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INTELLIGENT ROBOTS FOR PLANETARY EXPLORATION AND CONSTRUCTION

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Abstract

Robots capable of practical applications in planetary exploration and construction will require real-time sensory-interactive goal-directed control systems. A reference model architecture based on the NIST Real-time Control System (RCS) for real-time intelligent control systems is suggested. RCS partitions the control problem into four basic elements: behavior generation (or task decomposition), world modeling, sensory processing, and value judgment. It clusters these elements into computational nodes that have responsibility for specific subsystems, and arranges these nodes in hierarchical layers such that each layer has characteristic functionality and timing.

Planetary exploration robots should have mobility systems that can safely maneuver over rough surfaces at high speeds. Walking machines and wheeled vehicles with dynamic suspensions are candidates. The technology of sensing and sensory processing has progressed to the point where real-time autonomous path planning and obstacle avoidance behavior is feasible. Map-based navigation systems will support long-range mobility goals and plans.

Planetary construction robots must have high strength-to-weight ratios for lifting and positioning tools and materials in six degrees-of-freedom over large working volumes. A new generation of cable-suspended Stewart platform devices and inflatable structures are suggested for lifting and positioning materials and structures, as well as for excavation, grading, and manipulating a variety of tools and construction machinery.



## Introduction

The Real-time Control System (RCS) is a reference model architecture for intelligent real-time control systems. It partitions the control problem into four basic elements: task decomposition, world modeling, sensory processing, and value judgment. It clusters these elements into computational nodes that have responsibility for specific subsystems, and arranges these nodes in hierarchical layers such that each layer has characteristic functionality and timing. The RCS architecture has a systematic regularity, and recursive structure that suggests a canonical form.

Four versions of RCS have been developed. RCS-1 and 2 perform task decomposition using state tables similar in many respects to Brooks' behavior generators<sup>1</sup>. RCS-2 adds model based image processing. RCS-3 introduces an explicit World Model, an operator interface, and refines the task decomposition module into a Job Assignment, Planning, and Execution triplet similar to Saridis' model.<sup>2</sup> RCS-3 was applied to space telerobotics to become NASREM.<sup>3</sup> RCS-4, currently under development, includes explicit Value Judgment modules, as suggested by Pugh,<sup>4</sup> and sophisticated multilevel tracking filter interaction between sensory processing and world modeling<sup>5</sup>. It also contains object-oriented entity lists and multi-resolution maps as suggested by Meystel<sup>6</sup>.

Systems based on the RCS architecture have been implemented more or less for a wide variety of applications that include loading and unloading of parts and tools in machine tools, controlling machining workstations, performing robotic deburring and chamfering, and controlling space station telerobots, multiple autonomous undersea vehicles, unmanned land vehicles, coal mining automation systems, postal service mail handling systems, and submarine operational automation systems.

## A Machining Workstation Example

Figure 1 illustrates how the RCS-3 (i.e. NASREM) system architecture can be applied to a manufacturing workstation consisting of a machine tool, a robot, and a part buffer. RCS-3 produces a layered graph of processing nodes, each of which contains a Task Decomposition (TD), World Modeling (WM), and Sensory Processing (SP) module. These modules are richly interconnected to each other by a communications system. At the lowest level, communications are typically implemented through common memory or message passing between processes on a single computer board. At middle levels, communications are typically implemented between multiple processors on a backplane bus. At high levels, communications can be implemented through bus gateways and local area networks. The global memory, or knowledge database, and operator interface (described in reference 3) are not shown in Figure 1.

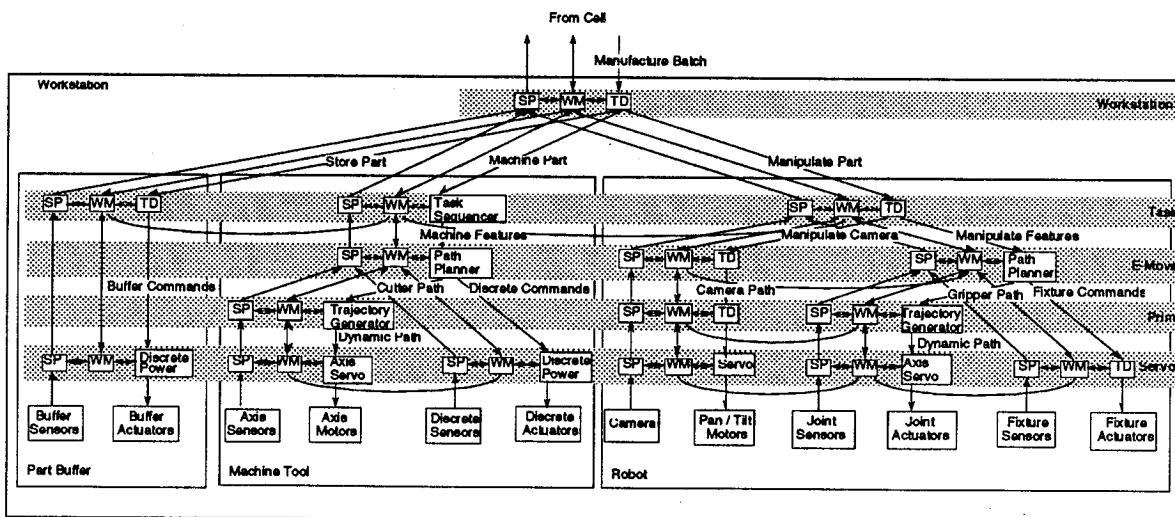


Figure 1. A RCS-3 implementation of a typical machining workstation.

*Figure 1* illustrates the ability of RCS-3 to integrate discrete sensors such as microswitches with more complex sensors such as cameras and resolvers. Discrete commands can be issued to valves and fixtures, while continuous signals are provided to servoed actuators. Notice that in some branches of the control tree, nodes at some levels may be absent. For example, in the case of the part buffer, discrete commands at the Task level can be directly executed by the Servo level. In the case of the part fixture, discrete commands issued from the robot E-Move level can be executed by the Servo level. In these cases, the missing modules can be thought of as degenerate computing nodes that produce unity gain pass-through of inputs to outputs.

