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Forward Kinematics Resolution of A Deployable Cable Robot

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***Abstract*—In this paper, forward kinematic derivation of a deployable suspended cable robot (DSCR) is investigated. Since the positions of the cable attachment points in this robot are not accurately available, the forward kinematics of the robot would not provide an accurate estimate for the end effector position. This paper proposes two methods to improve the accuracy of the forward kinematic solutions. First, an analysis on parameter sensitivity is presented and effective parameters are extracted. Then, based on these parameters and by using the redundant equations of the DSCR, a new set of equations for forward kinematic analysis are derived. The second method proposed in this paper is based on a geometrical analysis of kinematic uncertainty bounds. Finally, using the simulation results the effectiveness of the proposed methods is verified by illustrating the significant accuracy improvement in the obtained end effector positions.**

I. Introduction

In a parallel cable driven robot, the end effector is connected to the fixed frame by several cables. The large work space, great speed and high acceleration capabilities alongside with the simple mechanical structure are among the advantages of this robots. Over the last decade, many researches have studied in the field of cable robots; however, still their applications are very limited compared to that of conventional robots. Introducing a simple and deployable design for the cable driven robots may significantly influence their wider use in industrial applications. This causes the installation of the robot not to be limited to a fixed and well calibrated structure and a highly accurate calibration process is no longer required. By this means the robot may be easily moved from one place to another. Such designs are considered to have desirable deployable characteristics and faster installation process, which makes them more applicable.

The idea of rapidly deployable cable driven robots was proposed in [1]–[3] for the case of help and rescue applications. This design is very suitable as a rescue robot in natural catastrophe such as earthquakes [4]. In fact, the large workspace, the capability for carrying heavy loads and the possibility of fast installation make this class of robots suitable for many rescue missions. Agriculture industries and automated farm lands may also be named as another application which is readily accommodated by such robots [1].

Nowadays, cable driven robots called Spidercams are commonly used for imaging large sport stadiums. ARAS-CAM robot is also a DSCR which is designed for imaging purposes as shown in Figure 1. The main difference between this cable driven robots and the conventional ones is the simplicity of the installation which significantly reduces the cost of using them in the field of imaging.

Fig. 1. Prototype of a deployable suspended cable driven robot called ARAS-CAM.

In deployable cable driven robots, kinematic dimensions and parameters of the robot is not accurately measured, and this uncertainty in the measurement will affect many parameters of the robot model. This introduces many challenges in terms of controller design, meeting the required performance [2]. The first issue to be considered is to solve the forward kinematics of the robot. By sensitivity analysis of the kinematic equations one may find the influence of the parameters in the calibration process [5]. By recognizing important and effective parame-

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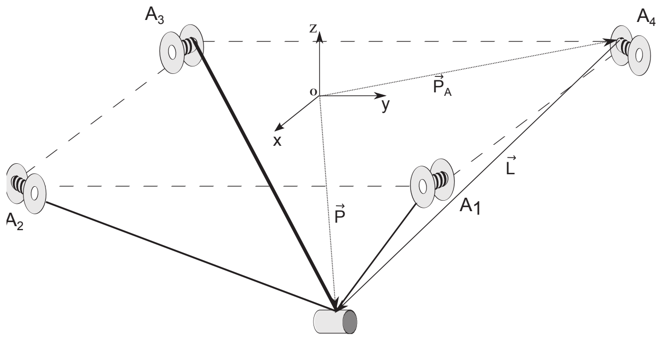

Fig. 2. Kinematic schematics of deployable suspended cable robot.

ters, the process of installation and calibration of the robot may be significantly improved [6].

Forward kinematic solution for a parallel robot is a challenging problem [7]–[9]. In deployable cable driven parallel robots for which the kinematic parameters are not known accurately, solving the forward kinematic problem is more challenging. In this paper, by using redundancy of the actuators and considering parameter sensitivity of the robot, a more accurate solution for the DSCR forward kinematic problem is represented. For this means and in the next section, ARAS DSCR kinematic analysis is investigated and inverse and forward kinematic relations are derived. Then, parameter sensitivity of the forward kinematic relations is addressed and sensitive parameters are reported. In section IV, based on the sensitive parameters, modified forward kinematic relations based on least squares method and geometrical algorithm are derived. Finally, by presenting simulation results of the ARAS DSCR, the efficiency of modified kinematic relations are verified.

