ALGAE HARVESTING FROM LARGE OUTDOOR PONDS USING A NOVEL PARALLEL ROBOT SYSTEM

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Abstract

This paper presents a novel method for effective, economical, energy-efficient algae harvesting from large (1-4 acre) outdoor circulating raceway pond systems: a portable 4-cable-suspended robot. Algae, used as an alternative energy crop to produce biofuels (and other consumer products), still remains too expensive. One of the greatest expenses in processing algae is the harvesting process. To replace the typical energy-intensive pumping of the entire pond water through algae filters, we propose using a cable-suspended robot to collect algae, which largely then drains of water while the robot translates the product to a collection point. An additional benefit of our concept, in additional to lower harvesting cost, is that the algae still growing in the pond is not shocked as in the current pumping process, leading to better, healthier yields. Further, the proposed robot system is portable, capable of harvesting multiple ponds while algae continues to grow.

Keywords

Cable-suspended robot, algae biofuels, algae harvesting, four-cable, pseudostatics, positive cable tensions, kinematics, singularities, stiffness.

1. Introduction

Commercial Algae Growing

The Algae industry has been around for years starting in the late 1950's with the production of methane gas and then in the 1970's with the energy crisis followed by the 1980's Aquatic Species Program work on the production of oil from microalgae sponsored by the US Department of Energy (ABO, 2016). Products related to algae range from biofuels to bioplastics and from nutritional to biochemical products. Alternatives to fossil fuel and a race to provide renewable sources of energy have created a vast market that leverages sun, wind, and hydroelectric sources of energy. Bio-based products have also been considered as future replacements and some companies have begun to explore this area especially liquid fuels derived from corn or ethanol. Ethanol has been used as a blended energy source with petroleum based fuels. The industry has continued to increase the level of ethanol being blended into gasoline.

As a source of fuel, "plantation oil crops, waste vegetable oil and animal fat are only available in limited amounts" (Chen et al., 2013), algae does not compete with food crops and could be grown in harsh environments making it an ideal alternative source to produce biofuels or biomass that can be converted into a liquid fuel. "Biofuels can be divided into five categories: bioethanol, biodiesel, biogas, biomethanol, and biohydrogen" (Deenanath et al., 2012).

Algae produces lipids (fats) that has been processed into biodiesel. These lipids are contained within the walls of the algae molecules. Algae oils are produced through photosynthesis when sunlight, CO2 and nutrients are fed into the algae but other mechanisms can also help produced oils when sugars are fed into some strains of algae. Algae not only produces oils that can be processed into biodiesel but other bioproducts can also be extracted for commercial purposes. Figure 1 shows a typical algae pond.

