TOWARD NEXT-GENERATION CONSTRUCTION MACHINES

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ABSTRACT

Construction equipment is typically massive and operated manually with minimal use of sensors or computers for measurement or control. Research in the Intelligent Systems and Structures Divisions at the National Institute of Standards and Technology has explored innovative ways to use sensors, computers, and light-weight, tensioned, cable machines for heavy manufacturing and construction tasks such as lift and position of heavy loads and manipulation of tools and parts for assembly, fixturing, welding, cutting, grinding, machining, macro stereo-lithography, and surface finishing. Recent research has yielded novel concepts for movable scaffolding and worker positioning systems that enable workers to maneuver themselves, parts, and tools throughout a large work volume for tasks such as ship repair and aircraft paint removal.

1. INTRODUCTION

This paper will address several novel concepts that have been developed for large-scale manufacturing and construction over the past two decades by the Intelligent Systems Division (ISD) and at the Structures Division (SD) at the National Institute of Standards and Technology (NIST). There are two basic principles used in these concepts: one is the use of multiple cables maintained in tension and configured to support a work platform rigidly, the second is the use of winches to control the lengths of the cables so as to maneuver the work platform. The initial concept was to use six cables arranged as a Stewart Platform [1] to stabilize a work platform and use six winches to maneuver the work platform through a work volume. Figure 1 depicts a basic (Stewart Platform) configuration. Figure 2 shows a 6 m RoboCrane® manipulating a 55 gallon drum. An operator with a six-axis joystick is shown controlling the RoboCrane manipulator. The winches are driven by power amplifiers controlled by signals generated by a control computer. The desired motion of the platform can be controlled from a joystick as shown in Figure 2, or from a computer program. The work platform can be programmed to move in a straight line between specified points in space, or to move over a surface while maintaining a specified distance from the surface or while applying a specified force normal to the surface.

Over the years, ISD has considered a number of different RoboCrane configurations designed for a wide variety of applications in large-scale manufacturing such as welding, cutting, grinding, assembly, fixturing, paint stripping, and machining. Other configurations have been developed for bridge building, nuclear waste tank remediation, construction, cargo handling, undersea salvage, and several other applications. [2, 3, 4, 5]

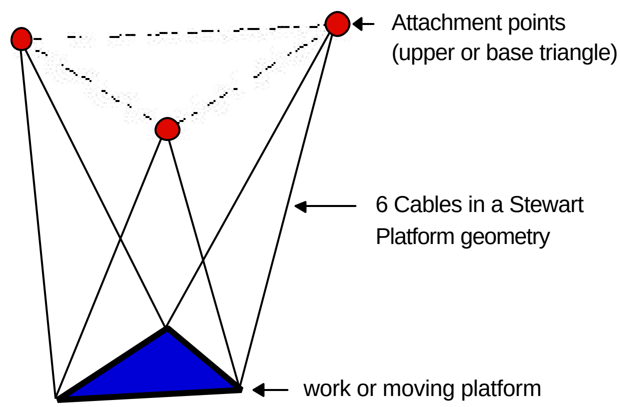

Figure 1 –Basic Stewart Platform with six cables attached to three points to support a work platform.

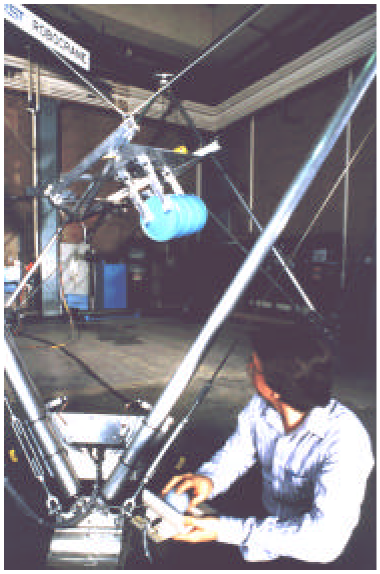

Figure 2 - The NIST RoboCrane with a three finger gripper manipulating a 55 gallon drum. Operator controls the position and orientation of the gripper using a six-axis joystick.

The configuration of six cables shown in Figures 1 and 2 can support and control loads, tools, and equipment in all six degrees-of-freedom (DOF) with minimal sway or rotation. In this configuration, the cables are maintained in tension under gravity loading. The result is a useable work volume that confines horizontal motion of the platform center-of-gravity to a circle inscribed inside the triangle formed by the three support points. The work volume is confined vertically to a region that is on the order of ten times the length of the shortest side of the support triangle.

Larger work volumes can be achieved by using more than six cables and adding a compressive spine to maintain tension in all cables. A spine enables the work platform to be pushed outside the support triangle, and even operate above the support triangle. Of course, if more than six cables are controlled in length, the system is over constrained. However, if the additional cables are controlled in tension, the stiffness of the work platform can be controlled to resist or apply forces to external bodies.

3. MANIPULATION OF TOOLS AND HEAVY OBJECTS

An example of the use of the RoboCrane to manipulate a welding torch is illustrated on the left side of Figure 3. In this example, the RoboCrane had been taught one point at the start and one point at the finish of a linear weld path. The computer then calculated a straight line between these two points and the welding torch was able to lay a weld bead along that line. Curve weld paths can also be programmed and have been demonstrated. In the center of Figure 3, the RoboCrane is shown using a disc grinder.

