A CABLE ARRAY ROBOT DESIGNED
FOR OVERHEAD RETRIEVAL

A Thesis in
Industrial Engineering
by
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ABSTRACT

The Cable Array Robot Technology (CART), first patented by Holland and Cannon in 2004, represents a new class of robots which have demonstrated the ability to precisely manipulate heavy loads, such as shipping containers, over large workspaces. These characteristics make the robots suitable for many tasks traditionally completed by cranes or other material handling equipment, while providing improved efficiency.

While the issue of load stabilization has been largely solved by using a cable array instead of a single vertical cable to suspend a load, a remaining issue with current cable array robot design, for some applications, is unintended collisions between the cables and obstacles in the workspace. This could damage the cables or the objects, poses a safety risk for anyone in the area, and reduces the size of the work envelope. Solving this issue, for cases such as lowering containers into the hold of a ship, could facilitate quicker acceptance of this robot class for widespread deployment.

For this Penn State Masters Degree effort, new prototypes of end effectors which allow for overhead retrieval, similar to the function of a typical crane, have been developed. Two of the prototypes used one set of winches and cables to drive the end effector while the other set drives the crane function. Of these prototypes, one locates the second set of winches on the end effector while the other locates the winches at the masts. Another prototype implemented a cable reeving structure that used one cable from each mast in a continuous loop from the winches, located at the mast, to the end effectors. Finally, a prototype was developed which uses a set of pulleys, fixed to the same shaft, which uses a clotheslines approach to wind a second set of cables for crane functionality.
The continuous loop and clothesline prototypes were tested using a cable array robot. While the continuous loop prototype failed to perform well, the clotheslines prototype was successful in providing crane functionality. Recommendations for improving the efficiency of the robot through nested arrays are suggested for future work.
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Chapter 1
INTRODUCTION

1.1 Motivation

Material handling equipment providers have developed numerous methods for moving an object, the payload, from point A to B. Solutions exist both in ground based and overhead forms. Ground based can be classified as conveyors, forklifts, automated guided vehicles, etc. Overhead solutions include cranes, monorails, helicopters, etc. Each solution suffers from trade-offs, including cost, mobility, speed, reconfigurability, and payload control. The term Cable Array Robot, coined by Cannon in his patent by that name, describes a set of three or more motor actuated cables connected to a central object (end effector), and offers a solution which improves performance compared to many other material handling configurations.

Cannon’s previous prototypes and field-deployed units have demonstrated that cable array robots are a viable choice for moving an end effector in three dimensions. Additional Researchers have developed alternate configurations, each of which has tended to exploit various benefits of a cable-driven robotic system. Work has been conducted to describe the kinematics and dynamics of the systems, along with developing numerous control strategies.

1.2 Problem Statement

Other cable driven mechanisms presented in literature typically have three or more cables connected to a single end effector. Cannon developed a material handling system which uses four cables connected to an upper (active spreader) and lower (messenger spreader) end effector (Cannon et. al 2001). As part of patenting the overall
Cable Array Robot Technology (CART) concept, as shown in figure 7, a portion of the ensuing patent (# US 6,826,452 B1 Nov.30, 2004) included the description of an active spreader having four winches, one at each corner, that control the vertical height of the messenger spreader. The end effector assembly is shown in Figure 1. A winch is considered to be an assembly consisting of a motor with rotational control, gear train, and a drum.

![Diagram of Active and Messenger Spreaders with Container](image)

Figure 1: Active and Messenger Spreaders with Container (Holland and Cannon 2004)

A configuration which enables vertical control of the messenger spreader allows the system to potentially avoid complications arising from unintended collisions between the cables and objects.

An alternative technique for controlling the height of the messenger spreader, subsequently proposed by Cannon, involves modifying the cable runs in the main array and changing the control structure. Termed the “clothesline” approach, each cable, instead of terminating at the active spreader, is instead looped around a drum at the active spreader. The cable is then routed back to the originating mast and wound around a
second drum powered by the motor. This avoids having to carry separate large motors on the spreader bar and instead utilizes the powerful existing winches. At each drum on the active spreader, a second cable is wound and terminated at the messenger spreader.

When both drums at the mast are rotated, at identical speeds, in such a way as to feed cable onto the drums (reverse) or feed cable off the drums (forward) the active spreader will exhibit motion typical of a standard cable array robot end effector. Alternatively, if the drums are rotated at either different speeds or different directions, the drum located on the active spreader will rotate. This will cause the messenger spreader to move in a vertical direction.

The intent of the work presented herein is to extend upon the system patented by Holland and Cannon for a cable array robot intended for material handling. In particular, different techniques for controlling the location of the messenger spreader were investigated.

1.3 Overview of Thesis

The remainder of this thesis is intended to provide the reader with an overview of existing cable array robotic systems and an explanation of the extension provided in this work.

Chapter 2 presents background information on previously developed prototypes and anti-sway control methods for cranes. Chapter 3 provides a description of the prototypes of this research, the cable array robot used to test the prototypes, and the test results. Chapter 4 provides a discussion of applications for cable array robots. Finally, Chapter 5 presents a conclusion of the performed work.
Chapter 2

LITERATURE REVIEW

2.1 Introduction

Previous researchers have investigated closed chain parallel robotic systems in many different forms. Initially work focused on devices containing rigid connectors, or links, in the system. These connectors could withstand tension and compression. Cable actuated systems, where the cables are acted on by winches, provide an alternative to the rigid connectors. Cables are flexible structures which only act on the end effector when in tension.

