APPLICATIONS OF THE NIST ROBOCRANE

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ABSTRACT

The Robot Systems Division of the National Institute of Standards and Technology (NIST) has recently been experimenting with a variety of applications for the NIST ROBOCRANE. The ROBOCRANE design utilizes 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. Depending on what is suspended from its work platform, the ROBOCRANE has land, air, water, and space applications. A 2-meter version and a 6-meter version of the ROBOCRANE have been built and critical performance characteristics analyzed. Through these and other conceptual models, example applications for ROBOCRANE are: flexible-structure mobility, heavy material handling, and flexible fixturing on land; rescue and personnel/ equipment maneuverability in air; subsea pipe-laying/removal, lifting, and salvage from stable or unstable references on water; and lightweight, long distance lunar rover capabilites in space. All applications of ROBOCRANE include a large work volume, six degree-of-freedom control, precision maneuverability, and enhanced crane capabilities. This paper describes ROBOCRANE's present and future performance measurements, control system designs, and the conceptual designs for a multitude of applications.

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 late 1980's. A NIST program on robot crane technology, sponsored by the Advanced Research Projects Agency (ARPA), 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 ARPA 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-moving platform. This platform can be used in typical crane operations, or as a robot base, or a combination of both.

These prototypes are based on the Stewart Platform parallel-link manipulator and instead use cables as the parallel links. By attaching the cables to a work platform and keeping all cables in tension, the load is kinematically constrained, and the work platform resists 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 has been developed that can control the position, velocity, and force of tools and heavy machinery in all six degrees of freedom (x, y, z, roll, pitch, and yaw).

Further NIST studies of Stewart Platforms have produced a similar geometry for a gantry to house such a work platform. An octahedral tubular gantry, containing three upper suspension points for the work platform, also provides sufficient stiffness. By connecting the legs in an octahedron configuration, forces and torques incurred from the work platform are translated into pure compression in the legs. Therefore, with only slight bending moments in the legs, the gantry can be made lightweight to produce a high lift-to-weight ratio for the robot. The robot can be made mobile by attaching vehicles to the feet so that it can be driven over rough terrain.

Applications of this new crane design are illustrated: in [2] for the construction industry, in [3] for the subsea arena, and in [4] for planetary exploration.

Figure 1 - Photograph of the 6 meter NIST Robocrane

The ROBOCRANE, has been equipped with tools such as grinders, saws, grippers, and inspection equipment (stereo vision and laser scanner). Various controllers and user options have been designed to increase ROBOCRANE functionality and provide user friendly, intuitive operation. Performance measurements have included a work volume study [1] and static loading compared to a computer analysis to produce basic criteria for future studies.

Two models of the ROBOCRANE have been designed and constructed. A two meter model has been used to test mobility and lunar rover potential. A six meter model has been used to test lifting and load positioning parameters, to analyze the size and shape of the work volume, and to test various applications.

The objective of this paper is to describe the previous and future efforts in developing the robot into the ROBOCRANE Integration Testbed (RIT). RIT has been selected to be the basic tool for systems and Real-time Control System (RCS) development for the Robot Systems Division. Also, applications geared toward many industries for such a robot crane are described.

Following this introduction is a section describing the previous developments of the NIST ROBOCRANE. This briefly includes the mechanical, electronic, and control system designs and performance measurements taken to date. The next section describes the future ROBOCRANE designs and performance measurements targeted for presentation in the 1994 International Symposium on Robotics and Manufacturing. An applications section follows describing the many uses of ROBOCRANE for land, sea, air, and space applications. Summary, conclusions, acknowledgements, and references conclude the paper.

2. PREVIOUS DEVELOPMENT OF THE NIST ROBOCRANE

2.1. Mechanical Design

The framework of the ROBOCRANE is a six legged structure resting on three support points (see figure 1). The legs are 6 m. aluminum tubes that are nine centimeters in diameter and constructed in an octahedron geometry. The top of the ROBOCRANE 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 for all the rigid members do not allow moments to develop, thus all members are either in tension or compression under applied load. The ROBOCRANE structure thus provides near maximum strength and stiffness possible for any given mass of structural material.

The lower work platform is supported by six braided steel cables 5 mm in diameter. The length of each cable is controlled by a winch having a 455 kg load rating. The cables run from the winches up and over pulleys at the vertices of the upper triangle, and back down to the lower work platform. By controlling the six winches, 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 maximum work platform stiffness occurs when the size of the upper triangle is approximately twice that of the lower platform.