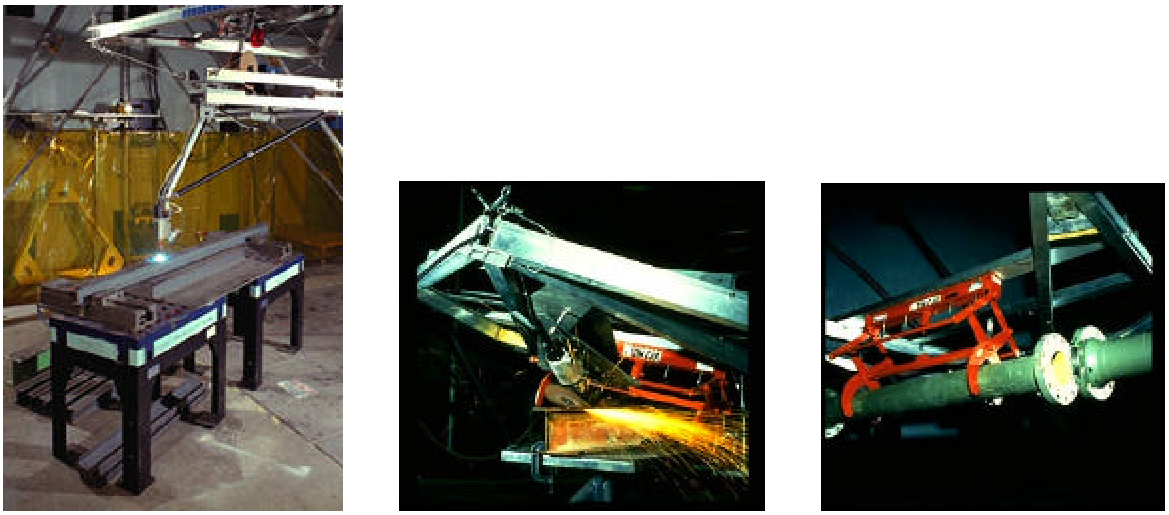

Figure 3 –RoboCrane performing three different tasks. (left) welding, (middle) grinding a weld bead, and (right) pipe-fitting flanged cast iron pipe.

The system was programmed to grind the weld bead by applying a specified force while moving at a specified speed along the programmed line. On the right of Figure 3, the RoboCrane is shown manipulating a 2 m (6 ft) section of cast iron pipe with a flange and bolt circle on each end. The task was to align the pipe with another section of pipe and orient the flange so that the bolt holes line up. This task was performed manually by first bringing the two pipe sections into alignment along their centerlines. Then the computer was instructed to constrain the RoboCrane motion to move only linearly along the centerline axis until the two flanges met. Finally, the computer was instructed to constrain the RoboCrane motion to only rotate about the centerline until the bolt holes lined up.

Other control algorithms were developed that enabled two operators to independently control opposite ends of a long beam using only one platform. This made it possible to assemble large steel beam structures by simultaneously aligning bolt holes at opposite ends of the beams. A construction application of a RoboCrane system was also demonstrated at NIST during a National Construction Automation Testbed project and is described in [6].

Recently, a small 1 m version of the RoboCrane has demonstrated the ability to machine wax, wood, and aluminum. Figure 4 shows the 1 m RoboCrane. The picture on the left shows the work platform suspended from three support points on a tripod frame. In the center is a close up of the work platform. Note that this version of the RoboCrane has the winches mounted on the work platform. Attached to the edge of the work platform is a spindle with a rotating tool. On the right is a circle-diamond-square test part that was cut from styrofoam.

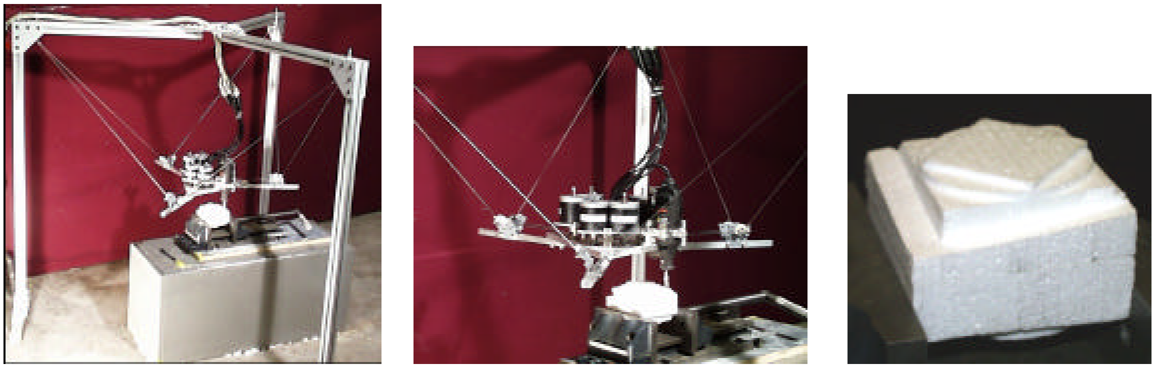

Figure 4 – A 1 m RoboCrane Machine Tool. (left) RoboCrane Machine Tool showing the support points. (middle) close up of work platform, (right) styrofoam part machined by the RoboCrane Machine Tool.