Existing literature for closed chain parallel robotic systems is dominated by rigid connector devices, such as the Stewart platform. Kinematic and dynamic descriptions, as well as workspace analysis, for rigid connector devices are well understood. Research into cable actuated systems is able to share many findings from rigid systems, with appropriate modifications for maintaining tension. Cannon’s students and collaborators present findings for the kinematic description and a sliding mode controller for cable actuated robots (Cannon et. al 2001). Others in Cannon’s laboratory also provide an analysis of dynamics for cable actuated robots, with a focus on at sea cargo handling (Shiang et. al 1999). Bosscher and Oh and Agrawal present an analysis of feasible workspace for cable actuated robots (Bosscher 2004, Oh and Agrawal 2006).

The remainder of this chapter will present designs for parallel robots and techniques for anti-sway control of traditional cranes.
2.2 Stewart Platform

Serials robots, such as articulated arm robots commonly found in industrial applications, suffer from numerous drawbacks, chiefly the cantilever structure of the arm. This inherently limits the load carrying capacity and workspace of the robot. An articulated arm robot is shown in Figure 2.

![Articulated Arm Robot (IRB 6640 from ABB)](image)

Figure 2: Articulated Arm Robot (IRB 6640 from ABB)

Dasgupta and Mruthyunjaya reviewed recent literature related to Stewart platforms. Stewart (alternatively Stewart-Gough) platforms represent a generic class of closed chain parallel robotic manipulators. Originally developed to provide motion control for flight and tire simulations, Stewart platforms provide a fully constrained system which is both fast and capable of carrying heavy loads, as shown in Figure 3 (Dasgupta and Mruthyunjaya 2000).

![Graphical representation of a Stewart platform](image)

Figure 3: Graphical representation of a Stewart platform (Dasgupta and Mruthyunjaya 2000)
2.3 Cable Array Robots - Applications

Numerous cable driven mechanisms have been developed by academic and industry researchers. Robots will be reviewed for their structural design and intended functions.

2.3.1 Robocrane

The development of the NIST Robocrane, more appropriately a Stewart platform with cables for links, serves as an ancestor from which each cable driven robotic mechanism is derived. Initially the Robocrane (or SPIDER – Stewart Platform Instrumented Drive Environmental Robot) was designed with a rigid base and a stated intent of providing the ability “to lift, maneuver, and position large loads with precise control of position and force in all six degrees of freedom” (Albus et. al 1992). Work was preformed which demonstrated mathematically and experimentally that the Robocrane did meet the design intent. Research branched into two main categories, development of controls and sensing capabilities as well as identifying applications for the crane.

Robocrane has been successfully applied to a number of manufacturing and exploration scenarios. NIST developed prototypes for welding, grinding, material handling, pipe fitting, inspection, bridge construction, fire fighting, and aircraft maintenance (Bostelman et. al 1994). The advantages of Robocrane, precise control of an end effector over a large work envelope, are realized in changing and hazardous environments. Figure 4 shows a self-contained welding system manipulated by a Robocrane. The system was developed for double-hulled ship construction (Bostelman et. al 1999).
2.3.2 FALCON

Typical serial robots used for assembly operations have a number of drawbacks, including weight, speed, and cost. FALCON, a fully constrained wire driven parallel manipulator, uses the benefits of a cable array robot to alleviate the issues with typical serial robots (Kawamura et. al 1995). FALCON can be seen in Figure 5.
FALCON uses a unique arrangement of cables to provide for high speed and high stiffness control of the end effector. Typical cable array robots require gravitational force to fully constrain the system. FALCON employs a set of three additional cables, attached to a rod mounted vertically to the end effector, to eliminate the need for gravitational forces. The system is able to achieve higher acceleration and velocity because it is not limited by gravity.

2.3.3 Air Vehicle Simulations

A research group looking to reduce the cost of investigating a wide variety of vision based control algorithms for aerial vehicles, static/moving target tracking, autonomous landing, pose stabilization, insect-based navigation strategies, terrain following, collision avoidance, struggled to fund research using traditional aerial devices. A working prototype was developed which uses four mast assemblies and a central control computer (Usher et. al 2004). The prototype is shown in Figure 6. The pod, or end effector, is designed with a rack to accommodate computers and sensors.
Much of this work relates closely to the issues faced by Cannon’s cable array robots for material handling in dynamic environments. The Cable Array Robot Technology (CART) was developed for large workspaces, where larger loads might be encountered. These advantages are clear for a specific application while the disadvantages of the cable array robot include cable interference, cable stretch inaccuracies, limited force in the downward direction, and limitations on overhead space in some cases.

Significant time was spent to solve engineering problems related to monitoring cable tensions and spooling of the cables. This work led to further developments in Cannon’s laboratory, such as those of Gorman et. al, involving two types of controllers. One controller was based on cable velocity and the other was based on position control of the end effector. Each strategy initially implemented the end effector as a point mass, but the authors suggested that their end effector was designed in such a way that the cables could be connected in multiple configurations.
2.4 Material Handling Robot

Cannon then developed and tested the Cable Array Robot Technology (CART) at ¼ scale (64 feet by 64 feet by 32 feet in dimensions) on a Navy ship at sea in 2005. This CART robot served as the basis for the work presented herein. The principle application is a robot which is used to manipulate ISO shipping containers that are as heavy as 55,000 lbs. Additional applications are suggested, including pallet handling in a manufacturing or logistics environment, radioactive waste container handling, de-icing airplanes on the tarmac, truck loading in open-pit mining, and at-sea ordnance maintenance. Figure 7 depicts the robot, mounted on the main cargo ship, interacting with a lighter ship.

