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# A ROBOTIC CRANE SYSTEM UTILIZING THE STEWART PLATFORM CONFIGURATION

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## ABSTRACT

The Robot Systems Division of the National Institute of Standards and Technology (NIST) has been experimenting for several years with new concepts for robot cranes. These concepts utilize the basic idea of the Stewart Platform parallel link manipulator. The unique feature of the NIST approach is to use cables as the parallel links and to use winches as the actuators. So long as the cables are all in tension, the load is kinematically constrained, and the cables resist perturbing forces and moments with equal stiffness to both positive and negative loads. The result is that the suspended load is constrained with a mechanical stiffness determined by the elasticity of the cables, the suspended weight, and the geometry of the mechanism. Based on these concepts, a revolutionary new type of robot crane, the NIST SPIDER (Stewart Platform Instrumented Drive Environmental Robot) has been developed that can control the position, velocity, and force of tools and heavy machinery in six degrees of freedom (x, y, z, roll, pitch, and yaw).

The SPIDER can perform a variety of tasks by using different equipment suspended from its work platform. Examples are: cutting, excavating and grading, shaping and finishing, lifting and positioning.

A 6-meter version of the SPIDER has been built and critical performance characteristics and control methods analyzed.

## 1. INTRODUCTION

A new crane design utilizing six cables to suspend a load platform was first developed by the National Institute of Standards and Technology (NIST) in the early 1980's. A NIST program on robot crane technology, sponsored by Defense Advanced Research Projects Agency (DARPA), produced the design, development and testing of three different sized prototypes to determine the performance characteristics of this proposed robot crane design. A description of the overall DARPA program and the results of this research are presented in [1]. Initial testing of these prototypes showed that this design results in a stiff load platform [2, 3]. This platform (see figure 1) can be used in typical crane operations, or as a robot base, or a combination of both. Applications of this new crane design in the construction industry are illustrated [4].

The objective of this paper is to briefly describe the SPIDER (Stewart Platform Instrumented Drive Environmental Robot), its functional capabilities, and its operational procedures. The primary function of the SPIDER is to lift, maneuver, and position large loads with precise control of position and force in all six degrees of freedom. The SPIDER has the following potential functional capabilities: cutting, excavating and grading, shaping and finishing, lifting and positioning, flexible fixturing, and transporting manipulators. We have already developed several applications with SPIDER. These capabilities can be targeted for a variety of specific applications such as fighting oil well fires or hazardous waste site inspection and clean-up.

In response to the oil fires set in Kuwait during the Persian Gulf War, NIST adapted its robot crane technology to assist in extinguishing oil well fires. A system called the NIST Oil Well Fire Fighting Robot (NOWFFR) was designed and constructed. Early in 1991, the NOWFFR design was modified for applications related to nuclear and toxic waste site cleanup. The new robot design is called the "SPIDER". The SPIDER is lightweight and easily assembled. The SPIDER can be made mobile by attaching vehicles to the feet so that it can be driven over rough terrain.

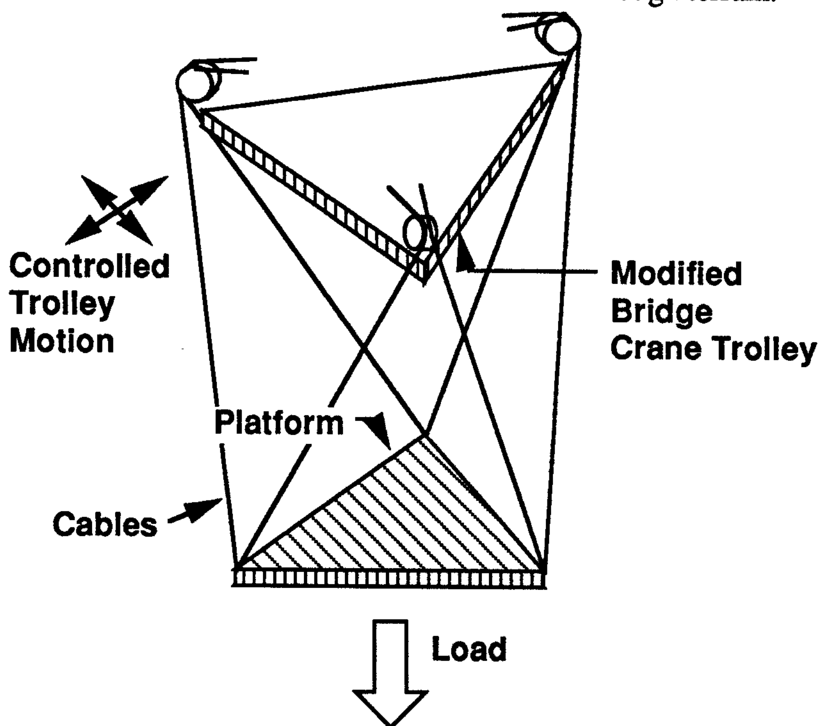


Figure 1 - Design Concept for Improving Stiffness of Crane Suspension Mechanisms

A number of advantages of the SPIDER over current technology are: rigid support and precise maneuverability of large loads, remote positioning of tools and equipment, executing precise motions with tools/equipment to accomplish complex tasks, high lift-to-weight ratio, resistance to environmental perturbations, accurate control of loads by a novice operator , reduced crew size.

