et al., 1999), while the principle was partly patented (Thompson and Campbell, 1996). In the 2000's further prototypes have been developed such as the SEGESTA robot (Hiller et al., 2005) and other prototypes (Barrette and Gosselin, 2005),(Fattah and Agrawal, 2005).

Recently there has been a renewal of interest for WDPR in view of new applications: wind tunnel (Yaqing et al., 2007), biomechanic and rehabilitation (Wu et al., 2011), haptic interface (V. Zitzewitz et al., 2009), rescue robotics(Merlet and Daney, 2010) and telescope (Z-F et al., 2011) to name a few. Type 2 robots are illustrated in (Michael et al., 2009) in which several quadrotors are used to tow a load.

In spite of all these works it appears that many issues that have been investigated for such robots need to be revisited as they are not fully understood.

2 Kinematics

We first define the *wire configuration* of a WDPR at a pose as the set of wire numbers which are under tension. Clearly the unilateral constraint imposed on wires requires to connect kinematics and statics. Indeed, the geometrical constraint that relates the wire length ρ to the distance d between the wire anchor points on the base and platform must take into account the tension τ in the wire (with $\tau > 0$ if the wire is under tension). More precisely we have $\rho = d$ if $\tau > 0$ and $\rho \geq d$ for $\tau = 0$ i.e. the number of kinematic equations will depend upon the wire configuration. This does not impact the inverse kinematics (IK) if we consider that it provides d (or equivalently the location of A for type 2 robot). But the direct kinematics (DK) is another story. Indeed it must be noted that the sensors of the robot provide the measurement of ρ, while the pose of the platform is a solution of the IK which uses only d. If we assume that $\rho = d$ (i.e. all wire are under tension) we end up with the DK problem of classical parallel robots, which has usually several solutions. But nothing guarantee that in the current pose of the robot all wires are under tension. If we focus on a n wire spatial cable suspended robot, the IK provides m equations (for the $m \leq n$ wires under tension), $n - m$ inequalities $\rho \geq d$, while the mechanical equilibrium provides 6 equations. As the number of unknowns is $6 + m$ (the 6 pose parameters and the m τ) we always end up with a square system, whatever is the wire configuration. All possible DK solutions will be obtained by considering all the systems obtained for $m = 1 \dots n$.

If $m = 1, 2$ the DK system can easily be solved, while for $m = 6$ the system may be decoupled into 2 sub-systems: the DK of a classical parallel robot (problem A) whose solving provides the pose parameters, and the linear system of the mechanical equilibrium that will provide the τ: the DK solutions will be obtained for the one of problem A for which the τ are positive. But the problem is much more complex for $m = 3, 4, 5$, for which there is no decoupling, and which have respectively 9, 10 and 11 equations, although it must be noted that it is possible to reduce the system to 6 equations. Indeed the mechanical equilibrium condition is equivalent to have the wires lines and the vertical line going through the center of mass of the platform spanning a linear complex, resulting in $6 - m$ geometrical conditions, which, added to the m IK equations, provide the necessary 6 equations (note however that after solving the system it is necessary to check the τ and to retain only the solutions which have positive tension).

We have recently used this approach to exhibit a solution for $m = 3$ (Carricato and Merlet, 2011). After some intensive calculation we have been able to reduce the system of 6 equations to an univariate polynomial of degree 158. But solving the DK for $m = 4, 5$ is still eluding us and this is clearly a major issue for WDPR. We have also here a practical issue regarding numerical solving: the algebraic approach apparently leads to high degree polynomial that cannot be safely numerically solved. Consequently we will have to rely on other numerical approaches. Interval analysis has been successfully used for $m = 3$, but preliminary work for $m = 4, 5$ have shown that the task was much more demanding. Real-time solving of the DK is not an issue, provided that 1) a guaranteed solving scheme is used (Merlet, 2004)), 2) the number of wire under tension does not change (see section 3). For large-scale robot other factor may influence the IK and DK such as the sagging of the wire or their elasticity (Kozak et al., 2006),(Gouttefarde et al., 2012),(Riehl et al., 2009). Stability of a pose should also be evaluated to eliminate unstable DK solutions (Bosscher and Ebert-Uphoff, 2006),(Carricato and Merlet, 2011).

Determining the current pose of the platform without a priori information on the pose is still an open issue.Adding information is necessary (e.g. measuring the wire tensions or directions of the wires) but such measurement is noisy and it is unclear how robust the calculation will be.

