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THE FLYING CARPET: A TOOL TO IMPROVE SHIP REPAIR EFFICIENCY[1]

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ABSTRACT: NIST is working directly with industry to improve repair and conversion operations of ships in dry dock. The technology discussed is applicable to shipbuilding, aircraft maintenance, construction, and other industries requiring worker-access to large, external surfaces with minimum footprint and maximum system rigidity and control. The technology augments conventional suspended-scaffold systems by providing safe, rapid access to non-planar surfaces. This approach moves toward more autonomous large-scale manufacturing applications.

KEYWORDS: worker-access, ship repair, robotics, cable controlled, large scale manufacturing

INTRODUCTION

The Manufacturing Engineering Laboratory of the National Institute of Standards and Technology (NIST) teamed with Atlantic Marine, Inc. in Mobile, Alabama to study efficient methods to repair ships in dry dock or along a pier. This project, called Knowledge-based Modular Repair [1,2] is under the Navy National Shipbuilding Research Program Advanced Shipbuilding Initiative, where worker-, equipment-, and material-access to external ship surfaces was determined to be a key focus area. The concept developed in this project, called the “Flying Carpet,” combines two main technologies: the NIST RoboCrane and commercially available suspended scaffolding to produce an effective concept for worker access to ships, submarines, buildings, and other large objects.

The NIST Intelligent Systems Division developed the RoboCrane cable-controlled manipulator over several years [3,4,5] during a project for the Defense Advanced Research Project Agency that studied crane suspended load control. Since the DARPA project, NIST has expanded RoboCrane technology into a viable solution to address large-scale manufacturing and many other challenges [6]. The RoboCrane applies the (inverted) Stewart-platform parallel-link manipulator [7] technology to a reconfigurable, cable-driven system. While RoboCrane can lift large, heavy and awkward loads, its stability and maneuverability allow advanced programming techniques more analogous to robots than cranes. The RoboCrane combines sensors, a computer, a platform and tensioned cables to perform heavy manufacturing and construction tasks, such as: lifting and positioning heavy loads and manipulation of workers, tools and parts. The RoboCrane manipulator can improve worker accessibility to ships and buildings for performing tasks such as: assembly, fixturing, welding, cutting, grinding, machining, surface finishing and inspection.

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Recent research has yielded the Flying Carpet concept as a movable scaffolding and worker positioning system that enables workers to maneuver themselves, parts, and tools throughout a large work volume for tasks such as ship repair and aircraft paint removal with an expected 20-times improved efficiency. This efficiency is based on a comparison of scaffold set-up time observed at the shipyard (at least 64 person-hours) versus expected Flying Carpet deployment time, for the bow/stern access configuration, extrapolated from NIST RoboCrane experiments (3 person-hours). The Flying Carpet is a cable-supported platform that uses single-axis jog (displacement)-, velocity- and force-control modes. A photograph of the 1:120 scale concept model is shown in **Figure 1**.

Figure 1 – NIST Flying Carpet 1/120th scale concept model showing the ship bow/stern access configuration (right) and the ship side-access configuration (left).

We envision a combined closed-loop system, whereby the Flying Carpet can autonomously and rapidly lift, position, and attach heavy, bulky steel plates onto ships in dry dock during repair and conversion operations. Similarly, the system can be used for more autonomous assembly applications on construction sites. This paper details the Flying Carpet concept, status, and provides a look to the future toward building construction and more autonomous manufacturing.

CONCEPT

Small and full scale static physical models, a computer model for studying system work volume, and a full-scale working prototype have demonstrated the advanced functionality of the Flying Carpet as a tool for ship repair and other uses. **Figure 2** shows a photograph of the full-scale working prototype Flying Carpet configured for ship bow/stern access. Its basic geometry includes four upper support points, instead of three as used for RoboCrane, to match the rectangular dry dock configuration. The four points connect to three work-platform hard points with six cables in a unique configuration creating a relatively rigid system.

