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A CONCEPT FOR RAPIDLY-DEPLOYABLE CABLE ROBOT SEARCH AND RESCUE SYSTEMS

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ABSTRACT

This paper introduces a new concept for robotic search and rescue systems. This system uses a rapidly deployable cable robot to augment existing search and rescue mobile robots. This system can greatly increase the range of mobile robots as well as provide overhead views of the disaster site, allowing rescue workers to reach survivors as quickly as possible while minimizing the danger posed to rescue workers. In addition to the system concept, this paper presents a novel kinematic structure for the cable robot, allowing simple translation-only motion (with moment-resisting capability) and easy forward and inverse kinematics for a 3-DOF spatial manipulator. Also, a deployment sequence is described, a rapid calibration algorithm is presented and the workspace of the manipulator is investigated.

KEYWORDS

Cable-suspended robot, wire-driven robot, rescue robot, search and rescue, calibration, workspace

INTRODUCTION

Recent and past disasters including earthquakes, bombings, and other terrorist attacks have resulted in a need for effective tools for performing rapid search and rescue activities, particularly in urban environments. Robotic search and rescue systems have been proposed for such tasks because compact, portable robots can be quickly brought to disaster sites and deployed to investigate rubble and collapsed buildings for survivors.

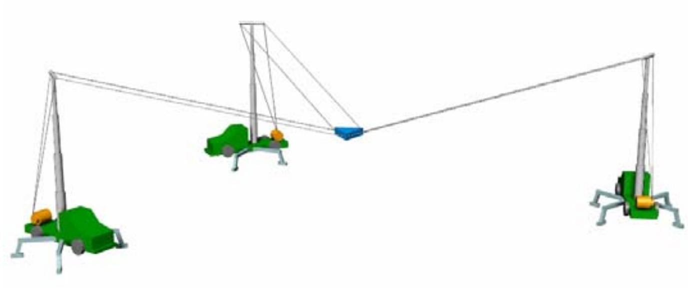

Figure 1. RAPIDLY DEPLOYABLE CABLE ROBOT.

Most robotic search and rescue systems are composed of mobile robots, including wheeled, legged and tracked robots. However, for large disaster sites (such as a collapsed office building) it is very difficult for mobile robots to access the entire site due to range limitations. This is partly due to the fact that the larger the distance a mobile robot is expected to traverse, the higher the likelihood of the robot becoming snagged, entangled or caught on obstacles. These types of failures were observed during robotic rescue efforts after the World Trade Center attacks on September 11, 2001 [1].

In addition, mobile robots often suffer from range limitations due to power supply limitations. If the robots are tethered (where a power cord is trailed behind the robot) the tethers have limited length and can snag on debris, thus decreasing their effective range at disaster sites. If the robots are not tethered they must carry a power source (such as a battery) with them. These power sources are often heavy and can drain quickly (sometimes in less than half an hour). In addition, if a mobile robot is maneuvering in a cluttered environment, a significant amount of energy is expended to travel even a moderate distance.

In order to improve the effectiveness of current mobile search and rescue robots, it is necessary to increase their search range. The system proposed here (shown in Figure 1) aims to accomplish this by using a rapidly deployable cable robot to augment the capabilities of mobile robots. Cable robots are a type of manipulator that has recently attracted interest for large workspace manipulation tasks. Cable robots are relatively simple in form, with multiple cables attached to a mobile platform or end-effector as illustrated in Figure 2. The end-effector is manipulated by motors controlling the cable tensions. These motors may be in fixed locations or mounted to mobile bases. In addition to large workspaces, cable robots are relatively inexpensive and are easy to transport, disassemble and reassemble. Thus, they are ideally suited for this task.

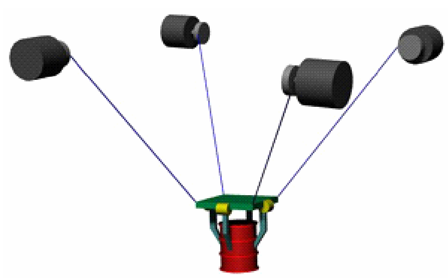

Figure 2. EXAMPLE CABLE ROBOT.

The organization of this paper is as follows. First, related work is discussed in the areas of rescue robot systems and cable robots. Second, the description of the proposed system is presented, including discussion of the main components of the system and a description of how the system is deployed and used. Third, the kinematics of the cable robot are discussed, including how the geometry of the manipulator allows for easy translation-only motion, with simple forward and inverse kinematics. Next, calibration of the cable robot is discussed and a calibration algorithm is presented. The workspace of the cable robot is then examined, resulting in guidelines for attaining the desired coverage of the disaster site when deploying of the system. Lastly the implementation of the system is discussed, followed by conclusions and future work.

RELATED WORK

There is a large amount of literature on the use of mobile robots for urban search and rescue (e.g. [2] - [6]). In addition to more traditional mobile robot platforms, these papers include development of snake-like rescue robots [2], fire-fighting robots [4] and shape-shifting robots [3]. In [3] the concept of a 'mother-daughter' or 'marsupial' deployment of mobile robots was proposed. In this system the 'mother' robot is a larger mobile vehicle whose main task is to traverse rough terrain and long distances to the area of interest in the disaster site, where it deploys the smaller 'daughter' robot from inside. The daughter robot can then travel through pipes or small openings to search for survivors.

