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Toward the Creation of a Hybrid 4-UPS CDPR^{*}

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Abstract. A hybrid cable-driven parallel robot (CDPR) is being developed that expands the capabilities of conventional CDPRs by replacing one of the cables with a linear actuator that can be spooled and extended. This actuator uses three curved leaf springs connected using magnetic strips to provide compressive or tensile forces while being very compactly stored, and is kinematically similar to a cable that can push. When used in conjunction with a suspended CDPR, this actuator is being designed to be part of a novel pick-and-place robot that combines the benefits of cable robots (lightweight actuators) with those of a conventional manipulator (each of the actuators can be above the workspace to help avoid cable collisions). The developments of this novel actuator are outlined, showing how pointing motions were made possible through mechanical design.

Keywords: cable-driven parallel manipulator · telescoping actuator

1 Introduction

In the field of Cable-Driven Parallel Robots (CDPRs) two of the greatest challenges toward practical implementation come from cable interference, and developing manipulator configurations that are capable of completing tasks in a cluttered industrial environment. This is particularly apparent in spatial applications where tasks must be completed over a flat workspace (such as a conveyor belt) due to the requirement for cable tension to be maintained in order to retain control. This means that CDPRs with an antagonistic actuator configuration are the only ones capable of providing a downward force greater than the weight of the end-effector, while cable-suspended parallel robots (CSPRs), CDPRs with each of their cable anchor points above the workspace, are limited in the downward forces that they can apply [16]. The manipulator discussed in this paper attempts to solve some of these problems by combining a CSPR with

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a novel extensible linear actuator that can sustain forces both in tension and in compression.

The linear actuator used in this manipulator is being designed specifically for this application. The goal of the design is to create an actuator that retains most of the benefits of cable robots while also being able to provide a compressive force in order to have favourable actuator positions. It must be capable of being directed in pointing motions, similar to a universal joint.

Hybrid CDPRs or h-CDPR refer to a CDPR where one or more of the cable actuators has been replaced by a rigid kinematic chain, commonly using a linear actuator in order to have one actuator capable of providing compressive forces [2,5,9,26,27]. With universal and spherical joint connections to the frame and end-effector, respectively, the resultant manipulator is kinematically equivalent to a standard CDPM. While designing the extensible linear actuator there were several criteria that had to be met in order to be used as part of a h-CDPR. The first of which is that it must be lightweight to maintain low inertial properties and high efficiency. The second is that, like a cable, the material that is extruded should be coiled when not in use so that the linear actuator does not require excessive space above the workspace. The third requirement is that this actuator should be rigid and strong enough to supply a compressive force. In a CSPR, this will allow the cables to remain in tension and the manipulator to provide a downward force greater than the weight of the end-effector. This has an effect of an extended force closure workspace compared to a typical CSPM [7].

The goal of this actuator is to be used in a spatial pick-and-place parallel robot for lightweight applications similar to ABB's Flexpicker (IRB 360) [1]. This will fit into a class of medium-sized CDPRs alongside these examples [14,15,20,25]. This also fits into a more niche group of linear actuators being created for CDPRs alongside work at Université Laval [22]. Similarly, a high-speed CDPR with a similar architecture and goals has been constructed using a passive spring-loaded central rod for pick-and-place motions with a delta configuration [9,27]. In this work, for the designed linear actuator to be used in a spatial manipulator the rod must be capable of prismatic (linear) actuation as well as passive rotation for pointing motions, similar to the capabilities of a universal joint. This paper outlines the development of a novel leaf-spring actuator for prismatic actuation and pointing guidance developed at the University of New Brunswick. This actuator prototype uses standard measuring tapes as the leaf springs, connected using magnetic strips to form a strong, rigid rod to be used as part of a hybrid CDPR.

2 Project History

2.1 Development of the Tape Rod

This project is not the first attempt that has been made to create a linear actuator that can be extruded from a roll. This work has been reviewed in [12,13,17], and can be divided into thin-walled tubular booms [12], tape springs (most com-

monly in tape measures) in [24], and more specifically as part of parallel manipulators (PMs) in [11,23]. Helical band actuators have been manufactured by Spiralift [10]. Other types of compact linear actuators include collapsible tubular masts [8,18,21], triangular rollable and collapsible booms [3,4], and closed-section triangular booms in works such as [6,19]. The linear actuator developed and described in this work most closely represents a closed-section triangular boom and uses several tape measures attached using magnetic strips to keep them together.

