A Novel Serial/Parallel Pole Climbing/Manipulating Robot: Design, Kinematic Analysis and Workspace Optimization with Genetic Algorithm

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Abstract-This paper introduces an optimized multi-task novel 4 DOF pole climbing/manipulating robot for construction works. The robot can travel along poles with bends, branches and step changes in cross section. It is also able to perform manipulation, repair, testing and maintenance tasks after reaching the target point on the pole. A hybrid serial/parallel mechanism, providing 2 translations and 2 rotations, have been designed as the main part of the mechanism. Optimization of this robot contains workspace optimization of the proposed mechanism and decreasing the total time of reaching the target point, has been established with genetic algorithm method**.**

Keywords: Design, Optimization, Genetic algorithm, Parallel robots, Pole climbing

1. INTRODUCTION

Climbing robots have received much attention in recent years due to their potential applications in the construction and tall building maintenance, agricultural harvesting, highways and bridge maintenance, shipyard production facilities and etc.

Earlier research in this area has focused on 6-DOF U-P-S (universal prismatic spherical) mechanisms. R Slattern has modeled and simulated a 6-DOF parallel robot with pneumatic actuators. [1]

Later R Aracil et. al. fabricated a parallel robot for autonomous climbing along tubular structures. This robot uses the gough-stewart platform as a climbing robot. Their mechanism also uses 6 cylinders as the grippers (3 cylinders for each gripper) using a total of 12 actuators not counting the actuators needed for the manipulator arm. The robot is able to climb along structures such as trees which are not straight structure [2].

But in recent years some industrial applications such as machine tools has resulted in more attention to parallel mechanisms with less than 6 degrees of freedom. Most of the research in recent years has focused on 3-DOF mechanisms [4, 7, and 8].

While in most applications 3-DOF may be insufficient, complexities and the heavy weight of the 6-DOF mechanisms is also a forbidding factor. As a matter of fact for most pick and place applications at least four-DOF is required (3 translations and 1 rotation to orient the object in its final location) [3]. Also traveling along a pole or tubular structures with bends and branches requires four degrees of freedom (2 translations and 2 rotations along and perpendicular to the tubular axis). These same degrees of freedom are also essential for most manipulation and repair tasks required in the pole climbing applications. Specific examples are fruit harvesting and street/ highway light bulb change operations.

As most of structures made by human being are straight structures with bends and branches, there was a need for less complicated robot for climbing and manipulating along these kinds of structures.

To the best knowledge of the authors, there is no 4-DOF mechanism providing 2 translational and 2 rotational degrees of freedom suitable for such operations. The mechanism proposed in this paper takes advantage of a parallel/serial mechanism providing 2 degrees of translation and 2 degrees of rotation along the desired axes. The mechanism also takes advantage of a novel gripper design, making it suitable for safe pole climbing operations.

Although tasks accomplished by the proposed mechanism, can also be achieved using a 6-DOF Stewart mechanism [1,2], but the resulting mechanism becomes too heavy and complicated for most practical applications. Furthermore using a total of 2 actuators for grippers, the whole mechanism has only 6 actuators.

2. THE ROBOT DESIGN

The proposed pole climbing robot consists of three main parts (Figure1) which are: the 3-DOF planar parallel mechanism, the serial z axis rotating mechanism and the grippers.