Cable robots have been used for a variety of applications, including material handling [7],[8], haptics [9],[10] and many others. One of the better known cable robots is the SkyCam, shown in Figure 3, which is a cable robot that dynamically positions a video camera for use in stadiums and indoor arenas [11]. The use of cable robots for urban search and rescue was first proposed in [12], where a cable robot is proposed for picking up and removing rubble after an earthquake. However, this system relies on using load-bearing structures already at the site (such as neighboring buildings) for mounting pulleys and motors. The problem with this approach is that it is highly likely that the disaster has damaged many of the surrounding structures to the point that they cannot be load-bearing.

Figure 3. CLOSEUP OF THE SKYCAM END-EFFECTOR.

Calibration of robots has been widely studied (e.g. [13],[14]). However, the unique characteristics of cable robots often prohibit traditional robot calibration techniques from being used. In [15] a calibration method for a simple 3-cable manipulator was presented. In [12] an iterative calibration technique is presented for a cable robot. In [16] two inclinometers are used to calibrate a six degree-of-freedom cable robot. In [17] a set of six string-potentiometers is used to calibrate the pose of a cable robot.

Relatively little research exists on cable robots with mobile cable supports. In [15] it was proposed that a cable robot with three cables be suspended from poles mounted to remotely controlled vehicles for performing demining tasks. It has also been proposed that the frame of the RoboCrane can be mounted to mobile bases for use in fighting oil-well fires [18].

SYSTEM DESCRIPTION

The proposed rescue robot system, shown in Figure 1, consists of three major components: mobile support vehicles, a cable robot and small mobile robots. In the event of a disaster that causes one or more large structures to collapse, this system could be brought quickly to the disaster site and used to search for survivors. The mobile support vehicles provide raised supports from which a cable robot is suspended. The mobile support vehicles are positioned around the perimeter of the search area such that the cable robot can be suspended above the site. The sizeable workspace of the cable robot would allow it to operate over a very large area. The end-effector is equipped with sensing equipment, including cameras, that allow rescue workers to quickly scan the disaster site from above, creating a map of the site and identifying likely areas where survivors might be. The cable robot end-effector will also house one or more mobile robots. Thus once the areas are identified where survivors are likely to be, the cable robot can go to these areas and deploy one or more of the mobile robots to search through the rubble.

Each of the major components of the proposed system will now be discussed in more detail.

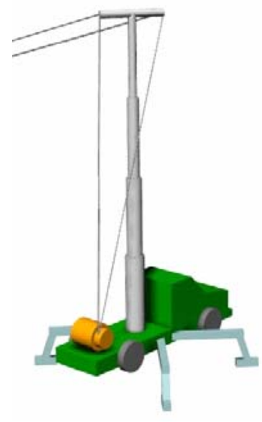

Figure 4. MOBILE SUPPORT VEHICLE.

Mobile Support Vehicles

The primary function of the mobile support vehicles is to act as rapidly deployable stanchions from which the cable robot is suspended, as shown in Figure 4. Each mobile support vehicle must be relatively large (comparable to a pickup truck) and must be positioned around the perimeter of the search area. Each vehicle has a telescoping support pole that can be extended upwards from the vehicle. At the top of each pole are one or more pulleys or eyelets through which cables can be fed. The configuration proposed in this paper consists of two pulleys mounted to the ends of a horizontal crossbar at the top of the support pole. The telescoping pole can be driven hydraulically or extended by hand using locking mechanisms to lock the pole in the desired extended position. Cable stays should also be used to provide lateral support for the support pole, which can be connected from the corners of the vehicle to the top of the support pole.

The mobile vehicle also contains one or more motors for reeling in and out the cables of the cable robot. The controllers of the motors communicate wirelessly with one central computer to allow synchronized control of the motors to achieve the desired motion of the end-effector. The system configuration detailed in this paper has a single motor per mobile vehicle, each of which controls a pair of cables.

Each of the mobile support vehicles will also require outriggers to provide stabilization of the vehicle while the cable robot is operating. The outriggers also allow for each vehicle to be leveled when operating on uneven terrain.

The mobile support vehicles must drive around the perimeter of a disaster site, thus they will need to traverse rubble and debris. A simple choice for these vehicles is commercial vehicles such as 4x4 trucks. Trucks could be easily retrofitted with the necessary equipment and are readily available nearly anywhere the world. The vehicles could be driven into place by rescuers; they could also be modified to be teleoperated, autonomous or semi-autonomous if necessary.

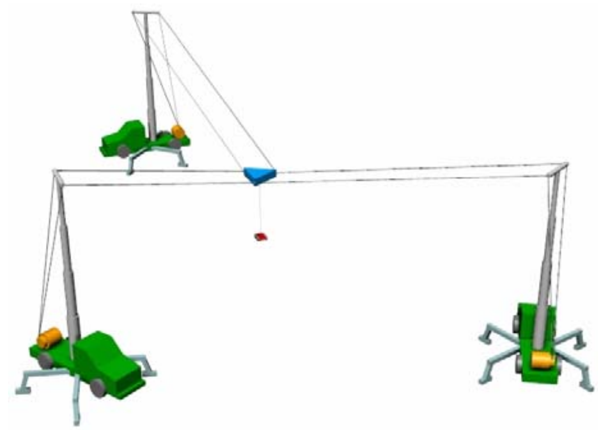

Figure 5. CABLE ROBOT DEPLOYING A MOBILE ROBOT.