Building from these developments in the field, some prior work at UNB was completed where sets of three tape measures were attached using various methods. The mechanical properties of several design options were tested using standardized methods, including bending and buckling. Further testing was performed on the top candidates using a custom-made dynamic testing jig shown in Fig. 2. This study resulted in a tape rod attached by magnetic strips along the outer edge that was capable of supporting a compressive load greater than 300 N at a rod length of 1 m [13]. This is significantly stronger than the tapes on their own as they readily buckle under compressive or bending loads. This design was the best among the tested methods using exclusively readily-available, off-the-shelf components. The rods were supported on both ends with a custom 3D-printed end block that matched the geometry of the attached tapes. Each rod was made of a fixed length for testing, and a cross-section of one of those rods is drawn in Fig. 1. The magnetic strips are glued to the tapes along the entire length, and each set of tapes is attached magnetically as shown.

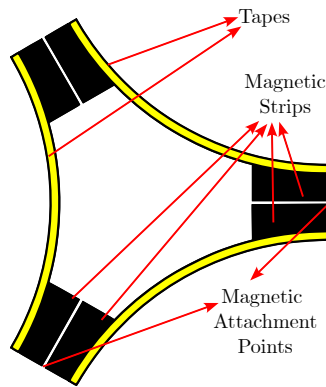


Fig. 1: Cross section of three tape measures attached using magnetic strips.

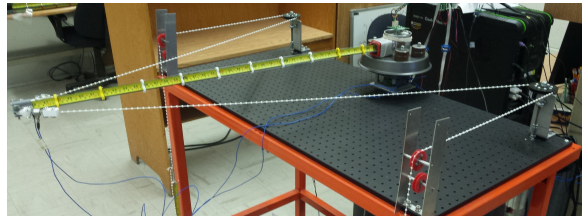


Fig. 2: Dynamic testing jig of a non-actuated tape rod [13].

3 Application in CDPRs

Conventional CDPRs require proximal anchor points (the points attached to the stationary frame) both above and below the workspace to be able to control the force in the vertical direction beyond what gravity will allow. With every proximal anchor point above the workspace (therefore above the distal anchor points on the mobile platform), it is a CSPR and has capabilities that are limited by both gravity and the minimum cable tension required to avoid slack. The goal of creating this actuator is to replace one of the cables in a CSPR to expand its capabilities. This can theoretically allow downward acceleration faster than gravitational acceleration and downward forces greater than the combined weight of the mobile platform and its hardware. The benefit of having every proximal anchor point above the workspace is to help avoid collisions between the cables and objects in the workspace, which could be applicable for a robot sitting over a flat surface such as a conveyor belt.

3.1 Planar Example

Although the manipulator under development is spatial, the expanded capabilities are most easily demonstrated with a planar CDPR. For this purpose, a 3-actuator planar CDPR with anchor points forming an equilateral triangle is considered. In order to qualitatively demonstrate the static equilibrium workspace (SEW) of this manipulator a few assumptions are required. First, the manipulator can be kinematically described as a 3-RPR parallel manipulator without any rotational limits for the revolute (R) joints, while the length of each actuated prismatic joints (P) can have any positive length. Each cable actuator has a minimum allowable tension force that would be the amount required to avoid having a slack cable. That is, it is a non-zero positive value. Also, it is assumed that there is a larger, positive tension value as a maximum actuator force that could correspond to the limits of safe operation based on the cable strength or the driving motor limits.

A second, similar CDPR can be used for comparison that replaces one of the actuated cables with a linear actuator, making it a hybrid CDPR. This actuator has an actuation distance limit from 0 to some finite length, and a force limit that can be negative (a compressive force) or positive (a tension). The manipulators are shown with an approximation of their workspaces in Fig. 3. The SEW of the 3-cable actuator has three sides, each of which are curved-in toward the centre of the manipulator. The requirement for finite tension in the cables makes it so the mobile platform can not be in-line between two of the proximal anchor points. The workspace of the 2-cable plus 1-linear actuator mechanism has an expanded workspace where the side opposite the linear actuator attachment point extends past the convex hull of the actuator base positions.

