Large-area Overhead Manipulator for Access of Fields

Jeffrey W. White, Roger V. Bostelman

Abstract—Multi-axis, cable-driven manipulators have evolved over many years providing large area suspended platform access, programmability, relatively rigid and flexibility-positioned platform control and full six degree of freedom (DOF) manipulation of sensors and tools. We describe innovations for a new six DOF manipulator, called ‘Large-area Overhead Manipulator for Access of Fields (LOMAF)” that is highly scalable and provides access to areas that can measure from several square centimeters to several hectares and can traverse level or irregular terrain, including vertical surfaces. Two scaled prototype have been developed and tested providing the basis for designing a much larger, computer-controlled system. The LOMAF design, prototypes, tests, results and suggested applications are presented in this paper.

I. INTRODUCTION

A. Current Field Access Methods and Issues

In many types of field research, including agronomy, natural resource management, environmental science, and ecology, situations arise where minimally invasive measurements are required over field areas on the order of 10,000 m² (107600 ft²). Typically, contact with the soil surface must be minimized, precluding use of wheeled vehicles or frequent entry by personnel on foot. Diverse types of sensors and imaging tools can perform the requisite measurements, but a means to position the instruments is needed. Current options include fixed and rotary-winged aircraft, aerostats and cranes. While each has niche applications, they all have limitations related to cost of operation, inability to rapidly position sensors near the field surface and to operate at night or under inclement weather.

The fundamental challenge thus is how to position an instrument platform over a potentially irregular surface, providing positional accuracy of 50 mm (2 in) or less, using a system that has low operating costs and can function continuously. Cable-suspended manipulators provide an attractive alternative, but current designs require support towers whose heights are approximately half the longest axis of the target area. Furthermore, these manipulators have a relatively large “dead” area near each of the support posts which the manipulator cannot access without increasing altitude or tilting the instrument platform.

B. RoboCrane

The National Institute of Standards and Technology (NIST), Manufacturing Engineering Laboratory (MEL) Intelligent Systems Division (ISD) developed a cable-suspended manipulator called RoboCrane [1] over many years and applied it to a variety of applications [2]. The RoboCrane is a cable driven, multi-purpose manipulator based on the Stewart Platform Parallel Link Manipulator. It provides six degree-of-freedom (DOF) load control via teleoperation, graphic off-line programming, hybrid control modes and computer programs for fully autonomous maneuverability [3]. The RoboCrane was first developed under a Defense Advanced Research Project Agency (DARPA) contract to stabilize loads suspended from conventional cranes. Current configurations have advanced to include land, sea, air-lifted, and space applications. It can be designed for high lift-to-weight ratio, stable gantry or other superstructure (e.g., masts) configurations, flexibility, precise maneuverability, and mobility over a variety of surfaces including very rough terrain.

The RoboCrane consists of a stable platform supported by six cables suspended from three base points on a fixed or mobile structure. The six cables are arranged to kinematically constrain the stable platform such that its stiffness is determined by the tensile elasticity of the cables. Maximum stiffness is maintained so long as perturbing forces and/or torques are below a threshold determined by the weight of the load. For forces or torques above that threshold, one or more cables will go slack, and stiffness will drop to that generated by pendulum forces of the load on the cables remaining taut. When all six cables are in tension, the stable platform is kinematically constrained, and there exists a known mathematical relationship between the lengths of the six cables and the position and orientation of the platform. The lengths of the six cables are controlled by six winches. These are controlled and coordinated by a computer. Input commands can be from a joystick or from a computer programmed to maneuver the stable platform and onboard tools or sensors over a very large work volume. The RoboCrane platform centroid work volume with only gravity loading is generally defined by an inscribed circle within an imaginary triangle joining the upper three suspension points as shown in Figure 1. A suspended, uniformly distributed load platform from three points can access approximately 60% of the triangular area formed by the base points. The inscribed square region to be accessed has about 36% of the area of the bounding triangle.
This paper will describe a case application from plant sciences followed by a description of two different LOMAF designs - with and without downhaul cables. Experiments that compare the two designs and their results are then explained.

