

# Concept Paper: Cable-Driven Robots for Use in Hazardous Environments

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**Abstract** - Cable-actuated manipulators, also termed Cable Robots, possess a number of unique properties which make them proficient with tasks involving high payloads, large workspaces, and dangerous materials. This relatively new type of manipulator has found isolated applications such as cargo transport (i.e. the NIST RoboCrane) and camera manipulation (i.e. Skycam), but is still far less common than traditional serial robotic mechanisms and cranes. The authors believe that these robots possess capabilities far beyond their current applications, particularly in interacting with hazardous environments. This paper therefore discusses the concept of cable robots, and describes their advantages over traditional systems while offering approaches for addressing their limitations. The authors hope that this paper will draw attention in the nuclear community to the field of cable robotics so that such robots may some day facilitate safer, more efficient, and more economical interaction with hazardous environments.

## I. INTRODUCTION

Cable robots, i.e. manipulators which actuate a centrally-located end-effector via cables (or “wires”) extending to motors mounted at the extremities of the workspace (Figure 1), constitute a new and promising field of robotics. These robots possess a number of desirable characteristics, including:

- 1) Remote location of motors and controls, resulting in low risk of damage or contamination.
- 2) Stationary heavy components and few moving parts, resulting in low inertial properties and high payload-to-weight ratios,
- 3) Potentially vast workspaces, limited mostly by cable lengths, interference with surroundings, and wrench/force exertion requirements,
- 4) Transportability and ease of disassembly/ reassembly,
- 5) Reconfigurability by simply relocating the motors and updating the control system accordingly,
- 6) Economical construction and maintenance, due to having few moving parts and having no delicate components near the end-effector.

Consequently, cable robots are well suited for many applications such as cleanup of disaster sites, access to remote areas, manipulation of heavy payloads, navigation of irregular terrain, and interaction with hazardous environments.

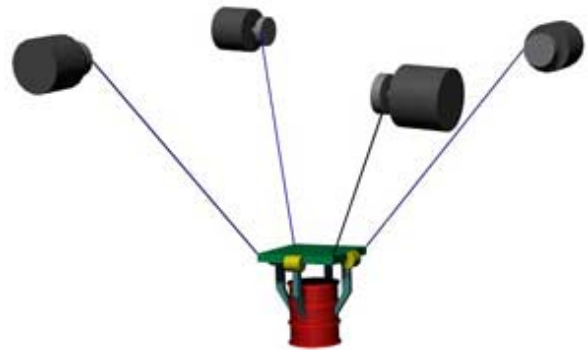


Fig. 1. Example of a spatial, underconstrained cable robot with four cables handling potentially hazardous material.

### I.A. Classification of Cable Robots

It has been shown that cable robots require  $(n + 1)$  wires to fully constrain the end-effector, where  $n$  is the number of degrees of freedom to be constrained. However, frequently fewer wires are used to help avoid cable-interference problems by taking advantage of the end-effector’s weight, which acts similarly to a “cable” pulling downward with constant tension. Such cable robots are termed *kinematically underconstrained*. A fully constrained cable robot possesses more cables, and therefore presents greater risk of cable interference, and therefore limits the usable workspace. The mechanical architecture and computations also increase in complexity for full constraint. Underconstrained systems, which contain fewer cables, offer greater simplicity and

larger workspaces at the expense of controlled degrees of freedom. Overall, underconstrained robots are often preferable, and are therefore the focus of this paper.

Additionally, cable robots may incorporate either a point-mass end-effector where all cables attach at a single point (thereby constraining only translational degrees of freedom) or a finite-size end-effector where rotational degrees of freedom are also constrained. The former results in vastly simplified computations and analysis, but the latter constitutes a more realistic situation. Both cases are addressed here.

Cable robots may also operate in planar or spatial arrangements, depending on the desired application. The descriptions in this paper address both scenarios. Figure 1 shows schematically an example of a four-cable, spatial cable robot with a finite-size end-effector.