Cable Robot

The second component of the system is the cable robot. The cable robot consists of an end-effector and six (or more) cables that suspend the end-effector over the disaster site, as shown in Figure 5. The cables are driven by motors that are mounted on the mobile support vehicles, and the cables are routed through pulleys on the tops of the stanchions. By reeling the cables in and out the position of the end-effector can be controlled. Because a lot of cable can be stowed on a motor reel, the manipulator can have a large workspace, allowing it to operate over large disaster areas. The geometry of the cable robot workspace will be discussed in greater detail later in this paper.

Once deployed, the cable robot has two main tasks. First, cameras and other sensors on the end-effector allow rescuers to perform an overhead scan of the search area. The camera images can be combined in order to form a map of the area and identify areas where survivors are likely to be. Other sensors, such as infrared sensors, may also be used to detect signs of survivors. This task can currently be performed by unmanned aerial vehicles [19], but these are often costly, sensitive to weather conditions, and cannot get as close to the disaster site.

The second main task of the cable robot is to deploy mobile robots. Such a system is sometimes referred to as a 'mother-daughter' robot system [3]. The cable robot (i.e. the 'mother' robot) houses one or more mobile robots (the 'daughter' robots). Once areas are identified where survivors are likely to be, the cable robot can go to these areas and deploy one or more mobile robots to search through the rubble. However, the cable robot often cannot be lowered into the debris due to the likelihood that a cable will become entangled in the debris. Thus each of the mobile robots is lowered into the search area, as shown in Figure 6. Each mobile robot is connected to the end-effector by a cable that is attached to a winch inside the end-effector. Each mobile robot is lowered into the search area and then begins to search.

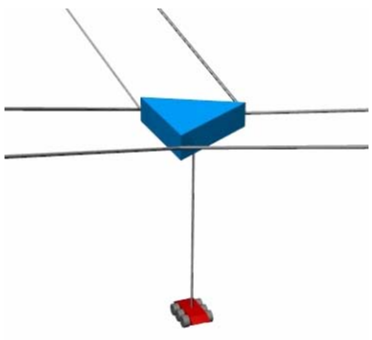

Figure 6. MOBILE ROBOT BEIING LOWERED FROM THE END-EFFECTOR.

In the case of tethered mobile robots, the cable for lowering the mobile robot can remain attached to the vehicle and is dragged behind it along with the tether, which attaches to the cable robot. In this case the end-effector needs to have a power source on-board to provide power to the mobile robots. In the case of un-tethered mobile robots, the cable for lowering the mobile robot can detach from the mobile robots. In this case it is still desirable to have a power source on the end-effector for recharging the mobile robots when they are stowed in the end-effector (as well as for powering the other cameras and sensors on the end-effector). By having the cable robot bring the mobile robots as close as possible to the area of the site that must be searched, the effective range of the mobile robots is greatly increased, allowing them to reach nearly any part of the disaster site, including areas that would otherwise be inaccessible to mobile robots. This also makes it possible for the mobile robots to get to the survivors much more quickly, as they do not have to spend as much time maneuvering through the cluttered environment. In addition, a small serial robot arm could be attached to the end-effector for moving small pieces of debris that may be obstructing the path of the mobile robots.

The configuration of the mobile robot presented here has an additional advantage. This configuration allows for easy translation-only motion as well as easy forward and inverse position kinematics. The end-effector is suspended by three sets of parallel cables. By orienting the tops of the stanchions such that they are parallel with the corresponding sides of the end-effector, pure translational motion is accomplished simply by keeping the lengths of any two paired cables the same. Proof of this plus the kinematic equations will be discussed later in this paper.

Mobile Robots

The third component of this system is the mobile robots. One or more mobile robots can be deployed from the end-effector and lowered into the rubble to search for survivors. As was mentioned in the previous section, these robots can be tethered if desired, as the cable robot can be positioned near the area of interest, decreasing the possibility of the tether snagging on debris and reducing the required length of the tether. The mobile robots can also be battery-powered, with a charging base located within the end-effector.

This system allows for many of the existing mobile robots for search and rescue to be incorporated with little or no modification. In fact, this system will allow existing mobile robots to operate more effectively. Because the cable robot can provide real-time overhead images of the site, the mobile robots will not have to rely solely on their on-board cameras. It has been shown that humans can improve their teleoperation of a 'daughter' robot by 31% when they use the views of both the mother's and daughter's cameras [3]. However, overhead imagery will only provide assistance so long as the mobile robot is not under debris or within a passageway.

Once a mobile robot has located a survivor, the location of the mobile robot (and the survivor) can be relayed back to the central control computer. The location and sensed condition of the survivor can be superimposed on the overhead map (that was generated by the images from the camera on the end-effector, including hazards), allowing rescuers to evaluate the site and determine the safest and fastest route to the survivor.

System Deployment

There are a number of possible ways to deploy the rescue system presented here. In order to verify the practicality of this system one approach is presented here. The mobile support vehicles drive to the site with all components stowed and the end-effector towed in a trailer behind one of the trucks as shown in Figure 7. At the site the trucks position themselves around the area that is to be searched. The spacing of the vehicles will be discussed more in the workspace analysis section. The trailer carrying the end-effector is detached from the truck. The outriggers of each truck are deployed to level each vehicle. The cable support poles are extended and locked in place. Each motor then reels out enough cable such that the cables can be connected to the end-effector. The two vehicles not towing the end-effector must have relatively clear paths between them and the third vehicle for the initial connection of the cables to the end-effector. The cables can then be reeled in until each cable is in tension, as shown in Figure 8. In Figure 8 the shaded area represents the footprint of the disaster site. The end-effector can then be raised from the trailer and the end-effector can be calibrated as will be described in the calibration section, and the rescue operations can begin. Once an area has been searched, the deployment sequence can be performed in reverse and the system can be quickly transported to a new site.