Figure 7: Cable Array Robot for Container Handling (Holland and Cannon 2004)

The intent is to provide a system such that “sufficient control is possible so that the present cargo handling system may unload, without crane pendulation, the deck and hold of a ship onto a sea-going lighter during sea state three conditions.” An attempt has been made to minimize the effects of lighter movements, sea states, port conditions, and
variations in operator skill. The system consists of mast assemblies, an off loading fairlead, end effector, sensor networks, and control system.

2.4.1 Mast Assemblies

Each cable array typically consists of four telescoping and collapsible masts. There may be more than one array on a single ship. The masts can be removed from the deck and stored in ISO containers for storage. Each mast extends over the sidewall of the ship to provide an expanded work envelope. A winch is positioned under the deck at each mast location. Each winch is wound with a single cable that runs from the drum assembly, over the mast, and dead ends at the rotating mechanism attached to the active spreader.

2.4.2 End Effector Assembly

The end effector assembly, as shown in Figure 1, has multiple features which aide in controlling the container. For controlling the vertical displacement of the messenger spreader four individually controlled winches are mounted on the active spreader, one at each corner. Additionally, this arrangement allows for the control of the pitch and roll of the messenger spreader. The rotating mechanism on the active spreader allows for the control of the yaw for the entire end effector. Two systems, in addition to the tension forces provided by the cables, are presented for controlling the pitch and roll of the active spreader. Screw jacks, positioned in the horizontal plane, offer one method of control. The more robust method is a four bar linkage which is capable of controlling the orientation of the active spreader.
2.4.3 Off-Loading Fairlead

Without constraining the work envelope with collision detection, it is possible for the end effector to reach regions which are outside the sidewalls and/or below the deck of the ship. This functionality is desirable in certain situations, such as that shown in Figure 7, when a cargo transfer occurs between the main ship and a lighter. If this were attempted, a collision would occur between two of the cables and the edge of the cargo ship. To alleviate this issue, a fairlead is used to modify the path of the cable. Unlike typical rigging situations, the cables are not typically engaged to the fairlead. The end effector, and potentially the cargo, must take a particular path to ensure that the cables properly engage the fairlead.

2.4.4 Sensors

A complex set of sensors, some of which are redundant, are used to perform a variety of tasks in the system. Sensor fusion techniques are performed by the control system to utilize the incoming data and apply it in the control algorithms. The purpose of different sensors may be grouped into three main categories, including visual operator aides, end effector control, and container pick-up/drop-off operations.

Visual operator aide sensors consist of pan and tilt live video cameras mounted on the mast tips, bridge, ship sidewalls, and end effectors. The cameras have night vision, enabling operations to continue in conditions with limited lighting. The cameras primary function in this role is to provide a supervisory view of the environment, including the deck, containers, and other objects. An auxiliary function of the cameras is to provide position information from the encoders on the pan and tilt motors.
End effector control is achieved through a variety of sensors. Differential global positioning system antennas are mounted on the mast tips, bridge, and at two points on the end effector. This highly accurate system is able to provide real-time position data of each of the antenna locations. Optical encoders are located at each winch, including the masts and active spreaders, to measure the cable lengths. Cable tension meters are located at each mast to measure the current tension.

Container pick-up operations are aided by a machine vision system. ISO containers have a female twist lock mechanism at each corner which is engaged by the messenger spreader to secure the container. In order to properly position the messenger spreader to pick-up the container, the location of each twist-lock mechanism is identified. Container drop-off operations are aided by laser range finders. As the distance between the drop-off location and the laser range finders change, the control algorithm can calculate the required distance and orientation to properly land the container.

2.4.5 Control System

The system uses a controller which fuses the data from multiple sensors and operator inputs to perform path planning and motion control. This system operates in a real-time and fault-tolerant manner to provide efficiency and safety to the operation. Live video feeds from the cameras are fed to the operator. The operator is not required to be on the ship. The data may be available over a network, such as the internet. Using an interface device, such as an instrumented glove or computer mouse, and a set of virtual tools, the operator can select a container on the screen and direct the computer to “put that there”. The algorithms generate the trajectory and provide the operator with a visual representation which checks for collisions. The operator can then initiate the cable robot
to perform the task. A result of this system, which automates the container handling
process, is a reduction in the number and skill of operators needed.

2.5 Anti-Sway Control

Prior to the cable array concept for stabilizing loads, others looked at using swing
free control techniques. Throughput of a port crane, either ship mounted or quay side, is
an important characteristic which should attempt to be maximized. With near certainty
the cargo container will experience forces which induce sway, which can result from both
internal and external forces, the crane operator must allow for the sway to subside before
setting the container for these vertical cable cranes with no cable array stabilization.
Control strategies have been proposed to compensate for this unwanted motion, which
will be reviewed below.

2.5.1 Image Sensor Based Control

Some authors present an approach for controlling the effect of acceleration and
disturbances on cranes, with a focus on container cranes (Kawai et. al 2009). Typically
research has focused on the use of trolley motion for suppressing spreader sway. Their
new solution implements a mass damper system which is mounted on the spreader. The
system consists of a damping mass, belt/ball screw, and a motor. A schematic of the
system is shown in Figure 8.
A video camera is mounted on the trolley and provides real-time feedback on the location of the spreader. The system uses two bulls-eye style targets on the spreader to determine the distance between the trolley and spreader as well as the sway. From the sway and distance calculations a controller was developed to control the movement of the damping mass.