2.2. Controller Electronics Design

The ROBOCRANE controller must control the position and orientation of the work platform. The electronics consists of six isolation transformers and power amplifiers connected to the six winches (see figure 2). Each winch has an incremental encoder attached to a pinch roller system that is in constant contact with the mechanical cable. Encoders roll against each winch cable and provide feedback to a signal conditioning interface for encoder input boards housed within a personal computer.

A Macintosh IIfx* personal computer was used as the central processor controller. Several specialized boards were added to the Nu-bus* of the computer to handle the data acquisition and servo control needs of the controller. These include two servo control boards, a DMA (Direct Memory Access) board, a D/A (Digital-to-Analog) converter board and an A/D (Analog-to-Digital) converter board. The D/A converter board can also be used to generate input commands to the six power amplifiers. Advantages and disadvantages are explained in reference [5]. The A/D converter board has sixteen input channels available and is used to monitor all the analog sensors, (e.g., load-cells and potentiometers).

The model 2003 Spaceball* joystick was tested for sending move rate commands to the controller. It communicates with the controller through the serial port of the computer.

* NIST does not endorse any products listed nor does it imply that this is the best product available.

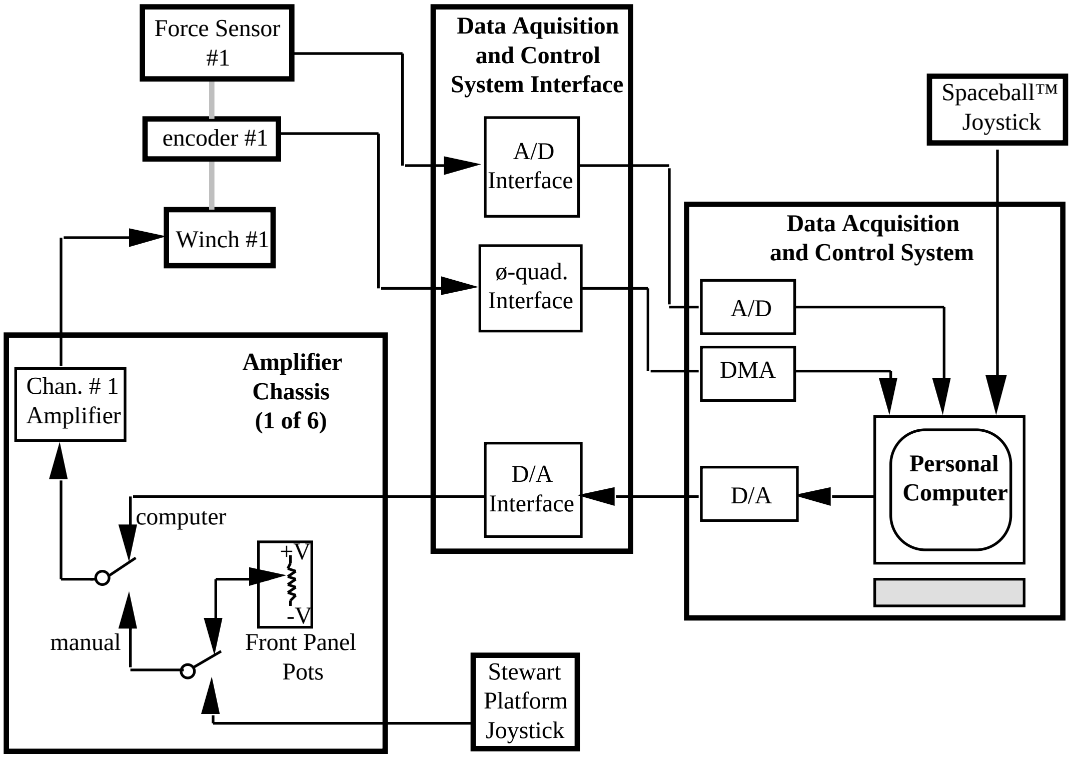

Figure 2 - Robocrane Control System Architecture showing one of six channels

The two servo boards accept the input signals from the six cable encoders (three per board) and translate them to cable length information from a reference home pose (moving platform position and orientation). The cable length information is compared to the commanded lengths and the appropriate power amplifiers command signals are produced. The servo boards use a PID control algorithm and are capable of either trapezoidal profile position control, velocity, or velocity profiling control operation. The output of the servo boards are the input commands to six power amplifiers which provide power to the six cable winches.