Figure 1 – Approximate accessible areas (circle and square) of a 3-point base (triangle) RoboCrane suspended platform’s center of gravity.

II. PLANT SCIENCE CASE STUDY AND LOMAF HYPOTHESIS

A. A Case Application from Plant Sciences

The grand challenge of plant science and crop improvement in the 21st century is to predict plant traits (phenotypes) such as yield and time of maturity from data on genotypes, environment and management. Gene detection and sequencing no longer constrains research in plant genetics. “Next generation DNA sequencing” is expected to allow sequencing of entire genomes at costs of less than US$2 per megabase [4], and high-throughput tools for characterizing germplasm with single nucleotide polymorphisms are attaining prices under US$0.50 per data point. Data on environmental conditions and field management, including experimental treatments, are routinely available. However, rapid and accurate measurement of phenotypes remains challenging, especially for phenotypes that cannot be directly assessed using visual criteria and for traits related to abiotic stresses that require precise control of stress regimes. Associating phenotypes with genotypes for dissection of complex traits and for efficient selection of stable, high yielding varieties requires analyses of hundreds to thousands of genetically distinct plants grown in environments that allow for differential expression of multiple genes.

This situation has led to proposals that “high-throughput phenotyping” (HTP) capabilities be developed for accurately characterizing large numbers of genetic lines or individual plants with a fraction of the time and labor currently required [5]. Accomplishing HTP in a cost-effective manner, however, requires new techniques and infrastructure. The most promising HTP approaches involve using a vehicle to deploy a platform bearing multiple sensors that can quantify plant traits on a time scale of a few seconds per plot. Previous experience in phenotyping for water and nutrient management, and to a lesser extent for breeding and genetics, has established that numerous plant traits can be measured reliably using remote sensing [6].

B. Hypothesis

A suspended platform with onboard sensors and plant care monitoring equipment is feasible using a RoboCrane design as demonstrated at NIST on a variety of applications. However, obtaining the desired higher ratio of access area to base size requires a new cable configuration. System costs are driven higher with added control axes and therefore the design should include a minimal number of cables and winches, but these costs are partially offset by the reduced mast heights and expanded work volume. The system would require manipulator access near the suspension points, as opposed to RoboCrane’s three point suspension geometry. A smaller access area to base size is expected with only gravity loading, as well as minimal platform stability unless additional platform weight is provided above the onboard sensor and equipment platform loading. Our hypothesis is that preloading the platform with downhaul cables should provide a higher access area to base size and require minimal platform loading, but added cables will increase system cost.

III. LOMAF DESIGNS

An innovative six DOF manipulator was developed at NIST and the Arid Land Agricultural Research Center (ALARC), called the Large-area Overhead Manipulator for Access of Fields (LOMAF). The manipulator maximizes the base to accessible area ratio while minimizing the height of supporting masts. LOMAF is highly scalable, providing access to areas that can measure from several square centimeters to several hectares and can operate on level or irregular terrain, including vertical surfaces. Convex and/or concave land surfaces can be autonomously accessed from above after setup without disturbing any surface features throughout the target area. Based on RoboCrane research, control modes could include manual, velocity and force with desired accuracy of within 25 mm (1 in). The manipulator includes four or five cables (without downhaul cables) or eight or nine cables (including downhaul cables) that are independently controlled by hand, weights or powered winches through the use of an operator controlled joystick, graphical user interface or by a computer. Two models have been built to study how a LOMAF is designed to access an 86 m x 86 m (2 acre) crop field, including a 1:160 scale model and a 1:17 scale model. Three specific design cases using these models are considered:

Case 1 - Suspended platform without downhaul cables or running lines
Case 2 - Suspended platform with platform downhaul cables moving along running lines
Case 3 - Suspended platform with platform downhaul cables fixed to the masts.
For a full scale LOMAF, the design is expected to include:

- four 20 m (65 ft) masts with 6 mm (0.25 in) diameter, 6 x 19 extra improved plow steel wire rope cables with a safe working load of 618 kg (1360 lb) [7];
- hinged pulleys mounted to the masts and platform; a 6 m (20 ft) square platform;
- and electric powered winches with rotary encoders mechanically attached to the winch motors and electrically connected through power amplifiers to a control computer similar to a RoboCrane. Additional tension sensors and/or motor current measurement can be used to provide cable tension or force control, as well as safety overrides. In all LOMAF designs, winches can be mounted to the platform or preferably, to the masts in order to minimize platform mass.

