Actas de las XXXVII Jornadas de Automática 2016
https://doi.org/10.17979/spudc.9788497498081.0043

CABLE DRIVEN ROBOT TO SIMULATE LOW GRAVITY AND ITS APPLICATION IN UNDERWATER HUMANOID ROBOTS

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Abstract

This paper addresses the main results obtained during the design and analysis of a cable-driven robot able to simulate the dynamic conditions existing in underwater environment. This work includes the kinematic and dynamic modeling as well as the analysis of the tension of the cables along different trajectories. The low-gravity simulator application is novel in the context of cable-driven robots and it is aimed to be implemented in an underwater humanoid robot. Therefore, this work can be seen as a test case of the complementary research contributions of the group of Robotics and Intelligent Machines at CAR in the recent years.

Palabras Clave: Cable driven robot, low gravity simulation, underwater robotics, modeling.

1 INTRODUCTION

In the past few years, cable-driven parallel mechanism have been increasingly studied since they are low-cost, light-weight robots that have all required physical features in industry regarding the load capacity or the workspace size. The application addressed in this work involves the design and analysis of a cable-driven robot as well as the implementation of different paths to be followed by the end effector. These results have been implemented in a CAE software to simulate the multibody dynamic of the whole system and obtain useful values like the variation of the tension of the cables along a trajectory or the position, speed and acceleration of the end-effector at any time.

A desired purpose of these developments is to manage and improve the dynamic of an underwater humanoid robot, as shown in fig. 1, attached to the end effector. With this cable-robot as a testing bench, it will be possible to simulate the usual forces that would appear when the robot is submerged in the water, like the buoyancy, which implies a vertical upwards force equivalent to a reduction of the gravity force. It can be possible also the application of lateral forces in order to simulate underwater currents or the effect of the waves on the surface of the sea.

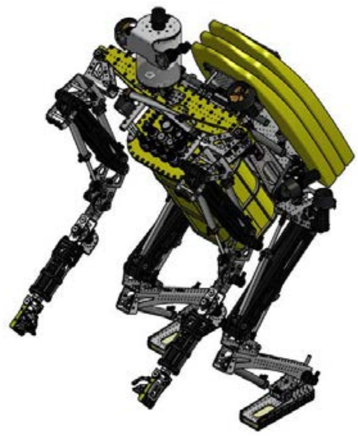

Fig 1. The underwater humanoid robot, DiverBot

The cable-driven mechanism has, as its end effector, the underwater humanoid robot. The configuration of the cables makes the load being suspended so that, the weight of the humanoid robot maintains the cables in tension. By simulating low gravity on the humanoid robot, the conditions are very similar to the underwater environment because the effect of buoyancy, so several tasks can be accomplished in this simulator device like walking on the seabed or rough terrain and pick and place or manipulation works.

This paper shows the main results obtained with analytic procedures in order to obtain the models and with the simulations in multibody dynamics software. Section 2 presents a brief state of art of the cable-driven parallel robots, section 3 describes the kinematic analysis of the robot with the obtainment of the Jacobian matrix of the system. Afterwards, section 4 shows the dynamic expressions obtained for the model. The implementation in the CAE software is presented in section 5 and finally, a summary and short conclusion can be found in section 6.

2 STATE OF THE ART

Cable-driven parallel robots (CDPR) began to be studied in the 80s as a combination of crane technology, parallel robots and conveyance by cables. The combination of these three technologies allows the development of very lightweight robots with huge workspaces like the SkyCam and FAST telescope [1]. Because the low mass and inertia of the cables, these robots are suitable for high speed applications, besides they are easy to transport, deploy, reconfigure and to maintain.

The main practical uses of cable-driven parallel robots is the carriage of heavy loads, high speed manipulation, cleaning disaster areas, rescue robots of fast deployment and to have access to remote places and dangerous environments.

In this kind of robots, the end effector is linked to the base by a determined number of active cables. While the cable length is varied, the load is led toward the desired position and orientation. In order to hold heavy loads in any direction, a redundant cable system is needed because one cable does not have any compression stiffness. This is, more cables than degrees of freedom to stabilize the load. The study of the force distribution in cables is one of the biggest challenges of the study of cable-driven robots [2] [3] as well as other fields as path planning, kinematic and interval analysis, dynamic modeling, control [4], calibration or applications and prototyping.

One important objective to these researches is the development of a Cable-driven robot based on industrial based components, leading to a robust and reliable system. These characteristics are presented in robots of IPAnema family presented by Pott and collaborators [5] and evaluated with the norm ISO 9283 [6]. Other mechanism, the CoGiRo [7], by Tecnalia France is able to handle heavy payloads having a very large workspace and designed to allow its scalability.

