Puppets on a string

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PUPPETS ON A **STRING**

There's one mechanical element that most people use every day and have been doing so for over 10,000 years. It's cheap, easy to handle and, thanks to ongoing research, it has become even stronger and more lightweight over the millennia. This element is the cable, present versions of which have superb properties. For nearly twenty years, a community of engineering researchers has been using simple cables for sophisticated purposes, to develop and build extremely large and fast robots that open up new branches of automation.

TOBIAS BRUCKMANN, JEAN-PIERRE MERLET, STEFAN SPANJER AND JUST HERDER

Robots have changed production processes. Whenever the assembly of a product consists of repetitive steps, it is likely that something like an articulated robot or a SCARA can do the job fast, precisely and reliably. But when you look more closely, there are drawbacks. The mass of the moving robot is usually a multiple of the payload. This increases power consumption and limits acceleration and speed capabilities. Additionally, the use of this type of robot is limited depending on the size of the workspace. If the manipulator arms are longer than several meters, they become extremely heavy and elasticity begins to dominate the dynamic behaviour of the manipulator.

From a kinematic point of view, there is a different class of manipulators that also performs very well in terms of precision and velocity. This class comprises parallel kinematic manipulators, i.e. systems where the end-effector is connected to the base via multiple kinematic chains. The most dynamic robots on the market use parallel structures, like the delta robot that has been sold as the FlexPicker since 1999. But classic parallel kinematics reveal drawbacks that limit their application range. Compared to the construction space, the volume of the workspace is usually quite small because the strokes of linear actuators or the crank lengths of rotary drives, respectively, are limited. What's more, some types of parallel robots use sophisticated joints and actuators, something that increases manufacturing costs.

Cable robots

That said, there is a simple solution to eliminate both drawbacks. The stiff links can be replaced by cables, the joints replaced by pulleys and the actuators substituted by winches [1]. This creates a cable-driven parallel kinematic manipulator – in short, a cable robot – that has a number of interesting properties:

- An extremely large workspace
  Since the cable lengths are virtually infinite, very long distances can be spanned. Think of suspended cameras in a sports stadium; tens of meters can be easily bridged.
- Super-lightweight
  Steel cables, but even more modern fibre cables can carry enormous loads compared to their own weight. This facilitates building robots where (nearly) only the payload needs to be moved.
- Mechanically simple and reliable
  Only drums and motors are needed to build a winch. Winches have been used for thousands of years. They can be produced as identical modules. To build a wire robot, the only additional things required are cables, pulleys, sensors and a control system.

Engineers have been using cables for ages to lift heavy objects, e.g. to raise trade goods or submarines off the sea bed or to build ski lifts to reach the top of a mountain. Modern theatres use dozens of cables and winches to magically move objects and actors on the stage. And every day, millions of people put their lives into the hands of elevators, contraptions that are suspended for hundreds of meters.

Operation

Interestingly, the number of cables in use may vary. From a certain point of view, a crane suspending a load is the simplest cable robot possible. Obviously in this case the payload is prone to oscillations, which makes it difficult to use cranes for automated tasks. The simplest approach is to

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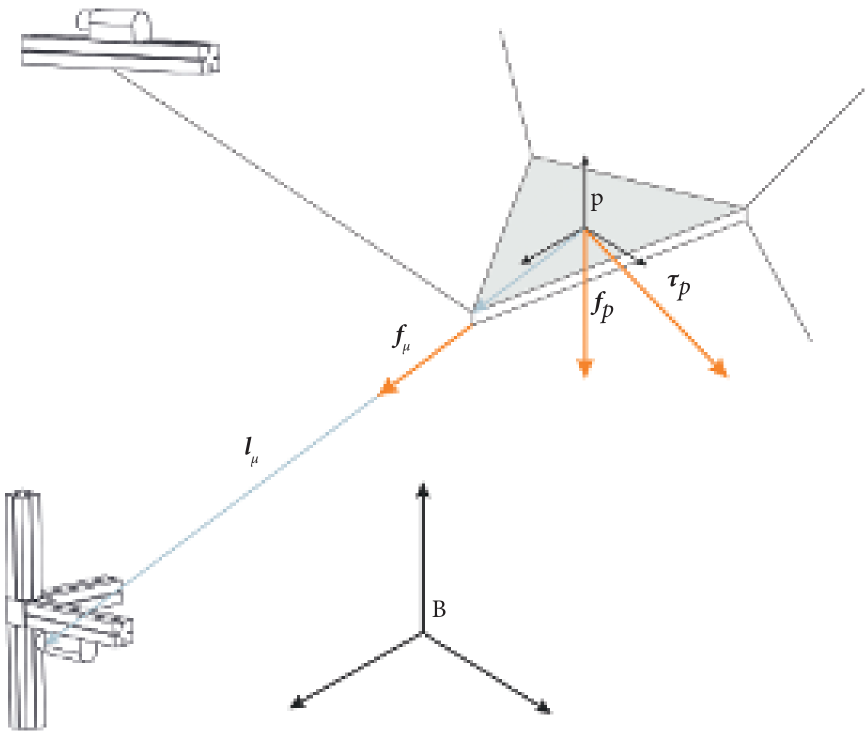