The four upper support points can be attached to towers mounted to a dry dock, ground, or along a pier, to a gantry, ceiling, walls, or other superstructures. Two front cable pairs provide platform lift while two rear cables mount lower to pull back on the platform creating a rigid system. Cables can be multi-part lines for added safety factor and lift capacity. By suspending the platform from above, the RoboCrane improves operating efficiency by “flying” over ground-clutter or landscaping that typically hinders wheeled vehicles at the work site.

Hoists that control each cable’s length can mount on the support structure or the work platform. The total hoist rigging capacity of the prototype, which uses two-part, 8 mm (5/16”) diameter wire ropes, totals 8200 kg (18,000 lb). In the prototyped configuration, the Flying Carpet carries its hoist motors, providing maximum platform set-up flexibility, as well as providing a counterweight to move the platform center of gravity to within the platform structure.

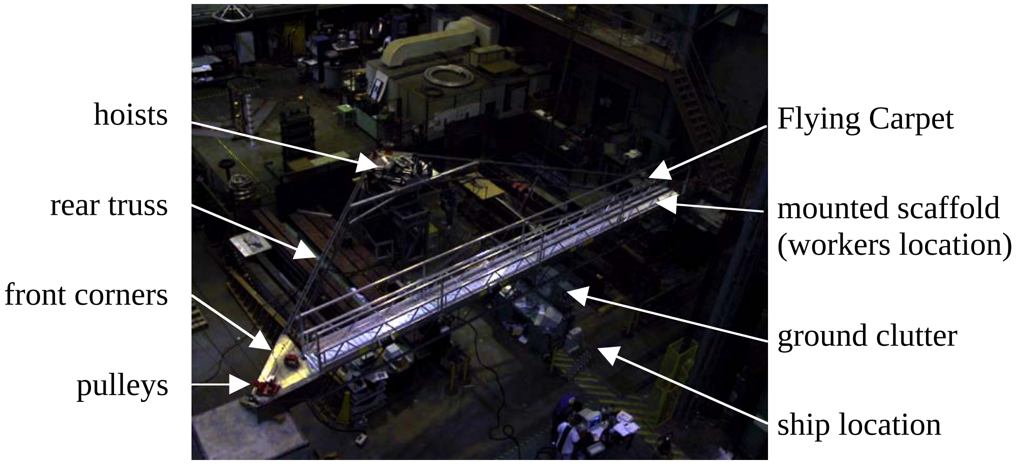

Figure 2 – Photograph of the full-scale Flying Carpet prototype top view shown in the ship bow/stern-access configuration and suspended over ground clutter. The platform measures 14.6 m along the front.

Welders, paint sprayers, or other equipment can mount to the Flying Carpet. The platform allows rapid fixturing of tools, equipment, or cargo to provide direct worker access to the equipment as needed at the site. An on-board supply hoist can also attach to the platform to bring tools, workers, and supplies up to the work site while the platform is parked in position. The Flying Carpet cable configuration provides a constrained and easily maneuvered work platform as compared to conventional worker-access systems typically used for ship repair, thereby aiding ship repair and inspection tasks.

The platform provides minimized sway and rotation, and can exert forces and torques with full six degree-of-freedom control. The operator commands platform motion through the tethered joystick, either worn by the operator or mounted to the platform. With the platform an on-board or remotely-located operator can manipulate and hold attached materials, such as heavy steel plates, or tools, such as welders, grinders, robots and other cargo dependent upon the platform rated capacity. Tension sensors in-line with each cable can prevent hoist or platform overloading and sense slack cables. Experiments with the Flying Carpet demonstrated installation of a tilted, mock-steel plate, measuring approximately 1.2 m x 1.2 m x 19 mm thick (48 in x 48 in x _ in thick), into a mating, tilted frame having a clearance of approximately +/- 6 mm (_”).

CONTROL

Flying Carpet moves in Cartesian and “joint” modes. Cartesian control allows the worker to intuitively move the platform front-to-back, side-to-side, up-and-down, and yaw about the vertical axis all while maintaining platform level. Joint mode allows single-hoist motion for setup or cable replacement for normal maintenance.