A reconfigurable cable-driven robot is presented by Izard and collaborators with ReelAx [8]. It has been tested in an industrial environment with different configurations, operational workspaces, different platform and cable configurations and different restrictions.

3 KINEMATIC EXPRESSIONS

Once the position of the end effector is defined with its 6 degrees of freedom (position and orientation), we want to obtain all the values in the cables. This problem can be solved with an inverse kinematic analysis of the mechanical model. In the general case, this problem is reduced to solving all the algebraic equations of a multivariable system.

The dimensions chosen for the cable robot structure to develop the path planning and force analysis, considering the load of the humanoid robot is conformed by four pillars of 10m high with a square section of 50cm side. These pillars are at the corners of a square of 10m on each side. There are eight actuators on the top of the pillars (two actuators per pillar) with their eight cables connected to them which can move the load along all the workspace. To relieve the strain on the engines, counterweights are attached at the opposite end of each cable.

The kinematic model has a central moving platform constrained by the eight cables with their length L_i variable with time and their orientation defined by unitary vectors u_i. These cables are connected to the pillars in the points B_i and connected crossed in the in points P_i in order to avoid singularities in the central position (i = 1, 2… 8)

When the platform moves, the position of its center of mass, P_G, linked to the moving coordinate system, K_P, varies in accordance the fixed coordinate system, K_B.

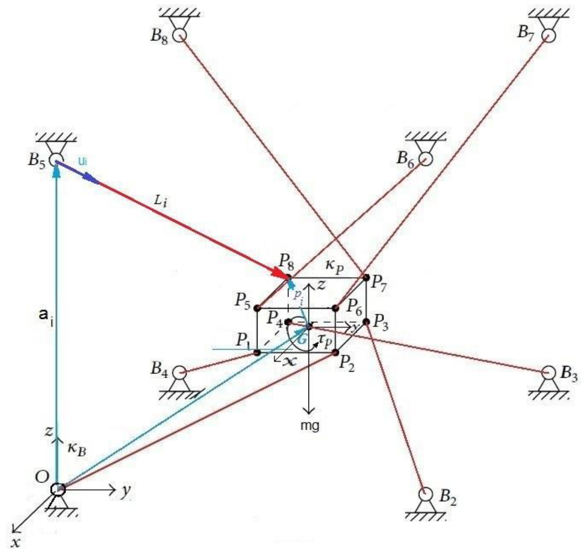

Fig 2. Kinematic scheme of the cable robot of 6 DOF

Following the kinematic notation (Fig. 2) the position of the end effector can be written as:

$$L_i = P_G - a_i + p_i \tag{1}$$

Where a_i is the position of each actuator in the fixed reference system and p_i is the position of P_i in the reference of the end effector. The Jacobian matrix can be obtained in order to know the relation between cable velocities ($\dot{L}_i$) and the velocities of the moving platform in 6 degrees of freedom ($\dot{T}_i$) by the following expression:

$$\dot{L} = J^T \dot{T} \tag{2}$$

To obtain the Jacobian matrix, (1) must be derived respect time. It is non-symmetric matrix of dimension 8x6 as it is shown in (3):

$$J^T = \begin{pmatrix} u_1 & p_1 \times u_1 \\ u_2 & p_2 \times u_2 \\ \cdots & \cdots \\ u_8 & p_8 \times u_8 \end{pmatrix} \tag{3}$$

Some considerations have to be taken when this expression is obtained: the catenary geometry of the cables is not considered, it is not considered neither the elasticity of them, so we have a mathematic model of rigid cables linked to the end effector.

4 DYNAMIC ANALYSIS

The dynamic model relates all the movements of the robot with the forces involved on it in order to make multibody simulations and obtain the dynamic values like forces and accelerations.

When all cables are tensed, Newton-Euler laws can be used in order to obtain the moving equations respect to a vector of generalized coordinates defined as $\mathbf{x} = [P_{Gx}, P_{Gy}, P_{Gz}, \alpha, \beta, \gamma]$. The vector $\theta = [\alpha, \beta, \gamma]$ defines the Euler angles (yaw, pitch and roll) of the platform and it is related with angular speed by [9]:

$$\omega = S\dot{\theta} = \begin{pmatrix} \cos(\beta)\cos(\gamma) & -sin(\gamma) & 0 \\ \cos(\beta)\sin(\gamma) & cos(\gamma) & 0 \\ -\sin(\beta) & 0 & 1 \end{pmatrix} \begin{pmatrix} \dot{\alpha} \\ \dot{\beta} \\ \dot{\gamma} \end{pmatrix} \tag{4}$$