3.2 Current Research (Spatial 4-UPS)

Extending into the spatial case, a similar effect on the workspace is expected, where the workspace can be extended based on the addition of a linear actuator

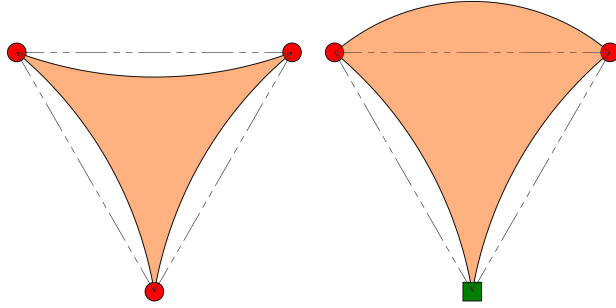


Fig. 3: Qualitative SEW of two variants of a planar CDP. Red circles represent cable actuators and the green squares represents a linear actuator. The shaded area is an approximation of their respective workspaces.

for compressive forces. While the mass of the end-effector allows motions to take place underneath the actuators in a suspended configuration, the force capabilities are expanded by the addition of the extensible linear actuator making a spatial, hybrid CDP. The goal of this manipulator was to have a workspace similar to that of ABB's Flexpicker, which has a nearly cylindrical workspace with a diameter of 1.13 m and a height of approximately 0.3 m [1]. A simplified manipulator diagram is shown in Fig. 4. The reachable workspace of the designed CDP is explained more in Section 4.

To accomplish a similar workspace, the novel linear actuator is placed at the top centre of a cubic frame with a side length of 2 m. Three cable actuators are placed approximately 1 m from the central linear actuator, equally spaced around the outside of the top of the frame. A finalized CDP with the extensible linear actuator could complete the same pick-and-place motions as the Flexpicker with lower costs and reduced energy consumption due to the mass of the cables being less than that of rigid actuators.

In a spatial manipulator, the kinematic model treats each cable actuator as a \underline{UPS} chain, with U representing a universal joint and S representing a spherical joint. The novel linear actuator should be capable of movements similar to a universal joint, or pointing motions. The kinematic complexity of this manipulator comes from the extensible linear actuator not being a true universal joint. The twisting and bending motions do not take place about coinciding axes, meaning that the point where the rod begins changes as a function of the location of the end-effector, as well as the length of the tape inside the guides between the spools and the beginning of the rod. Consideration will need to be made in the control algorithm in order to maintain reasonable accuracy by approximating the effect of this actuator.

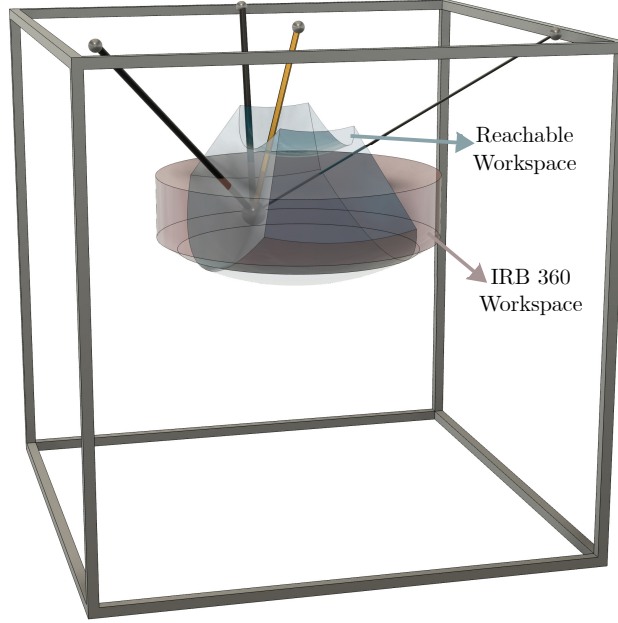


Fig. 4: Simplified model of the manipulator showing the IRB 360 workspace (cylindrical) and reachable workspace of the designed manipulator (wedge of a sphere).