RoboCrane mast or suspension point height is generally set to allow a platform cable angle of 10º or more with respect to the horizontal axis depending upon the application. Below 10º the cable tensions exponentially increase with increased platform lift. The LOMAF workvolume is similar to the top portion of the RoboCrane workvolume having cables at up to 10º with the horizontal and with a maximum platform loading of no more than 50 kg (110 lb). For relatively short mast heights as compared to mast separation distances (MSD), for example a 20 m (65 ft) mast height to 86 m (280 ft) MSD, the platform could access the lower 60% mast height field volume of 12 m (39 ft) high. An approximate Case 1 mast height and cable tension estimate is shown in Figure 2. The LOMAF can also access well below the suspension points similar to RoboCrane, for example in open pit applications, with much higher cable angles and lower cable tensions.

Example lift cable tensions for Case 1 with the platform at the maximum height at the field center are \(\frac{1}{4} \text{load}/\sin (10^\circ)\) where ‘load’ is the total platform weight and the angle is with respect to horizontal. This approximates the cable tension to be \((1.5) \times \text{full load}\) and nearly equals the lateral mast top loading of \((\text{cable tension}) \times \cos (10^\circ)\). Positioning the platform along an edge causes cable tensions and lateral mast loading of \((1/2) \text{load}/\sin (10^\circ)\) or nearly \((3) \times \text{full load}\) as shown in Figure 2. Therefore, a suspended load of 50 kg (110 lb) would produce maximum cable tensions along a field edge of approximately 71 N (317 lb-f) on one of two cables with 70 N (312 lb-f) horizontal mast top loading on one of two masts. Minimal Case 1 lift cable tensions and mast loading are approximately \(\text{load}/\sin (90^\circ)\) with the platform next to a mast. At this platform position, the remaining two of the four total masts experience much less loading. Minimal Case 1 lift cable tensions and mast top loading occur with the platform next to a mast are approximately equal to the load.

Case 3 includes cable tensions resulting from both lift cables and downhaul cables which are controlled to maintain platform level and increase field access. This design’s variables of force and cable angles include lift and downhaul cable tensions, lift and downhaul cable attachment heights, and platform weight. These parameters are useful to size masts, cables, winches, and the platform.

### A. 1:160th scale model LOMAF

A 1:160 table-top sized, scale model LOMAF without downhaul cables was built at NIST and is shown in Figure 3. The physical working model uses spring-loaded cable spools (black circles) and allows the operator to move the platform manually to test accessible areas of an 86 m x 86 m field. Red dotted cables have been added to Figure 3 to show how two platform yaw control cables would replace one cable. The same yaw control cable design can be used with four downhaul cables totaling nine cables. A nine cable LOMAF design with downhaul cables is shown in Figure 4a and an eight cable design is shown in Figure 4b as in Case 2.

![Figure 3 – 1:160 scale model LOMAF without downhaul cables. Cables are numbered 1 through 4. Red dotted cables depict two cables 1a and 1b that can replace cable 1 to control platform yaw rotation.](image)

The green rectangles below the platform signify crop beds where a 6 m (20 ft) square platform can reach across two crop beds simultaneously. Running lines, in this design, are connected between each mast and a sliding tube that slides along the running line is connected to downhaul cables connected to the platform. In a full scale LOMAF, a set of rollers would roll along each running line in place of the sliding tube to reduce friction. These cables are expected to be force-controlled while the mast lift cables are expected to be position-controlled.

Without downhaul cables, the spring-loaded model cables appeared to lift a platform corner closest to the nearest mast.
By adding downhaul cables, they pull the platform close to the running line height thereby allowing positive control along the vertical axis. Using downhaul cables, the model platform allows access to all areas of the square ‘field’ of crop beds including access to each mast, along all edges and throughout the center of the field. For example, as shown in Figure 4a, if a +X axis downhaul cable and a +Y axis downhaul cable were each given a force command to spool in cable and the lift cables are commanded to position the platform against post 3, the platform can in fact contact the mast. Either an X or Y only force command allows edge access. We therefore, prove that the LOMAF design allows a maximized access area to base size (tower separation).

