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CABLE-BASED RECONFIGURABLE MACHINES FOR LARGE SCALE MANUFACTURING

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INTRODUCTION

Reconfigurability means low cost and short time to change machine configuration to meet application demands. Typical machining and positioning systems use hard actuators, like screws and pistons, and are built with slideways and hard frames. These components provide good stiffness, are well-proven, and can be packaged into modules to build reconfigurable machines. They are also relatively expensive, however, and for large-scale applications, modules based on ballscrews and ways would be unwieldy and difficult to move and align during reconfiguration. This paper explores winch-driven cable systems—in particular, cable-based Stewart platform machines—as candidates for reconfigurable, large-scale, manufacturing systems. Cable-based systems are less expensive and more compact for a given range of motion and are more lightweight and easier to reconfigure than large scale systems that use ballscrews and ways. Thus, cable-based machines are appealing as an economical choice for applications that require a large range of motion, such as aircraft or ship manufacturing and construction.

The disadvantage of cable-based systems is their lower stiffness and accuracy. Stiffness is limited by the cross section of the cables (typically much smaller than a ballscrew), cable strand twist and catenary droop, and compliance in machine components such as pulley supports and pivots. Error sources include effects such as cable stretch and thermal growth. Also, Stewart platform machines typically have a complex work volume and a relatively limited range of orientational motion. Cable systems must be preloaded to keep the cables in tension. However, properly preloaded (by gravity acting on the payload or by redundant cables) cable-based machines can exert forces up to the preload levels in all directions.

Like systems that use hard actuators, cable-based systems can be driven by motors under computer control. This allows them to be programmed like conventional machine tools and automation equipment.

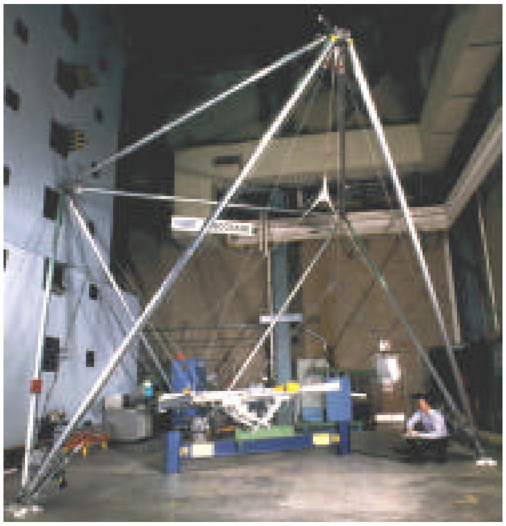
CABLE BASED MACHINE CONFIGURATION

NIST has built several prototype cable-based Stewart-Gough platform machines, called RoboCranes [1]. These machines use six cables to support a triangular work platform to which a tool or load is attached (Figure 1). The position of the work platform is controlled relative to three points on the ground (or overhead) by using six computer-controlled winches to control the length of the six cables. The work platform uses gravity to maintain tension in all six cables. The six cables constrain the suspended work platform in all six degrees of freedom. This configuration is essentially a cable-based version of the Hexapod parallel kinematic machine tools that have received considerable interest recently (Figure 2).

The arrangement of these positioning cables along with the tension preload provided by the weight of the suspended platform allow it to resist and exert forces in any direction (limited by the preload). By applying computer control and kinematics similar to the Hexapod machine tool, this cable-based system can maneuver the suspended platform with stability throughout a large work volume. The range of Cartesian positions (x, y, z) through which the platform can maneuver is related to the size and elevation of the overhead mounting triangle.

The platforms x-y range of motion is limited generally to the inscribed circle within the overhead triangle. Its vertical motion is limited generally at the top by the shallow angles of opposing cables, and at the bottom by loss of lateral stiffness due to the increasing parallelism of the cables. This cable-based machine provides stable control of all platform orientations (roll, pitch, and yaw). The range of motion in yaw is about ±30 degrees, and the range of motion in pitch and roll is about ±15 degrees (workspace is configuration dependent).

(a)



(b)

Figure 1. RoboCrane Prototypes. (a) Supported from six-meter octahedral frame. (b) Supported from facility ceiling/walls (shown with micro-manipulator attached).

