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Cable-suspended Parallel Robot hanged on the four points and powered by four motors – reference frame

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Abstract— **In this paper a special case of the constructive aerial robot, Cable-suspended Parallel Robot - CPR model solution, has been analyzed. This paper describes geometry, kinematic model of the CPR. The complex system is made to accurately carry camera in the 3D space. The geometric relationship between the camera motion in the Cartesian coordinates and motors angular positions is defined by the Jacobian matrix, which represents the solution of the kinematic problem. The solution of the calculated matrix directly depends on the system's geometry. The final goal of this research is to ensure the accurate and highly automated guidance of the camera in 3D space with the minimal involvement of the human factor for the task generation. In order to define a dynamic model of the CPR system used for observation of moving objects in the 3D space, the kinematic model has been generated first.**

Keywords - observation; workspace; geometry; kinematics; analysis.

I. INTRODUCTION

A well-defined mathematical model of CPR is a step closer to the realization of highly automated CPR, which will lead a camera precisely in the area with as less human participation as possible. Similar systems have been analyzed and modeled which has been presented through numerous publications.

In paper [1], the design of a planar three-degree-of-freedom parallel manipulator is considered from a kinematic viewpoint. Four different design criteria are established and used to produce designs that have optimum characteristics.

The paper [2] presents the first and second order kinematic analysis of a three-degrees-of-freedom 3-RPS parallel robot mechanism. There are six parameters of position and orientation of the moving platform of this mechanism.

In paper [3] authors present algorithms that enable precise trajectory control of NIMS3D, an under constrained, three-dimensional cabled robot intended for use in actuated sensing. They begin by offering a brief system overview and then describe methods to determine the range of operation of the robot. Next, a discrete-time model of the system is resented.

In paper [4] author presents several prototypes of wire-driven parallel robots, recently designed and which use two different actuation schemes. Two of them have been completed and submitted to extensive tests. These tests have allowed determining interesting open problems related to kinematics that are presented.

The wrench-closure workspace of parallel cable-driven mechanisms is the set of poses of their mobile platform for which the cables can balance any external wrench. The determination of this workspace is an important issue in [5] since the cables can only pull and not push the mobile platform.

Parallel cable-driven Stewart-Gough platforms consist of an end-effector which is connected to the machine frame by motor driven cables. Since cables can transmit only tension forces, at least $m = n + 1$ cables are needed to tense a system having n degrees-of-freedom. This results in a kinematical redundancy and leads to a $(m – n)$-dimensional solution space for the cable force distribution presented in [6].

This paper presents the recent results from a newly designed parallel wire robot which is currently under construction. Firstly, an overview of the system architecture is given and technically relevant requirements for the realization are identified. A technique to compute and transfer an estimation of the workspace to CAD tools is presented in [7].

The paper [8] presents an auto-calibration method for over constrained cable-driven parallel robots using internal position sensors located in the motors. A calibration workflow is proposed and implemented including pose selection, measurement, and parameter adjustment.

Wire-driven parallel robot has attracted the interest of researchers since the very beginning of the study of parallel robots [9]. This type of robot has the advantage of having light mobile mass, simple linear actuators with possibly relatively large stroke and less risk of interference between the legs. On the other hand their major drawback is that wire actuator can only pull and not push.

This work was done for the suspension system in four points, i.e. to be hung on all four edges of the workspace shape parallelepiped. It is a necessary geometric condition so as to provide camera motion through the entire space. See Fig. 1 and 2.

Camera's carrier moves in space freely allowing the capture of objects from above. It gives a unique feeling to the event viewer to follow smoothly from an unusual proximity, and that is very close to the action regardless of the size of observed space. Free motion in space opens up completely new and unique perspective.

The commands for the synchronized motion of each winch are provided, with control of motion of each motor, which ultimately provides three-dimensional continuous camera motion.

The gyro sensor, which is installed in the carrier, is stabilized towards the horizon.

Video from the camera is sent to the user via a separate fiber-optic cable. See Fig. 1 and 2. Winch 5 is driven by the motor that produces the angular motion θ_5 by winding or unwinding fiber-optic cable, depending on the position of the camera carrier in the 3D space. The motor motion θ_5 is used to ensure that the fiber-optic cable is never tight or loose, or to close to the recorded surface.

It's already out of date solution and therefore the wireless communication with the camera would be better for implementation.

The camera carrier motion was controlled by the operator using a joystick. The system performance directly depended on the operators skills.

Lack of operator’s concentration or fatigue during the recording period, could have indicated a significant influence of the human factor to the whole process.

The system has different areas of applications and promising research future. Our goal is to implement this system with maximum precision.