The forces of the actuators (τ) can be obtained from the forces applied to the end effector (F) by using the Jacobian matrix:

$$F = J\tau \tag{5}$$

The expression for the movement of the platform is:

$$M(x)\ddot{x} + C(x,\dot{x})\dot{x} + G(x) = -\tilde{J}\tau \tag{6}$$

M is the mass and inertia matrix, C corresponds to Coriolis and centrifugal matrix and G is the gravity vector. The Inertia matrix, I_G, present in M related to the reference system of the platform is expressed in the fixed reference system by the similarity transformation: $S^T I_G S$. In a similar way, the Jacobian matrix has been referenced in the fixed system.

In order to have a better comprehension of the movement, a dynamic model of the electric actuators has been implemented and incorporated to the general dynamic equations.

5 SIMULATIONS

With the multibody dynamics software MSC ADAMS, the model of the cable-driven parallel robot is developed following the structure detailed in section 2. In the end effector, the underwater humanoid robot has been attached adding an additional load of 150Kg. For these simulations the cables have considered rigid links with their corresponding mass.

The inverse kinematic of the model is known so the length of all cables can be identified in any position or orientation of the moving platform. With this information, a path planning has been developed to set different trajectories for the end effector and study the behavior of the load, its varying dynamic parameters, the tension of the cables or the force needed by the actuators in any time.

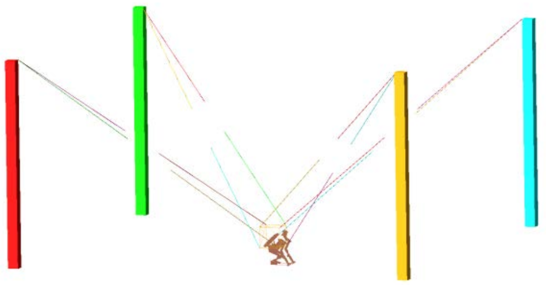

Fig 3. Simulation of the model with the humanoid robot attached

The workspace of the load is bounded not only by the geometric limits of the pillars but the maximum strain that cables can support, this is the wrench-feasible workspace (WFW) [11] and it is smaller than the workspace defined by the volume of the space between the four pillars.

In order to know the maximum forces that the cable robot has to manage during its working, the load is moved towards several singularity points situated on the frontier of the static workspace. A vertical trajectory has been defined in order to obtain the curves of tensions in the cables when the load is elevated 3 meters from the ground. Some results are presented in figure 4 and figure 5.

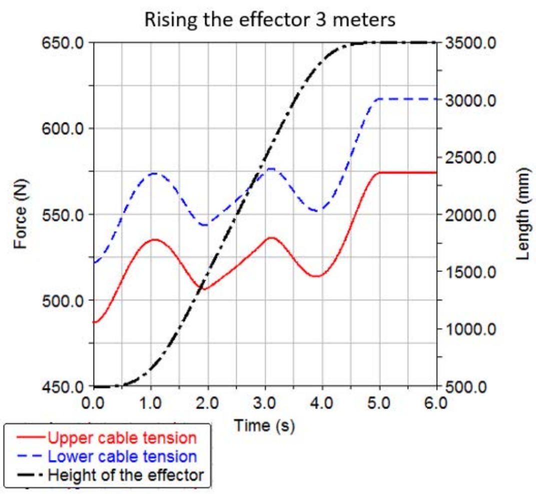

Fig 4. Tension in cables rising the load

The dynamic values and the forces in the cables under greater tension. The higher tension value corresponds to the cable linked in a lower part of the end effector due to the weight of the own cable which is more extended. The shape of the tension graph shows the dynamic effects. At the beginning of the movement, a high effort is needed from the actuators which generates high tension in the cables. After that, the load goes up with constant speed increasing the tension of the cables until the deceleration, where the tensions are lower. When the underwater robot is situated in a higher position, actuators have to generate higher force in order to hold it in that static position. Tensions of the cables, will be bounded above by 800N taken into account a situation where the robot is totally suspended. To maintain this boundary, top speed will be about 1 m/s with accelerations until 1m/s^2.