II. Kinematic Modeling

This section is devoted to deriving the kinematic relations of the DSCR. Firstly, the inverse kinematic relations of a cable robot with four actuators are derived. Then the Jacobian matrix of the robot is calculated. Fig. 2 illustrates a DSCR with four cables. The loop closure relationship for the robot as shown in Fig. 2 is given as follows.

$$\overrightarrow{L_i} = \overrightarrow{P} - \overrightarrow{P_{A_i}}, \quad i = 1, 2, \ldots, 4. \tag{1}$$

In what follows, inverse and forward kinematic relations are derived.

A. Inverse Kinematic Solution

Rewrite the loop closure relation algebraically as follows:

$$(l_i)^2 = (P - P_{A_i})^T (P - P_{A_i}) \tag{2}$$

where l_i is the length of i'th cable. One may rewrite this equation componentwise as:

$$l_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} \tag{3}$$

in which, the x, y, z and x_i, y_i, z_i denote the position of the end-effector and the attachment points of the i'th cable, respectively.

B. Forward Kinematic Solution

In order to solve the forward kinematic of the ARAS–DSCR, from the set of four equations of (3) for $i = 1, 2, \ldots, 4$, one may select three of them, and directly calculate the position of the end-effector. If equations related only to the cable one to three are selected, DSCR forward kinematic solution may be written as follows:

$$\begin{aligned} x &= \frac{1}{2a}(l_2^2 - l_3^2), \;\; y = \frac{1}{2b}(l_1^2 - l_2^2), \\ z &= h \pm \sqrt{l_1^2 - (x + \frac{a}{2}) - (y + \frac{b}{2})} \end{aligned} \tag{4}$$

where z has two solutions and according to the work space specifications of the suspended robot, the negative solution is correct.

It should be noted that in the above relation the loop closure equation of the fourth cable is not used. Regardless of the length of the forth cable, by using the first three equations the end-effector position may be found. Furthermore, based on equation 4, for the forward kinematics to be solved, the exact values of parameters a and b are to be known. In this paper, this approach for calculating the forward kinematics is called the conventional method. However, for the case of DSCR, the exact values of kinematic parameters are not available, and use of this approach is not recommended. Thus, sensitivity of the robot to each geometric parameters is evaluated and analyzed next to be used in the proposed algorithm.

III. Sensitivity Analysis of DSCRs

As mentioned before, DSCR suffers from the presence of kinematic uncertainty. In this section, the inaccuracy due to the uncertain installation process of the robot is investigated for the robot in hand similar to what is presented in [5], [10], and the most effective parameters are identified. For this reason, at the first step, the DSCR kinematic closed loop equation is rewritten as

$$f_i(x, y, z, x_i, y_i, z_i, l_i) = 0, \qquad i = 1, \cdots, 4. \tag{5}$$

Through differentiation of the above relation with respect to each one of its arguments one may write:

$$\begin{aligned} &\frac{\partial f_i}{\partial x} dx + \frac{\partial f_i}{\partial y} dy + \frac{\partial f_i}{\partial z} dz + \frac{\partial f_i}{\partial x_i} dx_i + \cdots \\ &+ \frac{\partial f_i}{\partial y_i} dy_i + \frac{\partial f_i}{\partial z_i} dz_i + \frac{\partial f_i}{\partial l_i} dl_i = 0. \end{aligned} \tag{6}$$