The machine was controlled by a version of the NIST Enhanced Machine Controller (EMC) [7]. Part programs can be written in RS274 machine tool commands [8]. The EMC can accept part geometry specified by STEP (Standard for the Exchange of Product Model Data, officially ISO 10303) [9] files and generate machine tool commands automatically. The 1 m machine shown in Figure 4 has a work volume of approximately 0.36 m^3 (1 ft^3) and is scalable as demonstrated by other RoboCrane prototypes built and tested. Design studies have also been done for other configurations such as that shown in Figure 5.

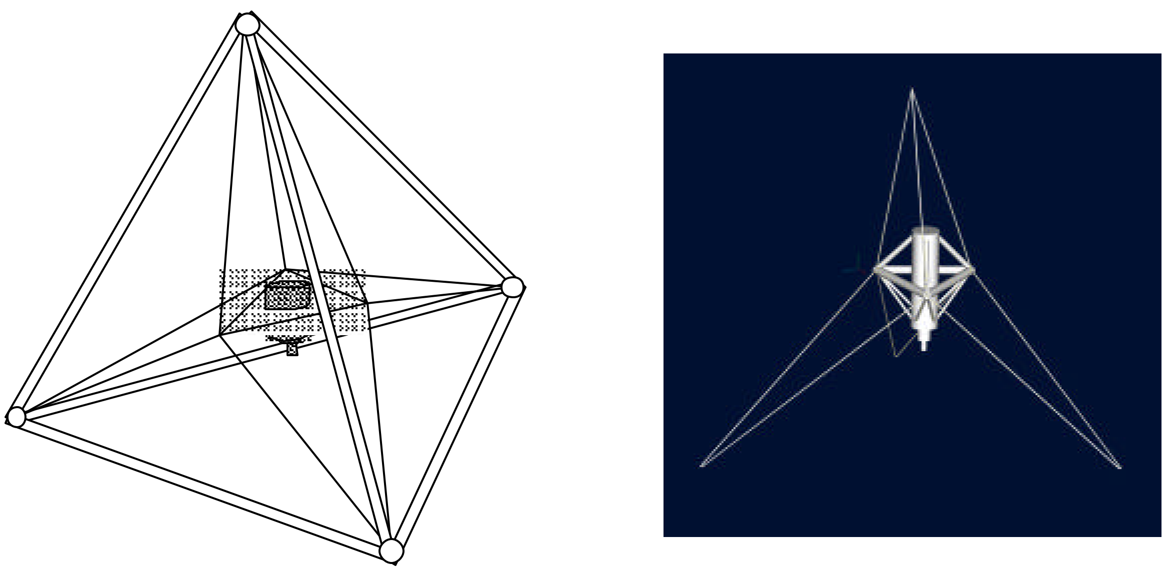

Figure 5. Cable-Actuated Machine Tool mounted in a tetrahedral tubular frame. (left) schematic drawing, (right) solid model rendering of a spindle platform and nine-cable mechanism without frame. (Winches not shown in either view.)

In this case, the triangular work platform is rigidly suspended within a tetrahedron using nine cables. The length of any six of the cables can be controlled to define the position (x, y, z) and orientation (roll, pitch, yaw) of the triangular frame relative to the tetrahedron. Tension in the remaining three cables can be controlled to provide the pre-load needed to stiffen the mechanism and assure that all cables remain in tension throughout the work volume, even in a zero-g environment. A spindle can be attached to the triangular platform. The spindle can then be moved through a work volume by changing the length of any six cables and controlling the tension in the remaining three.

Nine winches can control the cable lengths and tensions. Drive signals to the winches can be generated by power amplifiers in response to signals from a control computer as illustrated in Figure 6. The control computer can accept commands for x-velocity, y-velocity, z-velocity, roll-velocity, pitch-velocity, and yaw-velocity from an RS-274 Numerical Control code interpreter in a standard machine tool controller. The machine tool controller can access NC program files or accept input from a standard operator control unit. The control computer would also accept feedback signals from tension sensors in the 9 cables and length encoders on the 9 winches.