Figure 4 – 1:160 scale model LOMAF with downhaul and running line cables. The black circles are spring-loaded cable spools. The center square is the suspended platform, masts are at the corners and the small rectangles below the platform signify crop beds. The (a) end view and (b) side view showing a platform elevated above crop beds.

Figure 5 shows the table top model tilted to a variety of angles displaying that the LOMAF would be useful on level or sloped areas. In fact, with positive platform control along all axes as in the case of a LOMAF with running lines and downhaul cables, even vertical surfaces can be accessed in example applications such as building construction.

B. 1:17 scale model LOMAF

A 1:17 scale model of an 86 m x 86 m (2 acres) was built at the ALARC to test potential field access and cable tensions. Figure 6 shows the prototype set up as in Case 1.

Figure 5 – Variable angles of the LOMAF showing application to sloped (left) and even vertical (right) surface access.

Figure 6 - Manual 5 m prototype LOMAF at the ALARC.

Masts included four 2.4 m (8 ft) high by 50 mm (2 in) diameter posts with pulleys attached to their tops. Each of four lift cables was attached to a 0.3 m (1 ft) plywood platform corner between the top of each mast and the wooden platform corners. Buckets of weights were tied to the end of each rope to allow the platform to lift and settle in a raised field position. Cables can then be additionally loaded by an operator or by adding bucket weights to move the platform towards a mast. Synthetic polymer ropes were used in place of wire rope cables. Lift cables were made of 6 mm (1/4 in) nylon rope and 4.8 mm (3/16 in) braided polypropylene rope was used for the downhaul cable. Case 3 was also setup on the model using a single downhaul cable attached to one mast base and the platform corner as shown in Figure 7.

IV. EXPERIMENTATION OF SCALE PROTOTYPES

Basic issues related to platform leveling, cable tensions and usable work area were tested using the two models. Case 2 was tested using the 1:160 scale LOMAF model by moving the platform by hand to all areas of the field. The critical areas for the platform to reach are near the masts and at the outer field perimeter. By moving the platform to these areas, it was apparent that it could reach all field areas, even the perimeter. Therefore, Case 2 was not tested with the 1:17 scale prototype model. However, Case 2 also requires that 9 cables and winches plus running lines be used to provide this ideal case.
The 1:17 scale LOMAF was tested with Cases 1 and 3 cable rigging configurations using two different platform weights (1.7 kg (3.7 lb) and 4.0 kg (9 lb)) and maintaining the platform at a constant height of 1.5 m (59 in) below the mast tops. Case 1 experiments included 4 ropes for platform lift and positioning between the platform and each mast top. Case 3 experiments added a downhaul cable between the platform and one mast base with the downhaul attached 0.5 m (19.7 in) below the target platform height (i.e., 2 m below the mast tops). To simplify testing of Case 3, a single downhaul was used to show access and cable tensions near a mast, as shown in Figure 7, and measurements focused on the area from the center of the LOMAF to the post with the downhaul.

The basic experimental procedure consisted of guiding the platform to an approximate X-Y position, while maintaining a constant elevation (Z), and then adjusting weights until a stable position was attained and if possible, the platform was level. Static cable tensions were measured by weighing the buckets when the platform was in a static, equilibrated position. Inclination of the platform was measured with an inclinometer with a resolution of 1° and distances were measured with a tape measure.

V. EXPERIMENTAL RESULTS

The Case 1 1:17 LOMAF relies only on gravity as a vertical force. When the platform was moved from the center position, it pitched and rolled up towards the nearest post, as shown in Figure 6. The platform was shown to lift towards the mast cable pulley as the platform approached it, therefore limiting the work volume for this case. Figure 8 shows a graph of platform inclination above horizontal versus platform distance from the mast with the platform positioned a constant height of 1.5 m (59 in) below the top of the mast.

