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# CABLE SUSPENDED MANIPULATION ROBOTS

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## Abstract:

This paper deals with the design study of cable suspended robotic manipulation systems for manipulation with heavy weight objects in relatively large operation workspace. A concept based on three cable winch systems working in mutual coordination is presented. Principal mathematical relations for kinamatic and force analysis are shows as well as direct and inverse control tasks are specified. The reconfigurable manipulation system is especially suited for operation in civil engineering, agriculture, forestry, etc., where its configuration can be modified according to conditions of the workspace. For this reason a simple calibration procedure is proposed.

**Keywords:** Robotic manipulator, Cable crane - robot, Kinematics, Control

## 1. Introduction

Yet traditional and well established is the use of robots for manufacturing in mechanical engineering industry. First applications and further expansion of robots have been conditioned and accelerated by several factors: repetitive character of operations, concentrated technology, well specified economical effect and, what is important, a relatively high level of technical education of people working in this domain. It can be said that contemporary needs and problems of industrial robotics are satisfactory solved. Further development is expected mainly in development of new sensory and sophisticated control systems.

Beside traditional applications in manufacturing (manipulation, welding, assembly), more attention and research effort is now oriented to new application areas.

There are several needs in civil engineering, in agriculture, in forestry or in military use where conventional manipulation technology can be hardly used for technical or economical reasons.
Let us mention some of these potential applications:

- Building and maintenance of large constructions
- Automatic inspection / monitoring large constructions or technologies (barrages, bridges, furnaces, transformers in electricity distribution systems, etc.)
- Surface mining
- Humanitarian demining
- Large stocks of materials (wood, garbage)
- Environmental restoration
- Underwater manipulation
- Different kinds of manipulation in large workspace (wood industry, forestry, orbit space, disaster / rescue situations, etc.)

One of domains where results of robotic research can be successfully applied seems to be manipulation with objects or masses in large operation space. Cranes for this purpose usually consist of a stable or mobile steel construction, a two or three D.O.F. mobility system and a lift mechanisms i.e. cable or chain set of pulleys. Typical examples are house building cranes, bridge or portico cranes etc. In general, the larger workspace for manipulation is required the bigger mechanical construction or track line for mobile cranes should be made. In order to satisfy the security and stability conditions the steel construction is robust, heavy weight and cumbersome to transport. The dimensions and mass of this moving construction with respect to maximal load (mass/power ratio) is relatively high what results in limited speed, energy consumption and worse dynamical performance due to inertia effects.

Naturally, due to other character of working conditions, there are some specific criteria on construction and performance for such manipulation systems. This effort results in design several non-conventional kinematic structures and control techniques. Some concepts of robotic manipulators especially suited for manipulation in relatively large operation space are discussed below.

## 2. Cable manipulation in large workspaces

Let us mention some common features and specifications corresponding intended applications that a manipulation system should satisfy.

***Dimensions of the workspace.*** In general, dimensions of the operation space are several times greater then dimensions of the robot mechanics. Usually, the volume of the operation space can be several hundreds of $m^3$. The form of the operation space directly corresponds to a given geometry and tasks.

***Payload capacity.*** Maximal payload is considered within hundreds kg to several tons. Comparing to standard constructions of industrial robots the own mass / payload ratio should be much smaller.

***Reconfigurable according to geometrical conditions specified directly on place.*** Each installation of the manipulation system can be considered as a task oriented solution. An ideal concept includes as many as maximal number of general units and their flexible configuration according to real geometry. This concept naturally requires fast and simple installation of particular units and to create the manipulation system.

***Low weight and simple transport.*** One expects that the manipulation system will operate for a limited time period in majority of intended applications. Then, the system is dismounted and transported on another place. Typical examples are manipulation systems with materials in building constructions, humanitarian demining or forestry applications. Usually such a system will work in out door conditions.

***Low energy consumption and good dynamical performance.*** Manipulation in relatively large operation space requires fast motion velocities. Considering possible constructions of mechanics for these types of manipulators and comparing them with respect to classical rigid mechanics of industrial robots there is a serious problem of vibration damping and control.