The next section describes the system design, showing both the SPIDER design and a comparison to conventional cranes, followed by a section describing the different control modes of the SPIDER. A summary and conclusion section follows, as well as a list of references for the paper.

## 2. SYSTEM ARCHITECTURE

The SPIDER design evolved from previous Stewart Platform work with actuators and cables and winches in place of actuators. When all six cables are in tension, the stable platform is kinematically constrained, and there exists a known mathematical relationship between the lengths of the six cables and the position and orientation of the platform. The theory of this mathematical relationship has been known for many years and was first embodied in a Stewart platform for testing tires in the 1950's [5], and applied to aircraft flight simulators during the 1960's and '70's. It was applied to cable driven manipulators by Landsberger [6,7] and to cranes by NIST in the 1980's [1].

## 2.1 SPIDER Design

The framework of the SPIDER is a six legged structure resting on three support points. The legs are 6 meter aluminum tubes that are ten centimeters in diameter and constructed in an octahedron geometry. These can be seen in Figure 2, which is a photograph of the NOWFFR taken before it was modified to become the SPIDER.

Figure 2 - Photograph of the NOWFFR before it was modified to become the SPIDER. Centered is a heat shield/chimney and a chain saw attached to the platform and ready to cut an oak log.

The top of the SPIDER structure consists of a triangle. Each vertex of the triangle supports two cables. Together, the six cables support a lower work platform. The connecting joints at the vertices consist of ball and socket joints. Due to its octahedron geometry, all forces are directed through points at the vertices. As a result there are no bending or twisting moments generated by the load. Each member of the structure is always in pure compression or tension except for supporting its own weight.

Figure 3 - One of three pairs of winches used to maneuver the platform.

The SPIDER structure thus provides near maximum strength and stiffness possible for any given mass of structural material.

Six 5mm diameter braided steel cables, supporting the lower work platform, are arranged to kinematically constrain the work platform such that its stiffness is determined by the tensile elasticity of the cables. The length of each cable is controlled by a winch (see figure 3) having a 455 kg load rating. By controlling the six winches simultaneously, an operator can maneuver the lower work platform in six degrees of freedom. The work platform is made of aluminum I-beams. It can be a variety of sizes. Studies at NIST have shown that a 2 to 1 ratio of the upper triangle size to the lower platform creates the stiffest Stewart Platform configuration for lateral force loading [2]. A mathematical model of the robot and a preliminary investigation of its workspace limits are discussed in [4].

The three support points of the octahedron are carried by three vehicles for mobility. To accomplish steering and velocity commands provided by an operator, computer coordination of vehicle track motions is necessary.

### 2.2 Comparison to Conventional Cranes

Existing cranes of many different types from many manufacturers are able to lift comparable loads, but cannot stabilize the loads in rotation or sway and have no means of controlling forces or torques on the load. Under ideal conditions, a highly skilled crane operator can provide some measure of oscillation damping. However, for precise orientation, a crew of riggers is needed to manually stabilize the load from rotating and swinging and to manually guide the load into its final desired position with adverse conditions such as wind. An expert operator cannot prevent perturbations such as wind from causing the load to sway, in some cases by more than a meter. Novice operators of conventional cranes may have difficulty in preventing heavy loads from colliding with objects in the environment.

The principal advantage of the SPIDER is that it provides sufficient control to allow even a novice operator to position a load without sway to within a few millimeters in x, y, and z, and to control orientation without oscillation to within one degree in roll, pitch, and yaw. Force sensors on the SPIDER winch mechanisms could also allow the operator (with computer assistance) to control forces and torques on a load after it comes into contact with the environment. The control provided by the SPIDER could thus reduce the size of the crew needed to manually position loads from three or four, to zero or one. An additional advantage of the SPIDER is its high lift-to-weight ratio. Due to its octahedron geometry, the SPIDER requires no counter weight and experiences no twisting or bending moments. As a result, it can lift at least five times its own weight. This is significantly more than any robot or crane in current use.

## 3. CONTROL MODES

The lengths of the six cables on the SPIDER are controlled by six winches. These can be controlled and coordinated by a computer. Input commands from a six-axis joystick enable an operator to control the motion of the work platform in all six degrees of freedom (x, y, z, roll, pitch, and yaw). The operator can thus maneuver the stable platform, and whatever load or tool that is attached to it, over a large working volume. The SPIDER has three control modes: Manual mode, Computed Manual Mode with a Stewart Platform Joystick and Computed Manual Mode with a Spaceball Joystick.

### 3.1 Manual Mode

The joystick used to control the SPIDER in the Manual mode is a Stewart Platform with linear potentiometers as the parallel links. The joystick potentiometers generate analog voltages for amplifiers to control the winches. By orienting this joystick so that the potentiometers are roughly parallel to the SPIDER cables, the pose of the platform can be controlled under master-slave rate control. In this mode, the operation of each winch is controlled by the displacement of its corresponding potentiometer. Over a limited range wherein the cables and potentiometers remain roughly parallel, the SPIDER motion can be controlled directly by the potentiometers without a computer.

