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Modeling, control and simulation of cable robots

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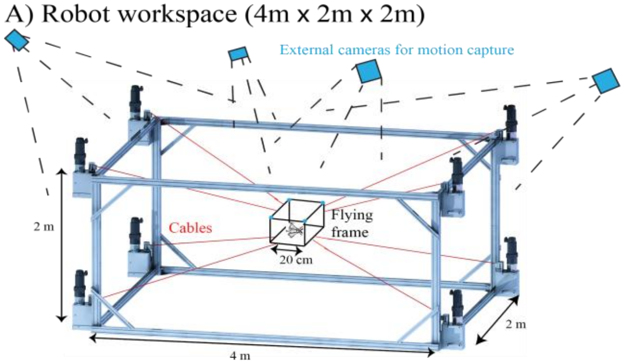
***Abstract*— The proposed work deals with modeling, control and simulation for a class of non linear dynamic systems that is cable robots in order to analysis behavior of insects in free flight. One of the main features is to establish, from the geometric and kinematic equations, the mathematical model that describes evolution of the gripper robot. The second part presents analysis and design of control laws that assures stabilization under severe constraints on the robots' cables. The last section is devoted to numerical simulations to show high performances of the proposed approach.**

Keywords— Cable robots, Nonlinear systems, Modeling, Control, Numerical simulations.

I. Introduction

Robot manipulators are often used in various industriel productions in order to improve product quality assembled and to reduce the time of assembly [1]. Their use is not only limited to this kind of activity but it also extended to various other fields such as military, medical, sea or space exploration [2]. The aim of this work is to develop dynamic model and control laws for cable robot in order to study behavior of insects in free flight as shown bellow:

A) Robot workspace (4m x 2m x 2m)



This kind of robot is known for its high speed and high precision in order to record biological signals of the insects by moving the electrophysiology device to stay closer to the insect. We know that for this robot, the cables connecting the base fixes at the mobile platform (effector) are used as transmission resource. The coordinated control lengths and/or tensions in the cables makes it possible to move and apply efforts to the level of the effector. The modeling of the robot then consists in making a geometrical, kinematic and dynamic analysis by the adaptation of a mathematical tools of the behavior of the robot [3-6,17].

This kind of robots pulled by cables is a special class of parallel robots in which the rigid links are replace by flexible

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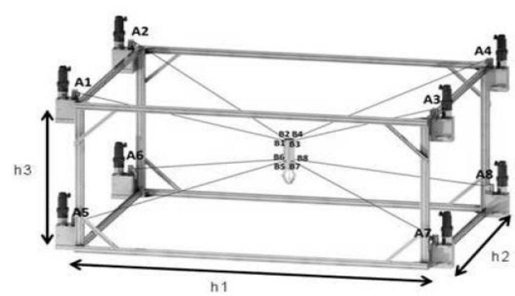
links which are obtained thanks to the use of cables. The effector, terminal of the latter, east connects to the base by a number of active cables of which the lengths make it possible to control the desired position and the orientation of this last. This structure offers to us several advantages compared to that of the classical robots [7]. Indeed, the use of cables facilitates the work on robots of high speed such as, for example, those present by the work of Sadao Kawa walled, Hitoshi Kino and Choe Won where the speed was of 13 m.s−1 (all with observing some the stability conditions and absence of the vibrations of the system) [8] and on Robots of big spaces of work [9]. In the field as of parallel robots, much of research tasks are published on the dynamics and the aspects of control of the latter [10-12]. However, in comparison with the great quantity of articles published on the control of the classical robots, only some articles were published on the control of cable robots. One finds there various approaches based on the use of robust regulators PID [13], on the basis of use of the approach of Lyapunov [8, 14] or on the basis of use of fuzzy regulator [4.18]. For this case we quote the work of Hwang and Kim [15] who used a method of adaptive fuzzy logic to control a robot with electric training and the work of Cho HJ and al. [16] which applied the genetic algorithms to generate a fuzzy PID.