***Operation / control in Cartesian or other suitable coordinates defined directly on place.***

***Low cost.*** Because of a manipulation system can not be considered as a product of mass / serial production its cost should be minimal.

Two illustrative examples are shows Fig. 1.

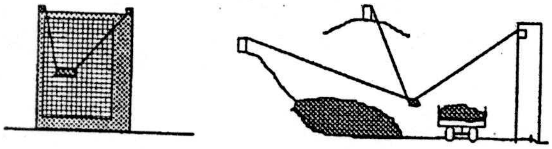

Fig. 1 Two examples of the cable suspended manipulation

## 3. Cable manipulation systems

Structural possibilities

The goal of this paper is not a comprehensive study of all possible structural configurations for solving cable manipulation systems. Some next examples could show manipulation possibilities in 2 and 3 d.o.f.

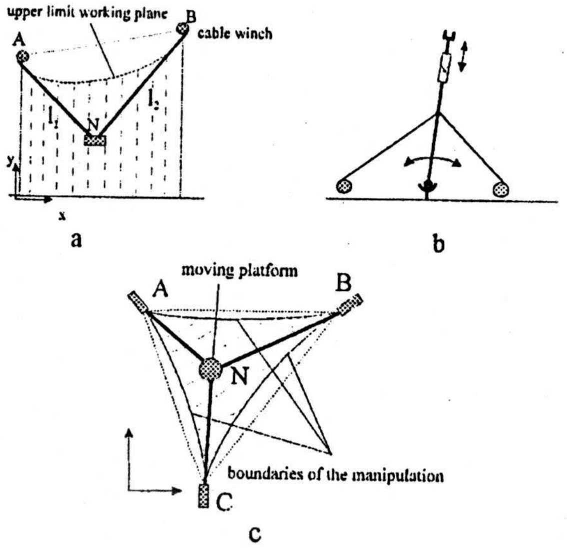

Fig 2. Two d.o.f. systems

Fig.2a depictes a cable suspended platform for operation in vertical plane. The scheme on Fig.2b is a modification of cable driven rotating arm and Fig 2c represents a configuration able to work in space without the gravity effect. As obvious the range of operation space is limited by maximal forces in cables.

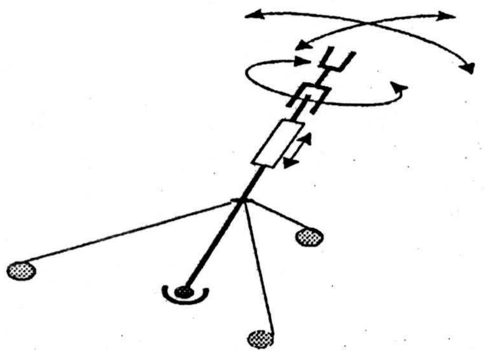

Fig.3. A three d.o.f. system

The scheme on Fig.3 represents a 3 d.o.f. spherical system equipped by two additional axes. Another concept of the cable suspended platform is discussed in more details.

## 4. A 3 d.o.f. cable suspended manipulator

### *4.1 Mechanical configuration*

In principle the system, as schematically depicted Fig.4, consists of three cable winches fixed over the working space. The ends of cables from particular winches are connected on the moving platform.

It is obvious that the operation space is given by the triangle created by the fixation positions of the end pulleys. It is approximately above the ground projection of this fixation triangle. As can be seen later, the upper boundary surface is given by the limit force in particular cables / fixations.

Each winch mechanism is equipped by the cable length measuring and position/velocity servo control logic. Thus for such a parallel mechanical system the actual position of the moving platform determine three distances i.e. measured lengths of cables between the platform and the end pulleys of the winch mechanisms. The central control system performs the transformations and coordinated motion control of the platform with respect to the world reference frame defined on place.