The authors suggest that their laboratory experimentations reflect a system which is capable of controlling sway in changing environments. Additionally, the target system used for the vision system is robust to changing conditions. An issue with this system is that it is not capable of controlling degrees of freedom which are not parallel with the applied damping forces.

2.5.2 Inclinometer Sensor Based Control

Other authors present an approach for controlling the spreader sway which avoids the use of a vision system. An argument is made which describes vision systems as having high procurement costs and the difficulties related to maintenance of a field deployed crane. In lieu of tracking the spreaders position via image acquisition and
processing, an inclinometer is used to detect the sway angle. From the sway angle and the known cable lengths, the position of the spreader is known.

A controller is developed which uses the spreaders position and velocity to counteract the effects of uncontrolled environment variables. The controller commands the trolley to adjust its position, velocity, and acceleration in one degree of freedom in an attempt to minimize sway. Using the trolley in this manner is a common approach, but the proposed system models the reeving structure of a typical quay crane as opposed to a simple pendulum. As shown in Figure 9, the hoist cables exert forces with components in both the horizontal and vertical directions. This provides greater control over the spreader than a simple pendulum configuration.

![Figure 9: Rail Mounted Quay Crane Reeving Structure](image-url)
Chapter 3

MODEL DEVELOPMENT

3.1 Introduction

Previous researchers working with Cannon have successfully demonstrated robust prototypes of cable array robots deployed in dynamic environments. The systems are capable of precise control of heavy loads over large workspaces. An issue that affects all cable array robots is that objects in the workspace constrain the movement of the end effector due to collisions between the cables and objects in the environment. The remainder of this chapter will explore various end effectors, cable reeving structures, and control methods for collision avoidance.

3.2 Concept Exploration

Cable array robots can support large three dimensional workspaces. A constraining factor for accessibility is objects in the work space. Figure 10 shows an end effector attempting to retrieve the target object. Dashed lines represent the cables. The end effector has overhead visibility of the entire target object, but because of the masts used in the system and the size/location of the objects, a collision occurs between the cables and objects. Figure 11 shows an end effector attempting to retrieve the target object. Again, the end effector has overhead visibility of the entire target object, but this configuration enables retrieval without a collision.
There are multiple methods for target retrieval without a collision, including moving the object, adjusting the masts, fairleads, and overhead retrieval. Moving the object that is causing the collision is appealing, given its simplicity. Given that there is a place to move the object and the object is moveable, no changes in the structure or control of the robot are required. Unfortunately, this method does not comply with a lean principle of no double handling. Mast adjustment is described as changing the location of a mast tip relative to the other masts. This includes height changes and position changes. This method requires mobile mast platforms to change the position and telescoping masts to change the height. A unique arrangement such as this is impractical in certain applications, such as material handling on a cargo ship. Fairleads, as demonstrated in Figure 7, are commonly used for modifying the direction of a cable run. For moves which are repeated frequently performed and the additional equipment is not overly restrictive, a fairlead may provide the necessary adjustment to avoid the collision. For infrequent moves, a fairlead must still be secured in the proper position and orientation before the move occurs.

Overhead retrieval, as shown in Figure 11, requires modification of the end effector, control methods, and possibly reeving structures. It eliminates the need for additional equipment, moveable masts, double handling, and fairleads.
3.3 End Effectors

The end effector used in the overhead retrieval process, the active spreader, performs a function analogous to a fairlead. Unlike fairlead operations, the end effector can be positioned anywhere within the work envelope without prior set-up. An additional piece of hardware is required, the messenger spreader.

3.3.1 Prototype A

Holland and Cannon initially presented an active spreader, as seen in Figure 1, which uses a set of independently controlled motors to adjust the height of the end effector (Holland and Cannon 2004). Building on that concept to envision new approaches, Prototype A operates with the same principles and is shown in Figure 12 and Figure 13. The rotator allows for unlimited rotation between the cable array connection points and the rest of the active spreader assembly. This results in rotational control of the messenger spreader and its load.

![Prototype A End Effector](image_url)

Figure 12: Prototype A End Effector
The reeving structure for Prototype A is shown in Figure 14. The primary array consists of a set of cables, in this case three, with one extending from the mast to the primary array connection point. Similarly, the secondary array consists of three cables, each originating at a winch mounted on the active spreader, and terminating at the messenger spreader. Compared to typical cable array robots, this arrangement is similar in that each cable, including the primary and secondary cables, must be designed according to Equation 1.

\[
\text{Cable Design Load} = \frac{1}{\text{Number of Masts}} \times \text{Maximum Load} \tag{1}
\]
Prototype A is controlled using techniques similar to existing cable array robot controllers. An exception is that motor controllers mounted on the active spreader must be able to communicate with the main system controller.

3.3.2 Prototype B

In Prototype A, the motors mounted on the active spreader control the height of the messenger spreader. In certain situations, this arrangement might not be ideal. The size of the motors and gear train necessary to manipulate large loads may be prohibitive. This adds unnecessary weight to the end effector. Prototype B presents a new approach for controlling the messenger spreader height. As shown in Figure 15 and Figure 16, Prototypes A and B interface with the primary array identically.
Prototype B consists of the pin, primary array connection points, and three subassemblies. The subassemblies consist of a knuckle, finger, and pulley. Each knuckle fits over the pin and interlocks with the other knuckles. The knuckles are able to rotate about the z axis. The finger is connected to the knuckle by a dowel pin, allowing it to rotate about the horizontal plane.
Prototype B uses a secondary array, as shown in Figure 17. Instead of mounting the winches on the active spreader, as in Prototype A, the winches are moved to the mast locations. There are three cables in the primary array. At each mast, one end of the cable is wound around the drum while the other end terminates at the primary array connection point. The primary array cables in Prototype B perform only a positioning function, except for the weight of the active spreader. Therefore, smaller diameter cables may be used for the primary array. The secondary array, also consisting of three cables, runs from the mast location, over the pulley at the active spreader, and terminates at the messenger spreader. The cables used in the secondary array must be able to handle loads equal to Equation 1. This is the same as Prototype A.