In this paper we propose first to establish a mathematical model to describe behavior of the cable robot. After, a useful approach is proposed to design control law with global stabilization under severe constraints on cables' tensions. In the last section, performances are shown through simulation results

II. Modeling of cable robots

A. *Geometrical modeling*

As shown in figure 1, the robot considered in this work is composed of eight cables connecting a base, of parallelepipedic form provided with eight engines and with a mobile effector with six degrees of freedom. The geometrical problem consists in determining the lengths of the cables (vector with eight elements) starting from the vector with six elements (X) describing the position and the orientation of the effector. The engines allowing roll up it cables and thus to control the position of



th e mobile effector [4].

Figure 1. Motorized system with eight cables.

Choosing A_5 like origin of a fixed reference mark R_0 is the second pointer R_1 placed at the centre of gravity of the effector.

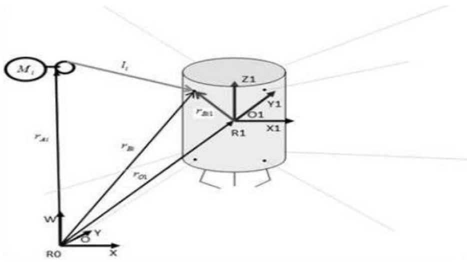


Figure 2. General diagram of the system.

As shown in fig.2, one can as follows determine the lengths l_i of the cables :

$$l_i = r_{Bi} - r_{Ai} \quad , \left(i = 1, 2, 3, ..., 8\right) \tag{1}$$

With :

- r_{Ai} the vector of position of Ai (i = 1, 2,…,8) compared to R_0.
- r_{Bi} the vector of position of Bi (attachment of cable I on the effector, i = 1, 2,…,8) compared to R_0.

The vectors r_{Ai} are obtained by a simple projection on the reference mark R_0.

$$\left.\begin{array}{ll} r_{A1} = (0, 0, h_3)^T & r_{A2} = (0, h_2, h_3)^T \\ r_{A3} = (h_1, 0, h_3)^T & r_{A4} = (h_1, h_2, h_3)^T \\ r_{A5} = (0, 0, 0)^T & r_{A6} = (0, h_2, 0)^T \\ r_{A7} = (h_1, 0, 0)^T & r_{A8} = (h_1, h_2, 0)^T \end{array}\right\} \tag{2}$$

In the same way one can obtain the vectors r_{Bi} after a transformation of the R_1 reference mark towards the R_0 reference mark :

$$r_{Bi} = r_{O1} + R \cdot r_{Bi1} \, , \left(i = 1, 2, 3, ..., 8\right) \tag{3}$$

- r_{O1} : The vector of position in the beginning O1 of the R_1 reference mark compared to R_0.
- R being the matrix of orientation of the effector compared to the R_0 reference mark with: α the swing angle compared to axis Z, β the swing angle compared to the axis Y and γ the swing angle compared to axis X.

$$R = \begin{bmatrix} c\alpha c\beta & c\alpha s\beta s\gamma - s\alpha c\gamma & c\alpha s\beta c\gamma + s\alpha s\gamma \\ s\alpha c\beta & s\alpha s\beta s\gamma + c\alpha c\gamma & s\alpha s\beta c\gamma - c\alpha s\gamma \\ -s\beta & c\beta s\gamma & c\beta c\gamma \end{bmatrix}$$

- r_{Bi1} : the vector of position of Bi compared to R_1.

Another projection on the R_1 reference mark (Fig.3) gives us the vectors r_{Bi1} :

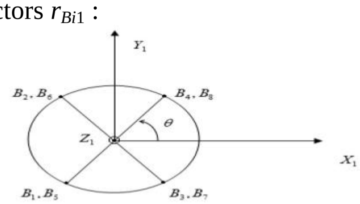


Figure 3. Connections between the cables and the effector.