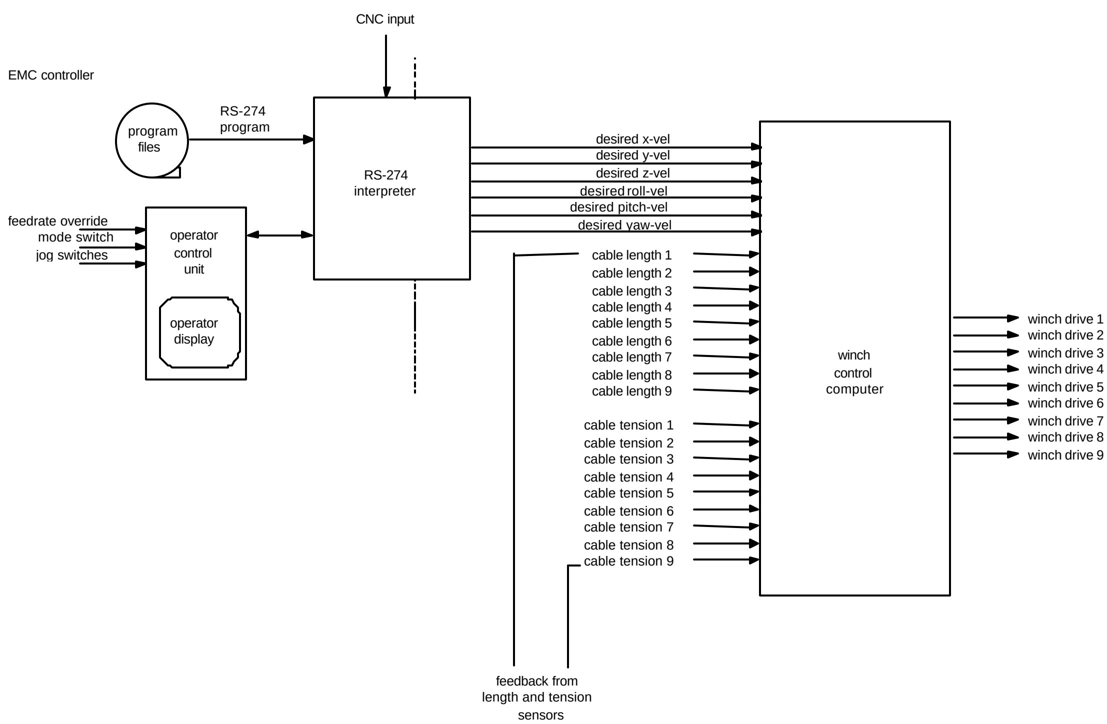

Figure 6. Block diagram of the controller for Cable-Actuated Machine Tool shown in Figure 5.

The result is a machine tool consisting of a spindle mounted on a work platform and controlled in six degrees of freedom by nine winches and cables. Accuracy and repeatability of this machine have currently not been measured. This machine can be extremely lightweight based on previous RoboCrane designs and analysis. The size of the winches depends on the force and speed required. For slow, low-force machining, the winches can be very lightweight. The only compression members of the machine are the struts of the tetrahedral frame, which can be constructed of lightweight tubing. An example representation of the machine's work volume is shown in Figure 7.

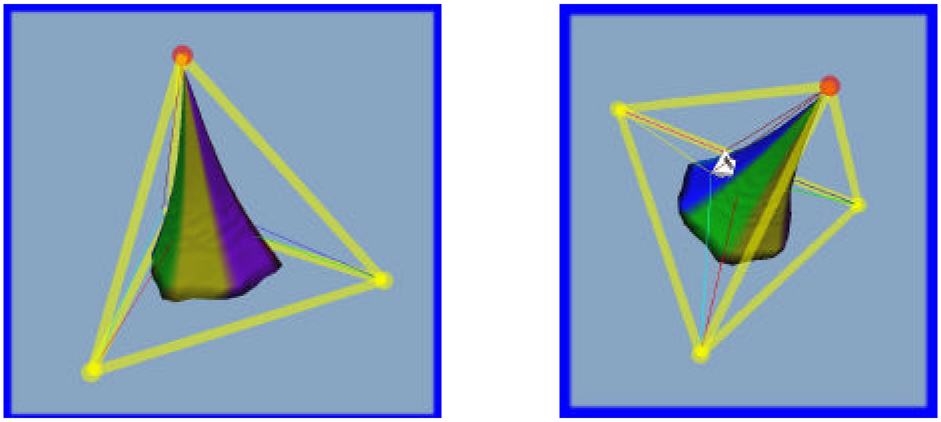

Figure 7. Example work volume representation of the Ultra Lightweight Machine.

Yet another configuration for a cable-driven machine tool is shown in Figure 8. This machine uses eight cables and a tetrahedral frame and is designed to manipulate tools outside of the support structure.