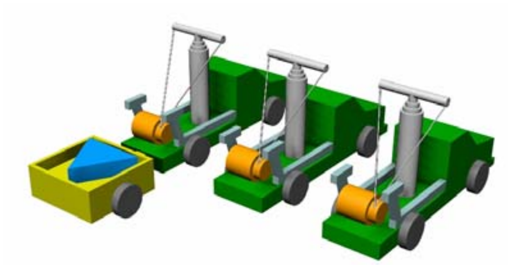

Figure 7. MOBILE SUPPORT VEHICLES READY TO DEPLOY AT A DISASTER SITE.

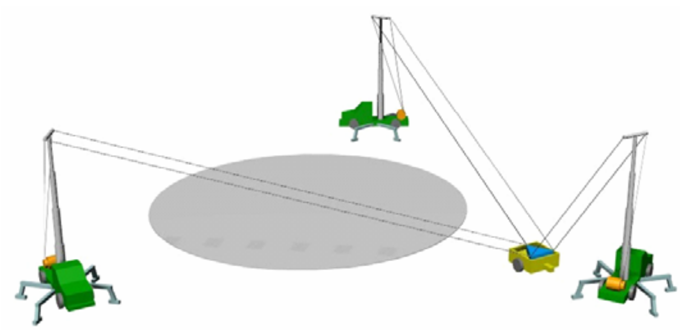

Figure 8. DEPLOYMENT OF CABLE ROBOT.

If the system needs to be slightly repositioned, it is possible to raise the outriggers of one or more vehicles and drive them slowly to a new location while the cable robot remains above the search area. However, caution must be taken during such an operation as driving over uneven terrain could cause large uncontrolled motion of the suspended end-effector.

CABLE ROBOT KINEMATICS

In this section we present some basic kinematic equations for control of the deployable translational cable-suspended robot portion of the system. Mobile robot kinematics and control are not addressed in this paper.

The cable robot concept of Figure 1 shows six active parallel-drive cables (three independent cables since each pair is tensioned and length-controlled by a single motor). This is the minimum number required for general *x*-*y*-*z* translations. Gravity is critical to maintain cable tensions for all motion, as is the case for all underconstrained cable robots.

The authors are also developing a concept with eight active parallel-drive cables (four independent cable pairs; not shown); the extra cables will not produce any more kinematic freedom, but could be useful for optimization of cable tensions to ensure no slack cables during dynamic motions. The kinematics methods of this section apply equally to the 6- or 8-cable concept.

Due to the cable manipulator arrangement (the pairs of cables are parallel and the horizontal crossbar at the top of each support pole is parallel to the corresponding side of the end-effector), the orientation of the end-effector does not change. This has been proven, but the proof is not included here due to length limitations. The proof is similar to that of the translation-only end-effector of the well-known Delta robot [20].

Figure 9 shows a kinematic diagram for the 6-cable, parallel drive, deployable translational cable-suspended robot. In Figure 9 the mobile support vehicles are not shown. We assume that the cable base points B_{ia}, B_{ib}, i=1,2,3, (i.e. the locations of the pulleys) are known to sufficient accuracy (see section on calibration). Also, the cable attachment points on the end-effector are known: P_{ia}, P_{ib}, i=1,2,3. The three sets of parallel-drive cables have lengths L_i, separated by a fixed length l_P at the platform and base to ensure parallel driving cables for all motion.

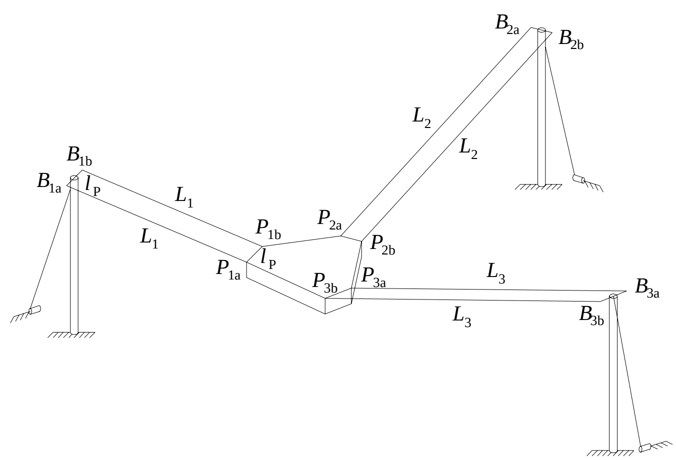

Figure 9. CABLE ROBOT KINEMATIC DIAGRAM.

Figure 10 shows the vector-loop-closure diagram for parallel cable set i. The world or base frame is $\{B\}$; the moving platform frame is $\{P\}$, whose origin is the control point, P_C. Since this cable robot arrangement allows translation only, the orientation of $\{P\}$ is always the same as that of $\{B\}$. Therefore, the orthonormal rotation matrix giving the orientation of $\{P\}$ with respect to $\{B\}$ is always ${}^B_P\mathbf{R} = \mathbf{I}_3$.