The Section II represents a detailed description of the kinematic model for the CPR. The example of the system response is analyzed on reference level in section III. In the section IV concluding remarks are presented.

II. THE KINEMATIC MODEL OF CCPR SYSTEM

In this paper a special case of the constructive CPR model solution has been analyzed. This model is named CCPR, and it is presented in Fig.1 and Fig. 2.

The novelty of this research is a methodology for generating a mathematical model of the CCPR system.

A CCPR operates by using four ropes that are fixed at highest four corners of the observed space. See Fig.1and Fig. 2.

By rotating the angular positions of each motor, θ_1, θ_2, θ_3 and θ_4, the winches of radius R rotate directly, which will wind or unwind ropes synchronously and it will accordingly move camera carrier in the Cartesian space x, y, z.

The desired trajectory of motion of the camera is defined in the Cartesian three dimensional space, and implemented by angular positions of each motor, θ_1, θ_2, θ_3 and θ_4.

The calculation shows that there is a strong coupling between the motion of the camera in the Cartesian space x, y, z and angular positions of each motor θ_1, θ_2, θ_3, θ_4 .

This relationship is defined by the Jacobian matrix J_∇, which connects velocities of external coordinates $\dot{p} = [\dot{x} \quad \dot{y} \quad \dot{z}]^T$ and velocities of internal coordinates $\dot{\phi} = [\dot{\theta}_1 \quad \dot{\theta}_2 \quad \dot{\theta}_3 \quad \dot{\theta}_4]^T$.

For any trajectory generated in x, y, z space, it is necessary to provide very precise and mutually coordinated motion for all four motors θ_1, θ_2, θ_3, θ_4.

The dimensions of the recorded space (length d , width s, and height v) are much larger than the distances between hanging points of the rope which are holding the camera.

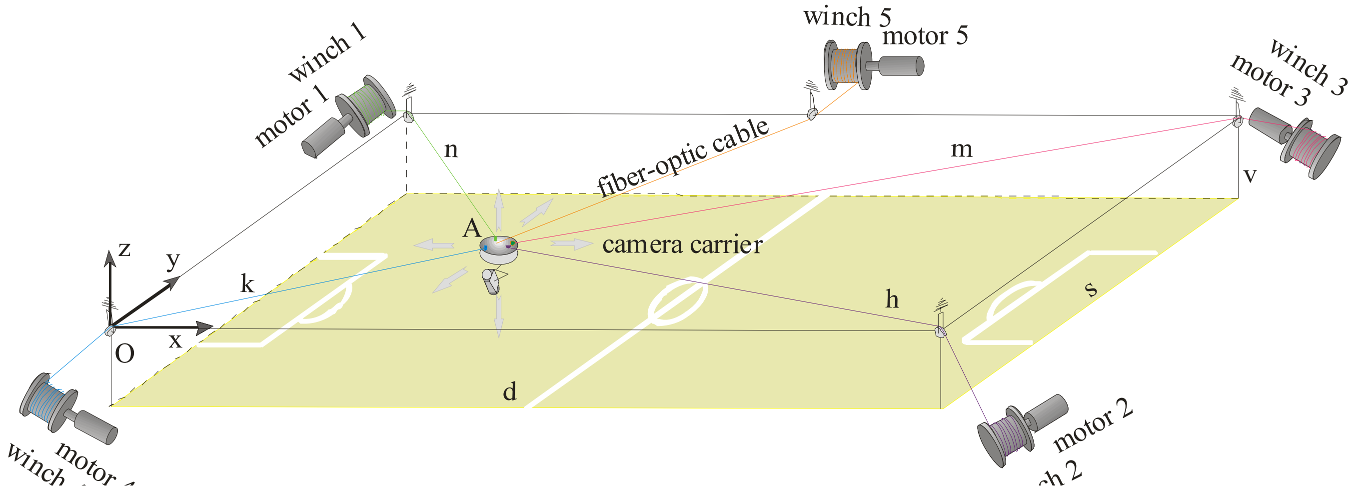


Figure 1. CCPR, in the space.