4 Actuator Design

4.1 Methodology

The portion of the actuator that needs to be guided is the driven tape, as it must withstand compressive forces while not having the added strength of being combined into the rigid rod of three tapes. In order to effectively guide the tape it is necessary to prevent unsupported bending and buckling, as that would cause the actuator to be unable to transmit force. Fig. 5 shows a cross sectional view of the tape actuator. A tape enters the actuator on the right, is driven by two wheels that compress it, freely twists through one guide, bends in the next, then is combined with the two other tapes at outlet of the actuator.

In order to allow the tapes to twist about their longitudinal axis the chosen method of support was to create a series of disks with a hole matching the profile of the tapes with the magnetic strips on the outer edges. The holes have a cross-section slightly larger than the tapes, allowing for some motion throughout

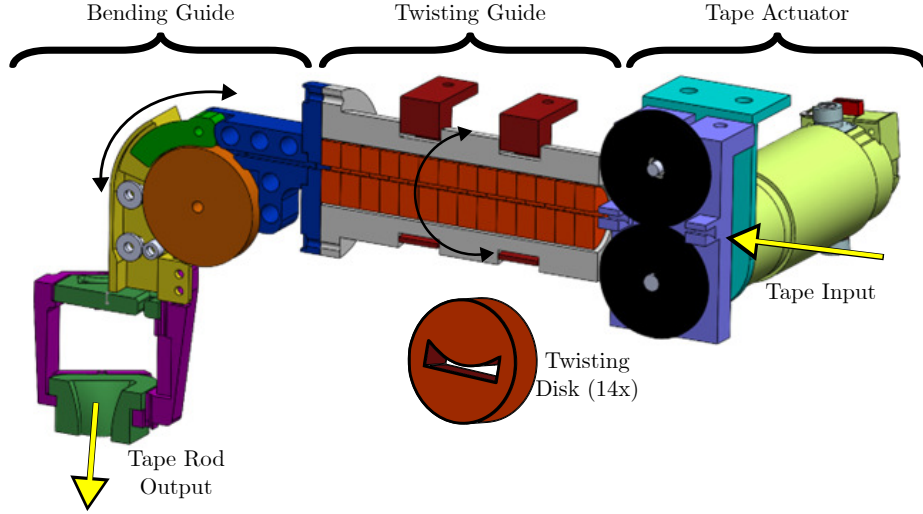


Fig. 5: Full actuator assembly cross section.

their thickness, and the disks can slide relative to one another to allow the tape to experience a significant level of twist while still being supported against buckling throughout the entire length. During the design stage, a length of ≈ 14 cm was adequate to allow the tape to twist throughout the workspace within the $\pm 90^\circ$ range, which is the most that this actuator could move with its current design. To reduce friction during actuation and strain in the driven tape this is artificially decreased to $\pm 45^\circ$. After printing a test disk with the chosen hole spacing it was found that there was adequate clearance and support for approximately 1 cm of length without issues. This discretized the twisting between 14 disks so that each one supports an equal angular displacement. Fig. 5 shows an outer case that is bolted to the frame and the shape of the disks that are used to fill it.

4.2 Bending Guide

The bending guide proved to be a more complex problem as it was hung from the previous twisting guide frame, and the rotation of the tape required it to be bend while still being supported. In order to force the tape to bend in a controlled manner, the chosen method was to rotate it about a fixed radius of curvature by wrapping the tape around a guiding wheel.

To avoid damaging the magnetic strips (or breaking the adhesion between the strips and the tape measures), surface contact on the face of the magnetic strips should be avoided as much as possible. This combination of constraints led to a design with a rolling wheel contacting the flat face and a meshing guide contacting the centre of the tape on the opposite side, as the magnetic strips are

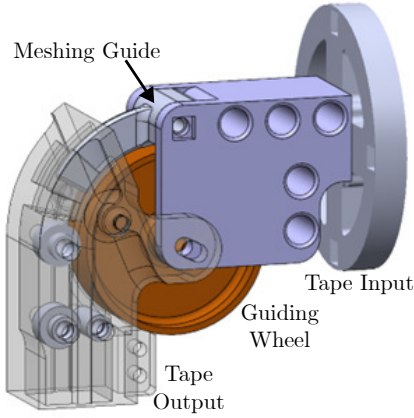


Fig. 6: Bending guide.