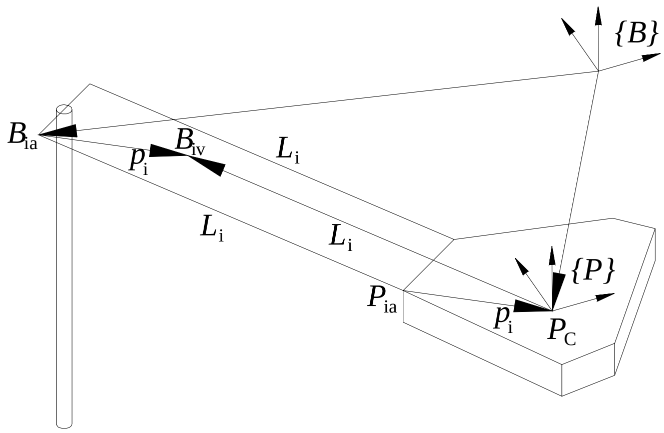

Figure 10. KINEMATIC DIAGRAM FOR PARALLEL CABLES *i*.

We can simplify the kinematics greatly by using a single control point P_C for translations and three virtual cables, in place of the six real drive cables as follows. From cable attachment point P_{ia} on the Mother robot, draw a vector $\mathbf{p}_i$ to P_C. Since the platform orientation is not changing, the orientation of $\mathbf{p}_i$ is constant. Now, from cable base point B_{ia} on the support pole, attach this same vector $\mathbf{p}_i$ to form a virtual cable pulley point B_{iv}. Connect a single virtual control cable between the two tips of these two vectors $\mathbf{p}_i$; the length of this virtual cable is also L_i, due to the parallelism. So the real kinematics problems may be significantly simplified without loss of generality by controlling the three virtual cables L_i to translate P_C.

The inverse position kinematics problem is stated: given the desired end-effector position $\mathbf{P}_C = \{x \quad y \quad z\}^T$, calculate the six parallel-drive cable lengths L_i (the same as the three virtual cable lengths L_i). The vector loop-closure equation from Figure 10 for virtual cable i is (where all vectors are in $\{B\}$):

$$\mathbf{B}_{ia} + \mathbf{p}_i = \mathbf{P}_C + \mathbf{L}_i \qquad (1)$$

The inverse position kinematics solution is straight-forward and computationally easy:

$$L_i = \|\mathbf{L}_i\| = \|\mathbf{B}_{ia} + \mathbf{p}_i - \mathbf{P}_C\| \qquad i = 1,2,3 \qquad (2)$$

These three virtual cable lengths are the same as the six required real parallel cable lengths (in three pairs).

The forward position kinematics problem is stated: given the three parallel-drive cable lengths L_i, calculate the associated end-effector position $\mathbf{P}_C = \{x \quad y \quad z\}^T$. In general, forward position kinematics for parallel (and cable-suspended) robots is very challenging, with multiple solutions. However, due to the virtual cable simplification, the current forward position kinematics solution is straight-forward and may be solved in closed-form. The solution to the forward position kinematics problem $\mathbf{P}_C$ is simply the intersection of three given spheres, where a sphere is referred as (vector center **c**, scalar radius r):

$${}^{B}\mathbf{P}_P \rightarrow (\mathbf{B}_{1v}, L_1), (\mathbf{B}_{2v}, L_2), (\mathbf{B}_{3v}, L_3) \qquad (3)$$

As shown in Figure 10, points B_{iv} are the virtual cable pulley points. The closed-form three spheres' intersection algorithm is presented in [17]. There are two solutions, from which the correct one may easily be selected by computer. There is the possibility of imaginary solutions only if the input data to the forward position problem is not consistent (i.e. sensing or modeling errors). There is an algorithmic singularity which may be avoided by proper choice of coordinate frames [17]. There are two additional mathematical singularities which are degenerate cases that never occur for the design of Figures 1 and 8.

Again, in both inverse and forward position problems, the orientation is always nominal, ${}^{B}_{P}\mathbf{R} = \mathbf{I}_3$, since the robot can only translate. There are no kinematic singularities in the workspace for either inverse or forward position solutions, allowing for quick and easy real-time kinematics.

The kinematic Jacobian matrix may be easily obtained by time differentiation of the inverse position solution (1). The inverse velocity solution is $\dot{\mathbf{L}} = \mathbf{M}\dot{\mathbf{X}}$ where $\dot{\mathbf{L}} = \{\dot{L}_1 \quad \dot{L}_2 \quad \dot{L}_3\}^T$ is the vector of 3 virtual cable rates, $\mathbf{M}$ is the inverse Jacobian matrix (see below), and $\dot{\mathbf{X}} = \{\dot{x} \quad \dot{y} \quad \dot{z}\}^T$ is the Cartesian velocity vector for the control point P_C.

$$\mathbf{M} = \begin{bmatrix} -\hat{\mathbf{L}}_1^T \\ -\hat{\mathbf{L}}_2^T \\ -\hat{\mathbf{L}}_3^T \end{bmatrix} \qquad (4)$$

Where $\hat{\mathbf{L}}_i$ is the unit vector along virtual cable i, pointing from P_C back to the virtual cable pulley at B_{iv} as shown in Figure 10. Considering the inverse velocity problem of conventional serial robots, the inverse velocity result $\dot{\mathbf{L}} = \mathbf{M}\dot{\mathbf{X}}$ is remarkable: the inverse velocity problem is solved directly with little computation and there is no singularity problem.