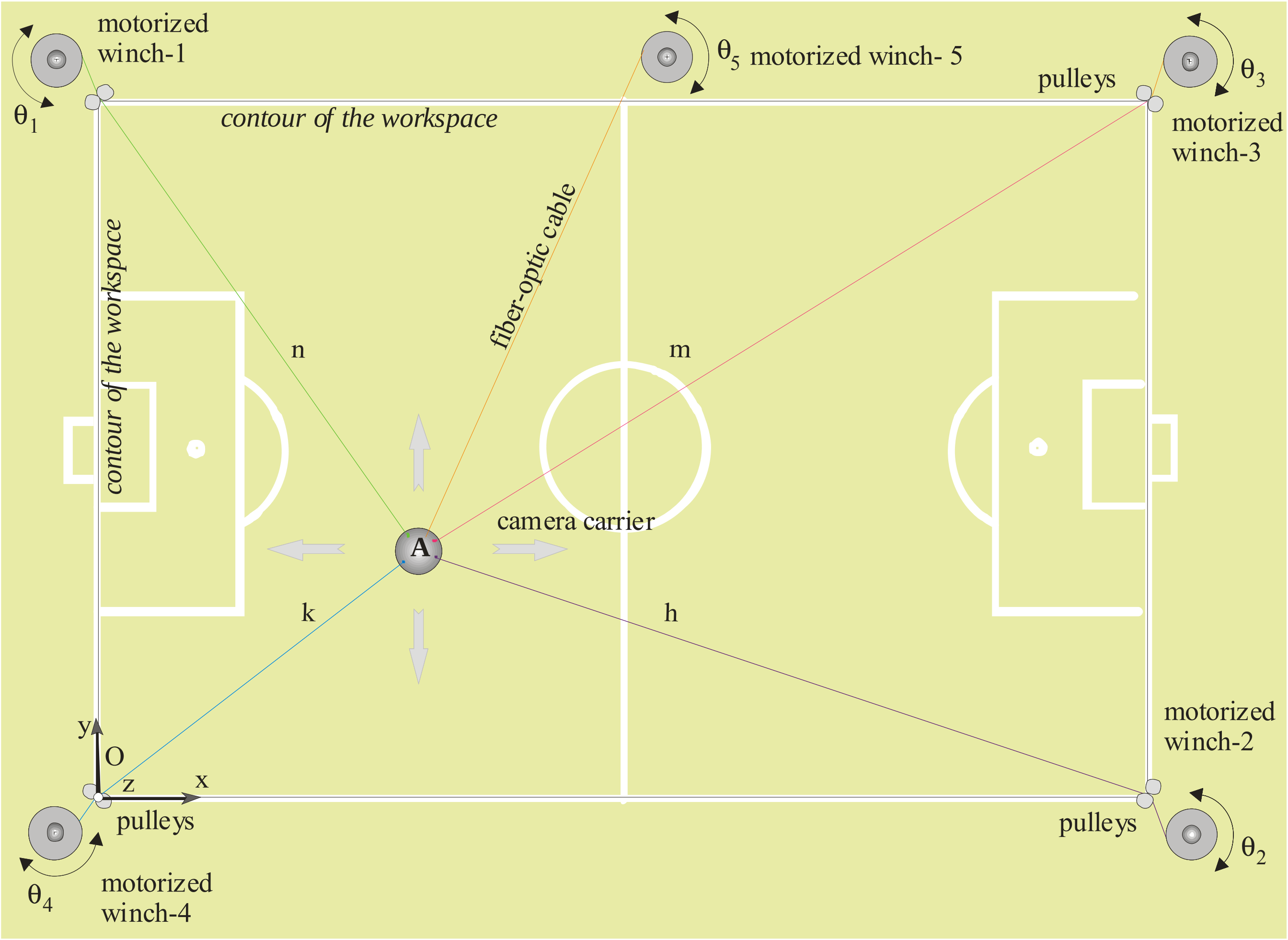


Figure 2. CCPR, top view.

This situation allows us to adopt the geometric assumption where the point A is used as a hanging point of the camera carrier. Constructively, this can be solved. Such assumption simplifies the definition of geometric relations between the camera carrier motion in the Cartesian coordinates and the coordinated motions of all motors.

For making of the CCPR system, it was necessary first to define the Jacobian matrix J_{∇}, as a connection between the velocities of the external coordinates changes $\dot{p} = [\dot{x} \quad \dot{y} \quad \dot{z}]^T$ and velocities of the internal coordinates changes $\dot{\phi} = [\dot{\theta}_1 \quad \dot{\theta}_2 \quad \dot{\theta}_3 \quad \dot{\theta}_4]^T$.