The branching of the control tree (for example, between the camera and manipulator subsystems of the robot), may depend on the particular algorithm chosen for decomposing a particular task. The specifications for branching reside along with other task knowledge in the task frames (defined in reference 4) of the tasks being concurrently executed in each of the TD modules. Similarly, the specifications for sharing information between WM modules within a level also are task dependent and may be specified in the appropriate task frames. In *Figure 1*, the horizontal curved lines represent the sharing of state information between subtrees in order to synchronize interacting concurrent tasks.

### **Functionality of RCS Levels**

Levels in the RCS command hierarchy are defined by temporal and spatial decomposition of goals and tasks into levels of resolution, as well as by spatial and temporal integration of sensory data into levels of aggregation. Temporal resolution is manifested in terms of loop bandwidth, sampling rate, and state-change intervals. Temporal span is measured in length of historical traces and planning horizons. Spatial resolution is manifested in the resolution of maps and grouping of elements in subsystems. Spatial span is measured in range of maps and the span of control. The functionality of each level in the control hierarchy can be derived from the characteristic timing of that level, and vice versa. For example, in the manufacturing workstation example, the following hierarchical levels have been defined.

#### *Level 6 – Cell*

The cell level schedules and controls the activities of several workstations for about a one hour look ahead. (The specific timing numbers given in this example are representative only, and may vary from application to application.) Batches of parts and tools are scheduled into workstations, and commands are issued to workstations to perform machining, inspection, or material handling operations on batches or trays of parts. The world model symbolic database contains names and attributes of batches of parts and the tools and materials necessary to manufacture them. Maps describe the location of, and routing between, workstations. The output from the cell level provides input to the workstation level.

#### *Level 5 – Workstation*

The workstation level schedules tasks and controls the activities within each workstation with about a five minute planning horizon. A workstation may consist of a group of machines, such as one or more closely coupled machine tools, robots, inspection machines, materials transport devices, and part and tool buffers. Plans are developed and commands are issued to equipment to operate on material, tools, and fixtures in order to produce parts. The world model symbolic database contains names and attributes of parts, tools, and buffer trays in the workstation. Maps describe the location of parts, tools, and buffer trays.

#### *Level 4 -- Equipment task*

The equipment level schedules tasks and controls the activities of each machine within workstation with about a 30 second planning horizon. (Tasks that take much longer may be broken into several 30 second segments at the workstation level.) Level 4 decomposes each equipment task into elemental moves for the subsystems that make up each piece of equipment. Plans are developed that sequence elemental movements of tools and grippers, and commands are issued to move tools and grippers so as to approach, grasp, move, insert, cut, drill, mill or measure parts. The world model symbolic database contains names and attributes of parts, such as their size and shape (dimensions and tolerances) and material characteristics (mass, color, hardness, etc.). Maps consist of drawings that illustrate part shape and the relative positions of part features.

#### *Level 3 - Elemental move (E-move)*

The E-move level schedules and controls simple machine motions require a few seconds, such GO-ALONG-PATH, MOVE-TO-POINT, MILL-FACE, DRILL-HOLE, MEASURE-SURFACE, etc. (Motions that require significantly more time may be broken up at the task level into several elemental moves.) Plans are developed and commands are issued that define safe path waypoints for tools, manipulators, and inspection probes so as to avoid collisions and singularities, and assure part quality and process safety. The world model symbolic database contains names and attributes of part features such as surfaces, holes, pockets, grooves, threads, chamfers, burrs, etc. Maps consist of drawings that illustrate feature shape and the relative positions of feature boundaries.

#### *Level 2 -- Primitive*

The primitive level plans trajectories for tools, manipulators, and inspection probes so as to minimize time and optimize performance. It computes tool or gripper acceleration and deceleration profiles taking into consideration dynamical interaction between mass, stiffness, force, and time. Planning horizons are on the order of 300 milliseconds. The world model symbolic database contains names and attributes of linear features such as lines, trajectory segments, and vertices. Maps (when they exist) consist of perspective projections of linear features such as edges or lines on parts, or trajectories of tools or end-effectors.

#### *Level 1 - Servo level*

The servo level transforms commands from tool path to joint actuator coordinates. Planners interpolate between primitive trajectory points with a 30 millisecond look ahead. Executors servo individual actuators and motors to the interpolated trajectories. Position, velocity, or force servoing may be implemented, and in various combinations. Commands that define actuator torque or power are output every 3 milliseconds (or whatever rate is dictated by the machine dynamics and servo performance requirements). The servo level also controls the output drive signals to discrete actuators such as relays and solenoids. The world model symbolic database contains values of state variables such as joint positions, velocities, and forces, proximity sensor readings, position of discrete switches, condition of touch probes, as well as image attributes associated with camera pixels. Maps consist of camera images and displays of sensor.

At the Servo and Primitive levels, the command output rate is perfectly regular. At the E-Move level and above, the command output rates typically are irregular because they are event driven. Details of how RCS represents and uses task knowledge, states, entities, events, and maps have been published elsewhere.<sup>5</sup>

For planetary exploration and construction robots, not all the levels defined above must be implemented. An operator interface to each of the levels provides the capability for teleoperation and supervisor control. Many near term applications can be accomplished without the upper levels defined in *Figure 1*. However, the RCS architecture provides for future expansion of capabilities leading toward greater autonomy and intelligence.

### **Structural and Mobility Issues**

Planetary exploration and construction robots must have more than intelligent controls. They must be structurally designed so that they can safely maneuver over rough surfaces at reasonably high speeds. They also must have high strength-to-weight ratios for lifting and positioning tools and construction materials over large working volumes.

The SPIDER -- which stands for Stewart platform Independent Drive Environmental Robot -- is a new type of robot crane that is well suited for many manufacturing or construction tasks, or for work in remote and hostile environments such as leaning up nuclear or toxic waste sites, or for construction and exploration tasks on the Moon or Mars.