### I.B. Obstacles

Despite these robots' obvious potential, they face a number of obstacles. Current challenges include the optimization of workspace properties, maintenance of positive cable tensions, design of suitable control algorithms, sensing of end-effector motion, avoidance of cable interference, and others. Many of these issues have been addressed by researchers, and this paper presents the general approaches to resolving them.

Workspace issues are particularly important, as many large-scale applications require the end-effector to operate in regions of a particular shape, and to exert certain minimum forces and moments (or *wrenches*) throughout those regions. (Note that for the point-mass case, the end-effector is one point and can therefore only exert forces). The *Force-Feasible Workspace* represents the set of end-effector positions, for a given robot design, for which the robot can exert a set of required forces on its environment. An understanding of this workspace is necessary for optimal cable robot design and has been investigated by the authors in [1] and [2], so a summary of that work is presented here.

### I.C. Paper Organization

Section II discusses general attributes, both positive and negative, which are characteristic of cable robots. Next, Section III summarizes current applications and research being performed in the field of cable robots, and Section IV proposes several future applications of cable robots. Section V outlines a number of practical considerations pertaining to the design and implementation of cable robots, including the important Force-Feasible Workspace. Section VI offers a brief discussion of the Force-Feasible Workspace and provides a table of general correlations between this workspace and cable robot design parameters.

## II. CABLE ROBOT CHARACTERISTICS

Cable-actuated robots possess many desirable attributes which make them well suited for applications in hazardous environments. However, cable robots experience certain limitations as well. Following is an explanation of the most significant positive and negative characteristics typical of cable robots.

### Advantages

- 1) **Remote Location of Actuators/Electronics:** Due to the placement of most delicate electronic equipment and motors away from the end-effector, damage incurred from manipulation of contaminated objects can be kept to a minimum.
- 2) **Large Workspace:** Cables possess relatively little mass, and can therefore extend over great distances without exceeding available motor torques. This allows for extremely large workspaces.
- 3) **High Load Capacity:** The load capacities are comparable to construction cranes.
- 4) **Very High Payload-to-Weight Ratio:** Cable robots can manipulate tremendous payloads in relation to their own weight, making them very energy-efficient to operate.
- 5) **Transportability:** Due to their minimal mass and bulk, cable robots can be easily transported to sites where they are needed.
- 6) **Easy Assembly/ Disassembly/ Stowability:** Similarly, cable robots are relatively simple to dismantle and store, and later reassemble.
- 7) **Modular:** Components are easily interchanged, leading to versatility and simplicity of repair.
- 8) **Fault Tolerant:** Cable robots lend themselves to redundancy of cables and other components, resulting in high fault tolerance.
- 9) **Reconfigurability:** Cable robots' geometry can be easily modified by moving motor mount positions, and their topology can be altered by adding or removing motors and changing end-effectors (i.e. cameras, grippers, magnets, etc.)
- 10) **Low Cost:** Due to the simplicity of components, cable robots are anticipated to be relatively inexpensive both to construct and repair.
- 11) **Variable Stiffness:** End-effector stiffness can be modified to meet task requirements by adjusting cable flexibility and sag properties, number and position of cables used for constraint, and stiffness in the control scheme.
- 12) **Reliability:** Cable robots take advantage of mechanical simplicity, and therefore exhibit strong reliability.

### Disadvantages

- 1) **Moderate Accuracy:** Inaccuracies at the end-effector can result from cable stretching and



Fig. 2. Skycam is a video camera system which traverses large volumes using four Kevlar cables. [3]

sagging, variation in cable spool properties (i.e., spool diameter increases with the number of windings), and calibration issues.