The Flying Carpet rigger must measure the anchor points with respect to a ground-based coordinate system. The anchor points of the cables to their sheaves on the platform must likewise be measured with respect to a platform-based coordinate system. The controlled position is then the position of the platform origin relative to the ground origin, which moves around as the cables lengthen and shorten. These calibration measurements need only be done once, when the platform is installed at the facility and can be set out rapidly using an off the shelf laser measurement system. Velocity servo amplifiers power the hoist motors. The amplifiers provide a serial interface over which velocity commands and position feedback are sent. Depending on the configuration, a single serial link may connect to a single amplifier serving a single motor, or several amplifiers each controlling several motors may share a single serial link. The Flying Carpet uses RS-485 multi-drop serial signaling instead of the usual RS-232 single-drop serial signaling.

Control Method

The controller implements resolved-rate teleoperation, in which a joystick generates the desired velocity of the moving platform in Cartesian space (X, Y, Z, roll, pitch, and yaw). This desired velocity is transformed into cable speeds through the inverse Jacobian function:

$$W = J^{-1} V \quad (1)$$

where W is the 6x1 cable speed vector, V is the 6x1 Cartesian velocity vector, and J^{-1} is the 6x6 inverse Jacobian transform matrix that depends on the current Cartesian position of the moving platform.

The Jacobian is an instantaneous relationship. In a sampled system, where some time elapses between successive recalculations of the inverse Jacobian matrix (100 ms in this case), the cable speeds will be constant during this interval. As a result, the moving platform will accumulate position errors and require correction.

Normally the operator would compensate for these errors, which are small, but in our case the Cartesian roll and pitch velocities are forced to zero to keep the platform level. However, as errors accumulate, the platform will go out of level and require some compensation. It is possible to correct these automatically, since the actual Cartesian position (including roll and pitch) are continually computed by reading the cable lengths from the motor encoders and running these through the forward kinematics function:

$$C = T\theta \quad (2)$$

where C is the actual 6x1 Cartesian position vector, θ is the 6x1 cable length vector, and T is the 6x6 matrix for the forward kinematic transform. Since actual roll and pitch are known, velocities in the compensating direction can be automatically computed and used to drive the platform toward level. This method will not work to level the platform in the presence of perturbations that cannot be sensed by the motor encoders, such as cable stretch or slack due to unbalanced platform loading. To compensate for these errors, a level sensor detects the roll and pitch angles and adjusts platform level as just described.

In the case of the Stewart Platform, the inverse Jacobian transformation J^{-1} is closed form. However, the forward kinematic transform T is not closed form, and iterative calculations estimate the true Cartesian position C. The iterative algorithm requires an initial estimate of the Cartesian position in order to converge. During normal operation, this estimate is simply the last Cartesian position computed, which changes little from cycle to cycle. However, initial computations need a matched pair of cable and Cartesian positions in order to begin the iterations. A short, 4 step homing procedure generates the matched pair.[8] If the controller can preserve its last Cartesian position upon shutdown and restore it when starting up later, then the homing procedure need be done only once when the system is first set up and calibrated. This has been demonstrated with the full-scale prototype Flying Carpet.

Controller Description

Our controller is a PC/104-based system with a Geode Pentium-compatible processor, running BusyBox Linux, kernel 2.4.1, with the RTL 3.0 real-time patch. Mass storage is a 96- megabyte Disk On Chip. Additional PC/104 I/O modules provide up to 8 serial connections, and digital and analog I/O. Portions of the system are shown in **Figure 3**.

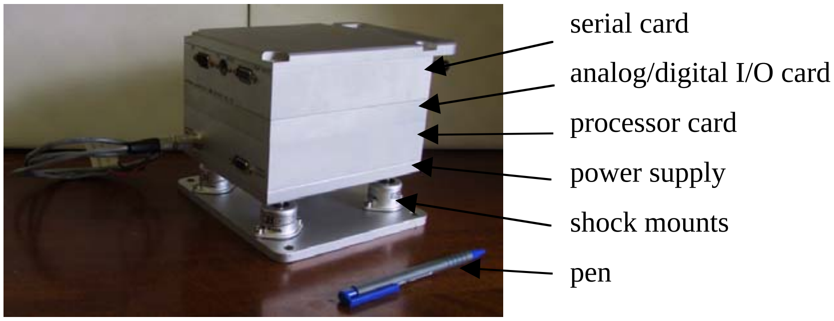

Figure 3 – Controller PC/104 modules for computing and I/O via a compact, assembled stack.