we obtained :

$$\left.\begin{array}{l} r_{B11} = (r.\cos(4\theta), \mathrm{r}.\sin(4\theta), d)^T \\ r_{B21} = (r.\cos(2\theta), \mathrm{r}.\sin(2\theta), d)^T \\ r_{B31} = (r.\cos(5\theta), \mathrm{r}.\sin(5\theta), d)^T \\ r_{B41} = (r.\cos(\theta), \mathrm{r}.\sin(\theta), d)^T \\ r_{B51} = (r.\cos(4\theta), \mathrm{r}.\sin(4\theta), -d)^T \\ r_{B61} = (r.\cos(4\theta), \mathrm{r}.\sin(4\theta), -d)^T \\ r_{B71} = (r.\cos(4\theta), \mathrm{r}.\sin(4\theta), -d)^T \\ r_{B81} = (r.\cos(4\theta), \mathrm{r}.\sin(4\theta), -d)^T \end{array}\right\} \tag{4}$$

B. *Kinematic and dynamic modeling*

The kinematic analysis consists in determining the principal relations between the cartesian variables and the articular variables de¯ning the movement of the robot. The kinematic problem consists in determining the variations in the lengths of cables:

$$\dot{l} = \begin{bmatrix} \dot{l}_1 & \dot{l}_2 & \dot{l}_3 & \dot{l}_4 & \dot{l}_5 & \dot{l}_6 & \dot{l}_7 & \dot{l}_8 \end{bmatrix}^T \tag{5}$$

The speed of the effector can be thus described by :

$$\dot{r}_{O1} = \begin{bmatrix} v & w \end{bmatrix}^T = \begin{bmatrix} \dot{x} & \dot{y} & \dot{z} & \dot{\alpha} & \dot{\beta} & \dot{\gamma} \end{bmatrix}^T \tag{6}$$

With:

- v $(m.s^{-1})$: The speed of the centre of gravity of the effector.
- w $(rad.s^{-1})$: Its angular velocity.

One can thus deduce the following kinematic model:

$$\dot{l} = J.\dot{r}_{O1} \tag{7}$$

Where: J being the matrix jacobian.

$$J = \begin{bmatrix} \frac{\partial l_i}{\partial x} & \frac{\partial l_i}{\partial y} & \frac{\partial l_i}{\partial z} & \frac{\partial l_i}{\partial \alpha} & \frac{\partial l_i}{\partial \beta} & \frac{\partial l_i}{\partial \gamma} \end{bmatrix}$$

The general dynamic equations of the movement can be obtained starting from the formulation of Lagrange whose equation can be written, by taking account of the generalized forces or the couples, in the following form:

$$\frac{d}{dt}\left(\frac{\partial T\left(q, \dot{q}\right)}{\partial \dot{q}}\right) - \frac{\partial T\left(q, \dot{q}\right)}{\partial q} + \frac{\partial V\left(q\right)}{\partial q} = \tau \tag{8}$$

V being potential energy and T kinetic energy of the system.

With:

$$T = \frac{1}{2} m v^T v + \frac{1}{2} w^T R I_{O1} R^T w \tag{9}$$

I_{O1} Tensor of inertia at the origin of the R1 reference mark.

$$I_{O1} = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{yx} & I_{yy} & -I_{yz} \\ -I_{zx} & -I_{zy} & I_{zz} \end{bmatrix}$$

In this study, each cable is supposed to be an element of force. Consequently, the potential energy of the system is due only to the forces of gravitation. This energy takes the shape then:

$$V = mgz \qquad (10)$$

The relations between outside, the effector and the tensions of the cables necessary to maintain the system in balance are given by following relation 11[4]:

$$\begin{bmatrix} F_x & F_y & F_z & M_\alpha & M_\beta & M_\gamma \end{bmatrix} = -J^T u \qquad (11)$$

Following a series of transformations and substitutions and after the simplification of expression 11, we can write the equations of the movement according to the contact q in the following general form [3]:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + \tau_d = -J^T u \qquad (12)$$