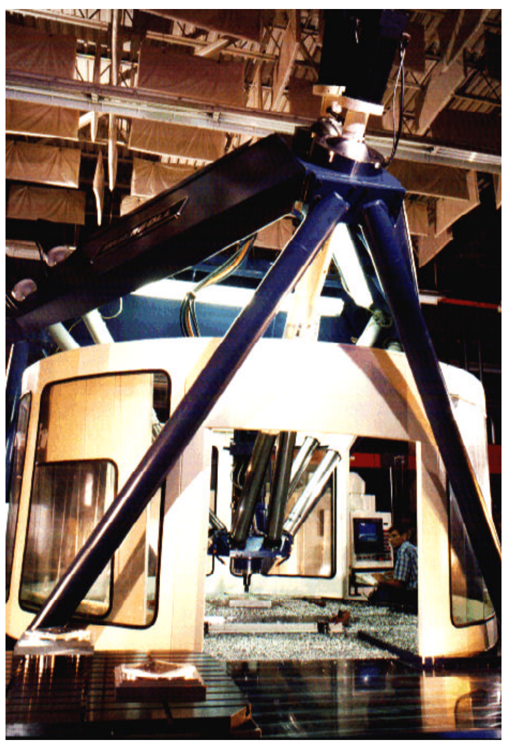
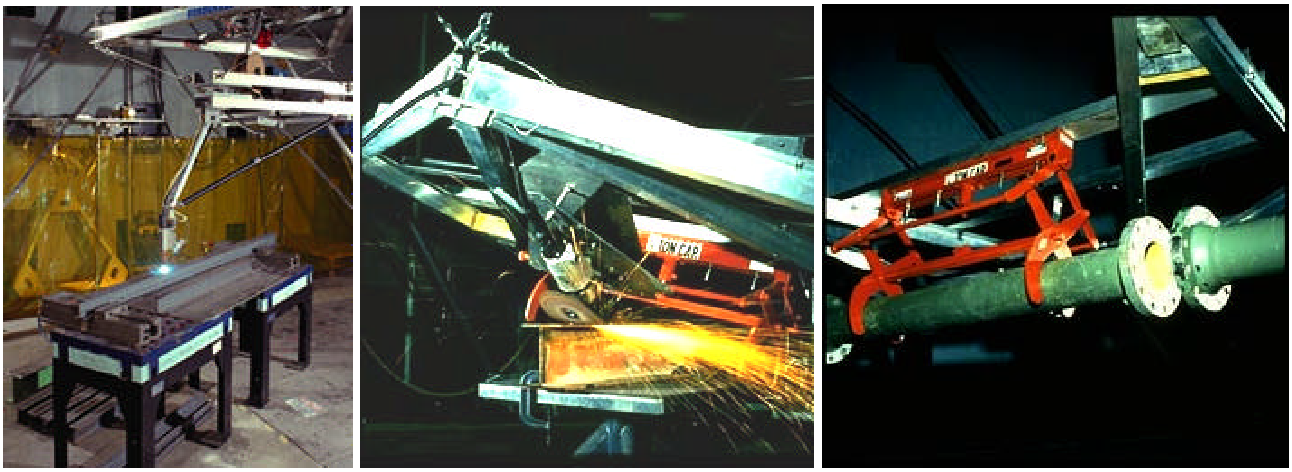


Figure 2. Example Hexapod Machine Tool.

The main advantage of these cable-based machines is that the length of travel for a cable is large compared to the size of the actuator. By contrast, the length of travel for a ballscrew strut is small compared with the size of the actuator. Also, a cable-based system can be reconfigured relatively easily and quickly to handle changes in mounting configurations at various work sites. In addition, they scale well in both size and payload capacity to allow application to a large variety of tasks. Since the winches and winch controllers for all six axes are identical, these systems are very modular and easy to maintain.



(a) (b) (c)

Figure 3 – Cable-based machine applications (a) Welding a beam under pre-programmed trajectory control. (b) Grinding a beam under remote operator trajectory control. (c) Pipe assembly using selectable reference frames (platform, tool, and part).

Another alternative for reconfigurability is the location of the control and actuator package. There are two distinct configurations. One configuration locates the winches and control equipment on or near the ground, and the cables are simply redirected over pulleys that form the overhead triangle (Figure 1a). This configuration allows a passive suspended platform. Another configuration places the actuation and control equipment directly on the suspended platform (Figure 1b). There is typically a power tether draped to the platform. Control commands may be generated from an onboard computer or radio linked from an off-board location. Cable-based machines can either be self-supported (Figure 1a) or facility-mounted (Figure 1b). Self-supported machines use a structural frame to provide the elevated mounting points that form the overhead triangle. The advantage of this configuration is that work can take place in areas where no overhead support structure exists, such as outdoors. Facility-mounted machines use the facility's structure, like walls or ceilings for example, to mount the fixed ends of the cables.