Serial connections to the motor amplifiers use two 1.2 kbytes/s links. Each link communicates with a low level driver that powers three motors. Velocity command messages and associated overhead occupy about 30 bytes. Motor commands are sent out in pairs for a lower bound on the complete control cycle of about 100 ms. The saved Cartesian position at shutdown is restored upon power-up so that homing need be done only once at installation time or periodically after maintenance. Also, other dry dock mount locations for the Flying Carpet can be stored (and retrieved) on the flash disk. No other information is written to the flash disk. Using the lifetime model provided by the flash disk's manufacturer, writing this small amount of data daily onto approximately 60 mB of free wear-leveled storage yields a lifetime far in excess of the device's quoted 148 years of mean time between failure.

SHIP BOW/STERN-ACCESS CONFIGURATION

The full-scale prototype configured for ship bow and stern access measures 14.5 m wide x 7 m deep x 2 m high. , Six 680 kg (1500 lb) hoists can carry 680 kg (1500 lb) of workers, materials, and equipment in addition to the 1400 kg (3000 lb) weight of the platform itself, with a safety factor of 5.

Performance measurements and cable configurations were tested on the full-scale testbed prior to planned testing in a shipyard dry dock. Constrained by the NIST facility, spacing of the upper support points simulated an 18 m tower height, a 21 m dry dock width, and 14 m between the tower and rear attachment points. The full-scale Flying Carpet prototype demonstrated: 10 m lift, 9 m forward-to-back motion, 5.5 m side-to-side motion, and yaw of more than ± 25°. The translational work volume should scale well to the larger dry dock environment. Since dry dock sizes vary greatly, a computer model (see **Figure 4**) of the dry dock and Flying Carpet was developed to study work volumes of various dry docks as the model can easily be changed. Earlier in the project, a Phase-1, full-scale, static Flying Carpet testbed was built and suspended including a tension sensor in-line with each of the 6 cables. Results of load experiments on the testbed were used to verify the computer model. The model shows the platform center-of-gravity work volume as well as, representative tension bars in-line with each cable to visually compare relative tensions as the platform is re-positioned.

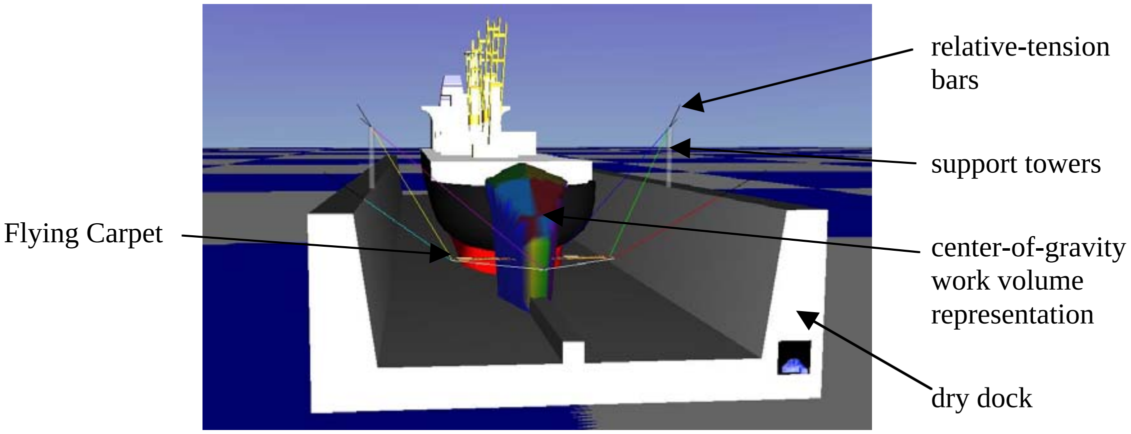

Figure 4 – Computer model of the full-scale Flying Carpet accessing the ships bow while in dry dock. The model shows work volume and tension representations and can be resized to test a variety of dry dock dimensions.