Figure 17: Prototype B Reeving Structure

Control of Prototype B is more complex than Prototype A. The winches controlling the primary array and the winches controlling the secondary array must be synchronized in their actions. To perform overhead retrieval, the primary array must maintain its position while the secondary array feeds forward and reverse.
3.3.3 Prototype C

An alternative to Prototypes A and B, which use the primary array for active spreader positioning and the secondary array for overhead retrieval, is the method proposed for Prototype C. Prototype C consists of an active spreader, as shown in Figure 18 and Figure 19, which attempts to re-route the primary array cables. Its function is identical to a fairlead.

Figure 18: Prototype C End Effector

Figure 19: Prototype C End Effector (Top View)
Prototype C contains only a primary array. The primary array consists of three cables. At each mast, the ends of a single cable are wound around separate winches. Each cable runs from the mast to engage the top set of pulleys at the active spreader, cross the mid section to engage the bottom pulley set, before meeting at the return pulley. Note that in Figure 20, the primary array represents two cables at each mast.

![Diagram of Prototype C Reeving Structure](image)

**Figure 20: Prototype C Reeving Structure**

In conjunction with the development of the active spreader for Prototype C, a messenger spreader was also developed, as shown in Figure 21 and Figure 22. The messenger spreader contains return pulleys, which are required for the continuous cable arrangement being presented.
The cables used for the primary array must be designed to handle half the load that the load bearing cables for Prototype A and B require. Equation 2 represents the cable design load for Prototype C.

\[
Cable \ Design \ Load = \left( \frac{1}{Number \ of \ Masts \ \cdot \ \text{Maximum \ Load}} \right) \cdot 0.5 \quad (2)
\]
Control of Prototype C requires synchronization of each winch in the system. To raise the messenger spreader, each cable must be fed in. Similarly, to lower the messenger spreader, each cable must be fed out. The position and orientation of the active spreader is not able to be modified unless the messenger spreader is in the fully raised position.

### 3.3.4 Prototype D

Prototype D builds upon a concept presented by Cannon which describes a pulley system which acts like a clothesline. As shown in Figure 23 and Figure 24, the pin, knuckles, and fingers are functionally equivalent to Prototype B. Missing from the pin are the primary array connection points. Each pulley assembly consists of three pulleys, one for the primary array and two for the secondary array, fixed to a shared shaft. Rotation of the primary array pulley causes rotation of the secondary array pulleys. For individual views of each part see PROTOTYPE D PART VIEWS in the appendix.

![Figure 23: Prototype D End Effector](image)

Figure 23: Prototype D End Effector
The reeving structure for Prototype D is shown in Figure 25. The primary array for Prototype D is similar to the primary array used in Prototype C. At each mast, the ends of a single cable are wound around separate winches. There are three cables in the primary array. Each cable runs from the mast to the primary array pulley at the active spreader. The secondary array consists of three cables, one for each pulley assembly. At each pulley assembly there are two secondary array pulleys. A single secondary array cable is used at each pulley assembly. One end of the cable is wound around a secondary array pulley and extends to the return pulley. From the return pulley, the cable is wound, in the same direction, around the other secondary array pulley. The messenger spreader used for Prototype C, as shown in Figure 21, was also used for Prototype D. For both the cables used in the primary and secondary arrays, the cables must be designed to handle loads according to Equation 2.
Control of Prototype D requires synchronization of all six winches used in the system. In order to maintain the position and orientation of the active spreader while either raising or lowering the messenger spreader, the feed rates of the upper and lower leads must be matched. Controlling the position and orientation of the active spreader requires that both the upper and lower cable be fed in or out simultaneously. By following this policy, the active spreader can move about the workspace similar to other cable array robots.

In the reeving structure shown in Figure 25, the secondary array on the left of the active spreader is wound counterclockwise. To lower the messenger spreader, the pulley assembly must rotate clockwise. This requires the primary array to feed out the upper lead and feed in the lower lead. The more challenging case is raising the messenger spreader. In order to raise the messenger spreader, the primary array must feed in the upper lead and feed out the lower lead to induce counterclockwise motion of the pulley assembly.
The difficulty arises from friction and gravity. The primary array must transfer energy to the pulley assembly to raise the messenger spreader. If the primary array cable slips over the pulley instead of causing it to rotate, it will be impossible to raise the messenger spreader. Increasing the coefficient of static friction is one way of reducing the slippage. As shown in Figure 24, the primary array pulley has a “u” channel for engaging the cable. If this were modified to a “v” channel, which would pinch the cable as larger tensions were applied, the coefficient of static friction would increase.

### 3.4 Cable Array Robot Development

In order to evaluate the prototypes, a cable array robot was built. The following section will describe the construction of the end effectors, mast assemblies, and controllers.

#### 3.4.1 End Effectors

Prototype A and B are appealing candidates for providing overhead retrieval capability to a cable array robot. A requirement for each is the usage of cables which can support loads from Equation 1. An advantage of Prototype C and D is the load forces are distributed over twice the number of cable leads. This allows for smaller cable diameters and smaller motors.