- 2) **Limited Force Application:** Downward force capabilities for underconstrained cases may be limited to the payload's weight, and other directions are limited by robot geometry.
- 3) **Potential Control System Challenges:** The incorporation of moving motor mount locations with changing wire lengths, as well as the coordination of redundant wires, may require complex control schemes and more sensors.
- 4) **Limited Workspace/Orientation:** Force exertion requirements and cable interference may limit useful end-effector positions and orientations.
- 5) **Set-up and Calibration Time:** Some time is required for assembly at the worksite, as well as calibration to determine the initial locations of the motor mounts and end-effector.
- 6) **Overhead Space:** Motors must be elevated from the desired workspace to achieve desired motion and wrench exertion capabilities.
- 7) **Cable Interference:** The potential arises for cables to interfere with each other and obstacles in their environment if operated in a confined space.

### III. CURRENT APPLICATIONS AND RELATED WORK

Currently most cable robots intended for specific applications are still in laboratory development. One of the exceptions is the Skycam [3], shown in Figure 2. Skycam is a broadcast-quality robotic camera suspended from a cable driven, computerized transport system with joystick control, and is used in stadiums and indoor arenas. The underactuated cable suspension uses four Kevlar braided cables able to apply up to 600 lbs (2670 N) each, yet are so thin, 0.1 in. (0.25 mm) in diameter that they are nearly invisible to spectators. They are actuated by stationary reels fixed to the stadium or arena, requiring little modification of the building, and enabling transverse speeds of up to 28 mph (44.8 kph). Gravity is necessary to keep the Skycam within the range of proper orientations, due to the underconstrained design. Because the Skycam



Fig. 3. RoboCrane for Material Handling at NIST, manipulating a payload. [4]

does not transport or manipulate any additional loads beyond its own weight, it is relatively straightforward to ensure static stability of Skycam throughout its workspace.

In addition, existing cable robot systems have been developed by the National Institute of Standards and Technology (NIST) for industrial applications. The NIST RoboCrane [4] is a large-workspace robot for painting and maintaining aircraft which is also suitable for material handling in warehouses and storage facilities. Figure 3 shows the RoboCrane for Material Handling picking up a pallet of munitions.

Other research has been previously conducted regarding various fields of cable-actuated robots. For instance, the design of these robots has received considerable attention, resulting in the WARP Manipulator [5] and the FALCON [6]. However, these designs frequently assume a fully constrained manipulator (often impractical due to interaction with the environment), and may not consider usable workspace issues. Cable robot controls research has been performed by [7], [8], and others. A few researchers have considered certain workspace issues in their designs, including the NIST RoboCrane and a six-DOF motion base in [9]. Dynamic workspace analysis has also been performed in [10], incorporating the motion of a moving end-effector.

The precise geometry of a cable robot's Force-Feasible Workspace and the parameters which influence it have been explored by the authors of this paper in [1] and [2]. These papers built upon the work of [11] and [12], and the concept of *force feasibility* explored in [13]. The first author has also explored the compensation for motor mount disturbances through a control system; this work will be presented in [14] upon the completion of his Master's Thesis.

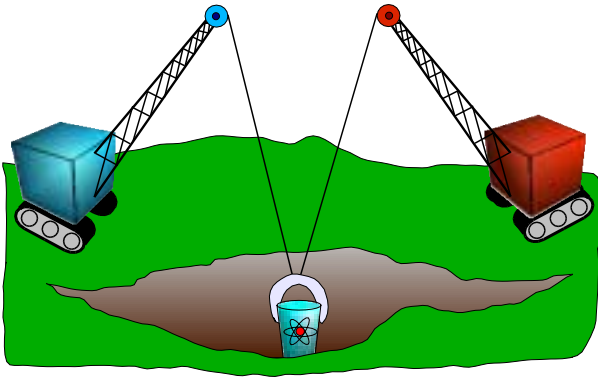


Fig. 4. Two retrofitted cranes working in collaboration to manipulate hazardous material underground.