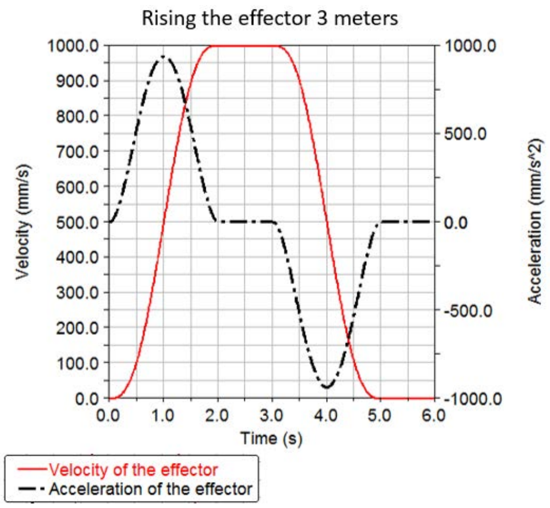

Fig 5. Velocity and acceleration of the rising effector

In figure 5, it is shown the curves of velocity and acceleration of the end effector that allow the actuators to make smooth movements able to be done by industrial motors.

Another trajectory is shown in Fig. 6. Where a rotation of 30º is applied to the end effector respect to the vertical axis. Measures are taken in the cables under greater tension.

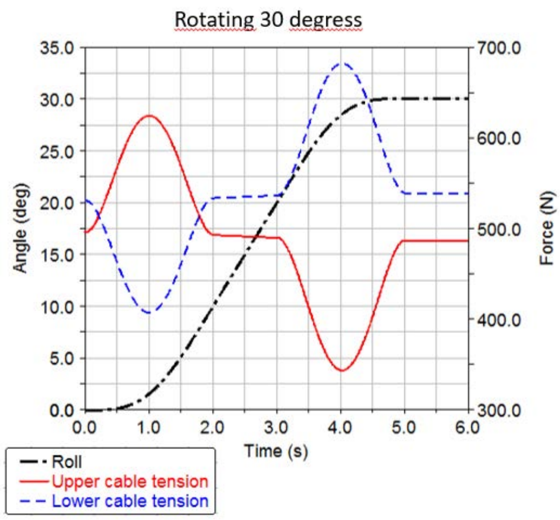

Fig 6. Tension in cables turning the load

As in the rising of the end effector, in the turning it can be seen the dynamic behavior of the cables and the load due to the acceleration and the geometrical configuration of the robot. In the same way, figure 7 shows the curves of angular velocity and angular acceleration of the effector to make feasible the movements in the motors.

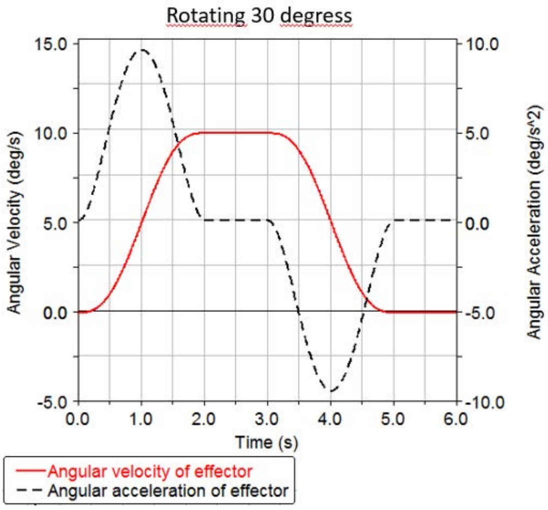

Fig 7. Velocity and acceleration of the turning effector

6 CONCLUSIONS

With the knowledge acquired with the kinematic and the dynamic model of this cable-driven parallel robot it is possible to continuing with the researching on this kind of parallel robot like the sizing of the components, the definition of the different workspaces for the end effector, path planning, control models or calibration and identification works.

Relevant knowledge has been obtained for the model of the cable-driven robot that is going to be used as a test bench of underwater humanoid robots. This information is related to kinematic values like velocities and accelerations of the load when some trajectories are defined and forces and tensions in different parts of the robot. This dynamic analysis has been done applying typical movements as displacement and turning of the load.

The next steps to follow with this investigation should be the implementation in a real prototype that enables deeper research on the behavior of 6 degrees of freedom cable robots and direct application in the simulation of low gravity and underwater environments on the previous prototypes developed by the group of investigation in CAR and other prototypes in general suitable for this kind of simulator.

Acknowledgements

The research leading to these results has received funding from the Spanish Government CICYT project Ref. DPI2014-57220-C2-1-P, DPI2013-49527-EXP, the Universidad Politécnica de Madrid project Ref. AL14-PID-15, and the RoboCity2030-III-CM project (Robótica aplicada a la mejora de la calidad de vida de los ciudadanos. Fase III; S2013/MIT-2748), funded by Programas de Actividades I+D en la Comunidad de Madrid and cofunded by Structural Funds of the EU.

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