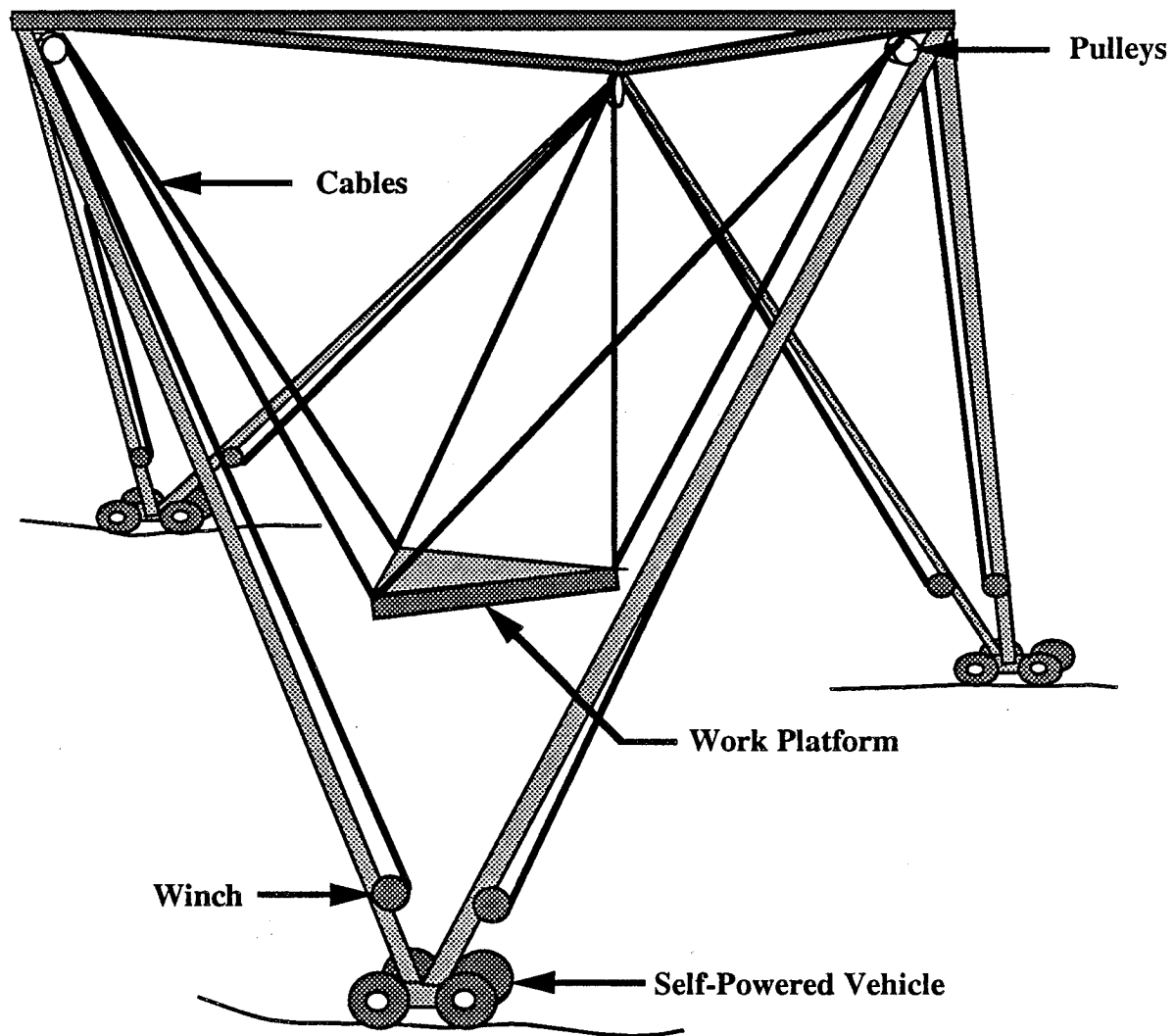
Conventional cranes can lift heavy loads, but they cannot rigidly position those loads so as to exert large rotational torques or lateral forces. The SPIDER overcomes these deficiencies. It can rigidly support heavy loads and exert the large lateral forces and torques needed to operate excavators, chain saws, and various kinds of drilling or grinding tools.

For several years, the Robot Systems Division at NIST has been experimenting with new concepts for robot cranes.<sup>(7-12)</sup> These concepts utilize the basic principle of the Stewart Platform. A unique feature of this approach is to use six cables instead of six rigid legs to form the Stewart Platform. So long as all six cables are in tension, the lower work platform (from which the robot is suspended) is kinematically constrained, and can resist perturbing forces and torques up to a threshold determined by the weight of the load. This means that the suspended robot can exert forces and torques to maneuver and operate tools such as drills, saws and grinders. The position, velocity, and force of tools and heavy machinery can be precisely controlled in all six degrees of freedom (x, y, z, roll, pitch, and yaw).