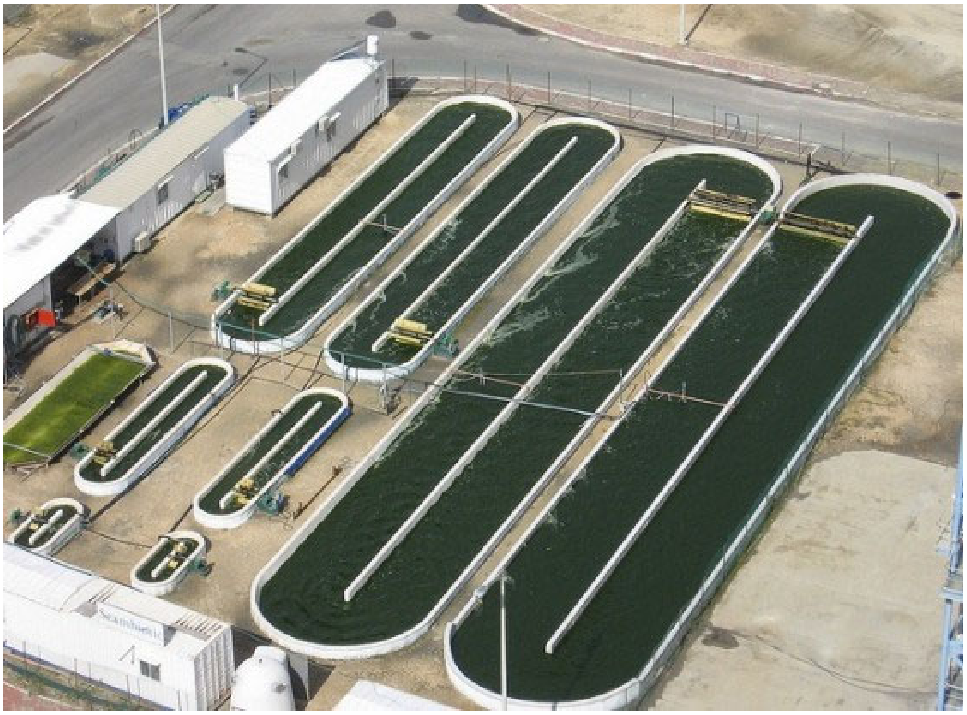

Figure 1. Typical Algae Pond/Raceway

https://www.greenprophet.com/wp-content/uploads/2011/09/seambiotic-algae-pond-israel-560x413.jpg

Current algae-harvesting methods of filtration, centrifugation, or flocculation all share the same disadvantages of the necessity for expensive pumping, and disturbing the remaining algae cultures.

Cable-Suspended Robots

The NIST RoboCrane (Figure 2) is the world's first cable-suspended robot (Albus et al., 1993). This is a radical, new (at the time), robot concept in that the entire motive structure of the robot is lightweight, stiff, strong, efficient cables, torqued by electric motors driving a cable reel, often over overhead pulleys. Compared to conventional serial robots, the robot workspace is huge, the robot is lightweight, the payload-to-weight ratio is excellent, and the stiffness to resist forces and maintain accuracy is high.

Figure 2. The NIST RoboCrane (six-cable-suspended robot)
https://www.nist.gov/sites/default/files/images/2017/12/07/tensiletruss_inside_chernobyl_nsc_chnpp.jpg

Cable robots have been used for a variety of applications, including material handling (Kawamura et al., 1993; Albus et al., 1993; Gorman et al., 2001), haptics (Bonivento et al., 1997; Williams, 1998), International Space Station (Campbell et al., 1995), and large outdoor construction (Bosscher et al., 2007). One of the better known cable robots is the SkyCam, which is a cable robot that dynamically positions a video end-effector for use in stadiums and indoor arenas (Cone, 1985). The use of cable robots for urban search and rescue has been proposed (Tadokoro, 1999). For this purpose a cable robot is proposed for picking up and removing rubble after an earthquake. Williams et al. (2004) and then Bosscher et al. (2007) proposed a cable-suspended robot system for large outdoor construction via contour crafting (essentially 3D printing a building). A recent, large-scale (500 m diameter) six-cable-robot application is the FAST Radio Telescope (Nan, 2011) in China (Figure 3).

Figure 3. FAST Radio Telescope (500 m cable-suspended robot) in China

http://fast.bao.ac.cn/en/FAST.html

2. Four-Cable-Suspended Algae-Harvesting Robot Concept

This document presents a novel cable-suspended robot concept to harvest algae in large outdoor algae farms. The system is intended to be portable to handle a number of differently-sized algae ponds, from which algae can be harvested in a regular rotation.

This section describes the Four-Cable-Suspended Algae-Harvesting Robot concept. Figure 4 shows the robot diagram. The base Cartesian reference frame is **{*A*}**, attached at the surface of the algae pond, in the center of the base rectangle, with X_A, Y_A, Z_A coordinate axes directions as shown. The algae-harvesting control point is ***P***. Since we are only controlling position, the orientation of the moving Cartesian reference frame **{*P*}**, attached to point ***P*** has coordinate axes directions identical to the **{*A*}** frame. Frame **{*P*}** is not shown, for clarity. An orientational system can be added for controlling rotations of the harvested-algae payload. Each of the four active drive cables runs from fixed overhead-cable-pulley point P_i to algae-harvesting control point is ***P***.

As shown Figure 4 and the CAD model of Figure 5, each tensioning torque motor/cable reel is fixed to the ground at points A_i, and the drive cables pass over pulleys on top of their respective telescoping support poles at points P_i. The telescoping pole base points are called B_i. As seen in Figure 4, the active cable lengths are $\mathbf{L} = \{L_1 \quad L_2 \quad L_3 \quad L_4\}^T$. The vector $P = {}^A\mathbf{P}_P = \{x \quad y \quad z\}^T$ gives the position of algae-harvesting control point ***P*** with respect to the **{*A*}** origin, expressed in **{*A*}** coordinates.