Rewriting the above relations in the matrix form one may write:

$$\Delta x = J_x^{-1} J_p \Delta p = J \Delta p \tag{7}$$

where

$$
J_x = \begin{bmatrix} x-x_1 & y-y_1 & z-z_1 \\ x-x_2 & y-y_2 & z-z_2 \\ x-x_3 & y-y_3 & z-z_3 \\ x-x_4 & y-y_4 & z-z_4 \end{bmatrix},
$$

$$
J_p = \begin{bmatrix} v_1 & 0_{1\times4} & 0_{1\times4} & 0_{1\times4} \\ 0_{1\times4} & v_2 & 0_{1\times4} & 0_{1\times4} \\ 0_{1\times4} & 0_{1\times4} & v_3 & 0_{1\times4} \\ 0_{1\times4} & 0_{1\times4} & 0_{1\times4} & v_4 \end{bmatrix}_{4\times16} \tag{8}
$$

in which,

$$
v_i = \begin{bmatrix} x-x_i, & y-y_i, & z-z_i, & l_i \end{bmatrix},
$$
$$
0_{1\times4} = \begin{bmatrix} 0, & 0, & 0, & 0 \end{bmatrix}.
$$

In this representation, Δx denotes the robots error in the work space and Δp denotes kinematic parameter error which is expressed as follows:

$$
\Delta x = \begin{bmatrix} dx & dy & dz \end{bmatrix}^T,
$$
$$
\Delta p = \begin{bmatrix} dx_1 & dy_1 & dz_1 & dl_1 & \cdots & dx_4 & dy_4 & dz_4 & dl_4 \end{bmatrix}^T \tag{9}
$$

By this means, kinematic parameter error is mapped by Jacobian matrix J to the error of end-effector. It should be noted that this Jacobian matrix is different from the conventional Jacobian matrix, by which the relation between the speeds of the joints and the speed of the end-effector is found. Analyzing this Jacobian matrix would reveal effective information about the sensitivity value of the robot movement to the geometric parameters [11]. By studying this Jacobian matrix, precious information about the value of end-effector position error and the mechanism by which the geometric uncertainties is being influenced is obtained. Therefore, if the error of a parameter is highly effective in the value of the robot motion error, special attention must be paid to the accuracy of the construction and assembly of the robot with respect to that parameter. Especially in deployable cable driven robot for which the geometric parameters repeatedly change, the parameters with high sensitivity have to be well calibrated. In what follows some criteria are proposed for better investigation of the Jacobian matrix.

A. *Kinematic Sensitivity to Geometrical Parameter*

In order to investigate the proposed Jacobian matrix, the index of kinematic sensitivity of the robot to geometric parameters is defined. It is proposed to use the upper bound of the end-effector error induced from unity-norm error of the robot geometric parameters. [12], [14].

$$
\sigma_{x_{c,f}} = \max_{||p||_C=1} ||x||_f \tag{10}
$$

In the above relations, C and f indicate the norm of constraint and the objective function in kinematic sensitivity, respectively. As mentioned before, the kinematic sensitivity indicates the upper bound of end-effector error due to the geometric parameters error as a criterion for the robot accuracy. As it is expected, the accuracy of geometric parameters of the robot are independent from each other, and therefore, using ∞-norm in the parameter space is suggested ($C = \infty$). Furthermore, based on what is reported in [16], using ($f = 2$) is more suitable for investigation of the robot workspace. In order to calculate this kinematic sensitivity, at the first step, it is necessary to find the multi-dimensional vertices of the robot work space. For this purpose, multi-dimensional vertices of constraints in the geometric parameter space should be mapped to the workspace using the Jacobian matrix:

$$
V_{x_i} = JV_{p_j} \tag{11}
$$

For the robot shown in the figure 2 sixteen geometric parameters exist, $j = 1, \cdots, 16$, and since the robot has three degrees of freedom, then $i = 1,2,3$. After finding multi-dimensional vertices in the workspace, the following relation may be used in order to calculate the kinematic sensitivity represented in the robot work space:

$$
\sigma_{x_{\infty,2}} = \max_{j=1,\ldots,16} \sqrt{x_j^2 + y_j^2 + z_j^2} \tag{12}
$$

B. *Kinematic Sensitivity of ARAS–DSCR*

Our suspended cable driven robot is installed on the walls of square-shaped Robotics Laboratory, with a dimension of about 8×6 meters, as shown in Fig. 1. Furthermore, the height of the end-effector is measured relative to the height of the anchors, in other words, parameter $z = 0$ at the anchors plane. Now we investigate the sensitivity of the robot to different geometric parameters. If in equation 11 the kinematic sensitivity only to the cable length variables is calculated, Fig. 3 is achieved. As it may be seen in the figure, the sensitivity of the robot near to the plane of anchors is relatively high. This configuration of the robot is near to singularities. However, by lowering the hight of the end-effector, the kinematic sensitivity is significantly decreased.