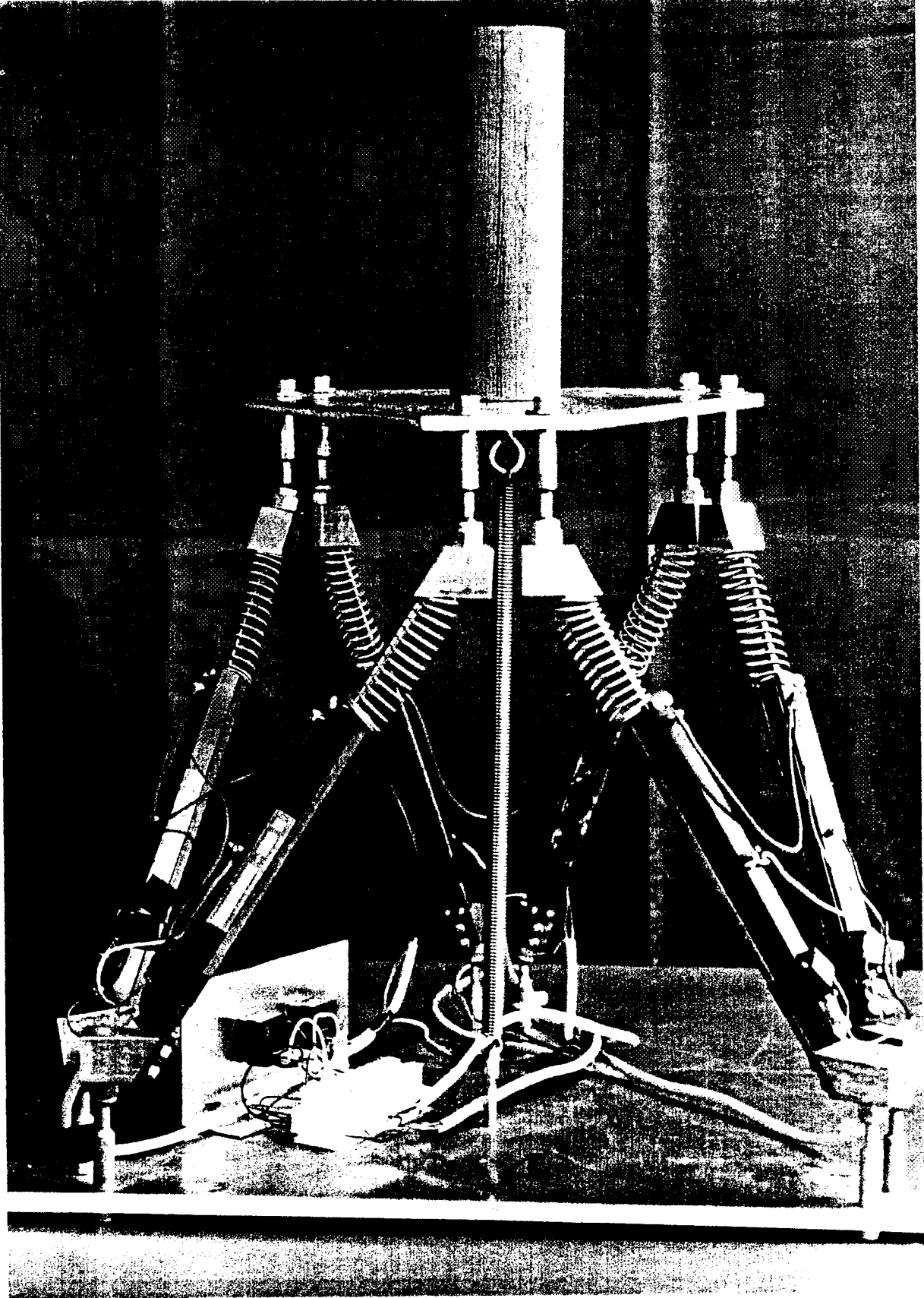
The basic configuration, shown in *Figure 2*, consists of a triangular work platform suspended from an upper structure by six cables controlled by six winches. In the configuration shown in *Figure 2*, an octahedron structure provides the mechanical support for the system. The top of the octahedron is an equilateral triangle. From each vertex of this triangle are suspended two pulleys, each of which supports one of the six cables.

By simultaneously controlling the winches in a coordinated fashion, the work platform can be precisely controlled. The winches can be controlled manually by a six axis joystick, such as shown in *Figure 3*, or can be automatically controlled by computer. Various combinations of position, velocity, and force control in both manual and automatic modes can be utilized. For example, x and y position can be automatically controlled and z position controlled manually, or, position can be controlled automatically and velocity controlled manually, as well as many other possible combinations.

The geometric shape of the NIST SPIDER gives it an extremely high strength-to-weight ration. All structural members are either in pure compression or pure tension (except for supporting their own weight). As a result, this SPIDER can lift and manipulate loads many time its own weight. This is an order of magnitude improvement over conventional cranes which typically weigh (including



**Figure 2.** The NIST robot crane. An octahedron structure with an equilateral triangle at the top supports a work platform that can carry various tools or equipment. The work platform is suspended by six cables that are controlled by six winches.



**Figure 3.** A Stewart Platform Joystick that can be used as a replica master for manual control, or with a computer for shared control.



counterweight) several times more than they can lift. Other configurations are possible. Designs for boom or tower cranes using six cables to stabilize and manipulate the load are possible. Designs using three towers supported by guy wires can be made up to several hundred feet on a side. This design can also be adapted to underwater applications and can be even larger.

The SPIDER scales easily to much larger sizes and versions with dimensions of several hundred feet made from cross-braced triangular trusses are feasible. Depending on the size and strength of the particular structural configuration, the work volume can range from 10 feet to over 100 feet on a side, and the lift capacity may range from 1000 pounds to over 20 tons. This makes the NIST robot crane design capable of manipulating heavy tools and machinery over large work volumes for cutting, excavating, shaping, and finishing applications.

For mobility, the three support points at the base of the octahedron can be carried by three vehicles, as shown in *Figure 3*. The light weight of the NIST robot crane and its three point suspension keeps ground pressure to a minimum. The SPIDER model shown in *Figure 3* is two meters high.