This cable-robot system has actuation redundancy since there are four active cables for three Cartesian motion components. The actuation redundancy will be used to ensure all cables maintain tension at all times, since cables can only exert tension and not push on the moving platform. The gravity loading on the moving platform from the significant water and algae mass will also help to maintain cable tensions for all motions. Despite the actuation redundancy and gravity loading, positions are still possible where one or more cable tensions can go slack, which must obviously avoided in this application. For instance, the moving control point ***P*** cannot move outside the footprint of the four telescoping poles. Positive cable tensions must be ensured for all motion control.

The fixed overhead-cable-pulley points P_i are constant in the base frame **{*A*}**, where ***L*** and ***W*** are the rectangular dimensions of the algae pond (length and width), ΔX and ΔY are the x and y offsets in the base frame, respectively, from the pond edges to the support poles, and h_i are the telescoping support pole heights.

Figure 6 shows another CAD model of the algae-harvesting robot concept, with a typical commercial algae pond/raceway.

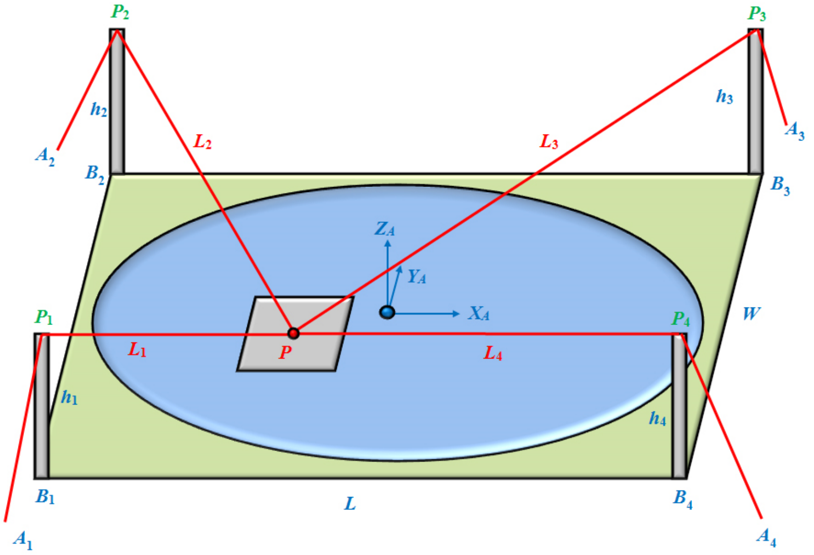

Figure 4. Four-Cable-Suspended Algae-Harvesting Robot Diagram

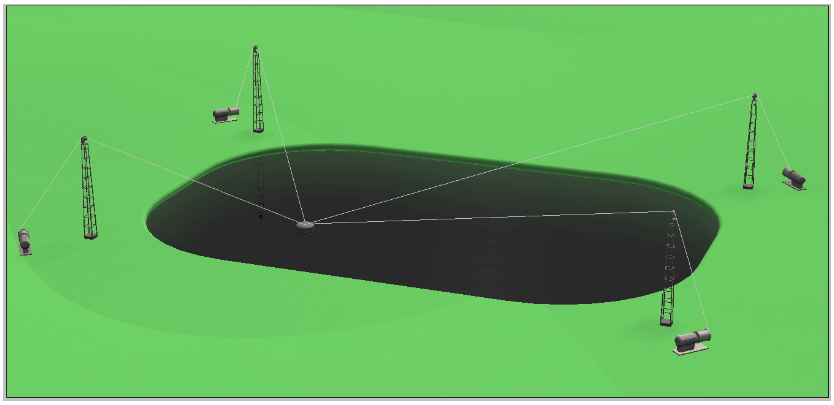

Figure 5. Four-Cable-Suspended Algae-Harvesting Robot CAD Model

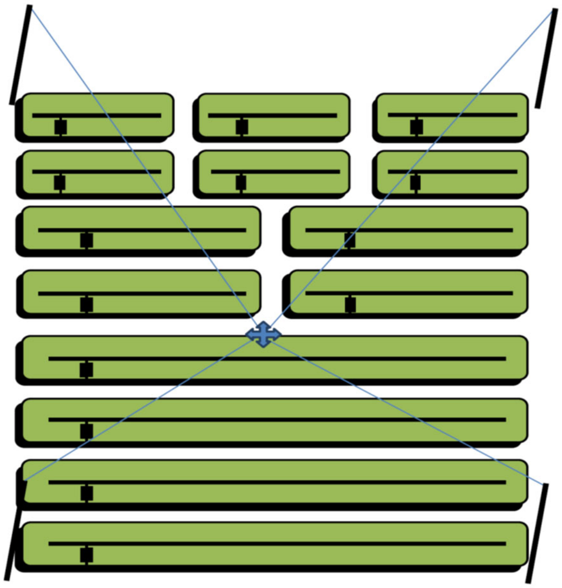

Figure 6. Algae-Harvesting Robot with Raceway Details

3. Technical Problems and Solutions

This section briefly presents an overview of the required technical problems we have solved for design and control of the proposed robot system in algae harvesting. For more details please contact the authors. Using MATLAB and Codesys software simulation we have solved the following problems:

Inverse Position Kinematics (IPK): Given the desired end-effector position ***P***, i.e. given desired vector ${}^{A}\mathbf{P}_P = \{x \quad y \quad z\}^T$, calculate the four active cable lengths $\mathbf{L} = \{L_1 \quad L_2 \quad L_3 \quad L_4\}^T$ to reach that harvesting point.

Forward Position Kinematics (FPK): Given the four active cable lengths $\mathbf{L} = \{L_1 \quad L_2 \quad L_3 \quad L_4\}^T$, calculate the Cartesian position of the resulting desired end-effector position ***P***, i.e. find ${}^{A}\mathbf{P}_P = \{x \quad y \quad z\}^T$.