With: $q = \begin{bmatrix} x & y & z & \alpha & \beta & \gamma \end{bmatrix}^T$

$$M(q) = \begin{bmatrix} mI_{3\times3} & 0_{3\times3} \\ 0_{3\times3} & E^T I_{O1} E \end{bmatrix}$$

$$E = \begin{bmatrix} \cos(\beta)\cos(\gamma) & -\sin(\gamma) & 0 \\ \cos(\beta)\sin(\gamma) & \cos(\gamma) & 0 \\ -\sin(\beta) & 0 & 1 \end{bmatrix}$$

$$C(q,\dot{q}) = \begin{bmatrix} 0_{3\times3} & 0_{3\times3} \\ 0_{3\times3} & E^T I_{O1}\dot{E} + E^T (E\dot{\theta})_\times \left(I_{O1}E\right) \end{bmatrix}$$

$$E = \begin{bmatrix} \cos(\beta)\cos(\gamma) & -\sin(\gamma) & 0 \\ \cos(\beta)\sin(\gamma) & \cos(\gamma) & 0 \\ -\sin(\beta) & 0 & 1 \end{bmatrix}$$

$$\dot{\theta} = \begin{bmatrix} \dot{\alpha} & \dot{\beta} & \dot{\gamma} \end{bmatrix}^T$$

$$(E\dot{\theta})_\times = \begin{bmatrix} 0 & -w_z & w_y \\ w_z & 0 & -w_x \\ -w_y & w_x & 0 \end{bmatrix} \quad G(q) = \begin{bmatrix} 0 \\ 0 \\ mg \\ 0_{3\times1} \end{bmatrix}$$

τ_d : Vector of the terms of the external disturbances.

C. *State space model*

Moreover, we pose:

$$\begin{cases} x_1 = q = \begin{bmatrix} x & y & z & \alpha & \beta & \gamma \end{bmatrix}^T \\ x_2 = \dot{x}_1 = \dot{q} = \begin{bmatrix} x & y & z & \alpha & \beta & \gamma & \dot{x} & \dot{y} & \dot{z} & \dot{\alpha} & \dot{\beta} & \dot{\gamma} \end{bmatrix}^T \\ x = \begin{bmatrix} x_1 & x_2 \end{bmatrix}^T \end{cases}$$

Where:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -M(x)^{-1}.(C(x).x_2 - G(x) - J(x)^T u - \tau_d) \end{cases}$$

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} x_2 \\ -M(x)^{-1}.(C(x).x_2 - G(x) - J(x)^T u - \tau_d) \end{pmatrix}$$

This model is then of the following form:

$$\dot{x} = A.x + f(x,u) \qquad (13)$$

With: $A = \begin{bmatrix} 0_{6\times6} & I_{6\times6} \\ 0_{6\times6} & 0_{6\times6} \end{bmatrix}$

$$f(x,u) = A'(x).x + B(x).u + G(x) + C$$

$$A'(x) = \begin{bmatrix} 0_{6\times6} & 0_{6\times6} \\ 0_{6\times6} & M^{-1}.C \end{bmatrix} \quad B(x) = \begin{bmatrix} 0_{6\times24} \\ J(x)^T \end{bmatrix}$$

$$G(x) = \begin{bmatrix} 0_{6\times1} \\ 0 \\ 0 \\ mg \\ 0_{3\times1} \end{bmatrix}$$

C: Vector of the disturbances.

III. Control of a cable robot

To determine the sequences of the order it is enough to solve the equation 12 whose solution can be written in the following form:

$$u = -(J^T)^{-1}(M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + \tau_d) \qquad (14)$$

In our case, the matrix J is not invertible (dimension of J = (24.6)), the equation 14 becomes then:

$$u = -J(J^T J)^{-1}(M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + \tau_d) \qquad (15)$$

IV. Numerical simulations

As we already mentioned, the robot considered in this work is composed of eight cables connecting a parallelepiped base of form of eight engines to an effector of mobile cylindrical form to six degrees of freedom. It also has a mass m = 20kg.

Dimensions of the base are:

h1 = 400 cm; h2 = 200 cm; h3 = 200 cm.

