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Design and Kinematics Analysis of a Novel Cable Driven Parallel Active Joint

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ABSTRACT: Cable driven parallel mechanisms have a vast range of advantages and application due to their minimal mass and inertial effects. Normally they consist an outer fixed frame and an inner mobile platform. In this paper, a completely novel configuration of these mechanisms has been presented. In this configuration outer frame is considered as mobile platform and inner frame has been fixed. The mobile frame is attached to the fixed frame by the 8 cables and moves through the tensioning and lengthening of the cables. This new structure can be applied to the wrist mechanism, motion simulators, power balances, haptic interfaces, and etc. Since the parallel mechanism is a closed system, forward kinematics cannot be solved analytically. Several methods can be used to solve the forward kinematic of parallel mechanisms, including numerical optimization methods, in which the Newton-Raphson numerical method is used here. cables must always be in tension. Hence, a tension optimization algorithm is presented and, by solving this algorithm for all possible positions, the workspace of the mechanism is obtained. The results show that the Newton-Raphson method has an appropriate convergence rate and the tension algorithm is capable of determining the forces of the cables in the desired range.

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1- Introduction

Cable driven parallel mechanisms are a new type of robot that recently has been considered by researchers in the field of robotics. The simplicity of the structure and the low cost of this kind of robots in addition to their ability to deploy in the very large workspace has led them to an ever-increasing expansion of these mechanisms. The position of end-effector in this type of robots is controlled by pulling a number of cables. The cable can only act in tension, so ensuring the positive force of the cables at all points of the work space is an important constraint in designing the cable driven parallel mechanism. Landsberger and Sheridan [1] inspired by Stewart [2] platform provided a parallel mechanism with a rigid link to ensure positive tension and 6 cables to assign different positions to the mobile platform. Ferraresi et al. [3] offered a mechanism similar to the Landsberger mechanism, except that they replaced the rigid interfaces with three cables. Liwen et al. [4] converted the forward kinematic to an optimization problem. Given the altitude position z of end effector as function of potential energy its value is minimized. finding the right tension for cables in a way that minimizes energy consumption is also an important issue in cable driven parallel mechanisms. Gao et al. [5] inspired by the Landsberger Mechanism [1] provided a cable mechanism with a flexible member in its center to provide a secure tension on the cables. verhoven [6] and Gosselin and Grenier [7] transformed the tension problem into an optimization problem.

2- Methodology

In this cable driven parallel active joint, design is in such way that the position of fixed and moving coordinates are switched together. Final total design of structure is shown in Fig. 1.

Because of the nonlinearity and the closed loop form of the mechanism and impossibility of separating the unknown variables from the equations, forward kinematic problem

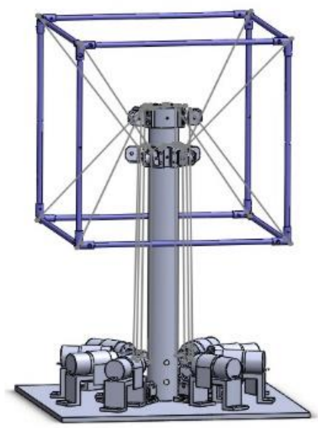

Fig. 1. The final design of the structure

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Table 1. Inverse and forward kinematics for two arbitrary positions

pose	Cable length (mm)	FK	error	iter	Pose	Cable length (mm)	FK	error	iter
	219.01					159.95			
50	181.33	52.30	2.3		0	168.73	0	0	
50	218.07	49.42	0.58		0	180.10	0	0	
50	254.31	47.88	2.12	66	0	168.15	0	0	5
0	161.71	0.27	0.27		10	180.10	9.98	0.02	
0	86.59	-1.19	1.19		1	168.15	0.94	0.06	
0	155.58	0.13	0.13		10	159.95	10.007	0.007	
	202.05					168.73			

Table 2. Calculated cable tension for 5 positions

Pose1	tension (N)	Pose2	tension (N)	Pose3	tension (N)	Pose4	tension (N)	Pose5	tension (N)
	1		5.639		1		26.776		1
0	1.953	20	13.422	0	16.558	40	91.344	1	2.806
0	1.953	20	9.173	0	11.454	0	49.840	1	2.175
0	1	20	1	0	11.827	40	1	1	1.570
0	3.494	0	12.711	20	14.234	5	53.321	1	3.798
0	2.796	0	11.644	0	13.677	0	79.676	1	3.516
0	2.796	0	9.489	20	1.033	5	22.162	1	2.729
	3.494		8.606		17.985		30.338		4.281