For the purpose of this work, Prototype C and D have been built. Each prototype was created using a combination of rapid prototyped (RP) parts and off the shelf components. The RP parts were created using a fused deposition modeler in ABS plastic. Prototype C can be seen in Figure 26. Prototype D can be seen in Figure 27. The messenger spreader can be seen in Figure 28.
Figure 26: Prototype C

Figure 27: Prototype D
3.4.2 Mast Assemblies

A three mast cable array robot was created. The design allows for flexible positioning of the masts. The purpose of this is to allow for testing the system performance under varying setup conditions. A mast assembly is shown in Figure 29 and the entire cable array robot assembly is shown in Figure 30.
Figure 29: Mast Assembly Model

Figure 30: Cable Array Robot Model
The controller used at the mast is a Serializer from Summerour Robotics. It communicates with the main control computer over XBee wireless mesh networking. The controller receives cable feed in or out commands and issues them to the motors. A PID controller is built into the Serializer, which uses data from the quadrature encoders mounted on the motors.

3.4.3 Cable Array Robot Controller

The controller is issued commands by a central computer. A program was written in C# which utilized the Serializer .Net application programming interface. The program is able to perform two main functions, setup and motor control. Figure 31 and Figure 32 show the screens for setup and control of the cable array robot.

![Figure 31: Cable Array Robot Controller - Setup Screen](image)

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![Figure 31: Cable Array Robot Controller - Setup Screen](image)
From the Setup screen, a number of functions can be performed. Connections between each mast and the central control computer can be created and destroyed. Current system parameters, such as mast and PID configuration can be set. Each winch in the system can be controlled via feed rate and length commands.

The Main screen is the primary place for motor control. It is capable of performing, coupled with the Serializers in the system, as a rudimentary CNC controller. The program instructs each Serializer to command the winches to spin a specific number of revolutions at a set speed. The controller is classified as a point-to-point device, as opposed to one which interpolates.

The Main screen is broken up into three main components, including CNC File Load, Jog, and Current Commands. CNC File Load serves to open CNC files and set
program run parameters. Lines can be stepped through using Single Block or the program can execute each line sequentially. When a command is issued to each Serializer, the main control computer will not issue new commands until each Serializer returns a command complete message. Jog allows for position control of the end effector assembly in user-defined step sizes. Current Commands provides information related to the kinematics of the system as well as the ability to send the end effector assembly to a specific set of coordinates.

3.4.4 Kinematics

Cannon et. al provided the basic kinematic description used for the cable array robot presented in this work (Cannon et. al 2001). Figure 33 shows the mast and cable layout. Each spreader is represented as a point mass, M1 for the active spreader and M2 for the messenger spreader. L1, L2, and L3 represent the cable lengths from the top of the mast to the active spreader. L4 represents the cable length from the active spreader to the messenger spreader. Figure 34 shows the mast layout. A Cartesian coordinate system is used to describe the workspace. a, b, and c represent the distance between each mast.
From the mast diagram and layout, equations for the mast coordinates and kinematics can be found. The mast coordinate are defined in Equations 3, 4, and 5
“where \((x_i, y_i, z_i)\) represent the Cartesian coordinates of the top of the \(ith\) mast” and \(h\) is the distance from the \(x-y\) plane to the top of the mast (Cannon et. al 2001).

\[
(x_1, y_1, z_1) = (0, 0, h) \quad (3)
\]
\[
(x_2, y_2, z_2) = (a, 0, h) \quad (4)
\]
\[
(x_3, y_3, z_3) = (c \cos \theta, c \sin \theta, h) \quad (5)
\]

Equations 6, 7, and 8 represent the inverse kinematic relationship.

\[
L_1 = (x^2 + y^2 + (z - h)^2)^{1/2} \quad (6)
\]
\[
L_2 = ((x - a)^2 + y^2 + (z - h)^2)^{1/2} \quad (7)
\]
\[
L_3 = ((x - c \cos \theta)^2 + (y - c \sin \theta)^2 + (z - h)^2)^{1/2} \quad (8)
\]

Equations 9, 10, and 11 represent the forward kinematic relationship.

\[
x = \frac{1}{2a} (L_1^2 + a^2 - L_2^2) \quad (9)
\]
\[
y = \frac{1}{2c \sin \theta} (L_1^2 - L_3^2 - \frac{c \cos \theta}{a} (L_1^2 + a^2 - L_2^2) + c^2) \quad (10)
\]
\[
z = h - (L_1^2 - x^2 - y^2)^{1/2} \quad (11)
\]

3.4.5 Prototype Tests

Prototype C and D were tested using a desktop sized cable array robot. Prototype C failed to perform the required tasks. While it might be reasonable to expect that the forces from each cable/pulley interaction would hold the active spreader in place while the messenger spreader was raised and lowered, during testing it was shown that any tension on the cables would drive the active spreader towards the messenger spreader. It is unknown if the concept behind Prototype C, a continuous cable run from each mast to the messenger spreader, can be made into a viable option.
Prototype D was tested to determine its ability to perform two operations:

1. Raising and lowering the messenger spreader while maintaining the position of the active spreader.
2. Active spreader movement around the workspace while maintaining the distance between the active and messenger spreader.

It was found through repeated tests that Prototype D was able to satisfactorily perform both operations. A couple of issues were identified during testing. The pin in the active spreader assembly is not naturally held vertical due to two set of forces. The pulley arrangement at the masts causes the primary array cables to twist. This force is exerted onto the pulley assembly at the active spreader. Additionally, the knuckles do not distribute their forces acting against the pin in a balanced manner. These two forces could be balanced by suspending weight from each finger.