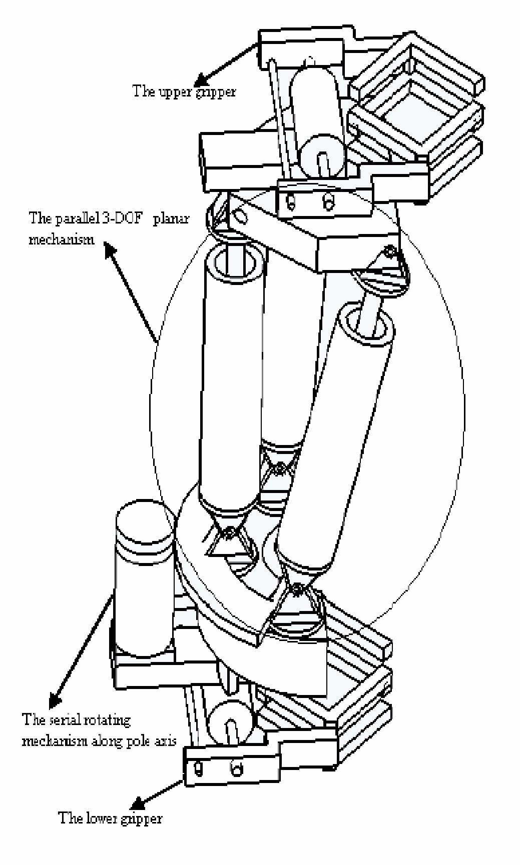

Figure 1. The pole climbing robot model

Combining the 3-DOF planar parallel mechanism with a rotating mechanism around the pole axis provides two rotations and two translations, which is necessary to achieve the design objectives. Furthermore, the linear cylinders used in the parallel manipulator are arranged to encircle the pole and thus reduce the grasp moments on the gripper.

One of the grippers is attached to manipulator, and the other one is attached to the base of the rotating platform. As a result, the grippers have four DOF with respect to each other, allowing for movements along the poles with different cross sections and geometric configurations.

Figure 1 shows the robot model passing the bend section. Using this model we were able to examine the robot possible movements and the robot configurations in order to select the best mechanism and design the mechanical parts. A detail concept of the design and necessarily of these 4 dof has been presented in another paper from the authors [3].

3.1. *The 3-DOF planar parallel 3-RPR manipulator*

A general planar three-legged platform with three-degree-of freedom consists of a moving platform connected to a fixed base by three simple kinematics chains. Each chain is consists of three independent one DOF joints, one of which is active [4].

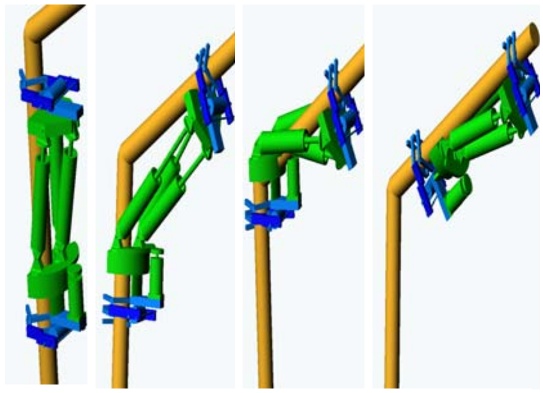

Figure 2. The robot model passing the bend

Since the displacements of the platform are confined to the plane, only R- and P-pairs are used. The possible combinations are therefore: RRR, RPR, RRP, RPP, PRR, PPR, PRP, and PPP. The last combination is excluded because no combination of pure planar translations can produce rotation of the moving platform. Thus, there are seven possible combinations of kinematics chains. These chains can be combined in either symmetric1 or asymmetric groups of three. The active joint in a leg is identified with underline. Since any of three joints, in any of the seven kinematics chain listed, can be actuated here are twenty-one possible leg architectures. On the basis of the following rule which is presented by Merlet [5]: "The chain obtained when locking the actuated joint is not of the PP type" the number of possible leg architectures reduces to eighteen, which are listed in Table 1. Hayes et al. [6] showed that there are 1653 distinct general planar three-legged platforms with three DOF. By neglecting the asymmetric manipulators and eliminating architectures in which the active joint is on the moving platform (these architectures have less rigidity than others), only 12 architectures remain. Since we want to use this mechanism in a hybrid pole climbing robot, the weight of this mechanism is a critical and decisive factor. Mechanisms having two prismatic joints are heavier than others due to the weight of the associated linear guides. The mechanisms with active revolute joints are also heavy because of their transmission systems. As a result, the PRR and RPR architectures are the only viable choice. Finally to minimize the manufacturing costs, the RPR architecture is selected as the more optimal mechanism for this application.