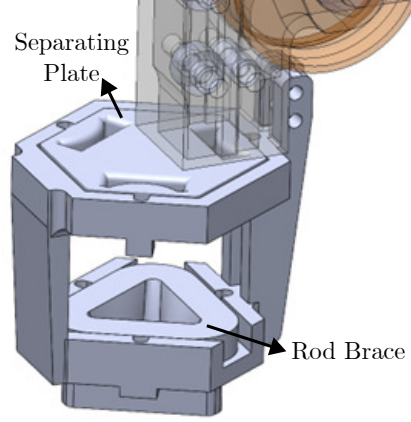


Fig. 7: Tape combining guide.

placed along the outer edges. This guide slots into the rotating part of the guide to support the tape at any feasible rotation angle, and is shown in Fig. 6.

The current design is capable of guiding the tape through a bending rotation of $\pm 23^\circ$, although this could be increased with a few minor modifications to the chosen joint limits. Fig. 6 shows the bending guide, which is bolted to a flange at the end of the twisting guide. The tape passes through the inside of the guide along a wheel, and several rollers support the tape as it straightens after the bend.

4.3 Combining Tapes

After the driven tape passes through the two guides (twisting and bending), it must be brought into contact with the two non-driven tapes to form a rigid rod. The chosen attachment method of having magnetic strips along the outer edges of each tape and a triangular combined configuration necessitates accurate positioning of each of the tapes. Without accurate alignment the tapes may not end up with proper contact and the strength of the actuator (and therefore the amount of force that can be transferred) can be substantially reduced.

The method used to combine the tapes was to have a “separating plate” that has three separated slots for the tapes, and a “rod brace” that smoothly guides each of the tapes together. This functions similarly to how the slider of a zipper separates and combines the teeth. The separating plate has three slots with the shape of the cross-section of the tapes with magnetic strips at the edges, and are angled toward the centre of the brace. The rod brace is shaped to support the three outer walls of the linear actuator and guide the final bend as the three tapes are combined. Fig. 7 shows the end of the bending guide bolted to the separating and bracing pieces. The driven tape is passed directly into the guide, while the non-driven tapes are fed from outside into the separating plate. These

design choices help keep the moment of inertia of the actuator lower than if each of the stored tapes were fixed to the moving rod.

The actuation of the driven tape happens immediately before any of the guides, and each of the parts is fixed to the frame. The driven tape passes out of its case into a frame with wheels used for actuation. There are two wheels, each of which has a slot for rubber O-rings on the outer face to have a high friction surface to contact the painted metal tapes. One wheel is driven and is connected to a DC gearmotor using a keyed shaft. A second shaft supports another wheel that is free to rotate on bearings, but extension springs are used on either side to pull the two wheels together to increase the contact force and reduce the chance of slipping. Fig. 5 shows the tape actuator, where the bottom wheel is driven by a motor, the top wheel is free to rotate, and the top of the brace is bolted to a plate on the frame.

4.4 Reachable Workspace

Given the limitations in the bending and twisting guides, the reachable workspace of the h-CDPR is the same as that of the designed linear actuator. This is shown in Fig. 4, and is compared directly with the workspace of ABB's Flexpicker (IRB 360) in Fig. 8. A maximum linear actuator length of 1 m was used for this reachable workspace because that is the length that has been tested in [13]. The minimum length was chosen to be 0.5 m, giving the reachable workspace a spherical shape as the inner and outer surfaces. The current reachable workspace is shown as a wedge of the area common to two spheres with radii of 0.5 m and 1 m, with bending limits of 90° and twisting limits of 46° . Future validation may allow for a linear actuator maximum length to exceed 1 m and modifications of the bending guides to allow for greater rotations than the current $\pm 23^\circ$ currently used, which would expand the reachable workspace. The static equilibrium and wrench-feasible workspaces will be a subset of this, and based on the final joint limits and actuator capabilities of the constructed manipulator, as well as the desired task.