Pseudostatics involves applying conditions of static equilibrium to systems in motion where the velocities and accelerations are small enough to ignore dynamics. This solution is necessary to calculate the required four cable tensions in order to move and lift harvesting loads (algae/water).

Cable-Suspended Robot Workspace is determined by:

- Kinematic motion ranges and constraints, actuator limits, and cable interference
- Requiring all workspace portions result in only positive cable tension to maintain pseudostatic equilibrium

Cable-Suspended Robot Singularities must be determined in order to avoid robot configurations where one or more degree-of-freedom to move is lost, hampering desired harvesting motions. More troubling, certain parallel robot singularities lead to an additional, uncontrolled degree-of-freedom which obviously must be avoided. Happily, both types of robot singularities have been totally avoided using design.

Cable-Suspended Robot Stiffness is calculated to design strong robot systems to resist the forces of algae harvesting with minimal unwanted displacements. Each of the four control cables are modeled as linear springs to determine this characteristic, which varies over the reachable workspace.

MATLAB Simulation has been implemented for each of these solutions, to provide a powerful tool for robot system design. Also, the design of robot system controllers can be accomplished using these MATLAB models in simulation, prior to deploying the real-world system. Figure 7 shows a MATLAB 3D image of a typical harvesting trajectory that we have simulated.

The following constants are used for this simulation: 1 acre algae pond with a rectangular shape using the golden ratio, with $W = 50.0$ m and $L = 80.9$ m (approximately). The four telescoping poles each have the same height $h_i = 7.6$ m, and are set back from the pond by $\Delta X = \Delta Y = 6.1$ m. The moving platform is a square with side $w = l = 1.2$ m.

The platform mass is 100 kg, the assumed mass of collected algae is 10 kg, and the assumed mass of water lifted (a rectangular parallelepiped full of water of dimensions l x w x 0.1 m high) is 148.6 kg, for a total end-effector mass of 258.6 kg. The total end-effector weight is 2537.3 N, assuming $g = 9.81$ m/s^2. The pseudostatic analysis includes only the total end-effector weight, i.e. the additional external force is ${}^{A}\mathbf{F}_r = \mathbf{0}$. For robot stiffness computations we assume steel cables ($E = 200\times10^9 N/m^2$) of 2 cm diameter.