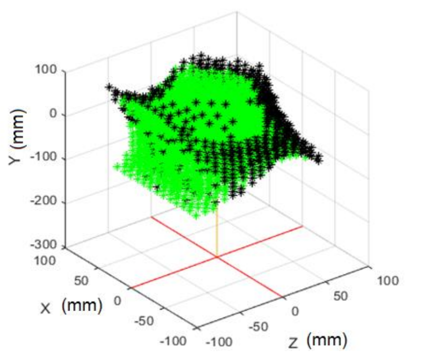

Fig. 2. Transitional workspace of mechanism

solution is not straight forward as inverse kinematic. Here, the Newton-Raphson numerical method is chosen to solve the forward kinematic by creating proper cost function as follows.

$$F_i = \left\| \left[a_i - p - Rb_i \right] \right\| - l_i \tag{1}$$

In next section, cable tension distribution analysis in static conditions is considered. The very important point in cable mechanisms is the unilateral nature of cable, which means that it can only withstand tension and will lose its performance in pushing. Therefore, the cables must always have a positive amount of force. In static conditions, the sum of external wrench and the tension of the cables will be zero. In this case that number of cables are more than degree of freedom, therefore the solution for cable tension has two particular and homogeneous part.

$$SM.\ \ (t_p + t_h) + W = 0 \tag{2}$$

In Eq. (2) the homogeneous part does not affect external wrench and can be considered as cables preload. This second part solution is resulted from kernel vectors that mapped to null space of mechanism's structure matrix SM. By an iterative optimization method this preload forces are obtained in such a way that corrects particular solution and generate all positive tension vector elements. The static workspace of the mechanism can be defined as any pose of mobile platform that a positive cable tension vector within the desired range can be found for it. For any arbitrary position, if all the elements of homogeneous solution $t_h = \mu_1 N_1 + \mu_2 N_2$ have same sign, it can be corrected by a suitable coefficient like C and adding this value to particular solution, there will be a positive cable tension force, and that position belongs to workspace of mechanism. where $\boldsymbol{N}_1$ and $\boldsymbol{N}_2$ are kernels of mechanisms structure matrix and μ_1 and μ_2 are two proper coefficients.

3- Results and Discussion

Results of Forward Kinematics (FK) solution are showing acceptable accuracy arbitrary poses. And for a continues path the calculated results by the forward kinematics solution is highly adapted to desired path. Table 1 is presenting calculated poses due to forward kinematic solution and its errors and number of iterations Also, the iterative optimization method

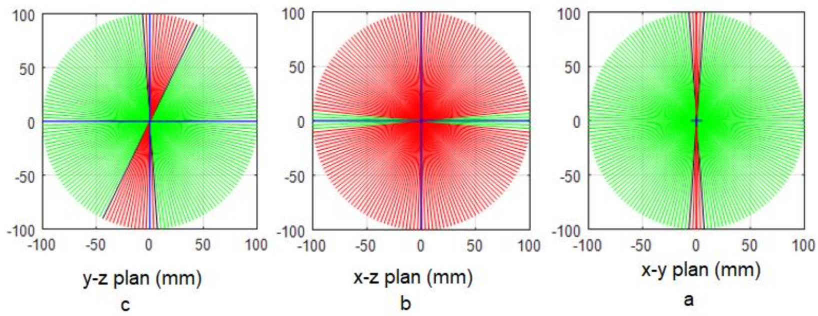

Fig. 3. Workspace in the (a) α and (b) β and (c) γ angles

for finding proper tension distribution based on null space approach of mechanism structure matrix is working properly and for different poses all positive tension vectors can be found with desired minimum values. Table 2 is showing achieved amounts for 5 arbitrary poses that all are showing positive values. Consequently, with solving the tension solution algorithm for all possible poses of end effector static workspace of mechanism has been obtained. Workspace analysis is running for 3 translational Degree Of Freedom (DOF) and 3 rotational ones. Figs. 2 and 3 are showing workspace of mechanism in translational and rotational workspaces.

4- Conclusion

In this paper, a new active joint was introduced using the cable driven parallel mechanism, which uses 8 cables to operate at 6 degrees of freedom. To obtain the position of the frame by knowing the length of the cables, the Newton-Raphson numerical method is used. The cost function analyzed based on difference between cable length equation and measured cable length. function had good results with desired accuracy. The equilibrium equations for the mobile platform were formed with 8 cable tension forces and the external wrench vector, and the relationship between the cable vector and the external wrench was determined in the form of a matrix called structure matrix. since the mechanism is redundant, the cable tension vector has a particular and a homogeneous solution. Tension solution algorithm is applied for some arbitrary points and calculated tension forces are evaluated to result the desired wrench vector. Paying attention to the minimum and maximum cable tension, all points that finding a positive tension vector is possible have been determined. It has been observed that when the fixed frame approaches to the corners of the mobile platform it goes out of workspace

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