A second issue, which could result in unpredictable motion of the spreaders, comes from the pulley assembly slipping. When this happens, the messenger spreader will lower in an uncontrolled manner. Two solutions for this are proposed. The first involves a twist-lock. When the messenger spreader is in the fully raised position, the twist lock can engage. This will prevent the messenger spreader from slipping. A second method uses a braking system located on the active spreader. This applies force to the pulley assembly, similar to a disc brake, and prevents slipping.

3.5 Field System Development

While containers being lowered into the hold of a ship will have guide tracks, it should be noted that for other free movement applications, the advantage of the cable array begins to be countered as a messenger spreader is lowered too far below the pivot
point. For a cable array robot deployed to the field it is anticipated that the messenger spreader will exhibit characteristics of a pendulum in the presence of base excitation. In Chapter 2, existing research into anti-sway control was presented. In addition to exploring the application of the techniques previously described, it is proposed that the active spreader (at the pivot point) can act as a counter balance to the messenger spreader. This action would be similar to anti-sway control methods which use trolley motion to dampen the pendulum.
Chapter 4

APPLICATIONS

4.1 Introduction

Many industrial applications have been proposed for cable array robots (Bostelman et. al 1994, Holland and Cannon 2004). Some of the proposed applications have been tested using prototypes. Only a few of the prototypes have succeeded to become field deployed robots (Bostelman 1999). With the addition of overhead retrieval for collision avoidance to the characteristics of cable array robots, existing applications are enhanced and new applications are enabled. This chapter is intended to expand on material handling applications of cable array robots.

4.2 Container Handling

Sea based cargo handling was the main catalyst for the work presented here. With greater control of the messenger spreader it may become unnecessary to include the fairlead shown in Figure 7. This will eliminate the need for positioning and orientation before engaging the fairlead, resulting in a time savings.

In addition to having dual cable arrays on a single ship, which creates two separate workspaces, cable arrays could also be nested within a single workspace. The central issue with nested arrays, without overhead retrieval, is path planning to avoid collisions between the cables. This problem can be greatly simplified if each array operates within a set vertical height range. Figure 35 shows a diagram of two nested cable arrays.
4.3 Manufacturing Systems

Many different types of manufacturing systems could benefit from the use of a cable array robot to move people, equipment, and material around the workspace. A job shop is useful for low volume production of a high volume of part types. Work cells are created, and these can be arranged by a number of different methods. When a spaghetti diagram is drawn of the material and resource flow through the system, it is typically quite convoluted. Fixed solutions, such as conveyors, are unsuitable for the variability in part and resource routing. Therefore, flexible material handling solutions are desirable. Ground solutions, such as fork trucks, require trained operators, large turning radii, and pose safety concerns. An advantage of fork trucks and other ground based solutions is the ability to have multiple material handlers operating in the same workspace. Overhead material handling systems, such as bridge cranes, are typically slow and are prone to blocking. Figure 36 shows three work cells serviced by two bridge cranes. From their current positions, Bridge Crane A can service Work Cell A and B, while Bridge Crane B can service Work Cell B and C. If Bridge Crane A moves to service
Work Cell B, and a request is made in Work Cell A for a material handler, the requestor must wait. This happens even when Bridge Crane B is idle.

Assuming that there is overhead clearance for running cables, which is correct if there are bridge cranes, a single cable array robot could provide a solution to this problem. The cable array robot is able to operate at much higher travel speeds than a bridge crane. An additional advantage compared to fork trucks is the elimination of wide aisles necessary for turns and passing trucks. This allows for better utilization of the space by adding more valuable equipment. Depending on the situation, the cable array robot may be able to position the work piece in the fixture of machine tool or another robot. This could reduce the need for operators and increase the automation level within the job shop.
Chapter 5

CONCLUSIONS

Cable array robots represent a class of robots which offer large workspaces, large load capacity, and precise movements. The advantages have been demonstrated in numerous prototypes with some field deployment. For many applications, however, unintended collisions between cables and objects in the workspace represent a concern that prevents widespread use of the concept thus far.

The work presented herein resulted in the development of four end effector designs to guide cables for collision free operation. Prototype A and B are candidates for providing overhead retrieval. Field tests of a design similar to Prototype A, by previous researchers, have demonstrated its capabilities. Prototype B operates by the same concept as A, except the secondary motors are moved from the active spreader to the masts. A drawback for each is that higher strength cable must be used. Prototype C is one end effector design that was shown to be limited, though modifying the reeving structure might lead to the development of a successful continuous cable loop design. Prototype D, on the other hand, consistently performed well. It was tested at laboratory scale and must undergo further testing at both a larger scale while using more robust control algorithms and sensors to reflect real operating conditions.
REFERENCES


Appendix A

PROTOTYPE D PART VIEWS

Prototype D Assembly

Pulley Assembly
Pulley Assembly (Top View)

Knuckle
Knuckle (Top View)

Finger
Finger (Top View)

Pin
Appendix B

CONTROL SOFTWARE DETAILS

To control the cable array robot used for prototype testing, the host computer must be able to communicate and issue commands to the Serializers. A control program was written in C#, under the .NET platform. This program utilizes the application programming interface published by Summerour Robotics under an open-source license. This API provides access to the commands used to control and communicate with the Serializers. The purpose of this appendix is to provide the reader with details of the hardware, control software, related documents and drivers.

Serializer Pinout (From Summerour Robotics)
The Serializer Pinout diagram shows all of the components that can be interfaced with or controlled by external devices. For the cable array robot, The Power Input, XBee Module Receptacle, Motor 1 & 2 Terminals, and Encoder Ports 1 & 2 are used. 12v DC power supplies are used to provide power to the Serializer, XBee module, motors, and encoders. From the as-built picture is it clear that many ports are available for future expansion. Additional sensors for the robot could be included, such as distance sensors for detecting the distance between the active and messenger spreaders.