SHIP SIDE-ACCESS CONFIGURATION

The Flying Carpet can be reconfigured from ship bow and stern access as discussed above to a thin, ship side-access configuration as shown in **Figure 5**.

Reconfiguration from the bow and stern access to the side access configuration includes: removing the hoist platform (computer, power, and attached cables); removing the rear truss assembly; moving the hoists and pulleys to match the new configuration; re-spooling the cables; and switching modes on the joystick to tell the computer that the configuration has changed. In the side configuration, the 7 m (23 ft) platform depth is reduced to 2 m, allowing it to fit between the dry dock wing wall and the ship side.

It took a team of 3 workers 13 man-hours to perform platform reconfiguration over about 4 clock hours. It is estimated that this time could be reduced to 3 to 6 man-hours (or (1 to 2) clock hours) with further experience. A second platform could eliminate the need for platform reconfiguration.

The side-access configuration was also demonstrated at NIST to test work volume. With support points forming a rectangle measuring approximately 8 m x 21 m in a plane 8.5 meters above the floor, platform center-of-gravity work-volume measures 6 m forward-and-back, 5.5 m side-to-side, and 6 m high above the floor. This also equates to worker accessibility from the platform totaling (12.5 m platform walkway + 5.5 m side-to-side motion =) 18 m side-to-side. Yaw motion is limited to approximately 5° due to the reduced front-back depth and reduced rear platform depth. The platform in this configuration includes similar rigidity characteristics as in the bow and stern access configuration.

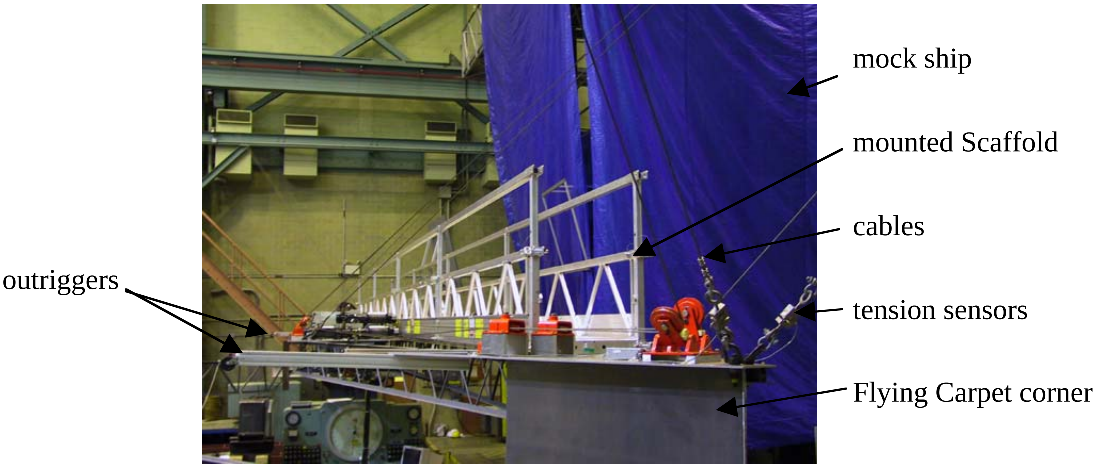

Figure 5 – Photograph of the full-scale Flying Carpet prototype shown in the ship side-access configuration. The platform is near a mock ship and in this test there was no dry dock wing wall to push against with the platform outriggers.

For platform heights above the dry dock wing wall, the cables are at smaller angles with the horizontal axis and therefore provide the lateral stiffness necessary for upper ship side-access, at a cost of increased cable tension and some reduced vertical stiffness. In this case, all cables are mounted at the same height, where two cables attach to one of two towers as shown in the model in **Figure 6.**

Two front cables can be crossed for additional rigidity and the towers (support points) can be separated by 30 m or more to provide a large, side-to-side range-of-motion. Along the wing wall, similar platform rigidity can be accomplished by pushing against the dry dock wall with outriggers. Outrigger length can be adjusted manually or automatically for in and out distance changes relative to the wall.