Figure 7 shows the prototype with both a lift and downhaul cable (Case 3) on one mast and the platform shifted near the mast. Note that in this design, the platform can maintain level even when near a mast. Directly between two masts neither Case 1 or 3 design would provide access along the edge since there is no lateral force pulling the platform towards the edge except for a minimal mast lateral component from lift and downhaul cables in that direction.

This force is zero at the field edge inline with two masts and the platform will not reach the edge while the cable tension rises exponentially. Therefore, a smaller platform work volume is inherent in Case 1. However, Case 3 provides platform access to the masts between the downhaul cable and lift cable attachment heights. Figure 9 shows a top view of approximated work volumes of Case 1 and Case 3.

Figure 10 a and b show plots of cable tensions versus distance from the nearest post with 1.7 kg and 4.0 kg platform weights. For these tests, the platform was maintained level (±1°) using downhauls as in Case 3.

With a 1.7 kg (3.7 lb) mass, the tension on the downhaul and lift cables remained stable and low up to about 100 cm (39 in) from the post, while with the 4.0 kg (8.8 lb) mass, the tension began to increase at about 150 cm (59 in) from the mast. Assuming for this prototype that the ideal work area is 25 m² (2690 ft²), a reduction in area corresponding to a 100 cm (39 in) diagonal from each mast would reduce the work area to 13 m² (140 ft²), and 150 cm (59 in) diagonal, to 8 m² (86 ft²). The results thus confirm that the downhaul line provides an effective method to level the platform, with the
important caveat that as the platform load is increased, the effective work area will be reduced (or that the system will have to be engineered for tensions considerably greater than the equivalent mass of the platform). Also note that the tensions decrease as the platform moves away from the mast indicating that the load is shared by the other lift cables.

Regardless of the platform loading, downward forces caused by downhaul cables were determined to control platform level as needed to maintain similar sensor-to-crops distances throughout the entire work volume.

VI. ADDITIONAL APPLICATIONS

The LOMAF has proven to be a viable field access system for level or sloped fields. Below are a list of potential LOMAF (underlined) applications and their associated potential tasks:

- **Agricultural production and research**: Crop Monitoring, Seeding, Spraying, Harvesting, Pruning
- **Mine Detection**: Scanning, Finding, Detonating, Accessing, Monitoring
- **Environmental Cleanup**: Detection of contaminants, Removal of contaminated materials
- **Excavation**: Grading, Monitoring, Installation of posts, equipment, and materials
- **Material Handling**: Lifting, Loading, Carrying, and Docking along horizontal or angled surfaces
- **Dynamic Sensor Positioning**: following a vehicle throughout large areas to maintain local sensing between the suspended platform and vehicle.
- **Nuclear Waste and Contaminant Management**: Inspection of stored waste and contaminated areas, recovery of contaminated material, Field monitoring and inspection.
- **Toys/Entertainment**: Cable-drive, small model or person manipulation and positioning.
- **Building Surface Access**: Panel insertion, Window washing.

Material handling along vertical, angled, and/or non-flat surfaces.

Figure 10 - Comparison of tensions on cables using a platform mass of 1.7 kg and 4.0 kg for: a. Cable to nearest mast, b. Downhaul, versus distance from the nearest mast.

VII. CONCLUSION

LOMAF prototypes provided useful cable tension, work volume and platform control information. The Case 1 configuration has limited work volume since no or limited lateral force is present as the platform approaches a mast or field edge. More efficient work volume, platform leveling and positional control is provided through Case 2 and 3 LOMAF configurations which use downhaul cables to counterbalance the upward tension of the lift cables. These cases improved control substantially because they add lateral platform forces. Cases 2 and 3 increased work volume over Case 1 with four added winches and cables. Case 2 provides an ideal nearly 100% work volume to MSD, but at an even higher cost of added running lines to Case 3.

To achieve similar Case 1 work volume as with Case 2, the MSD must be increased by approximately 30% to 50%. Our preliminary results suggest that the Case 1 LOMAF has utility for applications where a level-controlled crop sensor package can be mounted to the platform, the platform is low in mass, and platform pitch and roll and large MSD versus work volume are permitted. Further cable tension and mast height experiments for all three cases are planned with current and even larger prototypes.

VIII. REFERENCES