Fig. 4 illustrates the robot kinematic sensitivity with respect to the component x of anchors for four different moving platform heights. This figure shows that within the robot workspace, sensitivity is highly changing. Especially, at the vicinity of the anchors plane, the robot sensitivity is higher. Therefore, it is necessary to accurately calibrate the component x of the attachment points. Due to the symmetry of the robot, the sensitivity to the component y of the anchors is similar to that of x.

Fig. 5 depicts the robot kinematic sensitivity with respect to the component z of the anchors for four different moving platform heights. As it can be seen in this figure, in terms of the kinematic sensitivity, the component z is less significant compared to that of x and y components. That is because all the cable attachment points have almost the same z component, but their position in the x and y plane is totally different.

IV. Forward kinematic Resolution of DSCR

As shown in previous section, uncertainty in kinematic parameters is very influential on kinematic equations. In this section, two methods two consider the influenced uncertainties are introduced.

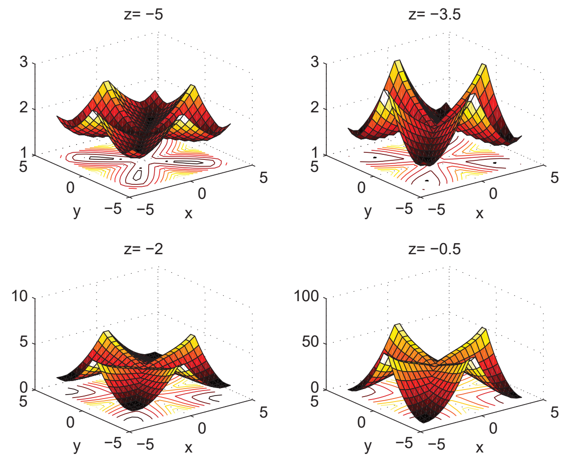

Fig. 3. Kinematic sensitivity to cable length variation.

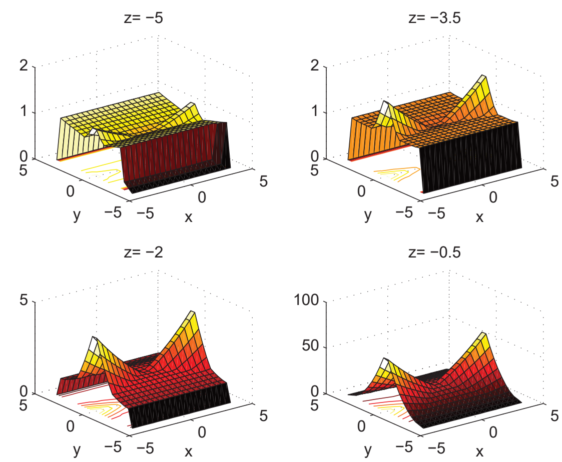

Fig. 4. Kinematic sensitivity to x coordinate of attachment points.

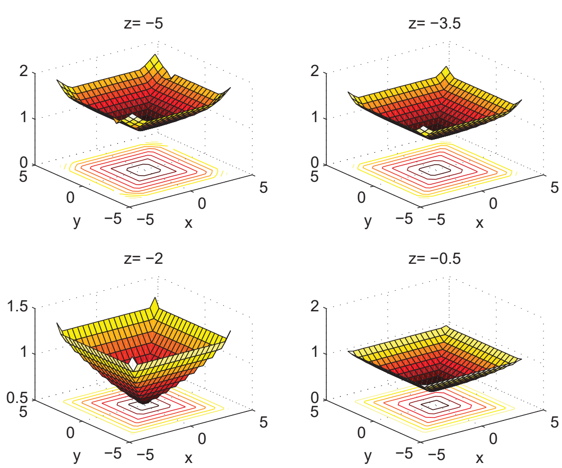

Fig. 5. Kinematic sensitivity to z coordinate of the attachment points.