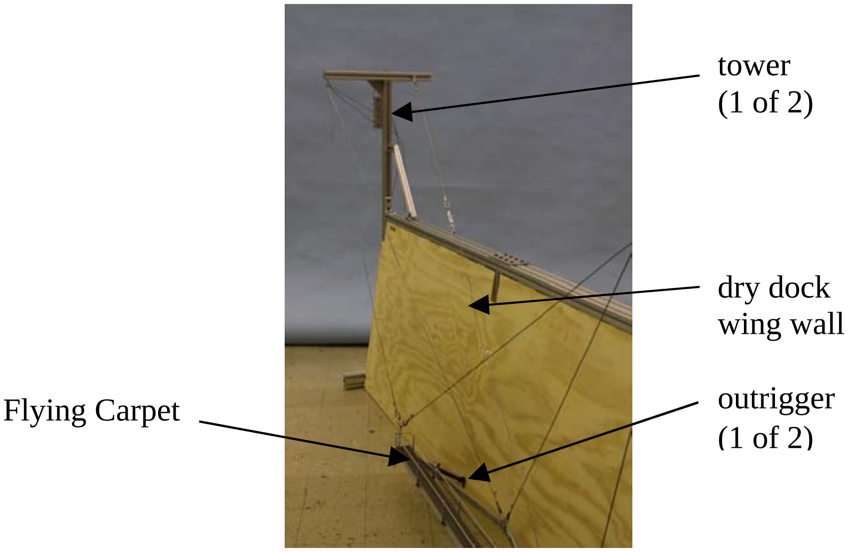

Figure 6 – Photograph of the Flying Carpet 1:12 scale model shown in the ship side-access configuration. The 1:12 scale model shows a tower attached to the dry dock wing wall and the platform pushing against the wall.

FUTURE CONCEPTS

Our next intentions are to transfer this technology to other industries and/or government organizations, to study construction applications [10], and to study autonomous navigation of the Flying Carpet. Autonomous navigation provides platform operation in semi-autonomous (e.g., platform is commanded to return to a taught position) or unmanned, fully-autonomous modes (e.g., paint an area of a ship hull or install, weld, grind, and paint a section of steel hull plate). Although relative platform movement can be derived from hoist encoders, encoders alone cannot reveal changes in platform position due to load variation or sway, nor will they easily map to the complex shape of a ship or submarine hull. A position reference system (absolute or relative) is desired to enable flight path trajectory planning for the Flying Carpet.

The Construction Metrology and Automation Group at NIST is instrumenting a RoboCrane platform with a three-dimensional, laser-based site measurement system (SMS) for absolute position control in all six degrees-of-freedom. [9] The project, part of the Automated Steel Construction Testbed, will be used to demonstrate autonomous steel pick and place operations. Follow-on experiments will incorporate registered LADAR (laser detection and ranging) scans of the work site for task analysis and navigation planning. A similar navigation package will be employed for the Flying Carpet using the registered LADAR scans to map the hull as a boundary surface. The SMS can then be used to track the Flying Carpet along that surface. An advantage of this method is that the LADAR data from the scan also provides detailed 3D information that can be used to map damaged areas, create cutting/rolling templates for repair material, analyze surface imperfections, and generate as-built data for pre- and post-repair.

SUMMARY AND CONCLUSION

The Flying Carpet is a reconfigurable cable-controlled platform based on the Stewart Platform parallel mechanism. The Flying Carpet provides the dexterity, relative precision, and large work-volume needed for dry dock and/or pier side ship repair, as well as for other large-scale manufacturing applications. The Flying Carpet can be reconfigured and can attach to appropriate towers or existing superstructures to eliminate unnecessary equipment costs. Tools and equipment can be attached to the Flying Carpet quickly and easily for many worker-assisted tasks. The Flying Carpet operator can be located at the work site or at a remote location to provide safe and efficient worker placement. The Flying Carpet is a demonstrated technology, ready for commercialization. Advanced concepts toward autonomous construction are also being considered.

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