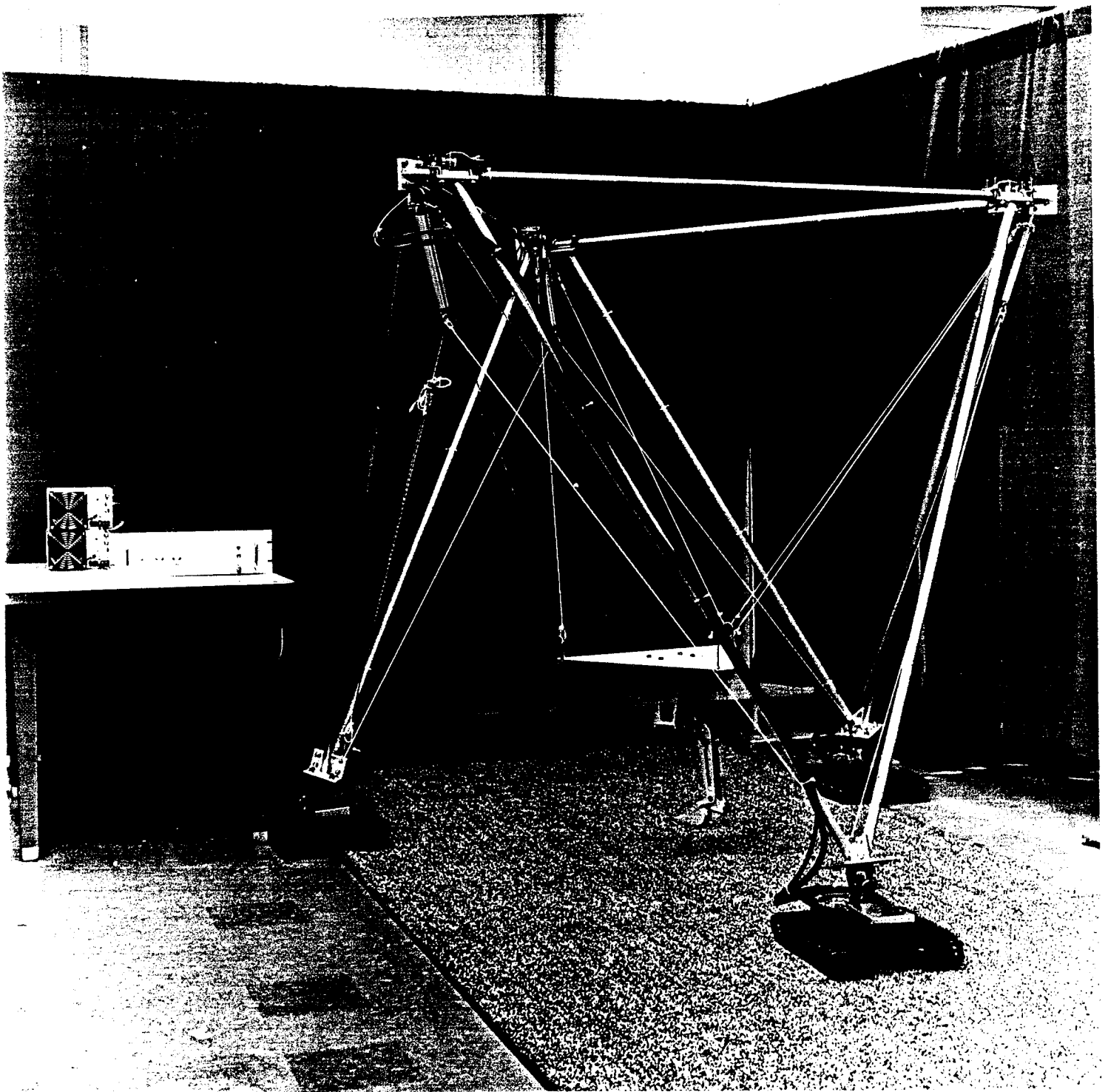
Recently the 2-meter SPIDER has been given a long neck to support a pan/tilt head with a suite of cameras as shown in *Figure 5*. This configuration has been nick-named, "The HORSE". The long neck lifts the HORSE'S head 3 meters above the ground and about two meters ahead of its front feet. This enables the HORSE to see far into the distance for mapping and path planning, as well as straight down immediately ahead so as to avoid holes and ditches. It can also see over obstacles up to 3 meters high. A laser scanner could be mounted at the base of the HORSE's neck so as to provide terrain elevation cues. Cameras mounted on the SPIDER platform suspended within the HORSE body, can be used for manipulating tools and deploying instruments.

Each of the HORSE's three legs are attached through a universal joint to a tracked vehicle. A sensor in each mounting attachment measures the orientation of the vehicle relative to the leg. The legs of the HORSE are constrained by a set of cables and springs so as to provide a flexible suspension. Sensors in the HORSE frame measure the spreading of the legs.

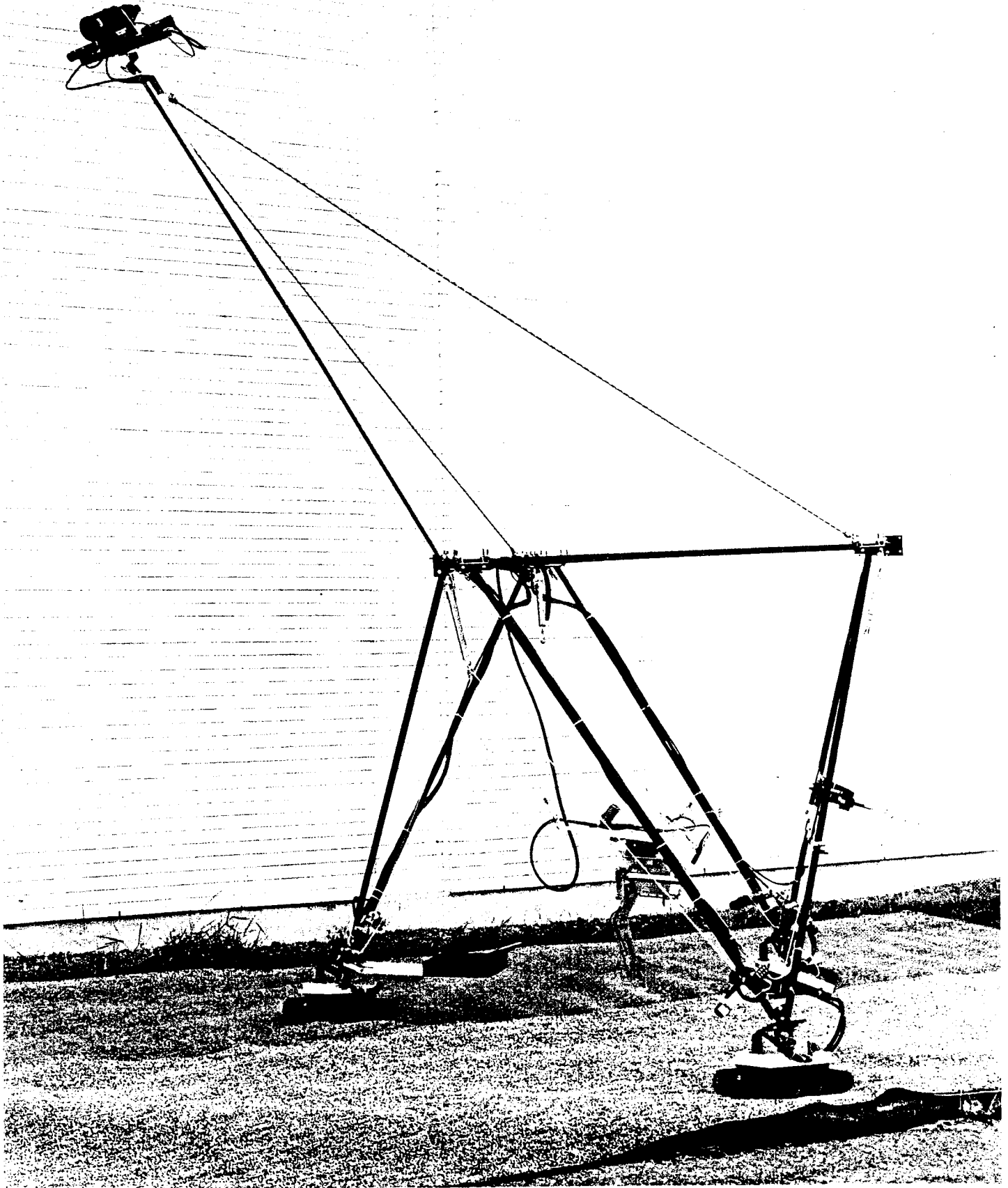
An operator can use a joystick to command the HORSE to move and turn. Steering algorithms were developed first on a graphics simulator, to be later implemented on the hardware model. Data from the vehicle orientation sensors are combined with data from leg position sensors and operator steering commands, and sent to a computer. The computer calculates the proper speed for each of the six tracks to make all three vehicles move and turn in a coordinated manner so as to maintain the desired spacing between vehicles while performing the commanded translation and rotation maneuvers.