A variety of tools and equipment can be attached for different applications. Tools may be mounted to the work platform and controlled by an on-board or remote operator, or by semi-autonomous trajectory control methods. Tools such as a welder, grinder, gripper, saw, and pipe-grabber have been demonstrated for a variety of applications (Figure 3), such as ship-building [2], ship and aircraft painting and paint removal, material handling, and equipment and part fixturing [3].

Parallel kinematic, cable-based systems like those described above rely on gravity to maintain tension in the cables. However, cable-based systems can also be configured with a central spine and opposing stabilization cables to maintain tension in the six positioning cables for any platform orientation (Figure 4). In this configuration, the cables attached to the spine are tension-controlled to avoid an over-constrained position control problem. The spine configuration increases the usable work volume and permits load forces to be applied in an upward direction.

CALIBRATION

Cartesian motion control of a reconfigurable, cable-based machine requires knowledge of kinematic parameters such as the locations of the stationary cable attachment points in world coordinates and the geometry of the platform cable attachment points in platform coordinates. These kinematic parameters may change during a reconfiguration. For example, the stationary cable ends may be repositioned to more widely separated points to increase the work volume, or the lower platform may be exchanged for one with different tooling or payload capacity. To apply cable-based machines to tasks with modest accuracy requirements, the cable attachment

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locations can be measured directly using surveying equipment or a tape measure. Once the geometries of the fixed attachment points and platforms have been determined, the appropriate set of kinematic parameters can be selected when the machine is reconfigured. More sophisticated means for calibrating Stewart platform machines are available [5]. But if improved accuracy is sought, it may be desirable to measure the position of the platform itself (perhaps with a laser tracker [4]) to mitigate the effects of cable stretch and other errors.

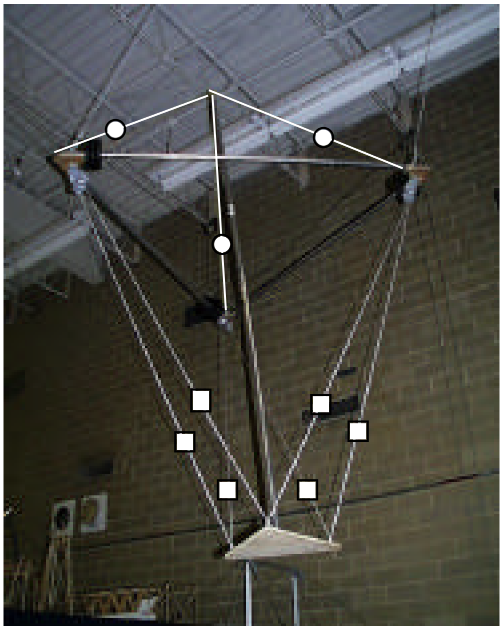

Figure 4. Suspended platform with center spine. Squares indicate positioning cables and circles indicate tensioning cables.

Once the kinematic parameters are determined, the initial position of the platform needs to be measured. This needs to be done each time the system is initialized. For machine tools, this procedure is known as homing. Typically, homing is accomplished by moving each axis until a switch trips, and recording the position of the next index or marker pulse from the feedback device. For cable-based machines, there are two alternatives. The direct analogy to machine tools is to move each cable until it is at a known length, either as marked on the cable or as sensed by a switch that can be tripped by a cam on the cable. The alternative is to move the platform to a known position and orientation, and then compute the cable lengths directly from the kinematics. In general, this approach is more difficult, since it requires maneuvering the platform to the Cartesian home position and orientation by adjusting cable lengths independently of one another.

Calibration requirements are reduced if a machine is to be controlled primarily through teleoperation. During teleoperation, the machine is moved manually to continuously adjust its position based on the operator's visual observations of the position and orientation of the platform. In this case, the primary machine attributes needed are resolution, the ability to move in the intended direction, and low control latency—absolute accuracy is not critical.

CAD/CAM/CNC

In any case, the use of cable-based systems requires computer numerical control (CNC) in order to generate the complex cable motion required to move the platform in Cartesian coordinates. It is virtually impossible for an operator to simultaneously control six cable lengths and get any meaningful motion. The computer controller may be equipped with an interpreter that reads in programs written in common industrial programming languages and outputs motion commands the controller can perform. This effectively turns the cable-based system into a machine tool. The programs are generated by computer-aided design and manufacturing (CAD/CAM) software or robotic off-line programming systems.