add cables. To guide a point-shaped payload with three degrees of freedom in space, three cables are required – but only if it can be guaranteed that the cables are tensed by an external force, e.g. gravity. This is due to the fact that cables can only pull, but never push, meaning they introduce only a unilateral constraint on the point's movement. Accordingly, a cable should always be tensed, otherwise it is rendered useless.

It follows that for the suspended way of operating a cable robot – called a suspended robot, with *n* degrees of freedom, operated using *m* cables – appropriate external forces like gravity are needed. In practical terms, these robots are able to oscillate if disturbance forces occur. To suppress oscillations, tension in the cables is necessary. This can be realised by additional cables fixed to the moving platform (Figure 1).

In a proper arrangement, the cables in certain areas of the workspace are able to pull against the other cables. Assuming a control system that maintains tension in all the cables (combined with a cascaded pose or cable length control, respectively), an inner tension can be created. This may increase stiffness, prevent cable slackness and suppress oscillations. A robot using wires that pull against each other is called a fully constrained robot; it needs $m \geq n + 1$ cables under tension. Many designs used in suspended configurations may also fulfil the latter condition, but

1 *Definition of forces and geometry of the moving platform.*

to allow for a workspace containing constrained platform poses, the aforementioned condition is required.

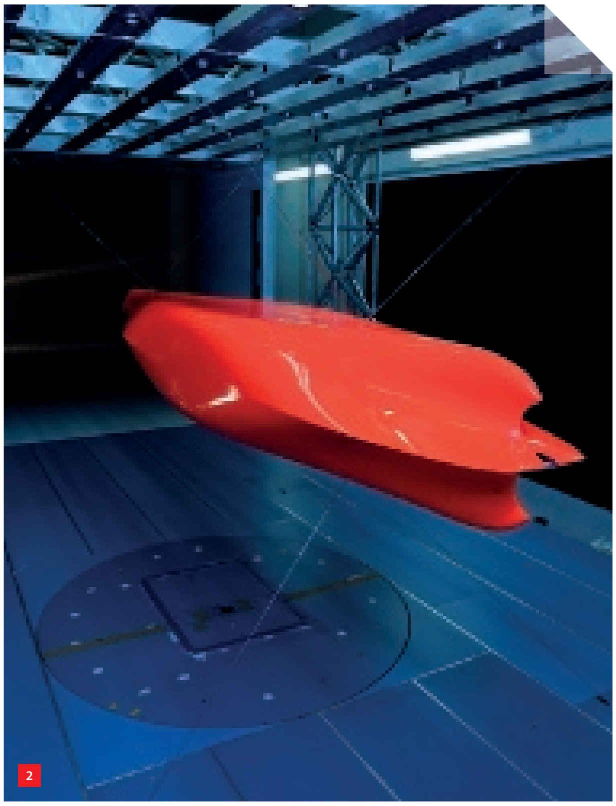
Control

While the mechanical components are simple, the control needs to ensure that the cables have an appropriate tension to support the payload or process forces at all poses and can accelerate or brake. Assuming vectors $\boldsymbol{l}_\mu$ ($\mu = 1, ..., m$) from the platform to the pulleys, cable forces f_μ and a vector of platform forces and torques $\boldsymbol{w}$ (including inertia and gravity), it holds [2]:

$$\underbrace{\begin{bmatrix} \boldsymbol{v}_1 & \cdots & \boldsymbol{v}_m \\ \boldsymbol{p}_1 \times \boldsymbol{v}_1 & \cdots & \boldsymbol{p}_m \times \boldsymbol{v}_m \end{bmatrix}}_{\boldsymbol{A}^T} \underbrace{\begin{bmatrix} f_1 \\ \vdots \\ f_m \end{bmatrix}}_{\boldsymbol{f}} + \underbrace{\begin{bmatrix} \boldsymbol{f}_p \\ \boldsymbol{\tau}_p \end{bmatrix}}_{\boldsymbol{w}} = \boldsymbol{0},$$

$$\text{where } \boldsymbol{v}_\mu = \frac{\boldsymbol{l}_\mu}{\|\boldsymbol{l}_\mu\|_2}$$