Four main problems have to be solved for this system. There are:
- kinematic and force analysis (motion and force transformation)
- coordinated motion control
- dynamic analysis and control
- calibration.

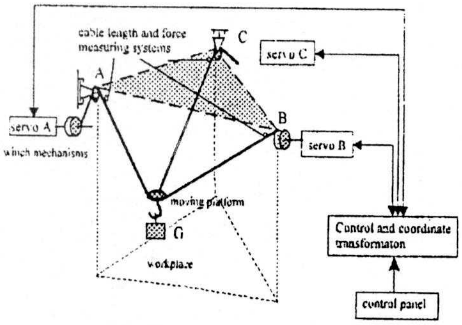

*Fig. 4 Principal mechanical configuration*

The task is to find the functions that relate actual motion and load expressed in world reference coordinates and internal representation of control parameters i.e. cable length and internal forces. For this purpose we introduce: (See Fig.5)

- O(x,y,z) the Cartesian world coordinate system of global positioning, Denote the fixation points A,B,C that create the triangle ΔABC above the working area. Each point of this triangle is given by three global coordinates $A(x_A,y_A,z_A)$, $B(x_B,y_B,z_B)$ and $C(x_C,y_C,z_C)$.

- A(x',y',z') the auxiliary Cartesian reference system where x',y' axes lie in the plane given by triangle Δ ABC

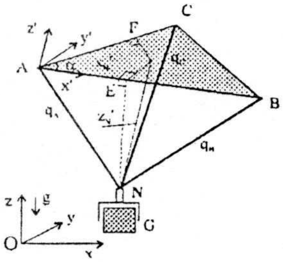

*Fig. 5 Geometry of the cable support*

Let point N be the reference on the moving platform. Its position gives the vector $p'_N = [x'_N, y'_N, z'_N]^T$ in the A(x',y',z') local coordinate system or $p_N = [x_N, y_N, z_N]^T$ in the global Cartesian references. These position vectors are mutually related using transformation

$$p_N = p_A + S \cdot p'_N \tag{1}$$

where $S$ is the 3x3 rotation matrix of local coordinates into global references..

Denote by the symbols $q_A$, $q_B$, $q_C$ measured lengths of cables as controllable parameters.

Express now the actual position of the platform in global world coordinates for any combination of three controlled lengths of cables. Solving the above relations we have a unique solution for the Cartesian position $p'_N$ when a combination of $q_A$, $q_B$, $q_C$ is given.

$$\begin{aligned} x'_N &= \frac{1}{2.\overline{AB}}\left(q_A^2 + \overline{AB}^2 - q_B^2\right) \\ y'_N &= -\frac{1}{tg\,\alpha} x'_N + \frac{1}{\sin\alpha} \cdot \overline{AF} \\ z'_N &= (-)\sqrt{q_A^2 - x'^2_N - y'^2_N} \end{aligned} \tag{2}$$

where according to Fig.3

$$\overline{AB}^2 = (x_A - x_B)^2 + (y_A - y_B)^2 + (z_A - z_B)^2$$
$$\overline{AC}^2 = (x_A - x_C)^2 + (y_A - y_C)^2 + (z_A - z_C)^2$$
$$\overline{BC}^2 = (x_B - x_C)^2 + (y_B - y_C)^2 + (z_B - z_C)^2$$

$$\overline{AF} = \frac{1}{2.\overline{AC}}\left(q_A^2 + \overline{AC}^2 - q_C^2\right)$$

$$\alpha = \arccos\left(\frac{\overline{AB}^2 + \overline{AC}^2 - \overline{BC}^2}{2.\overline{AB}.\overline{AC}}\right)$$