Once a machine is configured, calibrated, and homed, the operator must indicate the part so that its position is known relative to the world coordinate system shared by the machine. The job of the operator is simplified greatly through the use of a pendant or joystick. Therefore, the various control modes include the following:

- world coordinate motion, in which the position and orientation of the platform are controlled in a coordinate system fixed relative to the floor
- tool coordinate motion, in which the platform can be moved along its own coordinates, such as along its tool axis
- part coordinate motion, so that motion can take place along the edge of a part
- joint coordinate motion, in which cable lengths are changed directly

A small, working, prototype, cable-based system was built and demonstrated recently at NIST (Figure 5). This system includes six stepper motors and cable-spools mounted on a platform 0.50 m (18 in) on each side and suspended within a metal frame. A high-speed rotary tool was attached to the platform for use as a cutter. The stepper motor drivers receive desired motor positions from a PC. The PC executes a program containing Cartesian tool paths, computing inverse kinematics to translate the Cartesian motions into winch commands. The PC software includes an interpreter [6] for the RS-274 machine control language [7]. Output from the interpreter is in terms of motion commands from a set of canonical machining commands [1].

Execution of tool paths for cutting a standard tapered, circle-diamond-square part has been demonstrated to test the system. The resulting part, measuring approximately 10 cm x 10 cm x 8 cm high (4 in x 4 in x 3 in high), was cut from soft material (styrofoam) to demonstrate feasibility (see Figure 5c).

Larger and harder parts will be machined using the RoboCrane prototypes shown in Figure 2 supporting a heavy-duty cutting tool and moving over a work volume of approximately 14 m^3 (500 ft^3).

(a) **(b)** **(c)**

Figure 5. NIST table-top RoboCrane: a cable-based machine tool prototype. (a) Shown supported from a simple frame. (b) Machining tapered-circle-diamond-square test part. (c) Sample 4" x 4" tapered-circle-diamond-square test part machined with the table-top RoboCrane.

CONCLUSION

Cable-based machines may be ideally suited for large scale manufacturing applications that require reconfigurability. They are inherently low cost and easy to reconfigure. Their stiffness and accuracy are not as good as fixed-geometry machines, so their use is limited to applications such as construction or rough machining where high accuracy is not needed. Calibration is an issue, and several methods for calibrating these systems have been presented. Because they appear as a robot or machine tool to the shop designers and programmers, they can be easily integrated into existing businesses. A demonstration of CAD/CAM and CNC machining with a cable-based Stewart Platform system demonstrates the applicability of this technology. Further experimentation is needed to verify performance in industrial settings.

REFERENCES

1. Albus, James; Bostelman, Roger; Dagalakis, Nicholas; The NIST RoboCrane, Journal of National Institute of Standards and Technology, Vol. 97, Number 3, May-June 1992.
2. Bostelman, Roger; Jacoff, Adam; Bunch, Robert; Delivery of an Advanced Double-Hull Ship Welding System Using RoboCrane, Industrial Automation Conference Proc., Genova, Italy, June 1999.
3. Bostelman, Roger; Albus, James; Dagalakis, Nicholas; Jacoff, Adam; Gross, John; Applications of the NIST RoboCrane, 5th International Symposium on Robotics and Manufacturing, Maui, HI, August 14-18, 1994.
4. Lau, K.; Hocken, R.; Haight, W.; An Automatic Laser Tracking Interferometer System for Robot Metrology, Proc. CIRP – Precision Engineering Conference, Interlaken, Switzerland, July, 1985.
5. Soons, J. A., Measuring the Geometric Errors of a Hexapod Machine Tool, Laser Metrology and Machine Performance IV, Proc. Fourth Lambdamap conference, Computational Mechanics Publications, 1999.
6. Kramer, Thomas; Proctor, Frederick; “The NIST RS274/NGC Interpreter, Version 2,” NIST Internal Report 5739, October 1995.

7. National Center for Manufacturing Sciences; The Next Generation Controller Part Programming Functional Specification (RS-274/NGC); National Center for Manufacturing Sciences; August 1994.

8. Proctor, Frederick M.; Kramer, Thomas R.; Michaloski, John L.; “Canonical Machining Commands,” NIST Internal Report 5970, January 1997.