Assuming a robot with $m \geq n + 1$ cables under tension for a given pose and platform wrench, the computation of a set of cable forces where all cables maintain a minimum tension level f_{min} (to avoid slackness and minimise sagging) at least, but do not exceed the maximum workload f_{max} or the maximum torque of the drives, respectively, already presents an underdetermined problem. In this case, the inner tension can be varied, e.g. to save energy. This variation needs to ensure continuous results and consider



2 *Wind tunnel suspension system. (Courtesy of the Institute for Fluid Dynamics and Ship Theory, Hamburg University of Technology)*

3 *Artist impression of a green energy field with wind turbines and the NEMOS wave energy harvesters which are the yellow buoys with cables connecting generators and the seabed. (Courtesy of NEMOS)*

the minimum and maximum force limits at the same time. This results in a constrained optimisation problem:

$$\text{minimize } g(\boldsymbol{f}) = \|\boldsymbol{f}\|_2 = \sqrt[2]{\sum_{\mu=1}^{m} f_\mu^2} = \sqrt[2]{f_1^2 + f_2^2 + \cdots + f_m^2}$$

$$\text{subject to } 0 < f_{\min} \leq f_\mu \leq f_{\max}$$

While this ensures the appropriate tension level, a robot is usually expected to maintain a certain movement precision. Here, even the computation of the actual platform pose only using cable lengths – called forward kinematics – is already computationally demanding for most cable robot designs. Currently, the computation of forward kinematics using more realistic cable models, including elasticity and sagging, is the subject of ongoing research [3].

The need for tension control as well as elasticity introduces additional difficulties for precise motions. French researchers built a large prototype (15 m × 11 m × 6 m) and demonstrated a remarkable repeatability of a few millimeters, with an accuracy of approximately few centimeters [4]. Therefore, for precision applications, external pose measurements and high controller frequencies are recommended.

Projects

Nowadays, these challenges have been addressed extensively. The required control algorithms are available on modern industrial control hardware [5]. Analysis and design software for workspace computations [6] [7] has been developed, and even verified results for forward kinematics are available [8]. On the practical side, a couple of application prototypes have been developed, where European researchers played an important role.

Cable robots have been the subject of research at the University of Duisburg-Essen in Germany since the late 1990s, where prototyping was always focussed on evaluating developed algorithms. In 2011, a first application was realised in cooperation with the Hamburg University of Technology. In this case, a wind tunnel suspension system based on cable robot technology was realised to move aerodynamic probes of up to 150 kg (Figure 2). Actually, there is no other concept available that is able to move these probes without disturbing the air flow.

In 2013, the research team in Duisburg realised a cable robot control system for the prototype of a wave energy harvesting system developed by the company NEMOS (Figure 3). In the project, energy conversion realised though a floating buoy was drastically improved by replacing the single cable of conventional approaches by a wire robot with three cables. A scaled prototype is currently being tested in Denmark and a full-size version can be expected soon.

A demonstrator of a cable-driven high-rack storage and retrieval machine was built in Duisburg in early 2012 in

4 *Cable-driven storage and retrieval machine at the University of Duisburg-Essen. The moving platform is in stand-by position on the ground. Boxes can be picked from and stored to the shelves, respectively, using a push-and-pull device on the platform.*

close industry cooperation (Figure 4). In this case, several advantages of a cable robot could be used. Instead of moving a massive lifter device in a rail in front of a high rack, only the payload is moved by a tensed system of cables. This drastically reduces the moving masses and allows for extremely high dynamics or a decrease in energy consumption. A prototype 12 m long and 6 m high has been tested extensively since 2014.

To conclude

This technology is driven towards applications at a European level too. A consortium of academic institutions and industry parties looked at applications in the domain of large-scale handling and manipulation, e.g. for aircraft maintenance, as part of the CableBOT project[9]. The idea behind the project is to identify application potential in industrial sectors that could not accommodate automation up to now due to the required robot sizes.