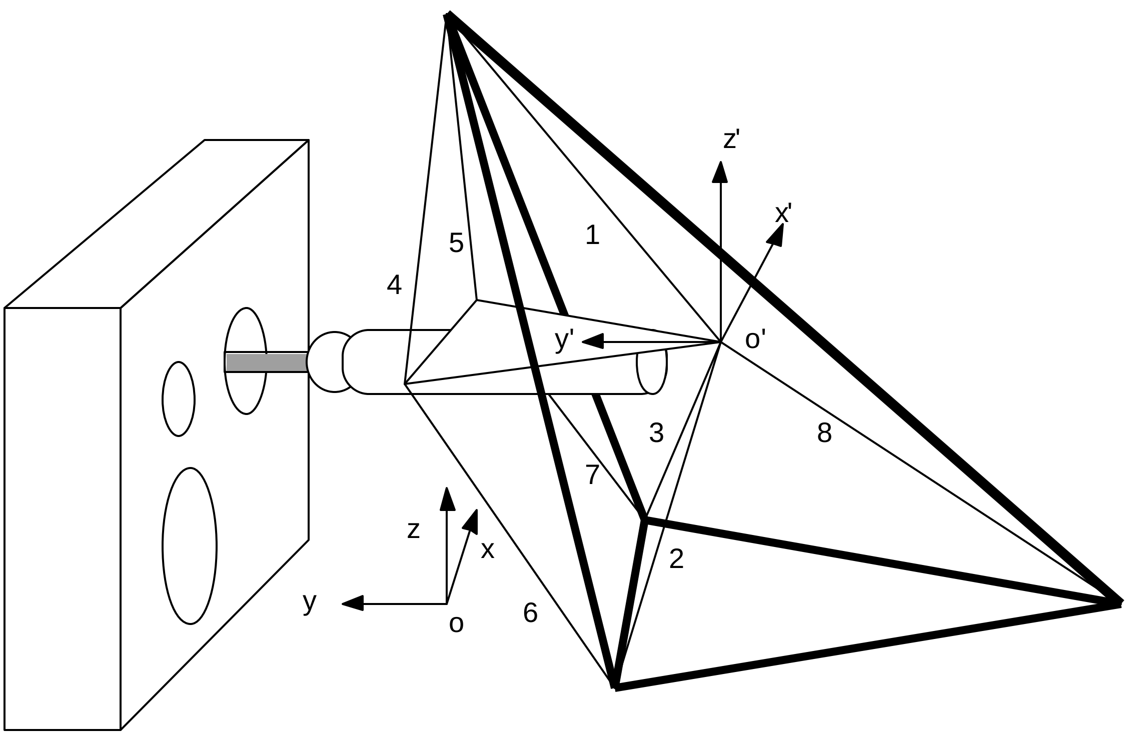

Figure 8. A Cable Actuated Machine Tool. On the right is the tetrahedral frame supporting the tool platform by 8 cables. On the left is a part that is being machined by a rotary tool. The heavy black lines represent the tetrahedral frame. The thin lines represent cables that support the tool platform. Control winches are not shown.

In figure 8, a coordinate system for the tetrahedral frame is defined by the origin o and the three axes x, y, and z. A coordinate system for the tool platform is defined by the origin o´ and the three axes x´, y´, and z´. The position of o´ in the machine coordinates is determined by the length of cables 1, 2, and 3. Tension in cable 8 maintains cables 1, 2, and 3 in tension under all operating conditions. The length of cables 4 and 5 determine the pitch and roll of the tool platform. The length in cable 6 determines the yaw of the platform. Tension in cable 7 maintains tension in cable 6 under all operating conditions. Thus, the lengths of cables 1 – 6 determines the position and orientation of the tool platform and control of tension in cables 7 and 8 maintains tension in all eight cables. A set of winches, one for each cable, can be used to control length or tension in each cable. Computer control of the winches can cause the tool tip to move through space along desired trajectories. Encoders on the winches can be used to measure cable lengths. Alternatively, string pots or string encoders can measure cable lengths independent of the cables that actuate the tool platform. This produces more precise platform position measurements than using actuated cable length measurements because it eliminates errors due to cable stretch or uneven wrapping on the winch drum. Tension sensors measure tension in each cable. Both forward and inverse kinematics can be computed in closed form.

The device shown in Figure 8 can be fitted with a rotary bit or saw blade for cutting materials such as concrete, stone, stucco, aluminum, wood, or plaster. Speed and depth of cut depend on the strength and stiffness of the cables and winches. The machine can also be fitted with a high-speed grinding wheel for grinding steel or ceramics. It can be equipped with a cutting or welding torch for cutting or joining steel plates. It can be equipped with a gripper for picking up and holding parts, or precisely positioning them for mating and joining. The size of part that can be worked on depends on the size of the tetrahedral frame and the tool platform. The mass of part that can be lifted or the power of the tool that can be manipulated depend on the strength and stiffness of the frame, cables, and winches. The machine can be scaled up to handle very large and heavy parts that are common in shipbuilding, construction, and manufacturing of heavy machinery. It can manipulate tools over very large surfaces such as ship propellers and hulls, bridge columns, or building facades.

6. MACRO STEREO-LITHOGRAPHY MACHINE

In Figure 8, the tool being manipulated is designed to manufacture parts by the process of material removal. In Figure 9, the tool is designed for the process of material deposition. The tool may be a pump and nozzle for extruding a fine bead of rapid setting material such as concrete, epoxy, or composite material. The tool may also be a spray metal nozzle or a welding wire for deposition of metal. As the tool moves over a surface, the deposited bead of material adheres to the existing surface due to surface tension. If the tool moves back and forth in a raster pattern, it deposits a layer of material. As soon as each layer sets, another layer can be laid on top of it, thereby building up a volume. Thus, the machine functions as a macro stereo-lithography machine (SLM) that can be portable for use at the work site as opposed to typical fixed-facility SLMs. The motion of the nozzle is controlled by a computer executing a part-program developed using a stereo-lithography software package. Given the proper path program of the nozzle, any arbitrary volume can be constructed. Floors, walls, or column of any desired shape and size can easily be formed. Horizontal beams, arches, and ceilings with sculpted shapes can be constructed so long as the surface tension is large enough to support the deposited bead of material until it sets. Even volumes containing inaccessible voids can be constructed.