CALIBRATION

Once the system is deployed, it is necessary to calibrate the cable robot before the kinematic equations can be used to control the motion of the end-effector. The manipulator performs translation-only motion due to the parallelism of each pair of cables and parallelism between each crossbar at the top of the support pole and the corresponding side of the end-effector. It is necessary to establish this geometry and also to determine the locations of the tops of the support poles in order to initialize the manipulator. A calibration routine is presented here for performing this initialization.

Once the mobile support bases are in place and leveled (using the outriggers), it is necessary to initialize the cable lengths. If the motors include relative encoders, it is only necessary to reel the cables out to a known length, and the amount reeled in and out from that point can be measured using the encoders and used to calculate the total cable length for each cable. The cables can then be attached to the end-effector as described in the system deployment section. The crossbars on the support poles must then be rotated such that they are parallel with the corresponding sides of the end-effector. This can be accomplished by having each vehicle at a known orientation with respect to the end-effector (found by gyroscopic sensors or a compass bearing), and each crossbar rotated a known amount (either manually or using an actuator) until each has the correct alignment.

The remaining challenge is to determine the locations of the top of each support pole (in the global coordinate frame $\{B\}$) once they are extended as desired. Fortunately, the translation-only motion of the end-effector facilitates a straightforward manner of calculating these locations.

Recall from the kinematics section that for each pair of parallel cables a single virtual cable can be constructed, which is connected from a virtual cable base point, $\mathbf{B}_{iv}$, to the control point on the end-effector, resulting in a virtual 3-cable manipulator. As a result, a calibration method for such a manipulator in [15] can be used (in that reference, the cables meet at a single point). In this method, three points must be chosen on the ground that have known locations. In Figure 11 these points are labeled $\mathbf{G}_a$, $\mathbf{G}_b$ and $\mathbf{G}_c$. The shaded area in the figure is not the end-effector, but rather the triangular area formed using the three known locations on the ground as vertices. These points may be known landmarks in an urban area or could be found by GPS. Using manual control of each pair of motors, the end-effector can be placed such that the control point is at each of these locations. At each location the resulting lengths of the cables can be measured (L_{ia}, L_{ib}, L_{ic} for i = 1,2,3) as labeled in Figure 11. Each virtual cable base point $\mathbf{B}_{iv}$ is the intersection of three spheres centered at the known ground locations:

$$\mathbf{B}_{iv} \rightarrow (\mathbf{G}_a, L_{ia}), (\mathbf{G}_b, L_{ib}), (\mathbf{G}_c, L_{ic}) \quad i = 1,2,3 \qquad (6)$$

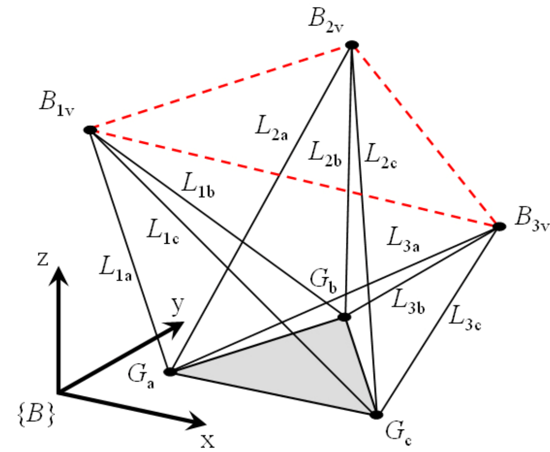

Figure 11. CALIBRATION GEOMETRY (DIAGRAM MODIFIED FROM [15]).

The location of each virtual cable base point can be found by applying the three-spheres intersection algorithm as described in the previous section. From these three locations, the locations of all six cable base points in the global reference frame are determined by geometry, using the known vectors p_i (i = 1,2,3). At this point the manipulator is calibrated and can commence searching the disaster site.

If three known locations cannot be established with a fair degree of accuracy, this calibration method will not be effective. Thus it is of interest to perform future work to determine alternative calibration approaches. For example, if available, GPS receivers could be placed at the top of each support pole to allow their locations to be found directly with minimal effort (differential GPS can provide sub-centimeter accuracy).

WORKSPACE ANALYSIS

When the rescue system is deployed at a disaster site it is important to provide guidelines for the rescue workers as to where the mobile support vehicles should be positioned. The main consideration for this task is to ensure that the portion of the disaster site that needs to be searched is contained within the reachable workspace of the cable robot. Here we will consider the static equilibrium workspace (SEW), which is the set of all poses that the end-effector can achieve statically with no external forces or moments other than gravity acting on the end-effector. If additional external forces and moments need to be resisted, the appropriate workspace to consider is the wrench-feasible workspace [21], [22].

Using the workspace-generation techniques developed in [23], it is possible to formulate analytical expressions for the boundaries of the SEW for this manipulator. However, due to space limitations these expressions are not included here, but can be found in [23]. In addition, the boundary equations can be very complex, resulting in expressions that are not easily reduced to simple guidelines for the placement of the mobile support vehicles.