The power amplifiers used are capable of either velocity or torque control mode. To keep the winch spooling mechanism simple, no tachometers are used. Thus in the velocity control mode, the power amplifiers are operating under armature feedback.

2.3. Measurements

Experiments were done on the ROBOCRANE to measure payload, work volume, and platform-movement precision. A mass of 455 kg was maneuvered by the work platform using the joystick. The load was carried to the limits of the work volume until cables began to go slack.

As discussed in reference [1], two conditions whereby cables begin to go slack can be shown mathematically. As the cables begin to go slack, a point on the edge of the work volume is defined. Experiments to define this volume were done to verify the mathematics of this phenomena.

Cable loosening conditions were tested for total platform masses of 68 and 455 kg. The platform was moved to cover a quarter of the workspace at an arc of 90 degrees. A cable loosening computer simulation program has also been developed which is being used to search for the locus of the platform poses that satisfy the cable loosening conditions.

Another experiment that was perfomed involved the platform-movement precision and stability. A chain saw was attached to the work platform at a 30 degree angle from the vertical axis and with the tip of the chain saw blade at the center of gravity of the work platform. The saw was attached to a 3 mm thick steel plate that acted as a leaf-spring. While in the manual mode, lateral position and depth of cut in a solid oak log could be controlled to within 1 mm. Deep cuts could also be made with ease either with the blade tangent to, or perpendicular to the oak log surface. With the stiffness of the platform, little vibration was seen on the chain saw or the steel leaf-spring plate even while driving the tip of the chain saw blade directly into the oak log. The saw was replaced with a surface grinder and a force sensor (linear potentiometer) was used as a computer feedback device. The computer compensates for the deflecting steel plate by raising/lowering the platform and dampens vibrations produced by the grinder.

Recently, the ROBOCRANE was statically loaded with mass to 855 kg and moved to three positions along a straight line and at the same height. While monitoring platform position, load cells were used to measure loads in two platform cables. Results agreed well with cable forces calculated by the control software, as well as with the results predicted by a structural analysis.

3. FUTURE ROBOCRANE PLANS

3.1. Mechanical Design

As discussed previously, the ROBOCRANE gantry has an octahedron geometry. Each gantry member is connected via ball and socket joints. This provides greater flexibility than is necessary. Provided the legs are attached to vehicles or to a solid base, ball and sockets on each leg member are not needed at the feet. Instead, as shown in the mobility study using the 2 m ROBOCRANE model, the vehicles were attached with a rotary joint attached to a U-joint. The rotary joint allowed the vehicle to rotate with respect to the leg, while the U-bolt allowed for uneven terrain and/or changing the gantry from a low-wide stance to a taller-narrower stance. Attaching the gantry to a raised rotary/U-joint with respect to the vehicle, produces a moment at the joint attachment point causing unwanted rotations. Recently, the Robot Systems Division (RSD) has been studying this problem and found a simple solution by fixing the legs to a 13 cm solid aluminum rod that rests on a base-plate to spread the loads experienced on the rod. The rod can also be part of a vehicle axel or attachment so that vehicle connectivity can be at or near the center of wheel rotation.

Similarly, a problem exists at the top vertices of the gantry. With ball and socket joints, leg rotations about these vertices do not allow the gantry to lay flat during ROBOCRANE erection. Hence, the upper triangle must currently be raised in order that the legs can be attached. RSD is designing leg joints that would allow the crane to self-erect at the job-site. The top triangle would be raised slightly and by winching the feet toward each other, the gantry would raise into the erected position. If vehicles are attached to the feet, they could drive toward the center for gantry erection.

3.2. Electronics and Control System Design

The electronics to date have provided the basis for development of a preliminary research system. A new system design is now being considered which changes the electronics considerably. Higher performance winches with grooved drums should eliminate the need for pinch rollers and provide encoder coupling directly to the winch shaft. Force control will be developed with the use of force feedback from Running Line Tensiometers (RLT)* attached to the winch cables. These will be mounted to the gantry legs for reference while the winch cable passes through the sensor. By sensing cable tensions, the computer can prevent cables from going slack and also provide force servoing capabilities.