### *Direct task of kinematics*

The position and motion of the platform is specified by the control parameters $q = [q_A, q_B, q_C]^T$ in the cable system. The task is to express the motion in the global references. As derived above we calculate the actual global position is given by transformations (1,2). Applying the time differentiation we have for velocities

$$\dot{p}' = J_A.\dot{q} \tag{3}$$

and because of the Jacobi matrices $J_A$,$J_0$ for incremental motion/velocity in local and global reference frames are related $J_O = S.J_A$ one get

$$\dot{p} = S.J_A.\dot{q} \tag{4}$$

### *Inverse task*

For a given global position $p$ we are looking for control parameters in the vector $q$. Considering (2) one can directly write for cable velocity and acceleration

$$\dot{q} = J_0^{-1}.\dot{p}$$

$$\ddot{q} = J_0^{-1}(\ddot{p} - J_0\dot{q}) \tag{5}$$

where inverted Jacobi matrix be in form

$$J_0^{-1} = \begin{bmatrix} 1/q_A & 0 & 0 \\ 0 & 1/q_B & 0 \\ 0 & 0 & 1/q_C \end{bmatrix} * \begin{bmatrix} x_N - x_A & y_N - y_A & z_N - z_A \\ x_N - x_B & y_N - y_B & z_N - z_B \\ x_N - x_C & y_N - y_C & z_N - z_C \end{bmatrix} \tag{6}$$

### *Force analysis*

Denote by $Q_A$,$Q_B$,$Q_C$ cable forces in tension and define the vector $Q = [Q_A, Q_B, Q_C]^T$. Considering a possible external force $P = [P_x, P_y, P_z]^T$ the load on the platform will be $F = G + P$. Applying principle of virtual works one can write

$$Q^T.\Delta q = F^T.\Delta p \tag{7}$$

Solving this relation the forces in cables and external load are related

$$Q = J_o^T.\ F \tag{8}$$

As follows from decomposition of an external load the values of three cable forces will increase with increasing $z$-coordinate of the platform position.

Naturally, in order to avoid an overload condition and to protect the system all cable forces should be supervised on maximal their values. These maximal cable forces give the upper boundary surface that limits the workspace. An example of the workspace analysis for a real geometry is given below. The upper limit surface of the operation workspace is given by boundary conditions

$$Q_i \leq Q_{lim}$$

The form of this upper boundary surface is analyzed in [1,2].

### *Dynamics*

The system dynamics in Cartesian space is described by equations

$$m\ddot{p} + G + P = J_0^{-T}.Q \tag{9}$$

As follows from principle each cable force should be non-negative ($Q_i > 0$). This fact states the limit condition for maximal acceleration of the desired trajectory of the moving platform. Thus from (8) it should be satisfied

$$\ddot{p}_{\text{lim}} \geq g \tag{10}$$

where $g = [0\ \ 0\ \ -g]^T$

### *Control*

In general, the dynamics of the system with rigid cables is described in cable coordinates as follows

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + D(q)q = Q \tag{11}$$

where ***M*, *C*, *D*** are (3x3) matrices that represent terms for inertia (**D**), Coriolis, centrifugal and friction forces (**C**) and gravity forces (**D**).

Rewriting equation (9) into this form the system has to be controlled will be

$$m.J^T.J^{-1}(u - \dot{J}\dot{q}) + J^T(G + P) = Q \tag{12}$$

where

$$u = \ddot{p} = `K_v(\dot{p} - \dot{p}_d) + K_p(p - p_d) - \ddot{p}_d \tag{13}$$

is the control vector, $K_v$, $K_p$ are positive definite matrices and index $d$ denotes desired values. Rem.: The choice of these matrices in some optimal sense is not the objective of this paper. In preliminary experiments the velocity / vibration control method has been adopted [2 ].

## 5 Calibration

As soon as all three winch mechanisms with end pulleys have been installed on place we do not know the coordinates of the fixation points vectors $p_i = [x_i, y_i, z_i]^T$, i = A,B,C ; need for kinematic and force transformations. There is an initial problem: we have to execute calibration i.e. to actualize the parameters in relations for motion and force transformations for a real arrangement of the whole system. Principal requirement is to perform this calibration without any additional equipment.