Let us assume that the effector is in the middle of the fixed base:

$$r_{O1} = \begin{bmatrix} h_1/2 & h_1/2 & h_1/2 & 0 & 0 & 0 \end{bmatrix}^T = \begin{bmatrix} 200 & 100 & 100 & 0 & 0 & 0 \end{bmatrix}^T$$

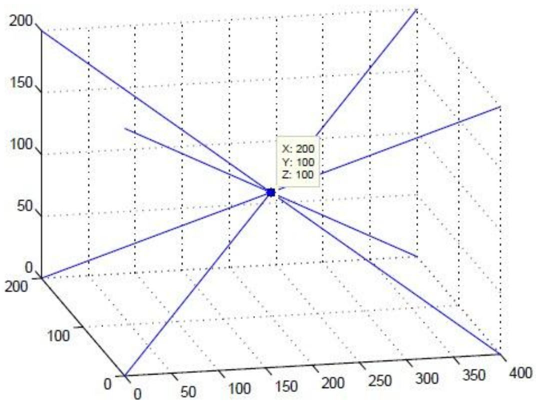


Figure 4. The effector in a position medium.

The ray r of the effector, the distance D between the center of gravity and a Bi point hangup and the angle θ which separates two points from hangup from the cables with the effector compared to the R_1 reference mark are respectively:

$$r = 4, d = 10, \theta = 60^\circ$$

The vectors r_{Bi1} are thus:

$$r_{B11} = \begin{bmatrix} r\cos(4\theta) & r\sin(4\theta) & d \end{bmatrix}^T = \begin{bmatrix} -1 & -1.732 & 10 \end{bmatrix}^T$$

$$r_{B21} = \begin{bmatrix} r\cos(2\theta) & r\sin(2\theta) & d \end{bmatrix}^T = \begin{bmatrix} -1 & 1.732 & 10 \end{bmatrix}^T$$

$$r_{B31} = \begin{bmatrix} r\cos(5\theta) & r\sin(5\theta) & d \end{bmatrix}^T = \begin{bmatrix} 1 & -1.732 & 10 \end{bmatrix}^T$$

$$r_{B41} = \begin{bmatrix} r\cos(\theta) & r\sin(\theta) & d \end{bmatrix}^T = \begin{bmatrix} 1 & 1.732 & 10 \end{bmatrix}^T$$

$$r_{B51} = \begin{bmatrix} r\cos(4\theta) & r\sin(4\theta) & -d \end{bmatrix}^T = \begin{bmatrix} -1 & -1.732 & -10 \end{bmatrix}^T$$

$$r_{B61} = \begin{bmatrix} r\cos(2\theta) & r\sin(2\theta) & -d \end{bmatrix}^T 7 = \begin{bmatrix} -1 & 1.732 & -10 \end{bmatrix}^T$$

$$r_{B71} = \begin{bmatrix} r\cos(5\theta) & r\sin(5\theta) & -d \end{bmatrix}^T = \begin{bmatrix} 1 & -1.732 & -10 \end{bmatrix}^T$$

$$r_{B81} = \begin{bmatrix} r\cos(\theta) & r\sin(\theta) & -d \end{bmatrix}^T = \begin{bmatrix} 1 & 1.732 & -10 \end{bmatrix}^T$$

The application of a control u_i makes it possible to move the effector with a position define by $\begin{bmatrix} x_d & y_d & z_d & \alpha_d & \beta_d & \gamma_d \end{bmatrix}^T$. For example to move the effector towards the desired position and the orientation $[100\ 150\ 100\ 30\ 60\ 30]^T$ we apply the command u_1 defined by the following equation:

$$u_1 = -J_1(J_1^T J_1)^{-1}(M(q)\ddot{q} + G(q) + \tau_d) \qquad (16)$$

It is supposed that the matrix C is negligible.