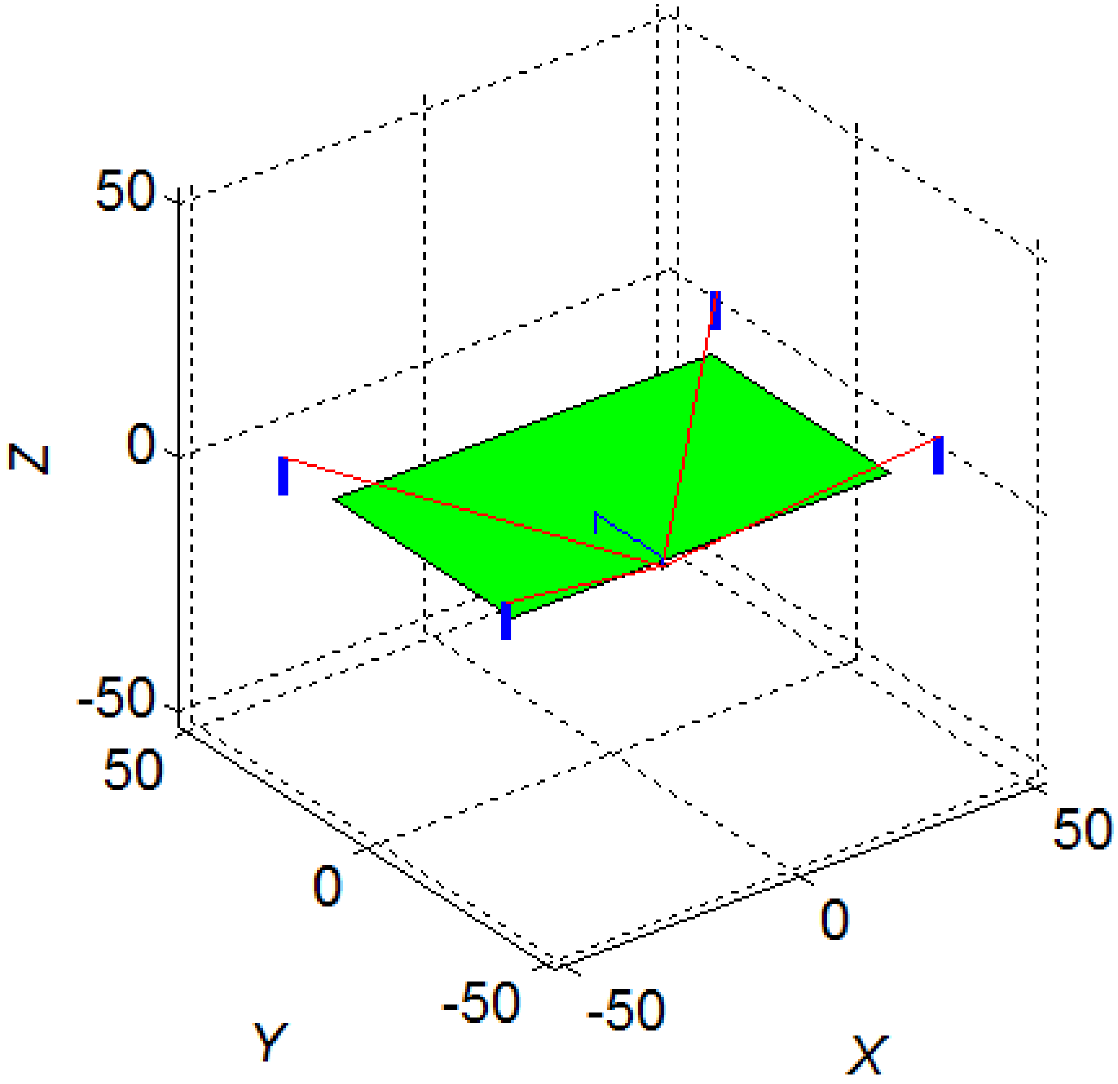

Figure 7. Full-Scale MATLAB System of a Typical Harvesting Trajectory (m units)

4. Four-Cable Algae-Harvesting Robot Prototype

A scale model prototype hardware has been designed and built to assist concept validation. Further, the control algorithms developed, implemented, and tested will be used in the future full-size system.

Figure 8 shows the CAD model of the scale model prototype hardware for the four-cable-suspended robot system proposed in algae harvesting.