The benefit of macro stereo-lithography is that any shape can be constructed without forms or supports to hold the material against gravity until it sets. The machine can fabricate structural walls, beams, door frames, window frames, ceilings, and floors from bulk material without any need for forms. Theoretically, any shape that can be defined by a computer program can be constructed.

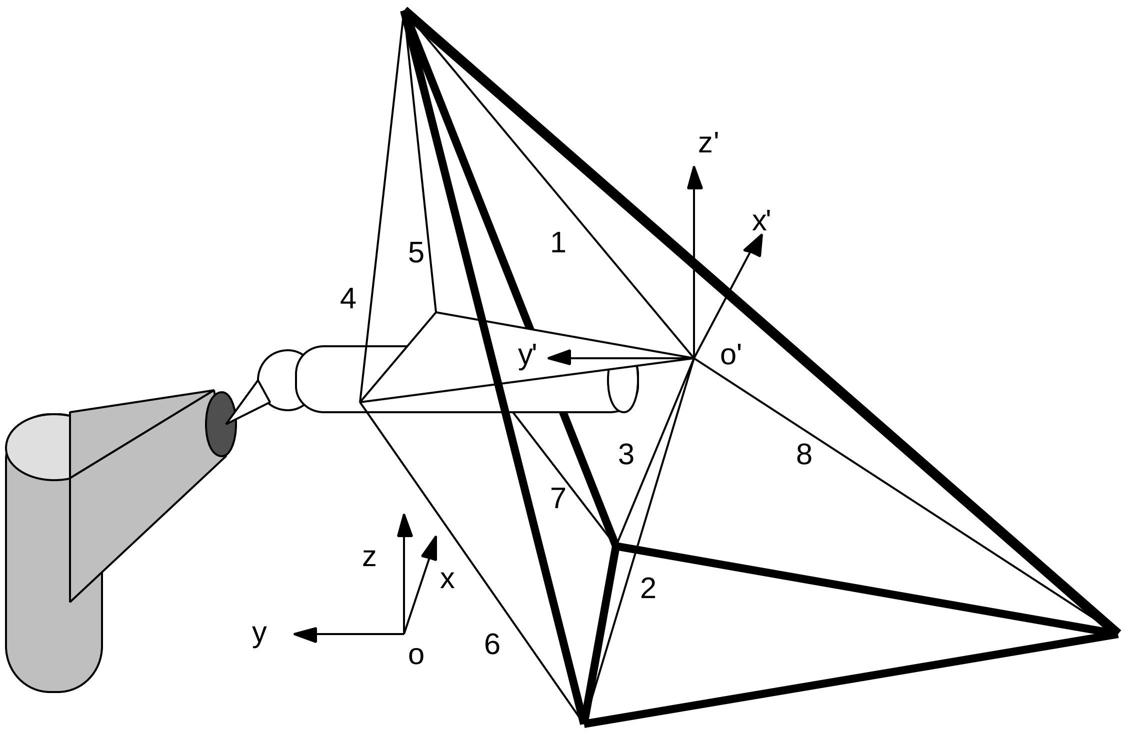

Figure 9. A Macro Stereo-Lithography Machine. On the right is the tetrahedral frame supporting the tool platform by 8 cables. On the left is a part of a structure that is being built up by depositing material from the extrusion nozzle.

It is important to recognize that one of the more far-reaching possibilities for such a machine will result if the deposition head can be rapidly interchanged or parallelized, thus permitting the deposition of materials of significantly differing characteristics within any planar section of the 3D deposited structure. This is analogous to that of a color inkjet print head in which each pixel on the 2D deposition surface can be covered by any monochromatic ink deposition (e.g. CMYK) or by any combination thereof, resulting in a digitized, continuous spectrum (256 colors, e.g. for an 8 bit digital combination of all three colors). When each 2D matrix layer is propagated -- with the achievable internal complexity determined by the in-plane pixel spacing and the inter-layer (vertical) spacing -- one can envision future composite structures being made in-situ using a macro deposition machine as described herein.

Perhaps the most dramatic practical application of such a system would be the complete elimination of forms for reinforced concrete casting. Presently, the closest this method of construction comes to automation is in the use of slip-forms for such things as cooling towers in which the forms are jacked automatically between casts and the concrete is poured automatically.

The tedious process of steel reinforcement placement and tying is still carried out manually and comprises more than 50 % of the overall construction cost, even in this efficient situation. Considering that construction accounts for 13 % of the U.S. GDP, the elimination of forms and the elimination of reinforcement steel placement would create an enormous advantage, particularly for capital infrastructure where the opportunity cost of money is high and project delivery speed is rewarded.

One may argue that in-situ buildup of reinforcement from either sintered or fluid metal deposition may presently result in unacceptable macro material behavior (e.g. brittle, lower fatigue life, lower strength) compared to cold forged steel. One may also argue that existing maturity and curing characteristics for traditional portland cement suggest limited speed of deposition. In fairness, neither of these issues has been substantially investigated and we believe that local closed-loop control processes can be developed to achieve both high strength and ductility in deposited metal as well as rapid set and strength gain in portland cement that would meet the requirements for practical macro stereo lithography structural construction. Reinforced concrete is but one example. Aerospace composites could also be built up similarly by selectively nozzle-depositing, nano-laminate fibers to achieve a layered composite system that is presently untenable with current pre-preg and strip layout machines.