#### IV. PROPOSED FUTURE APPLICATIONS

The positive attributes of cable robots far outweigh the negatives for many applications beyond those presently existing, particularly those involving hazardous environments. One such potential application involves the handling of explosives. These robots can be easily transported to a required site and tailored to meet the demands of the task. Once in operation, cable robots' high payload capacity allows them to safely transport very heavy explosives. Because of the potential for unanticipated detonation, it is desirable for all motors and electronics to be as far removed from the end-effector as possible. Cable robots' remote actuator placement, as well as their large workspaces, facilitate this. Furthermore, in the case of an explosion, cable robots benefit from inexpensive and simple part replacement due to their simplicity and modularity, and may also help minimize the effects of such a failure with redundant cables.

Similarly, cable robots may also be employed in military countermining tasks. Ground-penetrating radar equipment can be swept at low altitude over a potential minefield to detect mine locations without risk of accidental detonation. Once mines are detected, cable robots can then facilitate demining. For instance, by dragging a heavy object from the end-effector throughout a mine field, the mines can be harmlessly detonated with no damage incurred by the robot's motors or controls.

Materials contaminated by radiation, biological agents, toxins, or unknown wastes can also be safely handled within or outside a work cell. The robots' high reliability is a valuable attribute, and the large workspace and remote actuator placement permit the operator and motors to function in a shielded environment. And because much contaminated material has been stored in large steel drums, the robots' tremendous lifting capacity is beneficial. Additionally, cable robots provide an easy means of retrofitting old equipment, which is

useful because many less-adept machines are already being employed for the task of hazardous materials handling. For instance, in canyon decommissioning applications, cranes are frequently used which can control the horizontal position of a motor along the length of a narrow canyon, and can extend or retract a wire-mounted hook in the vertical direction. Two of these cranes could be retrofitted to operate in collaboration to provide improved control of a single end-effector, as shown in Figure 4. Finally, because cable robots are easily reconfigured and retrofitted, they are extraordinarily versatile. They can be modified in both the number and the arrangement of motors to obtain planar or spatial workspaces of different shapes and proportions.

Cable robots are also ideally suited for various types of sensory data acquisition applications. Possibly contaminated regions may be inspected without risking injury to personnel or damage to expensive equipment. Such inspections can be performed with cameras for surveillance, or with sensors for detection of dangerous chemicals or radiation. Cable robots permit such sensors to quickly traverse large regions, regardless of irregular ground terrain, and without disturbing their surroundings.

#### V. PRACTICAL CONSIDERATIONS

A number of practical issues exist which must be considered for the successful implementation of cable robots into any hazardous environment application. Recent research has addressed each of the following issues, so while some may pose limitations for cable robots, none is insurmountable.

- *Control of Robot.* A control system must be designed which governs the position, orientation, and motion of the robot, while maintaining positive cable tensions. For many user interaction tasks, the control system must operate in real time, and requires sensors for feedback. Much research has been performed in this area, and effective control schemes exist.
- *Motion Planning.* End-effector trajectories must be designed using inverse kinematics according to the desired path, and to ensure the cables do not interfere with one another. Inverse kinematics work has been performed which can be extended to motion planning in future research.
- *Disturbance Rejection.* The motors, which are often assumed to be stationary, may in some cases be subjected to external disturbances such as wind. It is possible to incorporate a routine into the control system which measures these disturbances and then adjusts the cable lengths to compensate for them, thus maintaining the desired end-effector trajectory.
- *Sensors.* Sensors are needed for both simple position control systems and systems which compensate for

motor mount disturbances. In many cases, position sensors are impractical to implement (most require a direct connection to ground or require line-of-sight between components, and motor encoders do not account for cable sag or stretch), so accelerometers are generally used instead. As these acceleration measurements are integrated twice to yield position, signal noise and offset are amplified, resulting in *accelerometer drift*, or position signals which “drift” toward infinity. Research has developed several control techniques to combat this, including the use of filters, dead bands, and periodic GPS measurements for recalibration.

- *Force-Feasible Workspace*. While cable robots generally possess enormous wrench-exertion capability, they may be very limited in certain directions and at certain points in the workspace. The usefulness of cable robots can be severely limited if an understanding of these workspace issues is not present. Thus, a more detailed explanation of this issue is included in this paper.