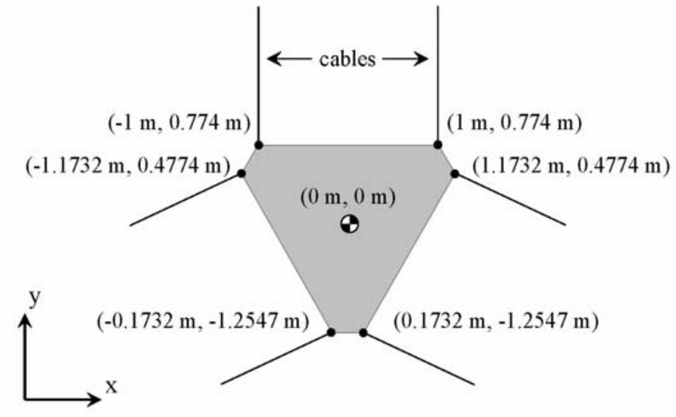

Figure 12. EXAMPLE END-EFFECTOR.

Instead, an example scenario is considered here, and using the resulting workspaces simple workspace approximations can be made. Consider the example end-effector, shown in Figure 12. The end-effector is shown from above, with all cable attachment points labeled. Every two adjacent sides form an angle of 120º and the three long sides are each 2 *m* long. The end-effector mass is assumed to be 50 *kg*, with uniform density and thickness.

Using Matlab, the SEW is found by discretizing the task space and checking each pose. If the manipulator can resist gravity with all non-negative cable tensions, then it is within the SEW. Because this manipulator is designed to perform translation-only motion, the workspace of the manipulator is three-dimensional (*x*-*y*-*z*). The workspace was first calculated for evenly spaced mobile support vehicles, located at the vertices of an equilateral triangle with 50 *m* sides, such that the bases of the support poles are located at $(25, 25/\sqrt{3}, 0)$, $(25, -25/\sqrt{3}, 0)$, $(0, 50/\sqrt{3}, 0)$ (all units *m*) with the origin of the chosen coordinate frame at the center of the triangle and the *z*-axis directed vertically. The support poles are assumed to be 10 *m* high with a 2 *m* upper crossbar. Each upper crossbar is aligned parallel with the corresponding side of the end-effector.

Figure 13 shows the resulting static equilibrium workspace of the manipulator, displayed in horizontal 'slices'. In order to visualize the placement of the support poles, dashed lines have been plotted connecting the tops of the support poles, forming an equilateral triangle. In addition, short lines with circular endpoints show the upper crossbars of the support poles, with each circle representing one of the six pulleys.

In Figure 13 the cross-section of the SEW remains the same regardless of the *z*-elevation. In Figure 14 a top view of one of these cross-sections is shown.

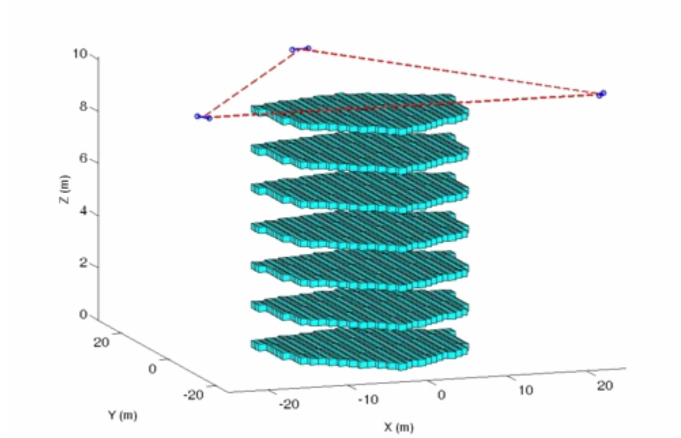

Figure 13. DISCRETIZED STATIC EQUILIBRIUM WORKSPACE FOR EVENLY SPACED SUPPORT POLES.

In order to investigate how the geometry of the SEW changes as the spacing of the mobile support vehicles changes, the location of the third mobile support vehicle was changed from $(0, 50/\sqrt{3}, 0)$ to $(10, 50/\sqrt{3}, 0)$. Due to the symmetry of the manipulator the choice of which vehicle to move is arbitrary. The resulting SEW also had constant cross-sections regardless of the *z*-elevation, thus the top view of the resulting SEW cross-section is shown in Figure 15.

The location of the third mobile support vehicle was then changed to $(20, 50/\sqrt{3}, 0)$. The resulting SEW also had constant cross-sections regardless of the *z*-elevation, thus the top view of the resulting SEW cross-section is shown in Figure 16.

We see that in every case when the workspace is viewed from above it is completely contained within the triangle formed using the support poles as vertices (i.e. the dashed triangles). Shifting the top support pole in the +*x* direction shifts the workspace generally in the +*x* direction, and in each case the centroid of the workspace (when viewed from above) is located approximately at the centroid of the previously described triangle.

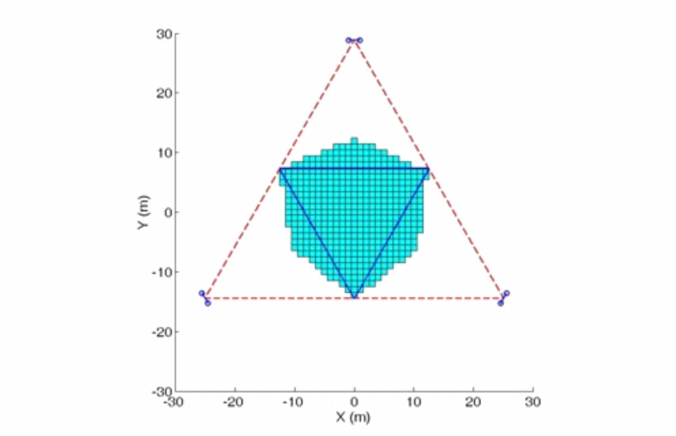

Figure 14. TOP VIEW OF THE STATIC EQUILIBRIUM WORKSPACE FOR EVENLY SPACED SUPPORT POLES.