The two configurations of the machine in Figure 8 and 9 can be used to manufacture parts from bulk materials. The configuration shown in Figure 9 can be used to build up a part or structure to near net shape, and then the configuration in Figure 8 can be used to machine critical surfaces to precise tolerance.

The cable machine can be scaled up to very large size and weight for modest cost. The most expensive parts are the winches. Encoders and tension sensors are the next most expensive items. The computing requirements are modest. The support structure can be constructed from lightweight tubing or truss-work and cables are inexpensive. Software development costs for part programs may be significant, but software is a onetime expense. Software development tools represent a one-time start up cost for production, and part programs represent a one-time cost for each part.

4. FLYING CARPET SCAFFOLD

A recently designed configuration of the RoboCrane concept has been dubbed the “Flying Carpet.” The Flying Carpet is a cable-supported platform that is intended to precisely manipulate workers, tools/equipment, and loads using position-, velocity- and force-control modes. It can be used to provide worker, tools/equipment, and/or load access to large surfaces such as ships in dry-dock and, potentially, commercial or residential building walls or structures. A 1:120 scale model of the Flying Carpet concept is shown in Figure 10. A photograph of a full-scale test bed version of the Flying Carpet is shown in Figure 11.

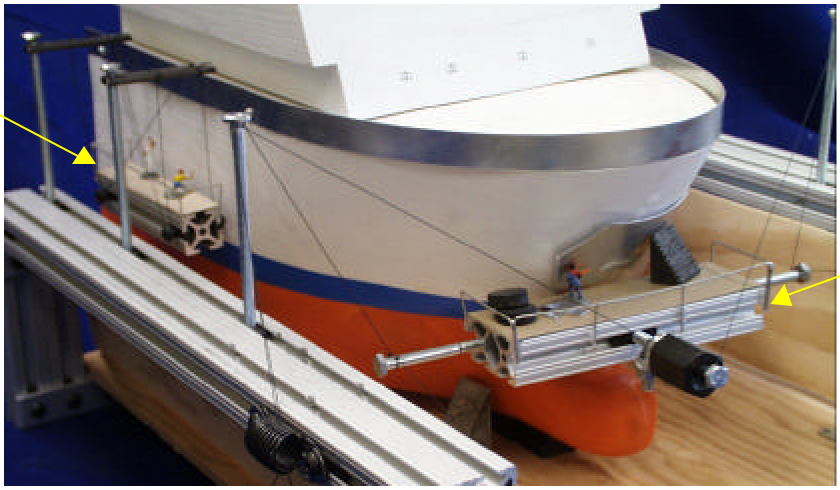

Figure 10 –NIST Flying Carpet 1/120th scale model applied to dry dock ship repair and conversion.

The Flying Carpet uses 6 cables that attach to 4 support points (as opposed to the Stewart Platform 3-point support) to stabilize and control the suspended platform. The cable lengths can be controlled independently by hoist mechanisms and coordinated to achieve predicted platform-movement in all six degrees-of-freedom. The platform can be reconfigured rapidly to adjust to worker/equipment access challenges in dry dock ship repair and conversion (see Figure 10).

In a typical dry-dock, ship repair operation of a bow that measured approximately 80 ft above the dry dock floor, conventional stick-built scaffold was constructed to access the target repair area. A conservative estimate of 64 person-hours was needed to erect conventional scaffolding to access the repair area. Removal of the scaffold upon task completion requires additional time. With a RoboCrane-based system called the Flying Carpet, an estimated (based on RoboCrane prototype set-up and deployment) 3 person-hours can access the same area as well as, provide predictable joystick repositioning of the platform to move to adjacent repair areas of the ship or to pick-up workers and/or equipment and tools.

We anticipate that the Flying Carpet concept can also be used for construction, building maintenance, and operations over nuclear-waste, burial pits. Various combinations of manual and automatic control can be implemented. The hoists can be controlled manually by a multi-axis joystick, or can be automatically controlled by computer.