The current electronics package has over 900 wires and cables carrying signals and power throughout the ROBOCRANE system. This design is costly, inefficient in fabrication, power, and signal loss, and provides unnecessary weight to the system. Instead, a network approach to signal transmission is proposed with the use of a CANbus network. This system will include a CANbus board attached to the computer bus. The board provides "signature" signals to "credit-card" size CANbus nodes that can output power amplifier signals, and input sensor signals. A node will be positioned at each winch and sensor on the gantry, while another set can be located on the work platform for tool or camera control as an example. A CANbus update rate of 1 msec. for four nodes providing 32-bit position and velocity information and including 50% bus loading, provides no delay in the current control system configuration for the ROBOCRANE application.

A new control system is being considered to replace the current system. A VME backplane with a PC user interface is being considered to provide both an advanced and highly specialized research and development system and an inexpensive industry accepted system with multiple vendor support. Previous NIST work on an Enhanced Machine Tool Controller (EMC) system produced a new approach to integrated systems that could use any vendor's computer boards to provide the same desired output. This type of system is being considered for the ROBOCRANE.

3.3. Measurements

Static measurements on the ROBOCRANE are to continue as mechanical and electronic components are added to the system. Also, more points are to be measured within the work volume to provide a more thorough picture of system performance. Compression member loading is to be measured and analyzed for the various weights maneuvered by the work platform. Dynamic response, frequency domain analysis, and modeling will then follow.

4. CONCEPTUAL APPLICATIONS STUDIED

On land, ROBOCRANE consists of a gantry resembling an octahedron geometry. Three triangular legs rotate about each member of the upper triangle providing a flexible structure ready for rough terrain mobility. ROBOCRANE's payload-to-weight ratio is higher than conventional cranes and therefore provides low support reaction forces.

Existing cranes 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. Novice operators of conventional cranes may have difficulty in preventing heavy loads from colliding with objects in the environment.

The ROBOCRANE 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 ROBOCRANE 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 ROBOCRANE could thus reduce the crew size needed to manually position loads from three or four, to zero or one and to remove them from a hazardous area.

At sea, a cable driven Stewart Platform can be suspended from a floating vessel (see figure 3). This conceptual system, called the "Submerged, Stabilized, and Suspended Platform" (S3P), includes bouyancy, tension, positioning, and navigation sensors to provide capabilities for lifting, maneuvering, and positioning large loads with precise position and force control in all six degrees-of-freedom despite wave action and currents. Depending on the application, the S3P operator could control the work platform from either the floating vessel or directly from the work site for potential salvage, pipe-laying/cutting/removal, and diver aid in subsea depths of 70 meters or more.

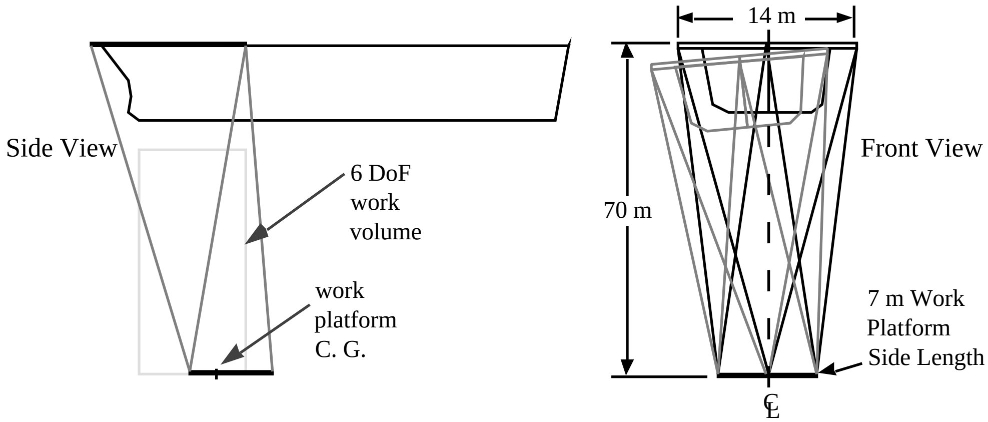

Figure 3 - Front and side views of the S3P suspended from a vessel. Front view shows orbital vessel motion with stable work platform. Side view shows 6 DoF work volume that the work platform center-of-gravity (C.G.) can reach.

If very deep Stewart Platform applications are necessary, two scenarios are possible: 1) a subsea vehicle could suspend the work platform like a robot arm beneath the vehicle, or 2) sea surface control is possible by separating the upper platform support points to larger distances than proposed here. For example, three barges with each carrying two winches can be separated several hundred meters to achieve depths of 1 km or more.