The mobility characteristics of the HORSE are extremely good, because the effective wheel base is the separation between the vehicles. The center of gravity of the HORSE can be controlled by maneuvering the work platform. This can enable the HORSE to cope with 30 degree slopes, and could be used to improve the dynamic characteristics of the HORSE while traveling at high speed.

Once the HORSE has moved into position over a work site, the SPIDER work platform can be maneuvered so as to collect soil samples or deploy instruments. The SPIDER has been fitted with a tool changer and a set of power tools representative of what might be used by NASA for lunar and planetary exploration or construction tasks. The platform can be maneuvered to pick-up tools or instruments from a storage rack. Using a backhoe, the SPIDER can gather soil or loose rock samples and deposit them in a processing unit.



**Figure 4.** Photograph of a small scale model of the SPIDER using remote controlled track vehicles for mobility. The structure is made from 6-foot sections of 1 inch aluminum tubing. A remote controlled model excavator is mounted to the work platform.



**Figure 5.** Photograph of the HORSE showing the mobility camera system mounted on a long neck.

Using an auger, the SPIDER can drill into the planetary surface to collect core samples or to deploy seismic sensors. Cameras mounted on the work platform are used to guide these operations.

In order to test and demonstrate heavy life and positioning capabilities, a six meter version of the SPIDER has been constructed. This is shown in *Figure 6*. It weighs a total of 1000 pounds, and can support and manipulate a load of 2 tons.

The six meter SPIDER is constructed of four inch diameter aluminum tubing and is powered by six electric winches. The cables are 3/16th inch braided steel. They run from the winches up and over pulleys at the vertices of the upper triangle, and back down to the lower work platform. The work platform is made of aluminum I-beams.

The winches are controlled by the joystick shown in *Figure 2*. The joystick can be located remotely, or mounted directly on the platform. The operator flies the platform much like a pilot flies an airplane. Laboratory tests have shown that a linear precision of 0.125 inches and an angular precision of 0.5 degrees can easily be achieved with loads of up to 3000 pounds.

### **Potential Applications**

Depending on what is attached to its work platform, the NIST SPIDER can perform a variety of tasks as illustrated by the following examples. In any of these applications, the robot crane motions can be controlled manually, or from computer programs such as those currently used for numerically controlled machine tools, or from databases generated by computer aided design systems.

#### *Cutting:*

The SPIDER can manipulate a variety of saws (chain saw, wire saw, or disc saw), rotary cutting tools (router, milling tool, or grinding tool), abrasive jet tools (water jet or air jet), flame cutters, or pneumatic or hydraulic cutters and chisels for cutting concrete, steel, wood, or stone. In the laboratory, NIST has demonstrated sawing an oak log with a chain saw attached to the work platform, as shown in *Figure 8*. The SPIDER can produce large forces with accuracies sufficient for many types of machining operations, including milling, routing, drilling, grinding, and polishing.