3. KINEMATIC ANALYSIS

The parallel part of the robot hybrid mechanism is a planar parallel robot with 3-RPR chain. The planar parallel 3-RPR manipulator consists of a fixed base plate, a moving platform and three RPR chains that connect these plates. The manipulator with the

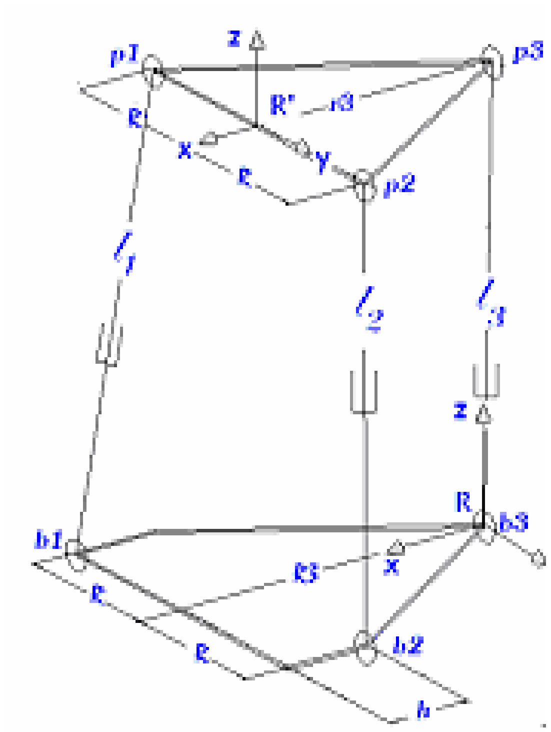

Figure 3. The geometric parameters of the manipulator

relevant geometric parameters is shown in figure 3. Combining the 3-DOF planar parallel mechanism with a rotating mechanism around the pole axis provides two rotations and two translations, which is necessary to achieve the design objectives. The following equations are the result of inverse kinematic analysis of the proposed 3-DOF mechanism.

$$l_1 = \pm\sqrt{(x-R_3)^2 + z^2} \tag{1}$$

$$l_2 = \pm\sqrt{(x-R_3+h)^2 + z^2} \tag{2}$$

$$l_3 = \pm\sqrt{(x-r_3\cos\theta)^2 + (z+r_3\sin\theta)^2} \tag{3}$$

Since the negative solutions for haven't any geometric interpretation, there are only one inverse kinematics solutions for a given pose of the parallel manipulator (i.e. the positive solutions of (1), (2), (3)).
Using inverse kinematic equations ((1), (2) and (3)), one can obtain following equations as forward kinematic equation of the 3-RPR mechanism.

$$x = \frac{1}{2}\left(\frac{l_2^2 - l_1^2}{h} - h\right) + R_3 \tag{4}$$

$$z_{1,2} = \pm\sqrt{l_1^2 - \frac{1}{4}\left(\frac{l_2^2 - l_1^2}{h} - h\right)^2} \tag{5}$$

$$tg\,\theta/2 = \frac{-A \pm \sqrt{A^2 + B^2 - C^2}}{B - C} \tag{6}$$

In which

$$A = 2r_3\sqrt{l_1^2 - \frac{1}{4}\left(\frac{l_2^2 - l_1^2}{h} - h\right)^2},$$

$$B = r_3\left(\frac{l_2^2 - l_1^2}{h} + 2R_3 - h\right)$$

$$C = l_3^2 - r_3^2 + \frac{1}{4}\left(\frac{l_2^2 - l_1^2}{h} - h\right)^2 - l_1^2 - \frac{1}{4}\left(\frac{l_2^2 - l_1^2}{h} + 2R_3 - h\right)^2$$

Which result in two solutions for forward kinematic equations.