![Serializer with Wiring and Components](image)

An XBee module must be located at the host computer to send and receive messages. If the XBee module is not used for communication, a USB interface can provide the same link to the host computer. A URL is provided at the end of this appendix for downloading drivers for the XBee modules.

The control software, located on the host computer, communicates with the Serializers, performs kinematic calculations, and provides the user with an interface for directing the motion of the robot.
From the Setup screen, a number of different functions can be performed. Each group of functions is separated into its own group box. The Communication group box allows for the communication between the host computer and a Serializer to be created and destroyed. A list box containing available communication ports is provided. Unless the name of the communication ports can be correlated with the physical port, trial and error must be used to identify this relationship. The user must select a communication port from the list box, enter a mast number (1, 2 or 3) into the input box, and press the connect button. These actions will instantiate a new object into memory. The controller will establish communication with the Serializer and read values stored in the Serializers non-volatile memory. Similarly, the user can select a communications port and press the disconnect button. This will destroy the communications link and the Robot object.

Setup Screen
The End Effector group box is used to select the prototype currently being tested.

The Motor Control group box provides direct control of the motors. Each motor can be individually controller for direction but not speed. The On/Off radio button group sends power to every motor that is checked to run. Also, each running motor must have a rotation direction specified. The speed value is unitless, ranging from 0 to 100. During testing it was discovered that the motors would fail to spin with values below 25 and values greater than 75 would cause erratic behavior. The reasons for this are unknown. The system does not track the amount of cable that has been released while the Motor Control functionality is in use.

The Mast Configuration group box enables the proper calculation of the kinematics of the system. All values are in inches. a, b, and c represent the distance between each mast tip. h1, h2, and h3 represent the height of the masts. L1, L2, and L3 represent the cable lengths from the mast tip to the center of the active spreader. The Write and Load button brings up an open file dialog. By selecting the appropriate file, the data from the file will be read in to populate the mast configuration fields. When cable lengths are changed in the Main screen, the new values are written to the file. The purpose of this is to enable easier testing of the system. From the information entered during the mast configuration, the coordinates of each mast location is used to populate the Mast Coordinates group box on the Main screen.

When communication is established between the host computer and the Serializer, the PID values are read from the Serializers non-volatile memory. These values then populate the PID Configuration fields. The values can be changed and loaded into the
Serializers non-volatile memory by selecting the Load button. Similarly, selecting the Default button will load the values that were initially stored in the Serializers memory.

The Main screen allows the user to control the cable array robot using point to point CNC and view current command information. The CNC File Load group box contains an open file button. By selecting this button an open file dialog box appears. A user then selects a .CNC file, which the program reads and uses to populate the list box. Each line represents the coordinates relative to the center of the active spreader. The values are in absolute coordinates. Each line in the file must be formatted as shown in the figure. No header information is allowed. Each (X,Y,Z) pair must include the coordinate identifier (“X”), a value to the left of the decimal, a decimal, a single digit to the right of the decimal, and a space in between each identifier and value pair. When the Open File button is selected, the values in the list box are cleared.
Main Screen

The program can execute the CNC code using two different methods. The most thoroughly tested function is single block. When the Single Block button is selected, the highlighted line will execute when the Run Program button is selected. The program parses the values contained in the highlighted line to the target coordinates. These values populate the Target Coordinate group box. It should be noted that the program does not check the target coordinates to determine if they fall within the work envelope. The target coordinates are then used to calculate the inverse kinematics, which provides the necessary cable lengths. These values populate the Inverse Kinematics group box.

From the cable lengths, the forward kinematics is calculated. These values populate the Forward Kinematics group box. The results obtained from the forward kinematics equation should be equal to the target coordinates. The system subtracts the
cable lengths needed to move the end effector to the target coordinates from the previous
cable lengths. These values, along with the difference between the current end effector
location coordinates and the target coordinates, are used to populate the Dist. To Go
group box. Finally, when the Run Program button is selected the motors will rotate the
appropriate distance to feed in or out the correct amount of cable. The CNC control is
used only to move the active spreader in three dimensional space. Control of the
messenger spreader is performed using the handle jog function.

Alternatively, when not in single block mode, the Run Program button will force
the each line to run sequentially. The program will not pause between lines. The Feed
Hold button stops the motors from turning. The system does not contain an emergency
stop. Removing the power to the system is the only guaranteed method of preventing the
motors from turning.

The speed of the motors at each mast is paired, but each mast can be set to run at a
different speed. In testing, a value of 25 for each mast resulted in the smoothest motion,
while using the factory default PID settings.

The Jog group box provides functionality similar to a handle jog on traditional
CNC machines. The program allows for simultaneous motion of the active spreader in
three dimensions. LE stands for lower end effector, or messenger spreader, and it may
only be controlled when the active spreader is not moving. Based on the values obtained
from the forward kinematics equations, the step size is applied to the selected
coordinates. This calculation results in target coordinate values. From here the target
coordinate values are used to calculate inverse kinematics. Each group box used to
display values is updated as previously described.
Similar to the Jog function, the active spreader may be commanded, using the Go To Commands, to travel to a certain set of (X,Y,Z) coordinates. The speed values in the CNC File Load group box are also used for the Job and Go To Commands.

Drivers are required to use the communications hardware. They can be downloaded at


The Serializer .Net API can be downloaded at