5 Conclusion

The development of a hybrid CDPR shows promise as a method to complete pick-and-place tasks with lightweight and efficient actuators. The novel extensible linear actuator extends past what many prior actuators were capable of by combining multiple tapes into a rigid rod. If the spatial actuator performs similarly to the prior tests with fixed-length test samples, this manipulator should be more than capable of expanding the capabilities of conventional CSPRs in terms of force capabilities. With further development, this system could be used in facilities that would otherwise use a conventional parallel manipulator, such as ABB's IRB 360, with improvements to the amount of overhead vertical space required. Theoretically, this manipulator can retain all the same benefits of a CDPR while providing more functionality, and these prospects will continue to be studied as this project develops.

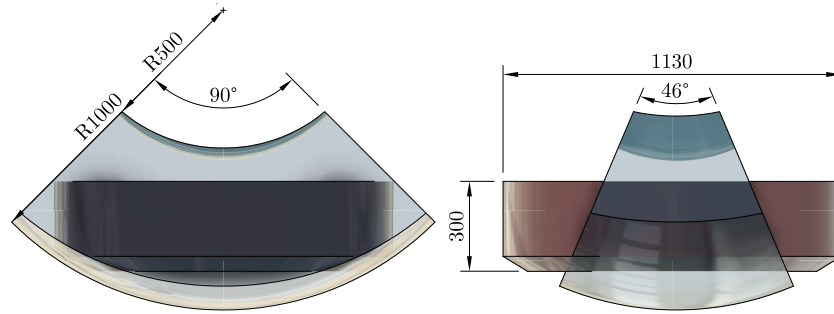


Fig. 8: Comparison of the workspace of the IRB 360 (cylinder) to the reachable workspace of the designed h-CDPR (wedge) Dimensions are in mm.

References

1. ABB: Product specification: IRB 360. Website (2021), <https://new.abb.com/products/robotics/industrial-robots/irb-360>
2. Alamdari, A., Krovi, V.: Modeling and control of a novel home-based cable-driven parallel platform robot: PACER, pp. 6330–6335. IEEE (Sep 2015). <https://doi.org/10.1109/iro.2015.7354281>
3. Arya, M., Lee, N., Pellegrino, S.: Ultralight structures for space solar power satellites. In: 3rd AIAA Spacecraft Structures Conference (2016)
4. Banik, J.A., Murphey, T.W.: Performance validation of the triangular rollable and collapsible mast. In: Proceedings of the Small Satellite Conference. vol. 24, p. 8. AIAA/USU, <https://digitalcommons.usu.edu/smallsat/2010/all2010/10/> (2010)
5. Behzadipour, S., Khajepour, A.: Cable-based robot manipulators with translational degrees of freedom. In: Industrial Robotics: Theory, Modelling and Control. Pro Literatur Verlag, Germany / ARS, Austria (Dec 2006). <https://doi.org/10.5772/5035>
6. Bobbio, S.M.: Spool-mounted coiled structural extending member. United States Patent No. 7,891,145 (2011)
7. Carretero, J.A., Gosselin, C.: Wrench capabilities of cable-driven parallel mechanisms using wrench polytopes. In: IFToMM Symposium on Mechanism Design for Robotics (Sep 2010)
8. Chu, Z., Lei, Y.: Design theory and dynamic analysis of a deployable boom. Mechanism and Machine Theory **71**, 126–141 (Jan 2014). <https://doi.org/10.1016/j.mechmachtheory.2013.09.009>
9. Duan, J., Shao, Z., Zhang, Z., Peng, F.: Performance simulation and energetic analysis of TBot high-speed cable-driven parallel robot. Journal of Mechanisms and Robotics **14**(2) (Sep 2021). <https://doi.org/10.1115/1.4052322>, 024504
10. Gala Systems: Spiralift Technology. Website (2023), <https://www.galasystems.com/en/spiralift/>
11. Guinot, F., Bourgeois, S., Cochelin, B., Hochard, C., Blanchard, L.: Hybrid tape-springs for deployable hexapod. In: 50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference. American Institute of Aeronautics and Astronautics (May 2009). <https://doi.org/10.2514/6.2009-2611>