3.1 VELOCITY EQUATION AND JACOBIAN MATRICES

Equations (1), (2) and (3) can be differentiated with respect to time to obtain the velocity equations, which leads to :

$$\dot{x}(x-R_3) + \dot{z}z = l_1\dot{l}_1 \tag{7}$$

$$\dot{x}(x-R_3+h) + \dot{z}z = l_2\dot{l}_2 \tag{8}$$

$$\dot{x}(x-r_3\cos\theta) + \dot{z}(z+r_3\sin\theta) + \dot{\theta}[r_3(x\sin\theta + z\cos\theta)] = l_3\dot{l}_3 \tag{9}$$

Rearranging (7)-(9) leads to an equation of the form:

$$\mathbf{A}\dot{\mathbf{x}} = \mathbf{B}\dot{\boldsymbol{\theta}} \tag{10}$$

And the vector of the input velocities, is defined as

$$\dot{\boldsymbol{\theta}} = \left(\dot{l}_1\ \dot{l}_2\ \dot{l}_3\right)^T \tag{11}$$

And matrices ***A*** and ***B***, respectively, the forward and inverse Jacobian matrices for the manipulator are expressed as:

$$\mathbf{A} = \begin{bmatrix} x-R_3 & z & 0 \\ x-R_3+h & z & 0 \\ x-r_3\cos\theta & z+r_3\sin\theta & r_3(x\sin\theta+z\cos\theta) \end{bmatrix} \tag{12}$$

And

$$\mathbf{B} = \begin{bmatrix} l_1 & 0 & 0 \\ 0 & l_2 & 0 \\ 0 & 0 & l_3 \end{bmatrix} \tag{13}$$

Assuming ***B*** is nonsingular, the Jacobian matrix for the parallel manipulator can be written as

$$\mathbf{J} = \mathbf{B}^{-1}\mathbf{A} \tag{14}$$

Full kinematic analysis of the 4-DOF hybrid mechanism has been presented in another paper from the authors [9].

4. OPTIMIZATION

Even though the most significant optimization in robotic applications is designing the robot with minimum required DOFs, but workspace and path planning optimization can result in using smaller actuators and lower weight of the whole system. As the robot has the ability of doing different construction works with a little change in design, the optimization process should be done with respect to the application. As the workspace area of the robot does not have a close form equation, the best way of optimization of the workspace is using the global search approaches. One of the most efficient methods of global search is genetic algorithm method. Using this method, one can find the best design parameters of the robot, which leads to the optimum system.

Using kinematic equations, some design parameters of the proposed mechanism has been optimized with genetic algorithm method. These parameters include: Lmin, the length of the cylinders at the zero stroke, Lmax, the length of the cylinders at the maximum stroke, R3, r3 and h as it has been shown in figure 3.So the parameters vector will be:

K= [Lmin,Lmax,R3,r3,h].For all objective functions, following parameters have been used for GA algorithm:

Number of generations: 100
Number of individuals in a population: 50
Crossover probability: 0.85
Mutation probability: 0.05

4.1. Genetic algorithm

Genetic algorithms, as powerful and broadly applicable stochastic search and optimization techniques, are perhaps the most widely known types of evolutionary computation methods today. As a matter of fact, genetic algorithm is an optimized global search method.

Genetic operators such as selection, crossover, and mutation are applied to individuals of a population for many generations as the method converges towards the desired solution. A genetic algorithm has the following structure:

Create an initial population.
Repeat the following steps:
Evaluate the fitness of each individual based on an objective function.
Determine the frequency of reproduction of the individuals.
If a probability of crossover is attained, perform a crossover operation (combination of two parents to produce two offspring).
If a probability of mutation is attained, perform a mutation operation (change one of the genes of the chromosome of an individual).
Continue until the maximum number of generations has been attained [10].

Every individual is a possible solution to the problem to be solved. Following above steps, each generation individuals have better fitness value than the previous generations.