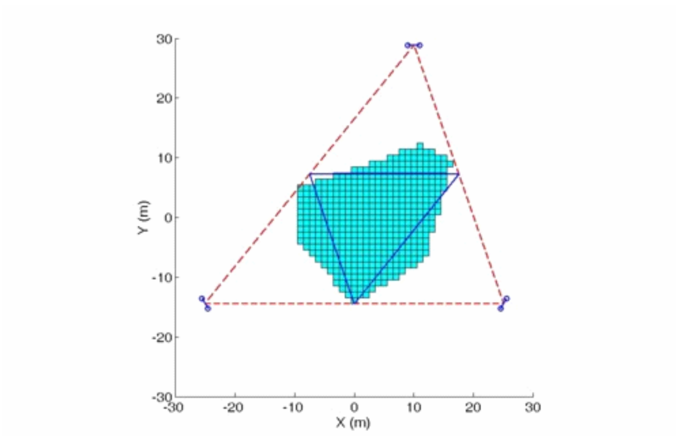

Figure 15. TOP VIEW OF THE STATIC EQUILIBRIUM WORKSPACE WITH THE TOP SUPPORT POLE SHIFTED IN THE X DIRECTION BY 10m.

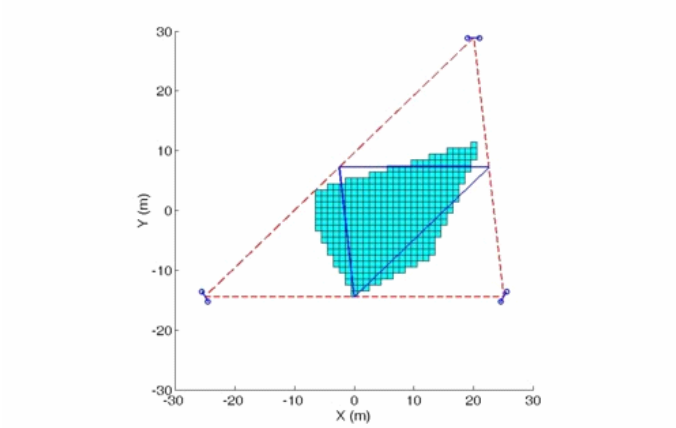

Figure 16. TOP VIEW OF THE STATIC EQUILIBRIUM WORKSPACE WITH THE TOP MOBILE SUPPORT VEHICLE SHIFTED BY 20m.

When deploying this system at a disaster site it is important to have guidelines for positioning the mobile support vehicles. The actual boundaries of the workspace are too complex to compute on-site, thus a simple rule-of-thumb for the workspace geometry is needed. For this example, we propose that a simple approximation of the workspace is the triangle whose vertices are the midpoints of the line segments connecting each of the support poles. This approximation is plotted in Figures 14, 15 and 16. While the approximation may be crude (good for Figure 14, somewhat worse for Figure 16), it is easy to perform quickly on site.

It is important to understand that this initial investigation of the manipulator workspace has only been performed for a few cases. More cases must be considered (including having the support poles be at different heights) before general guidelines can be made for positioning the mobile support vehicles to obtain a desired workspace geometry.

DISCUSSION

This system will not be appropriate for all search and rescue scenarios. The cable robot requires clear space above the disaster site in which to move. The presence of tall obstacles will decrease the workspace of the manipulator due to interference between these obstacles and the cables. Additionally, this type of system will likely not be useful for searching buildings that are largely intact, but rather is most effective in scenarios where structures have mostly or completely collapsed.

This system can also be modified for use in other applications where an easily deployable large-workspace manipulator is needed. For example, this system could be used in agricultural applications for inspecting plants or spraying chemical treatments. The system could be used for demining minefields (as suggested in [15]), where the ability to resist both forces and moments provides increased stability over the system proposed in [15].

A U.S. provisional patent has been filed for the system concept.

CONCLUSIONS AND FUTURE WORK

This paper has presented a novel concept for a deployable search and rescue robot system. It combines a translational cable-suspended robot (with moment resistance via parallel cables), deployable mobile cable supports, and a mother-daughter mobile robot deployment scheme. The mother robot, suspended via active cables, releases mobile daughter robots for detailed search and rescue work including mapping the site and locating and ascertaining the condition of human survivors. In addition to deploying mobile robots, the cable robot serves as a communications and power base for the mobile robots. The intent of this system design is to use the best features of cable-suspended and mobile robots to create an effective search and rescue system. In addition to the system design, the cable robot kinematics were presented, a calibration routine was detailed, and the workspace of the cable robot was discussed.

Our future work plans include: detailed mechanical design of the system components, alternative calibration routines, cable robot control methods, developing specialized mobile robots that take advantage of this new deployment method, and additional workspace studies which could lead to general guidelines for on-site placement of mobile support vehicles.

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