#### *Excavating and Grading:*

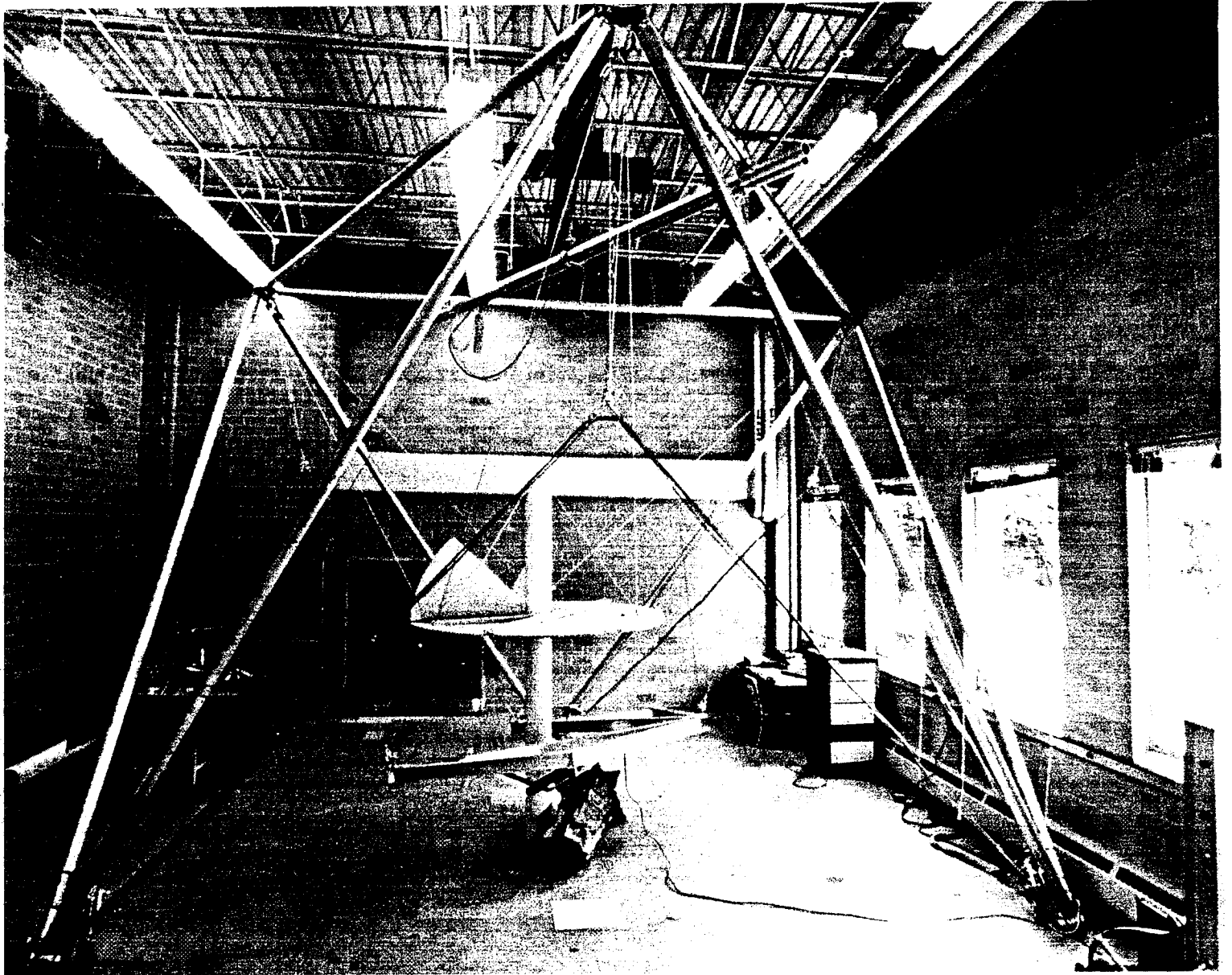
The SPIDER can manipulate digging devices (ditching or trenching machines, excavators, back hoes, augers, or scrapers) precisely over the ground in either a manual or computer controlled mode. Dirt, stone concrete, or asphalt can be removed from a large volume with great precision. The robot can easily maneuver loads of several tons. This implies that the robot work platform can carry a gasoline or diesel engine, power transmission system and tooling required to apply many horsepower to the task of excavating and grading. The SPIDER can also carry a large bucket for removing soil and loading it in trucks or conveyors.

#### *Shaping and Finishing:*

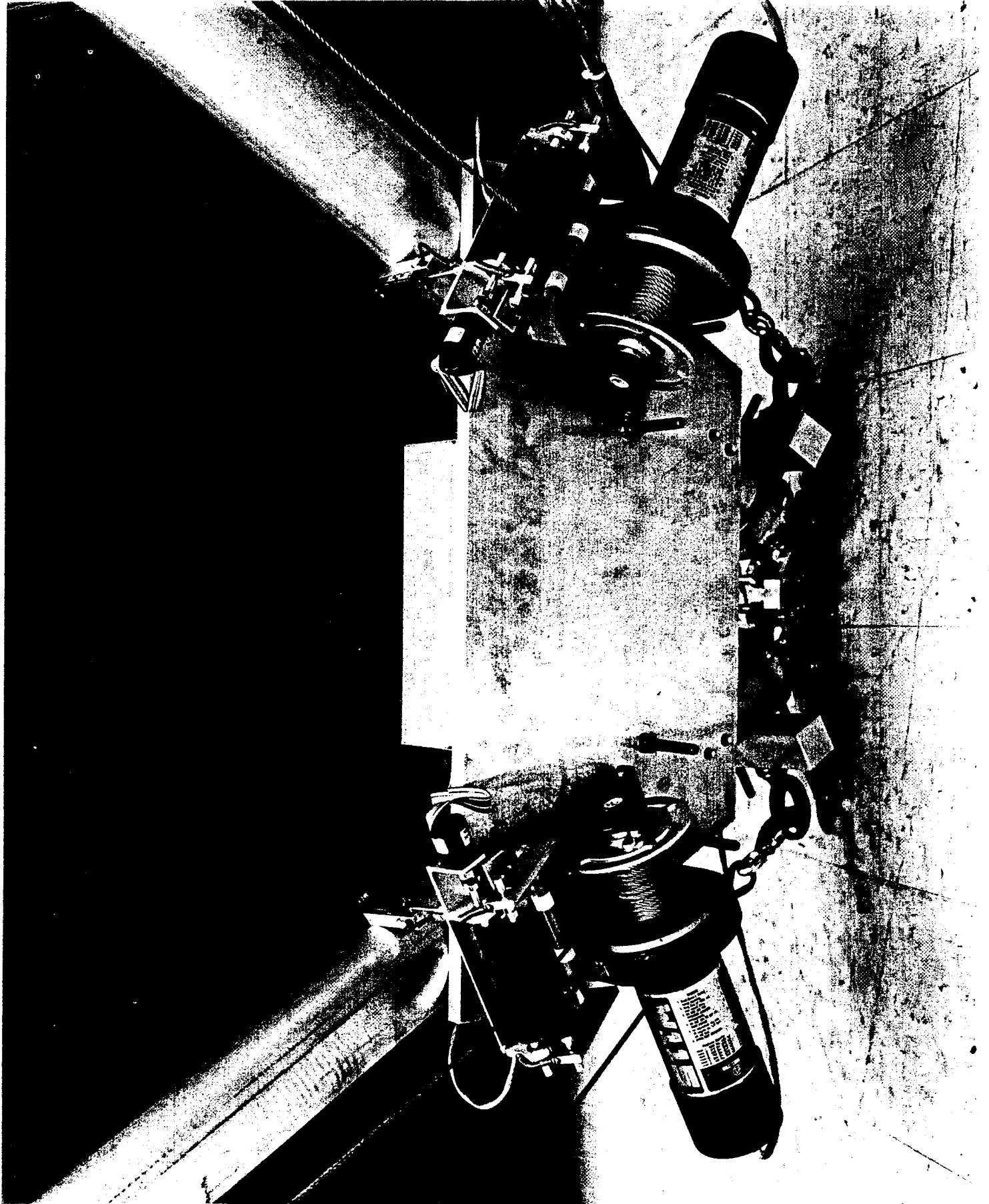
The SPIDER can manipulate grinders, polishers, buffers, paint sprayers sandblasters, and welding torches over large objects (ship hulls, structural steel, castings and weldments, or concrete structures). It can apply controlled amounts of force and resist perturbations in all directions.