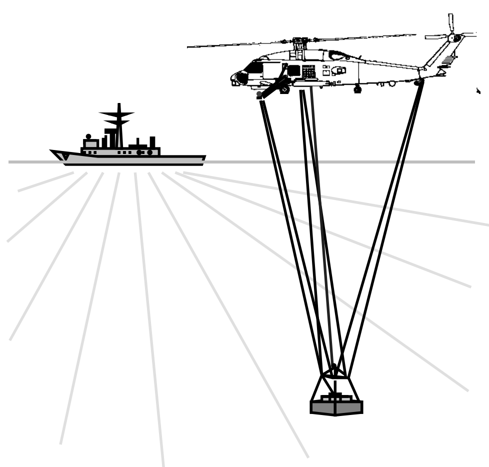

Figure 4 - (left) CAD drawing of the TETRA, (right) Photograph of a full-scale mock-up NIST Lunar Rover.

In the air, a system, called "Tetrahedral Robotic Apparatus" (TETRA) unites ROBOCRANE 's multi-cable suspended platform technology with existing single cable hoisting technology currently used with helicopters (see Figure 4-left) and other cranes. Prior to load acquisition, TETRA's additional six cables/winches will provide control and maneuverability of the existing hoist's hook within TETRA's work envelop (similar to ROBOCRANE). A Spaceball* will control the location and orientation of the hook allowing faster and more accurate load placement. This hook maneuvering capability can support advances toward teleoperation of the hook and eventually even autonomous acquisition of loads. After load acquisition has been accomplished, the suspended load will be largely supported by the existing single cable hoist, while TETRA's additional cables/winches control the position and orientation of the load. TETRA will not allow the pendulous swinging and unconstrained spinning associated with existing single cable hoisting techniques. In addition, since TETRA simply augments existing lifting equipment, it provides additional safety through redundancy and can be retrofitted to most vertical lifting equipment. Rescue and precision maneuverability of equipment/personnel are possible with limited rotations and sway.

ROBOCRANE applications on land, sea and in air have the following potential functional capabilities: cutting, lifting and positioning, flexible fixturing, welding, and grinding. A number of advantages over current crane technology are: rigid support and precise maneuverability of large loads, remote positioning of tools, equipment and materials, executing precise motions with tools/equipment to accomplish complex tasks, resistance to environmental perturbations, accurate control of loads by a novice operator, and reduced crew size.

For exploration on the moon, a modification to the land based ROBOCRANE can be used. Figure 4-right shows a full-scale mock-up of the NIST Lunar Rover. This rover has large wheels and a wide wheel base for traversing over rough terrain and for long distances. Within the legs are solar panels. The center "spine" has 3 additional winches attached that push the spine down onto the work platform providing downward forces for coring and/or digging applications. The work platform is equipped with a computer and experimentation package for retrieving samples, etc. The spine has stereo and zoom video cameras and a communications dish. The entire rover is designed to be folded into a 2.5 m diameter/high volume for potential transport within the nose-cone of the NASA Artemis lander.

5. CONCLUSIONS

The current 2 m and 6 m ROBOCRANE prototypes have proved much of the theory and performance of a Stewart Platform parallel link manipulator using cables as the parallel links. The rigidity of the octahedral ROBOCRANE geometry has also been demonstrated. Also, flexibility provided only at the joints creates mobility characteristics to the structure for land and lunar applications. Since the work platform needs only three suspension points for the six cables, the winches can be attached to air or water transport systems for air and sea ROBOCRANE applications. Hence, NIST has shown that the ROBOCRANE can provide rigidity of a platform for doing work in most any crane type application.

A static loading test of the ROBOCRANE and its supporting structure was completed. Cable tensions were measured, with work platform loading to 855 kg., and compared with those predicted by equations (8, 9) of reference [1]. Preliminary analysis results indicate that in most cases the difference between the predicted and measured values did not exceed 1% to 2%. Future ROBOCRANE testing will provide known performance characteristics to use the system as a testbed for further research.

Future modifications and enhancements to the current 6 m. ROBOCRANE have begun. Mechanical enhancements include upper and lower joint redesign for increased flexibility necessary to self-erect the robot. Electronic modifications will include a CANbus design for linking all electronic components to the computer instead of individual cables. The control system will include a VME-based computer with a PC user interface controller, and a Real-time Control System architecture.

Designs for S3P, TETRA, and the NIST Lunar Rover are now being addressed for prototype development. These will provide systems for study in the areas of sea, air and space applications.

6. ACKNOWLEDGEMENTS

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** These papers refer to external-NIST publications describing Stewart Platform development systems.