Autonomous window-cleaning robot

University of Twente spin-off KITE Robotics was founded in 2012, and together with the Laboratory of Mechanical Automation and Mechatronics (Prof. Just Herder, Dr Volkert van der Wijk and Kevin Voss, M.Sc.), it has conducted research into cable-driven robots. This November, a milestone was celebrated: the first building was cleaned using a cable-driven robot. The building in question was the almost entirely glass Spiegel building at the entrance of the university campus.

A system of four cables was developed to steer the robot on the building. By manipulating the cables, the position of the robot changes and the robot moves across the entire building. Apart from positioning the robot, one of the other challenges was how to ensure a high level of cleaning. As such, the KITE robot was given a special suspension system and brush design. During the cleaning process (four or six times a year on a subscription basis), the robot is attached to clamps mounted on the building.

The robot is suitable for cleaning large buildings that pose a high risk to traditional window cleaners. It is aimed at building managers and cleaning companies. Window cleaners usually have to work at great heights in all kinds of weather, so their job is dangerous as well as physically demanding (one of the most dangerous jobs in the world, according to insurance companies). The KITE robot can clean buildings (glass as well as frames and many other materials) up to a height of around 80 meters.

WWW.KITEROBOTICS.COM

The KITE cleaning robot in action. (Photos: Gijs van Ouwerkerk/KITE Robotics)

This technology has a great potential for robot applications where acceleration and lightweight manipulators are important and where large workspaces are essential. Additionally, since a cable robot allows for the automation of many tasks that are currently being done by cranes, there is a wide field of further opportunities yet to be explored. ■

REFERENCES

[1] Landsberger, S.E. and Sheridan, T.B. (1985), "A new design for parallel link manipulators", *Proceedings of the 1985 IEEE International Conference of Systems, Man and Cybernetics*.

[2] Bruckmann, T., Mikelsons, L., Brandt, T., Hiller, M. and Schramm, D. (2008), "Wire Robots Part I - Kinematics, Analysis & Design", In: J.-H. Ryu (Ed.), *Parallel Manipulators, New Developments*, Vienna, Austria, I-Tech Education, pp. 109-132.

[3] Merlet, J.-P. (2015), "On the real-time calculation of the forward kinematics of suspended cable-driven parallel robots", *14th World Congress in Mechanism and Machine Science*, Taipei, Taiwan.

[4] Nguyen, D.Q., Gouttefarde, M., Company, O. and Pierrot, F. (2013), "On the Simplifications of Cable Model in Static Analysis of Large-Dimension Cable-Driven Parallel Robots", *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Tokyo, Japan.

[5] Reichert, C. and Bruckmann, T. (2015), "Unified Contact Force Control Approach for Cable-driven Parallel Robots using an Impedance/Admittance Control Strategy", *Proceedings of the 14th World Congress in Mechanism and Machine Science*, Taipei, Taiwan.

[6] Gouttefarde, M., Krut, S., Company, O., Pierrot, F. and Ramdani, N. (2008), "On the Design of Fully Constrained Parallel Cable-Driven Robots", In J. Lenarčič and P. Wenger, *Advances in Robot Kinematics: Analysis and Design*, Springer Netherlands.

[7] Berti, A., Merlet, J.-P. and Carricato, M. (2014), "Workspace Analysis of Redundant Cable-Suspended Parallel Robots", In Pott, A. and Bruckmann, T., *Second International Conference on Cable-Driven Parallel Robots (CableCon2014)*, Springer Verlag.

[8] Merlet, J.-P. (2014), "The Forward Kinematics of Cable-Driven Parallel Robots with Sagging Cables", In Pott, A. and Bruckmann, T., *Second International Conference on Cable-Driven Parallel Robots (CableCon2014)*, Springer Verlag.

[9] www.cablebot.eu

Helping elderly people

At Inria, the French National Institute for computer science and applied mathematics, a low-cost cable-driven parallel robot is being used to help move elderly people. In this case, four cables are used to help elderly people weighing up to 200 kg to get up, stand and walk independently, wherever they are in the room. At the same time, the robot platform is instructed to monitor the walking pattern of the elderly people as required by the medical community for functional and cognitive assessment. Furthermore, this robot is non-intrusive: when not in use it can completely disappear into the ceiling.

WWW.INRIA.FR/EN/CENTRE/SOPHIA

A patient being transported by a low-cost cable-driven parallel robot that was developed at the Sophia Antipolis (France) location of Inria.