In order to find the unknown coordinates of the A,B,C points the following calibration procedure is proposed:

a) Let us stake out three points $N_1$, $N_2$, $N_3$ in the x-y plane. These points should create a triangle with known geometry. Although, in principle, this triangle could be chosen quite arbitrarily but is more advantageous to construct it equilateral, as showed in Fig.5.

b) Using the individual command of particular servo-drives we perform the positioning of the moving platform sequentially into points $N_1$,$N_2$ and $N_3$. Denote by symbols $q_{A1}, q_{B1}, q_{C1}$ $q_{A2}, q_{B2}, q_{C2}$ and $q_{A3}, q_{B3}, q_{C3}$ measured lengths of cables that correspond to particular positions according to Fig.5.

c) Solving three tetrahedrons $N_1N_2N_3A$; $N_1N_2N_3B$ and $N_1N_2N_3C$, the x,y,z coordinates of A,B,C points are found.

Consider now the equilateral triangle $N_1N_2N_3$; ($N_1N_2 = N_2N_3 = N_1N_3 = s$; $s = R\sqrt{3}$). The position vectors and coordinates of these points are

$$\begin{aligned} p_{N1} &= \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}^T \\ p_{N2} &= \begin{bmatrix} R\sqrt{3} & 0 & 0 \end{bmatrix}^T \\ p_{N3} &= \begin{bmatrix} \frac{1}{2}R\sqrt{3} & \frac{3}{2}R\sqrt{3} & 0 \end{bmatrix}^T \end{aligned} \tag{14}$$

Then, after substitution into ( 3) the solutions for i = A,B,C will be

$$\begin{aligned} x_i &= \frac{1}{2R\,.\sqrt{3}}\left[q_{i1}^2 + (R\,.\sqrt{3})^2 - q_{i2}^2\right] \\ y_i &= \frac{1}{6R}\left[q_{i1}^2 + q_{i2}^2 - 2q_{i3}^2 + (R\,.\sqrt{3})^2\right] \\ z_i &= \sqrt{q_{i1}^2 - x_i^2 - y_i^2} \end{aligned} \tag{15}$$

d) Relations for transformation of position and velocity of the platform for a given geometrical configuration of points A,B,C are calculated.[1]

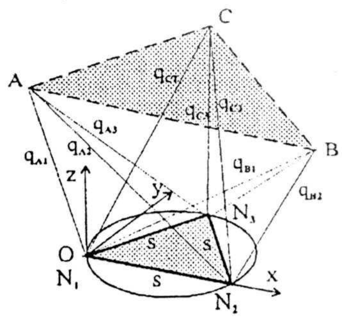

*Fig. 5 The geometry for calibration*

## 6. Conclusion

A simple cable suspended manipulation system devoted to manipulation with heavy weight parts in large operation space is proposed. As showed characteristics of the system can satisfy some specific requirements given by intended application. These systems could be applied in construction, forestry, military, agriculture, etc. An example is given below.

*Monitoring hazardous environments*

There are several examples in industry, environmental protection or in military use where sensing thermal images and evaluation actual situations in a given working space is need. Typical examples are: monitoring hazardous situations in nuclear / thermal power plants or in electricity distribution systems, examination dangerous inaccessible terrain or demining operations.

The system on Fig. 6, consists of two main parts: the positioning mechanics and the sensory equipment.

The infrared camera fixed on the platform allows to see / detect invisible objects and recognize dangerous situations. Fixation of the camera has two additional rotations what allows mapping the subspace in a given position of the platform.

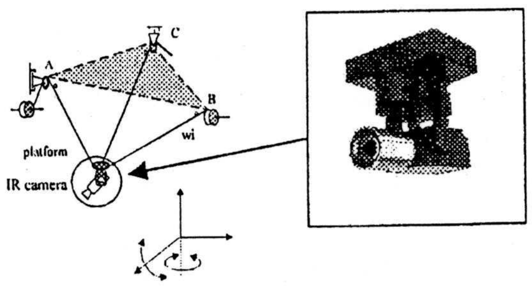

Fig.6. Monitoring system with IR camera

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