3 Singularities

Up to now it is considered that singularity analysis of WDPR does not differ from the one for classical parallel robots (Ottaviano and Ceccarelli, 2007). A first note is that for cable-suspended robot the mechanical equilibrium condition is equivalent to the singularity analysis of a set of lines (with a close connection to grasping (Ebert-Uphoff and Voglewede, 2004). A second note is that the singularity of fully constrained WDPR is still an open issue. This is especially true as we have to consider that the the infinitesimal motion obtained in a singularity may possibly leads to a different wire configuration and hence to a different set of kinematic equations whose jacobian may become full rank. A companion question for cable-suspended robot is to determine the singular configuration in which the wire tension may indeed become infinite. This is a complex issue because we cannot restrict the study to a local analysis: in the vicinity of a singularity the wire configuration may change in such way that the robot will never be in the wire configuration for which the singularity has been determined.

We propose also to classify as singularity the pose at which there are multiple possible wire configuration. Indeed the control law will depend upon the current wire configuration and may thus fail if an undetected change of wire configuration occurs. Furthermore as for classical singularity the platform may gain uncontrollable d.o.f. at such pose.

4 Workspace and planning

Workspace analysis for WDPR must consider that a pose lie within the workspace if the geometrical constraints are fulfilled but also if the tension in the wires are positive. Hence the load has to be considered: it may be fixed (e.g. for cable-suspended robot), or its components may be restricted to lie within some ranges or it may be arbitrary (*wrench feasible workspace*). There have been numerous works on this subject see for example (Barrette and Gosselin, 2005), (Diao and Ma, 2008), (Gouttefarde et al., 2011), (McColl and Notash, 2011), (Riechel and Ebert-Uphoff, 2004), (Stump and Kumar, 2006), (Verhoeven, 2004). Wire interference has also been considered Merlet (2004) although interference is less damaging and may be accepted (Y. et al., 2008). But we have to extend workspace calculation to take into account singularity and possible change in wire configuration. Similarly for trajectory planning a path planner should avoid singularity (in the broad sense defined in the previous section), while it is necessary to determine in real-time if a wire configuration change may occur in the vicinity of the current pose. A further issue is to be able to detect a wire configuration change: this may obtained either by wire tension measurements and/or measurements of the wire directions. However both measurements are noisy and the detection, if any, will not occur immediately after a change in wire configuration. We will then have to design a recovery strategy to get the robot back on track and with all wires under tension, whenever it is possible. Other criteria may be taken into account by the planner, such as energy.Clearly dimensional synthesis is also an open issue, especially as WDPR hardware may be designed in a modular way for allowing easy change in their geometry (provided an efficient communication means between the components of the WDPR).

5 Redundancy and control

Redundancy in WDPR is not a well addressed problem. From the kinematic viewpoint a WDPR is not a redundant robot as the IK has usually a single solution. It may however be thought that a WDPR is redundant from a static viewpoint, so that we can modify the tension distribution while keeping the platform at the same pose (Pott et al., 2009). Unfortunately its seems that this is not possible for cable-suspended robot with non-elastic wires such as the $N-1$ ($N \geq 4$ wires connected at the same point on the platform) as this robot will have always at most 3 wires under tension (Merlet, 2012). For completely restrained robot and non-elastic wires we have a control problem as we cannot control both the wire length (to keep the platform at the same pose) and the tension in the wires. For elastic wires the situation may be different as wire length control is basically equivalent to tension control in that case. But we still have the problem of wire configuration changes: it seems that such changes does not modify drastically the platform pose, while on the other hand large changes in the wire tensions will occur (Merlet, 2012). It appears also that small uncertainties in the wire stiffness have a small influence on the pose but a large one on tension in the wires. Hence position and velocity control should work fine while force control will be difficult Krut et al. (2004),(Oh et al., 2005) and should be robust with respect to error in the stiffness estimation (Yu et al., 2010) Clearly we have to find better ways to fully exploit the possible redundancy of WDPR. A possible approach and intriguing problem is related to the kinematics and tension distribution in multiple WDPR whose platforms and even wires may be interconnected in a flexible way by wires (with fixed lengths or variable lengths).

6 Dynamics

Dynamics of WDPR is clearly simpler than for classical parallel robots (Bruckman et al., 2008),(Korayem et al., 2010). It may even be used to increase the workspace of the robot (Barrette and Gosselin, 2005), (Gosselin et al., 2012). But an open issue is to investigate if dynamics can also be used to manage wire configuration.

7 Conclusion

Surprisingly although numerous works have been devoted to WDPR it appears that numerous issues, even fundamental one e.g. kinematics, are still not fully understood. The unilateral constraint imposed by the wire tension imposes to revisit all these topics. It greatly complexify the problems, leading to many of the more challenging contemporary problems in kinematics but is worth investigating as WDPR have a large potential for applications.

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