12. Jensen, F., Pellegrino, S.: Arm development review of existing technologies. techreport, Cambridge University Dept. of Engineering (2001)
13. Mathis, A.: A high packing ratio linear actuator for use in cable driven parallel manipulators. Master's Thesis, University of New Brunswick (2018), <https://unbscholar.lib.unb.ca/islandora/object/unbscholar%3A9763>
14. Mishra, U.A., Caro, S.: Forward kinematics for suspended under-actuated cable-driven parallel robots with elastic cables: A neural network approach. *Journal of Mechanisms and Robotics* **14**(4) (May 2022). <https://doi.org/10.1115/1.4054407>
15. Mottola, G., Gosselin, C., Carricato, M.: Dynamically feasible motions of a class of purely-translational cable-suspended parallel robots. *Mechanism and Machine Theory* **132**, 193–206 (2019). <https://doi.org/https://doi.org/10.1016/j.mechmachtheory.2018.10.017>
16. Pott, A.: Cable-Driven Parallel Robots. Springer International Publishing (2018). <https://doi.org/10.1007/978-3-319-76138-1>
17. Rauchenbach, H.S.: Solar cell array design handbook. techreport, NASA (Oct 1976)
18. Rehnmark, F., Pryor, M., Holmes, B., Schaechter, D., Pedreiro, N., Carrington, C.: Development of a deployable non-metallic boom for reconfigurable systems of small spacecraft. In: 48thAIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference (2007)
19. Saito, T.: Manipulator mechanism. United States Patent No. 20,100,242,659 (2010)
20. Sciarra, G., Rasheed, T., Mattioni, V., Cardou, P., Caro, S.: Design and Kinetostatic Modeling of a Cable-Driven Schönflies-Motion Generator. In: the ASME 2022 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2022. St. Louis, Missouri, United States (Aug 2022), <https://hal.archives-ouvertes.fr/hal-03758220>
21. Seifart, K., Göhler, W., Schmidt, T., John, R., Langlois, S.: Deployable structure for flexible solar generators. In: In Proceedings of the European conference on spacecraft structures, materials & mechanical testing (2005)
22. Servant, C.: Conception d'un actionneur prismatique rétractable. Master's Thesis, Université Laval (2021), <https://robot.gmc.ulaval.ca/fileadmin/documents/Memoires/clemence.servant.pdf>
23. Soetebier, S., Raatz, A., Maris, C., Krefft, M., Hesselbach, J.: Spread-Band: A smart machine element enables compact parallel robot design. In: Volume 2: 28th Biennial Mechanisms and Robotics Conference, Parts A and B. ASME-DETC (Jan 2004). <https://doi.org/10.1115/detc2004-57069>
24. Stanev, S., Heinz, R.: Linear drive mechanism. United States Patent No. 20,120,160,042 (2012)
25. Yang, J., Su, H., Li, Z., Ao, D., Song, R.: Adaptive control with a fuzzy tuner for cable-based rehabilitation robot. *International Journal of Control, Automation and Systems* **14**(3), 865–875 (Jun 2016). <https://doi.org/10.1007/s12555-015-0049-4>
26. Yuasa, K., Arai, T., Mae, Y., Inoue, K., Miyawaki, K., Koyachi, N.: Hybrid drive parallel arm for heavy material handling. In: Proceedings 1999 IEEE/RSJ International Conference on Intelligent Robots and Systems. Human and Environment Friendly Robots with High Intelligence and Emotional Quotients (Cat. No.99CH36289). vol. 2, pp. 1234–1240 (1999). <https://doi.org/10.1109/IROS.1999.812848>
27. Zhang, Z., Shao, Z., Wang, L., Shih, A.J.: Optimal design of a high-speed pick-and-place cable-driven parallel robot. In: Gosselin, C., Cardou, P., Bruckmann, T., Pott, A. (eds.) *Cable-Driven Parallel Robots*. pp. 340–352. Springer International Publishing (2018). https://doi.org/10.1007/978-3-319-61431-1_29