The geometrical relationship between the lengths k, h, m, n, and the Cartesian coordinates position x, y, z, of the camera carrier is defined by the following equations:

$$k = \sqrt{x^2 + y^2 + z^2}\,. \tag{1}$$

$$h = \sqrt{(d-x)^2 + y^2 + z^2}\,. \tag{2}$$

$$m = \sqrt{(d-x)^2 + (s-y)^2 + z^2}\,. \tag{3}$$

$$n = \sqrt{x^2 + (s-y)^2 + z^2}\,. \tag{4}$$

Four motors motions depend on their angular positive directions, which is produced by winding or unwinding of the rope. The relation between the change of angular motions of motors and relevant changes of ropes (k, h, m, n) in time is defined by following equations.

$$\frac{\Delta\theta_1}{\Delta t}\cdot R = \frac{\Delta n}{\Delta t}. \qquad (5)$$

$$\frac{\Delta\theta_2}{\Delta t}\cdot R = \frac{\Delta h}{\Delta t}. \qquad (6)$$

$$\frac{\Delta\theta_3}{\Delta t}\cdot R = \frac{\Delta m}{\Delta t}. \qquad (7)$$

$$\frac{\Delta\theta_4}{\Delta t}\cdot R = \frac{\Delta k}{\Delta t}. \qquad (8)$$

The winch used for winding ropes has radius R.

If the sampling time Δt is small enough then the (5)-(8) can be expressed, respectively, as:

$$\dot{\theta}_1 \cdot R = \dot{n}. \qquad (9)$$

$$\dot{\theta}_2 \cdot R = \dot{h}. \qquad (10)$$

$$\dot{\theta}_3 \cdot R = \dot{m}. \qquad (11)$$

$$\dot{\theta}_4 \cdot R = \dot{k}. \qquad (12)$$

By differentiating (1)-(4) and substituting them into the (9)-(12), the relation between velocities of external coordinates $\dot{p} = [\dot{x} \quad \dot{y} \quad \dot{z}]^T$ and velocities of internal coordinates $\dot{\phi} = [\dot{\theta}_1 \quad \dot{\theta}_2 \quad \dot{\theta}_3 \quad \dot{\theta}_4]^T$ can been obtained:

$$\dot{\phi} = J_\nabla \cdot \dot{p}. \qquad (13)$$

$$J_\nabla = \begin{bmatrix} J_{\nabla 11} & J_{\nabla 12} & J_{\nabla 13} \\ J_{\nabla 21} & J_{\nabla 22} & J_{\nabla 23} \\ J_{\nabla 31} & J_{\nabla 32} & J_{\nabla 33} \\ J_{\nabla 41} & J_{\nabla 42} & J_{\nabla 43} \end{bmatrix}. \qquad (14)$$

Equation (14) is defined only for CCPR.

If the camera motion is defined in Cartesian space, equation (14) is required in order to define the motion of all four motors.

But the reverse is not is valid. We need only three motors motion to define camera motion in Cartesian space. This indicates that the system is redundant. The fourth motion of the motor motion can always be defined later.

As previously mentioned, four-point suspension is necessary for the functioning of this system in parallelepiped space. However, the fourth motor, the fourth winch and all related equipment for the fourth drive are necessary for CCPR system.

III. PROGRAM PACKAGE ARRO

The CCPR is modeled and analyzed by the software package ARRO. The software package ARRO is used for validation of applied theoretical contributions.

It is important to notice that the software package ARRO contains few essential subroutines, for example subroutine for kinematics of CCPR system and subroutine for dynamic of CCPR system.

The CCPR model has been analyzed using the defined trajectory (only on reference level) and system parameters. The camera moves in 3D space (x^o, y^o, z^o, directions).

The position of the camera carrier with the starting point $p^o_{start} = [1.8 \quad 0.3 \quad -0.3](m)$, and the end point $p^o_{end} = [1.2 \quad 0.9 \quad -0.9](m)$ is presented in Fig. 3a), while its velocity is shown in Fig. 3b).

The shape of the velocity graph is trapezoidal with the maximum velocity $\dot{p}^o_{\max} = 0.417[m/s]$.

The dynamic analysis of the CCPR system can be done using the graphs of the motors angular positions θ^o_1, θ^o_2, θ^o_3, θ^o_4, and velocities $\dot{\theta}^o_1$, $\dot{\theta}^o_2$, $\dot{\theta}^o_3, \dot{\theta}^o_4$, in the reference level, presented in Fig. 4a) and 4b).

The motors are Heinzman SL100F type and gears are HFUC14-50-2A-GR+belt type.