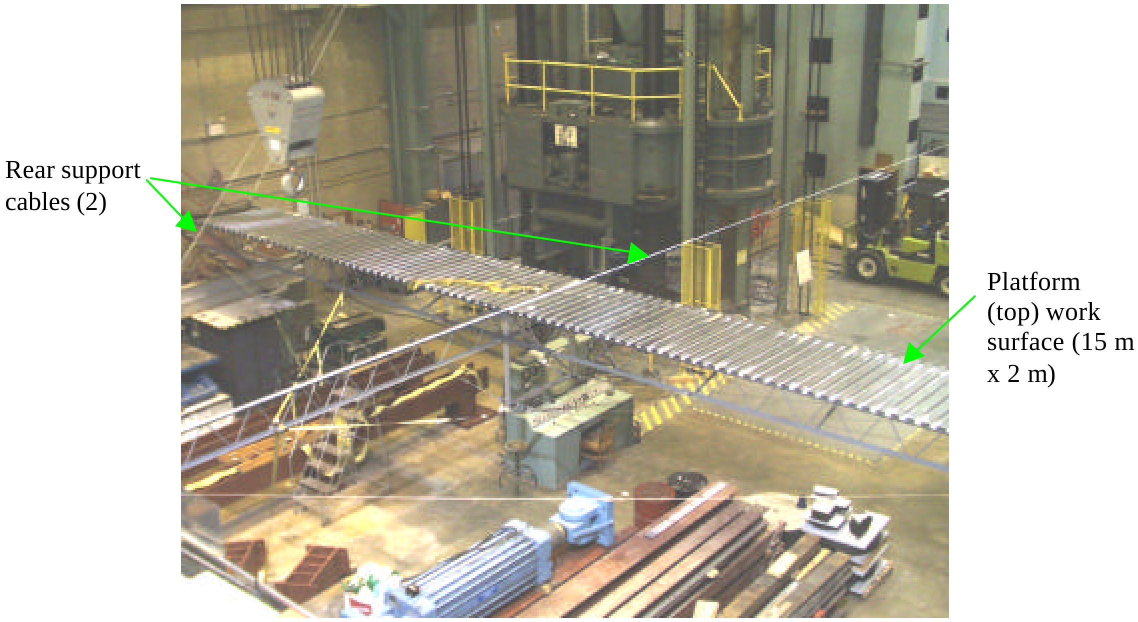

Figure 11 – Photograph of the NIST Flying Carpet full-scale testbed (15 m (50 ft) long) suspended in the NIST high-bay facility above laboratory equipment.

The Flying Carpet project is in support of a Navy Maritech Advanced Shipbuilding Enterprise project, called Knowledge-based Modular Repair. This project involves a partnership between NIST and Atlantic Marine Shipbuilders in Mobile, Alabama. Performance measurements and cable configurations are being studied on the full-scale testbed prior to testing in an Atlantic Marine dry-dock facility. The testbed is constructed of corrugated sheet steel welded to steel roof joists. The joists are bolted together in the center to allow easy disassembly for transport and ship-side access testing. Static testbed measurements have been made and used to verify a computer model resulting in platform work volume, loading, and cable (wire-rope) capacity limits. The testbed currently weighs 794 kg (1750 lbs). It will weigh approximately 1542 kg (3400 lbs) when outfitted with onboard winches. It is designed to carry a maximum payload (i.e., not including the platform) of 1224 kg (2700 lbs) at the top of the work volume, and maximum payload at the dry dock floor of 4173 kg (9200 lbs).

7. CONCLUSIONS

Research in the Intelligent Systems Division and Structures Division at the National Institute of Standards and Technology has explored innovative ways to use sensors, computers, and light-weight tensioned cable structures for heavy manufacturing and construction tasks such as lift and position of heavy loads and manipulation of tools and parts for assembly, fixturing, welding, cutting, grinding, machining, macro stereo-lithography, and surface finishing. Cable-driven systems can move heavy or light loads (equipment, tools, materials, people) over large work volumes with repeatability and resolution of several millimeters. This makes them feasible for performing many construction and large-scale machining tasks. Various combinations of manual and automatic control can be implemented. Several prototype cable-controlled systems have been demonstrated at NIST.

Recent research has demonstrated novel concepts for movable scaffolding and worker positioning systems that enable workers to maneuver themselves and parts and tools throughout a large work volume for tasks such as ship repair and aircraft paint removal. NIST research and development has proven feasibility and demonstrated prototype systems. Two of these systems are currently being considered for deployment by government and industry partners.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

[1] Stewart, D., “A Platform with Six Degrees of Freedom,” Proc. of the Inst. of Mechanical Engineering, Volume 180(15), Part I:371-386, 1965-1966.

[2] Albus, J. S., Bostelman, R. V., Dagalakis, N. G., “The NIST ROBOCRANE, A Robot Crane”, Journal of Robotic Systems, July 1992.

[3] Bostelman, R., Albus, J., Dagalakis, N., Jacoff, A., “RoboCrane Project: An Advanced Concept for Large Scale Manufacturing,” Association for Unmanned Vehicles Systems International Proc., Orlando, FL, July 1996.

[4] Bostelman, R., Albus, J., “Stability of an Underwater Work Platform Suspended from an Unstable Reference,” Proc. of Oceans ‘93, Engineering in Harmony with the Ocean, Victoria B.C. Canada, October 1993.

[5] Bostelman, R., Albus, J., Dagalakis, N., Jacoff, A., Gross, J., “Applications of the NIST RoboCrane,” 5th International Symposium on Robotics and Manufacturing Proc., Maui, HI, August 1994.

[6] Stone, W., Pfeffer, L, “Automation Infrastructure System for a Robotic 30-ton Bridge Crane,” American Society of Civil Engineers Conf. Proc., Albuquerque, NM, April 26-30-1998.

[7] Lumia, R., “The Enhanced Machine Controller Architecture,” 5th International Symposium on Robotics and Manufacturing Proc., Maui, HI, August 1994.

[8] Bostelman, R., Jacoff, A., Proctor, F., et. al., “Cable-Based Reconfigurable Machines for Large Scale Manufacturing,” Japan/USA Flexible Automation Conference Proc., University of Michigan, Ann Arbor, MI, July 2000.

[9] Step Tools Incorporated, “The ISO STEP Standards,” Online: http://www.steptools.com/library/standard/, 1999.