#### *Lifting and Positioning:*

The SPIDER can be fitted with a variety of gripping devices so as to lift and precisely position heavy loads such as concrete or steel beams and pillars. The robot can exert controlled forces to mate and seat loads and can resist perturbations such as wind and inertial forces. Precision motions can easily be achieved while maneuvering large loads.



**Figure 6.** Photograph of a midsize scale model of the SPIDER. The structure is made from 20 foot sections of four inch aluminum tubing.



**Figure 7.** Photograph of a pair of winches used on the midsize scale model NIST SPIDER.

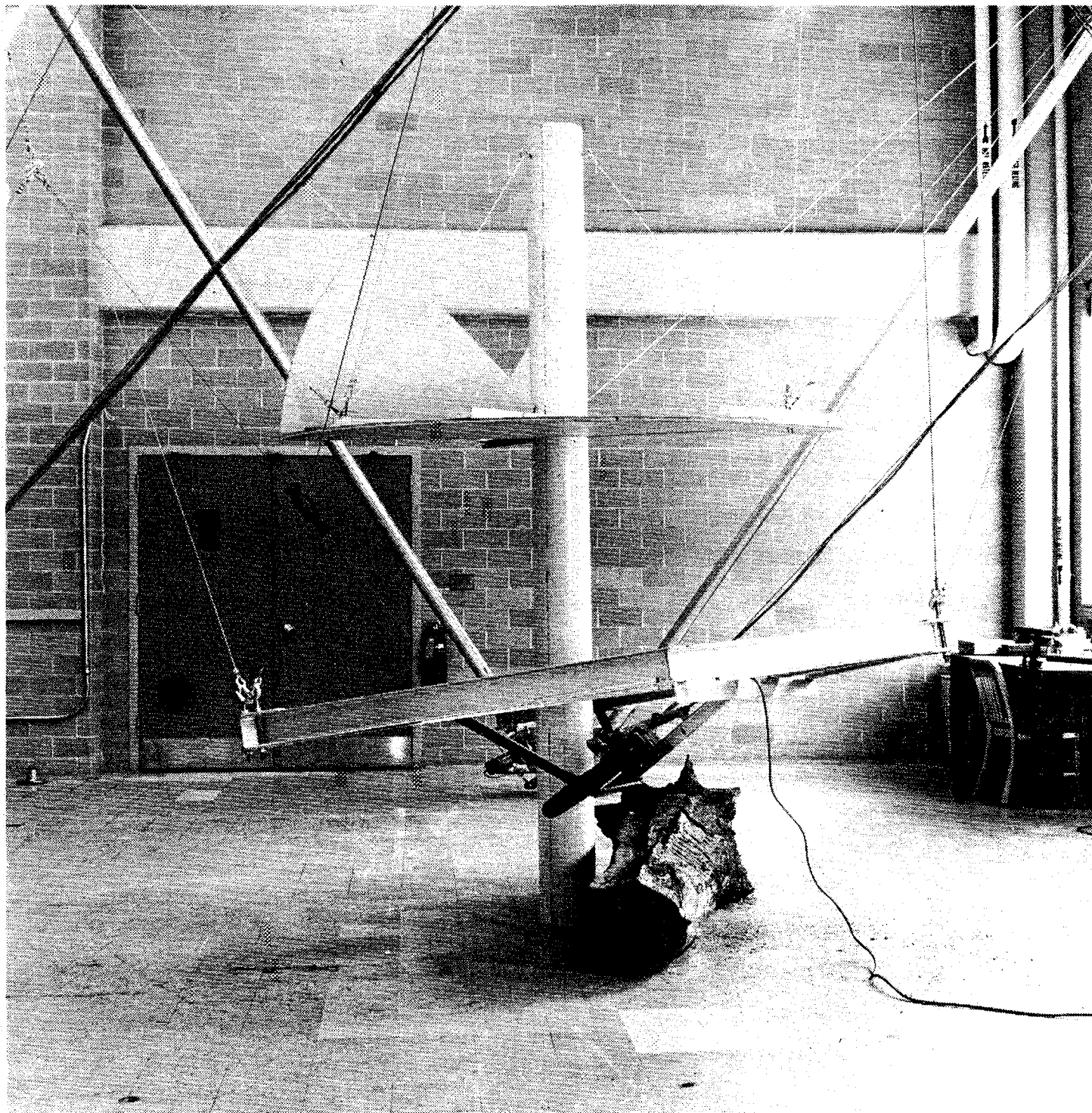


Figure 8. Photograph of a chain-saw attached to the work platform of the midsize scale model.

The work platform can exhibit sufficient stiffness to serve as a fixture for holding parts during assembly or construction operations. Parts weighing several tons can be held rigidly so as to resist forces of many hundreds of pounds and torques of hundreds of foot pounds with stiffnesses of tons per inch. An industrial robot can be mounted to the bottom of the work platform and it can, for example, perform assembly tasks on the load being positioned by the robot crane.

### Summary and Conclusion

In the future as part of an on-going research program, NIST will mount a pair of arms and a pair of cameras on the SPIDER work platform. These will be used to investigate a wide variety of teleoperation and autonomous control issues. For example, force controlled manipulation, hand/eye coordination, obstacle avoidance, and active foveal/peripheral vision will be studied. The mobility of the HORSE will be improved. Image-flow, fixation, stereo, and laser scanners will be used for navigation, path-planning, mapping, and obstacle avoidance. The long term goal is to integrate the SPIDER work platform with the HORSE mobility platform into a general-purpose intelligent man-machine system. In the short term, however, the technology has already been demonstrated for teleoperated applications such as are required for lunar and planetary exploration and construction.

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