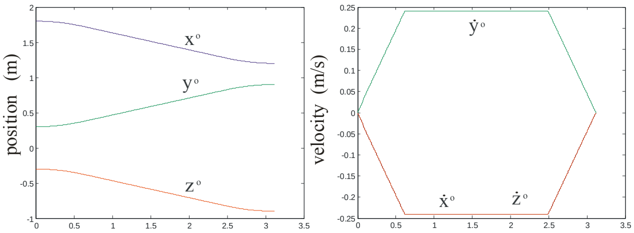
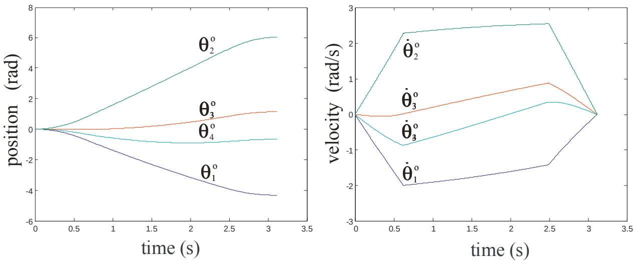


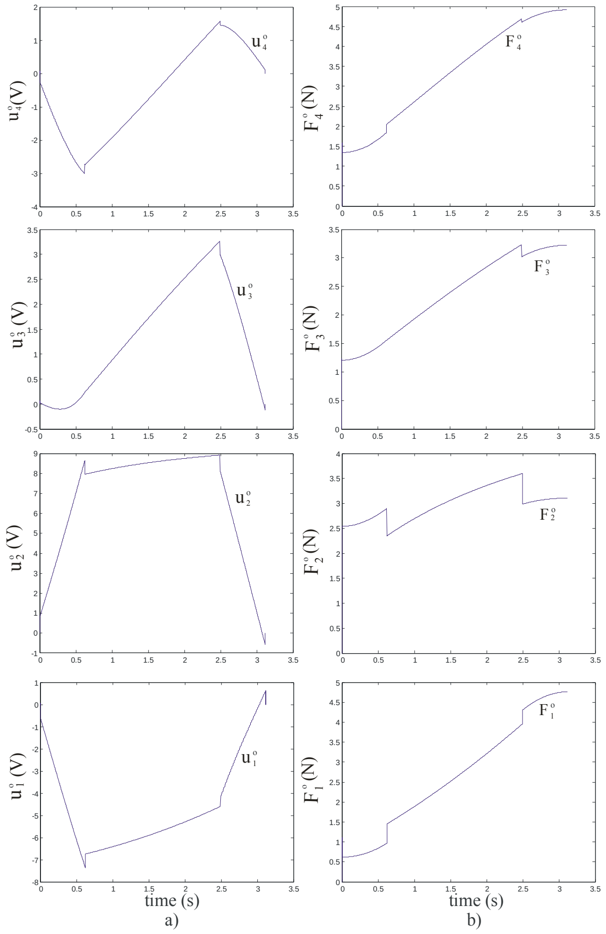
Figure 3. The reference trajectory motion of camera carrier a) position x^o, y^o, z^o, b) velocity $\dot{x}^o$, $\dot{y}^o$, $\dot{z}^o$.



a) b)

Figure 4. The reference trajectory motion of motor shaft a) position θ_1^o, θ_2^o, θ_3^o, θ_4^o, b) velocity $\dot{\theta}_1^o$, $\dot{\theta}_2^o$, $\dot{\theta}_3^o$, $\dot{\theta}_4^o$.

The level of control signals u_1^o, u_2^o, u_3^o, u_4^o, are given in Fig. 5a) and does not exceed the limits of $\pm 24(V)$ .The resultant components F_1^o, F_2^o, F_3^o, F_4^o, are presented in Fig. 5b).



a) b)

control signal (V) resultant force (N)

Figure 5. The reference trajectorya) Rresultant forces acting on the shaft of each motor F_1^o, F_2^o, F_3^o, F_4^o, b) Control signals u_1^o, u_2^o, u_3^o, u_4^o.

Figure 6. Organized work space with CPR system.

The CPR system is in a process of developing at the Mihajlo Pupin Institute. See Fig. 6 and paper [10].

IV. CONCLUSION

The main contribution of this work can be defined in the following way.

The unique general type of the CCPR kinematic model is defined. Kinematic model is generated for the system via Jacobian matrix. It shows the importance of generating the Jacobian matrix J_∇ of the CCPR system.

The relation between the camera carrier motion and the rotation angles motion of each motor has been established.

The Jacobian matrix plays an important role in the generation of the system dynamic model too.

Software package ARRO is formed and used for analysis of CCPR from various aspects. The impact of changing any parameter of the system (workspace dimensions, the reference trajectory, and a number of other characteristics) can be analyzed through this software package ARRO.

Future research intend at implementing the elastic ropes (type of nonlinear dynamic elasticity as defined in [11]-[16]) in the mathematical model of the CPR-C. In this research several different models were developed and new models will be developed for different applications. All these models will be unified according to their similarities into one reconfigurable model, using the approached presented in [17] and [18].

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