## VI. FORCE FEASIBLE WORKSPACE ANALYSIS

Because cable robots’ usable workspace may be irregularly shaped and non-trivial to determine, this is arguably their greatest limitation. Therefore, this section presents a discussion of this topic. This “usable” workspace can be described by the Wrench Feasible Workspace (for a finite-size end-effector) or Force-Feasible Workspace (for a point-mass end-effector), as presented in greater detail by the authors in [1] and [2].

This workspace constitutes the set of all end-effector positions for which a user-specified minimum set of wrenches/forces can be exerted. It is reasonable to assume a point-mass end-effector for the applications considered here, and it vastly simplifies analysis, so the remainder of this paper focuses on this case. Thus, only the *Force-Feasible Workspace* (FFW) is addressed here.

If a Required Force-Set (RF) is defined as the set of all forces which the robot is required to exert, and an Attainable Force-Set (AF) is the set of all forces which the robot is capable of exerting, then the FFW may be constructed as the set of all end-effector points for which the entire Required Force-Set is contained within the Attainable Force-Set. This is region inside which the end-effector can safely operate while exerting all required forces. Mathematically,

$$RF \subset AF \quad (1)$$

Figure 5 shows that for a spatial, three-cable, point-mass robot, the Attainable Force-Set is a parallelepiped. (This would be a parallelogram for a planar, two-cable robot.) It is formed as the region of all combinations

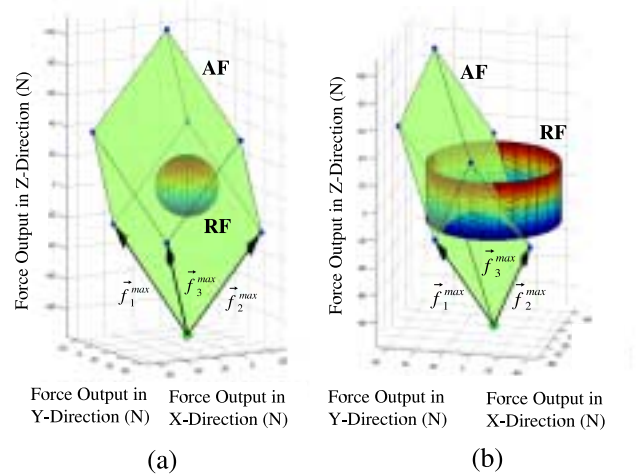


Fig. 5. Sample scenarios: (a) 100% of spherical Required Force-Set contained within Attainable Force-Set, indicating the Force-Feasible Workspace *includes* this end-effector position. (b) 24.9% of cylindrical RF is contained within AF, indicating the FFW *excludes* this end-effector position.

of achievable cable tension vectors, where the maximum tension in cable  $i$  is  $f_i^{max}$ ,  $i = 1, 2, 3$ , shifted downward by the payload weight vector. Note that the cable tension forces must be applied along each cable; therefore the AF changes shape for different end-effector positions. The Required Force-Set can be any arbitrary shape, but is most frequently a sphere or cylinder, as shown. Figure 5(a) shows a case where  $RF \subset AF$ , indicating that this end-effector position is contained within the FFW. Figure 5(b) shows a case where  $RF \not\subset AF$ , indicating that the end-effector is outside of the FFW.

The Force-Feasible Workspace may be determined either numerically (by discretizing the entire workspace and testing each point for the condition in (1)) or analytically. Geometric analysis reveals that in general, the FFW possesses  $\frac{2p!}{(q-1)!(p-(q-1))!}$  boundaries, where  $p$  is the number of cables and  $q$  is the dimension of the task space. Thus, the FFW of a planar, two-cable robot possesses four boundaries, the FFW of a spatial, three-cable robot possesses six boundaries, etc. These boundaries can be computed by determining functions of end-effector coordinates along which the Required Force-Set just touches a boundary of the Attainable Force-Set. Each boundary creates a region inside of which the FFW must lie. The FFW is therefore the intersection of these regions.