With:

$$I_{O1} = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{yx} & I_{yy} & -I_{yz} \\ -I_{zx} & -I_{zy} & I_{zz} \end{bmatrix} = \begin{bmatrix} 0.782 & 0 & 0 \\ 0 & 0.782 & 0 \\ 0 & 0 & 0.293 \end{bmatrix}$$

$$J_1 = J(100,150,150,30,60,30)$$

$$M = \begin{bmatrix} m & 0 & 0 & 0 & 0 & 0 \\ 0 & m & 0 & 0 & 0 & 0 \\ 0 & 0 & m & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.782\cos(\alpha)^2\cos(\gamma)^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.782\cos(\gamma) & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.293 \end{bmatrix} = \begin{bmatrix} 20 & 0 & 0 & 0 & 0 & 0 \\ 0 & 20 & 0 & 0 & 0 & 0 \\ 0 & 0 & 20 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.0004 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.0186 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.293 \end{bmatrix}$$

$$G = \begin{bmatrix} 0 & 0 & m.g & zeros(3,1) \end{bmatrix}^T = \begin{bmatrix} 0 & 0 & 196.2 & zeros(3,1) \end{bmatrix}^T$$

We obtain the position of the effector represented on figure 5 where the lengths of cabled are:

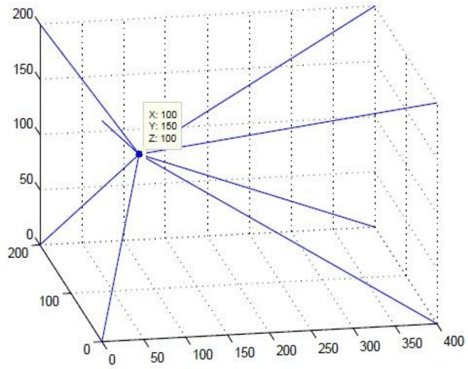


Figure 5. The effector in another position.

$$l_1 = r_{B1} - r_{A1} = (r_{O1} + R.r_{B11}) - r_{A1}$$
$$= [109.2945 \quad 151.0549 \quad -105.3385]^T$$
$$l_2 = r_{B2} - r_{A2} = (r_{O1} + R.r_{B21}) - r_{A2}$$
$$= [110.6722 \quad -50.8418 \quad -98.8190]^T$$
$$l_3 = r_{B3} - r_{A3} = (r_{O1} + R.r_{B31}) - r_{A3}$$
$$= [-291.2932 \quad 154.8190 \quad -104.1193]^T$$
$$l_4 = r_{B4} - r_{A4} = (r_{O1} + R.r_{B41}) - r_{A4}$$
$$= [-189.9154 \quad -47.0777 \quad -97.5997]^T$$
$$l_5 = r_{B5} - r_{A5} = (r_{O1} + R.r_{B51}) - r_{A5}$$
$$= [89.9154 \quad 147.0777 \quad 97.5997]^T$$
$$l_6 = r_{B6} - r_{A6} = (r_{O1} + R.r_{B61}) - r_{A6}$$
$$= [91.2932 \quad -54.8190 \quad 104.1193]^T$$
$$l_7 = r_{B7} - r_{A7} = (r_{O1} + R.r_{B71}) - r_{A7}$$
$$= [-310.6722 \quad 150.8418 \quad 98.8190]^T$$
$$l_8 = r_{B8} - r_{A8} = (r_{O1} + R.r_{B81}) - r_{A8}$$
$$= [-309.2945 \quad -51.0549 \quad 105.3385]^T$$

After having determined the field of definition of the order, some examples of order were treated. The table below summarizes the results got concerning the positions and the orientations of the effector body:

TABLE I. TABLE OF POSITIONS

Commande	x	y	z	α	β	γ
u_1	100	150	100	30	60	30
u_2	122	118	102	20	35	45
u_3	130	103	80	15	14	70
u_4	140	150	75	30	78	50
u_5	102	40	100	7	61	30
u_6	90	135	147	25	52	12
u_7	105	106	56	39	12	80
u_8	186	160	98	35	7	75
u_9	96	117	103	92	56	86

V. CONCLUSION

In this work, we focus on modeling and control of cable robots. A mathematical model was initially established starting from the physical relations and the nonlinear equations related to its running. A model based control strategy was developed to assure global stabilization. Simulations results were carried out to show validity of the obtained results.

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