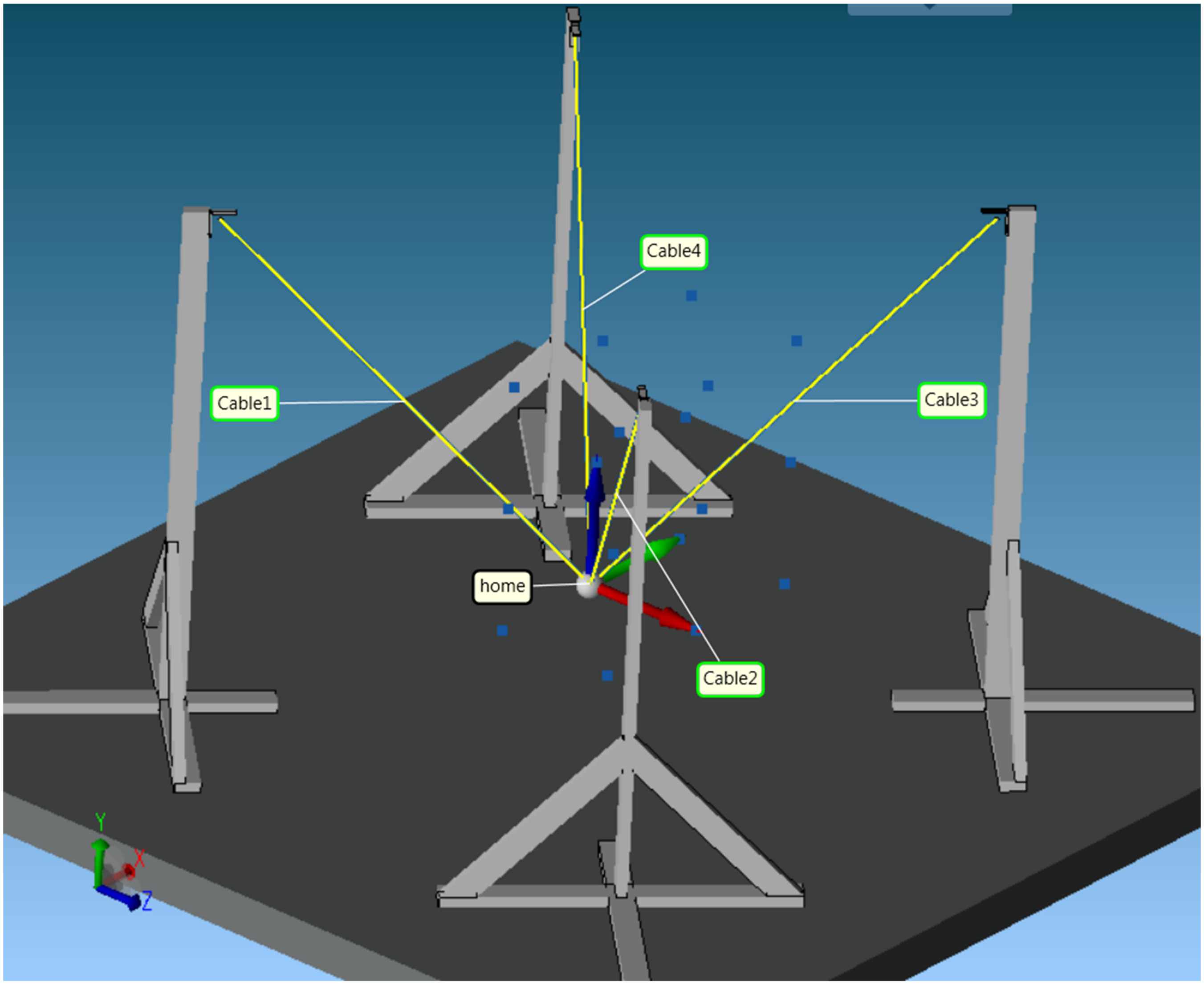

Figure 8. Prototype Robot System CAD Model

Figure 9 shows the scale model prototype hardware for the four-cable-suspended robot system proposed in algae harvesting. The size can be inferred from the 5-gallon blue plastic containers weighting down the four cable pulley stands. Each motor is mounted to a stand, and the cable is routed over the top of each stand via a pulley.

Figure 9. Prototype Robot System Hardware

5. Conclusion

This paper presented a novel system for harvesting algae from large outdoor circulating algae-growth pond systems: a portable 4-cable-suspended robot. The great potential of algae for biofuels and other consumer products will not be realized until an efficient harvesting method is developed, to replace the inefficient pumping harvesting. The main benefits of the proposed cable-suspended robot algae harvesting system are: economical, energy-efficient harvesting; portability to serve multiple ponds; and a process that does not disturb the remaining algae, to ensure good growth for ensuing harvesting.

We have solved robot system inverse and forward kinematics, pseudostatics, workspace, singularities, and stiffness analysis. These various analyses are useful for robot system design and off-line controller development and evaluation, A prototype hardware system has been design and built, to test real-time control algorithms to accomplish the harvesting task.

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