4.2 Workspace optimization

The aim of workspace optimization in this problem is not to maximize the reachable workspace of the manipulator. As mentioned earlier optimization process should be done with respect to the application of the robot. Here maximizing the movement of the robot along x-axis is a good objective function. This is due to need for long movements along x direction, for the time that the robot has been received to the target point and need to manipulate along the radial direction of the pole. For this aim, we consider objfun1 in a manner that the program maximizes possible movement along x-direction in constant orientation of the manipulator. This could be done for a specific θ, in which the manipulability of robot along x-axis is important. Here θ depends on the application of the robot. So we have objfun 1=δx

4.2 DEXTERITY OPTIMIZATION:

In some applications optimization of kinematic properties is an important factor. The global dexterity index (GDI) of a manipulator is a measure of its precision over its actual workspace [10].

Gosselin and Angeles defined and computed the GDI based on condition number of the Jacobian matrices [11].One can obtain GDI factor using following equations:

It is well known that the Jacobian matrix is obtained with following equation:

$$J = -B^{-1}A \tag{15}$$

In which A and B is obtained from kinematic equation:

$$A\dot{x} + B\dot{\Psi} = 0 \tag{16}$$

The condition number of the Jacobian matrix J is:

$$k = \|J\|\|J^{-1}\| \tag{17}$$

In which

$$\|J\| = [tr(JWJ^T)]^{1/2} \quad (18)$$

Where W=w**1,** w=1/n, n is the dimension the matrix, **1** is the identity matrix, and "tr" indicates the trace of the matrix.

k may has a value from 1 to ∞.So using ŋ=1/k is a good solution to bound the k value. So ŋ has a value between 0 and 1. ŋ=1 shows a perfect isotropic dexterity and ŋ=0 shows a singular condition. ŋ is a local property of the manipulator and should be integrated over the entire manipulator's workspace in order to get the GDI[10].

$$GDI=A/B \quad (19)$$

Where:

$$A = \int_\theta \int_y \int_x (1/k) dx dy d\theta \quad (20)$$

And B is the area of workspace.
If we take constant orientation workspace, the formula will be:

$$A = \int_y \int_x (1/k) dx dy \quad (21)$$

The mechanism with an average dexterity of about 1 has a good dexterity. So objfun2 = GDI.

4.3 Path planning optimization

As mentioned earlier, the robot has the ability of traveling along poles with bends and branches. For the robot, it takes several steps to travel along bends.
Number of these steps depends on the bend angle and the robot workspace. This means that the robot workspace should be optimized due to bends angle of the structure in a manner that the robot can pass the bends with minimum number of steps. For this purpose we should maximize Δz and Δx of the workspace in constant orientation of "θ =180- α" in a way that the equation Δz=tag θ*Δx is satisfied.
In which α is the bend angle and θ is the manipulator angle. Δz is the maximum movement in z direction and Δx is the maximum movement along x direction. The above equation should be satisfied because traveling along bend section of the pole needs a movement of Δz and Δx in which Δz=tag θ*Δx. With larger amount of Δz and Δx in bend angle, the robot can overtake the bend section of the pole with lower number of steps (figures 2&3).So the aim of objfun3 is minimizing the number of steps when the robot is overtaking the bend section of the pole and we consider objfun3=δx in a specific θ with respect to equation: Δz=tag θ*Δx.

5. RESULTS

Above analysis has been done for a typical application of the pole climbing robot. One may use the robot for highways light bulb changing. For this application path planning optimization and optimization of maximum movement along x-direction is considered. Also dexterity optimization has been done for better dynamic properties.
The results have been obtained for a set of typical dimensions. We considered below constraints:

100 mm< Lmin < 300 mm
70 mm< R3 < 400 mm
70 mm< r3 < 400 mm
5 mm< h < R3
1 < α < 5
In which α is Lmax/Lmin.
Then optimization for objfun1, objfun2 and objfun3 has been accomplished and K= [Lmin, Lmax, R3, r3, h] for each objfun has been obtained. (Dimensions are in mm).

The results for objfun1 are:

K= [300 mm, 494.8 mm, 130 mm, 400 mm, 83.3 mm].
In this case dexterity after 10 generation was: 0.2683 and after 100 generation was: 0.2872.