Figure 6 shows the construction of the Force-Feasible Workspace for a planar, two-cable, point-mass robot with a circular Required Force-Set. Thus, this could represent the usable workspace (i.e. the set of all configurations where sufficient force can be provided) of the two-crane-

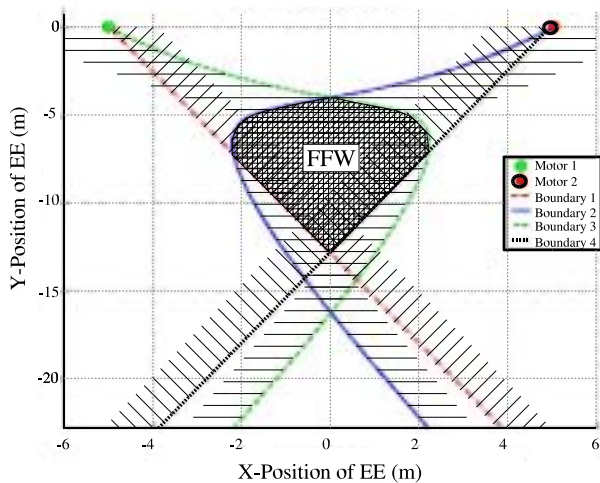


Fig. 6. The construction of the Force-Feasible Workspace (dark region) for a two-wire, point-mass cable robot with a circular Required Force-Set such as the dual-crane scenario pictured in Figure 4.

collaboration scenario pictured in Figure 4. In Figure 6, the green upper-left point represents the motor mounted on the left crane, and the red upper-right point represents the motor on the right crane. It can be seen that the bottom two FFW boundaries are straight lines, while the upper two boundaries are higher-order polynomials.

Table I presents a synopsis of how several design variables effect the FFW (where  $\vec{m}_i$  represents the position of motor  $i$ ,  $f_i^{max}$  is the maximum tension in cable  $i$ ,  $m$  is the combined mass of the end-effector and payload, and  $r$  is the radius of the RF).

These trends generalize to the spatial case, where the lower boundaries are planes and the upper boundaries are curved surfaces. A more detailed analysis that can be used for the design of a cable robot with optimized workspace characteristics is presented in [1].

## VII. CONCLUSIONS

Cable-actuated manipulators possess a number of unique properties which suit them exceptionally well for tasks involving interaction with hazardous environments. While this classification of robots has been used in certain applications, it is still far less common than traditional serial robotic mechanisms and cranes. The authors believe that this new type of robot possesses capabilities far beyond its current applications. Potential future applications involve transportation and manipulation of contaminated materials, countermine tasks, and reconnaissance and sensing. This paper has presented the concept of *Cable Robots*, and has described their advantages over traditional systems. It has also offered approaches for addressing their limitations, focusing on

TABLE I  
GENERAL CORRELATIONS BETWEEN THE FFW BOUNDARIES AND  
VARIED PARAMETERS.

By Increasing This Parameter	Effects on Force-Feasible Workspace Boundaries (↑ = Expands ↓ = Contracts ⇕ = Mixed — = No Effect)				
	Boundary 1	Boundary 2	Boundary 3	Boundary 4	Overall FFW
$\vec{m}_1$ (vert. component)	↓	↓	↑	—	⇕
$\vec{m}_2$ (vert. component)	—	↑	↓	↓	⇕
$\vec{m}_1$ and $\vec{m}_2$ (vert. components)	translates	translates	translates	translates	translates
$f_1^{max}$	—	↑	—	—	↑
$f_2^{max}$	—	—	↑	—	↑
$f_1^{max}$ and $f_2^{max}$	—	↑	↑	—	↑
$m$	↑	↓	↓	↑	⇕
$r$	↓	↓	↓	↓	↓

issues pertaining to the Force-Feasible Workspace. The authors hope that this paper will draw attention in the nuclear community to the much-deserving field of cable robotics so that such robots may some day facilitate safer, more efficient, and more economical interaction with hazardous environments.

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