### 3.2 Computed-Manual Mode with the Stewart Platform Joystick

The SPIDER also has a Computed-Manual mode. In this mode the joystick signals are switched to send analog voltages from the joystick to a computer. The joystick potentiometer signals are fed into an analog-to-digital (A/D) board embedded in the computer. From these signals the computer calculates the joystick input position and orientation and translates it to SPIDER command cable lengths. Feedback is received from cable length and force sensors located near the winches. This enables closed loop platform pose control. Cable travel encoders generate phase quadrature signals for an encoder input board embedded in the computer. Cable tension sensors are input into an A/D board in the computer. Command signals are output from the computer via a digital to analog (D/A) board and sent to the winch amplifiers. Control algorithms being developed for the SPIDER include forward and reverse kinematics that are necessary to allow control of the platform.

### 3.3 Computed-Manual Mode with the Spaceball Joystick

This is similar to the previously described control mode except that in this case a spaceball joystick is used in order to input the platform position and orientation rate control commands. The controller of this joystick measures the Cartesian axes

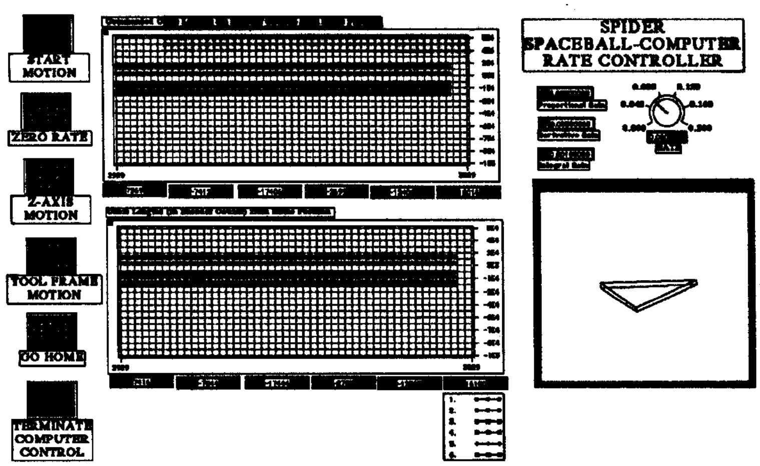


Figure 4 - Computer Control Panel used as Operator Interface to the SPIDER

components of the force and moment applied to a ball and sends them to the computer it is interfaced with, every time they exceed a threshold. The computer then interprets them to translation and rotation motion commands respectively. It also supports nine True/False Boolean buttons which allow the selection of a large number of control options. Currently only a few of these buttons are used. Three are used in order to increment, decrement or set equal to zero the commanded motion rate. A few more are used in order to constrain the platform directions of motion.

The computer display front panel was designed to be simple, intuitive to understand, and real time interactive. Figure 4 shows the current version of the front panel. In the default state, motion takes place with respect to the base frame attached to the suspension plane of the moving platform. Pressing the "Z-AXIS MOTION" button forces the computer to accept the Z axis motion commands only. Pressing the "TOOL FRAME MOTION" button forces the computer to command motion, with respect to a frame attached to the moving platform. The function of the rest of the buttons is obvious from their labels. An animation window will allow, in its final form, the three dimensional space display of the moving platform and its workspace.

The issued motion commands will be executed and displayed in that window. An impact of the platform with objects in its workspace will be detected ahead of time and proper action can be initiated. The operator can set the rate of motion to zero and then try different motion scenarios in the animation window, save the commands and play back any desired sequence. Currently the computer uses a PID servo motion controller. The gains of the controller can be set interactively from the screen and keyboard.

## 4. SUMMARY AND CONCLUSIONS

Two models of the SPIDER have been designed and constructed. A two meter model has been used to test mobility issues. A six meter model has been used to test lifting and load positioning parameters and to analyze the size and shape of the work volume. Experiments were done on the SPIDER to measure payload, work volume, and platform-movement precision. A weight of 455 kg. was maneuvered by the SPIDER platform while in manual mode. The load was carried to the limits of the work volume until cables began to go slack.

Two conditions under which two of the cables always become loose for any value of the weight W have been identified. The first condition occurs when the vector of the weight W crosses a vertical place through one of the suspension lines. The second condition occurs when the weight vector W crosses an imaginary line created by the intersection of two planes through two pairs of active cables. These two conditions are mathematically explained [4].

An experiment to show platform-movement precision and stability was done with a chain saw attached to the work platform. A depth of cut to within 1 mm resolution could be made in a solid oak log. Deep cuts could also be made with ease even while driving the tip of the chain saw blade directly into the oak log.

Future research on SPIDER will include integrating more advanced sensing capability, such as machine vision, and additional mechanical analysis and testing. The long range goal is to build a full-scale working prototype jointly with an industrial partner.

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