The results for objfun2 are:
K= [300 mm, 1200 mm, 310 mm, 261 mm, 302 mm].
In this case δx after 10 generation was: 2236 mm and after 100 generation was: 2351 mm.
As it was mentioned before, objfun3=δx in a specific θ with respect to equation: Δz=tag θ*Δx.
The GA optimization for objfun3 was performed with bend angle of π/4. It means that θ=π/4.

The results for objfun3 are:
K= [300 mm, 1200mm, 150 mm, 72.7 mm, 140.6 mm].
In this case δx after 10 generation was: 558.6 mm and after 100 generation was: 609.6 mm.
Also objfun4 has been defined as a linear combination of objfun1 and objfun2 and objfun3 it means that:

objfun4= $\alpha_1 w_1$objfun1+ $\alpha_2 w_2$objfun2+ $\alpha_3 w_3$objfun3.

In which w1, w2 and w3 are weight factors and α_1, α_2, and α_3 are factors for mapping all objective functions into one range.
In this example using α_1= 8000, α_2=1 and α_3 =4 and weight factors of w_1=1, w_2=4 and w_3=1 following results has been obtained:

K= [300 mm, 973.2 mm, 190.8 mm, 240.6 mm, 209.6 mm].

6. CONCLUSION

In this paper a solution to autonomous robot pole climbing problem is presented. Some of the advantages of the proposed robotic mechanism over similar fully parallel 6-DOF robots are smaller number of actuators, lighter weight and a less complex mechanism. Also, a unique multi-fingered gripper with the ability to adapt to various poles cross sections and dimensions with only a single actuator is presented. Finally the optimization of the 4-Dof mechanism for a typical application has been studied. Future works include prototyping and control of the proposed pole climbing robot.

REFRENCES

[1] R Salataren, R Aracil, J M Sabater, O Reinoso, and L M Jimenez, "modeling, simulation and conception of parallel climbing robots for construction and service," 2nd international conference on climbing and walking robots, pp.253-265.

[2] R. Aracil, R. Saltarén, O. Reinoso, "Parallel robots for autonomous climbing along tubular structures," Robotics and Autonomous Systems 42 (2003) pp 125–134, November 2002.

[3] M.Tavakoli, G.R.Vosoughi, S.Bagheri, M.R.Zakerzadeh, "Design, Modeling and Kinematics Analysis of a Novel Serial/Parallel Pole Climbing and Manipulating Robot, 7th Biennial ASME Engineering Systems Design and Analysis, Manchester, UK July 19-22, 2004"

[4] C.M. Gosselin, J.Sefrioui, M.J.Richard,"Polynominal solution to the direct Kinematic problem of planar three degree of-freedom parallel manipulators," Mechanism and Machines Theory , vol. 27 pp. 107-119,1992.

[5] J.P. Merlet, "direct kinematics of planar parallel manipulators," proceedings of IEEE international conference on robotics and automation, Minnesota, vol.4, pp.3744-3749, April 1996.

[6] M.J.D Hayes, M. Hysty, P.J. Zsombor-Murray,"Solving the forward kinematics of a planar three-legged platform with holonomic higher pairs, ASME J.Mech, vol.121, p. 212-219, 1999.

[7] Gosselin C.M. et al., "On the direct kinematics of general spherical 3-degree-of-freedom parallel manipulators," ASME Biennial Mechanisms Conference Proc., Scottsdale, Arizona, pp.7-11.

[8] Tsai L.W., "Kinematics of a three-dof platform with three extensible limbs," In Recent Advances in Robot Kinematics, pp. 401-410, Kluwer, 1996.

[9] Mohammad paper

[10] Marise Gallant and Roger Boudreau, "The Synthesis of Planar Parallel Manipulators with Prismatic Joints for an Optimal, Singularity-Free Workspace," Journal of Robotic Systems 19(1), 13–24 (2002)

[11] C. Gosselin and J.Angeles,"A global performance index for kinematic optimization of robotic manipulators, Journal of Mech Design 113(1991), 220-226