A. Least Squares Method

In this part based on the effective parameters found in past section and by using kinematic redundancy equations, equation 4 will be modified and represented by a linear regression form. Then by using a least-squares solution the forward kinematic problem in DSCR will be solved. For this purpose at first, consider 3 which consists of four equations. Subtract each two following equations from one another in order to eliminate the squared terms and to form four linear equations with respect to x.

$$\frac{1}{2}(l_i^2 - l_j^2 - p_i^T p_i + p_j^T p_j) = x^T(p_j - p_i), \quad i = 1,2,3,4, \quad j = 2,3,4,1 \tag{13}$$

In these equations, p_i denotes the i'th anchor vectors and x denotes the end-effector position vector. As it is seen these set of equations for a linear regression model with respect to x and a least–squares solution may be easily obtained to estimate the optimum solution in terms of miming squared error. It should be noted that the change of variable z_i is much smaller than that of x_i, and y_i's. Furthermore, as it is observed in the previous section, the sensitivity of kinematic equations to component z_i is much smaller than to that of the other two components x_i and y_i. Therefore, one may neglect the variations in z_i's from the resulting equations, and write the final linear regression formulation as follows.

$$U \times X = \boldsymbol{\theta} \tag{14}$$

where

$$U = \begin{bmatrix} \alpha_1 & \beta_1 \\ \alpha_2 & \beta_2 \\ \alpha_3 & \beta_3 \\ \alpha_4 & \beta_4 \end{bmatrix}, \qquad X = \begin{bmatrix} x \\ y \end{bmatrix}, \qquad \boldsymbol{\theta} = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \end{bmatrix} \tag{15}$$

where

$$\alpha_k = p_{x_i} - p_{x_j}, \qquad \beta_k = p_{y_i} - p_{y_j} \tag{16}$$

$$\theta_k = l_i^2 - l_j^2 - p_i^T p_i + p_j^T p_j \tag{17}$$

Using this linear regression form, one may easily obtain the minimum least-squares solution by:

$$X = (U^T U)^{-1} U^T \boldsymbol{\theta} \tag{18}$$

By using the above equations, the x and y components of the end-effector position vector may be estimated. Using this values for x and y and equation 4, the z component of the end-effector position vector may also be calculated. by:

$$z = h - \sqrt{l_1^2 - (x + \frac{a}{2}) - (y + \frac{b}{2})}. \tag{19}$$

B. Geometrical Method

Another method proposed in this paper to solve forward kinematics problem is based on a geometrical analysis of kinematic uncertainty bounds. The main idea of this method is to find all possible positions for the end effector by geometrical analysis, and then to select an optimal solution among them. Fig. 6 schematically demonstrate the proposed algorithm. As it is shown in this flowchart, from the robot workspace, a reference coordinate is chosen and the nominal positions of all the anchors relative to this point is marked. This origin point is considered as the home of the robot which is optionally selected in the workspace. At the next step, the uncertainty bound of the anchor installation, which is the maximum assumed position error of the anchors, is specified. One other required parameter used in this method is the accurate length of the cables which in practice is measured by the motor encoders.

At first, consider a sub-robot formed by a single cable whose anchor position is uncertain. According to the cable length, L and considering the amount of uncertainty in anchor installation, R, the end-effector of this robot may be placed in a volume limited by two spheres with radius $L-R$ and $R+L$. This volume is named the feasible space of end-effector. In the case of a four cable robot, position of the end-effector is located in the intersection of four sub-robot feasible spaces. Figure 7 shows such a domain for ARAS–DSCR. If the geometrical center, of the intersected feasible spaces (GCIFS) is computed in the home position, one may obtain a mapping which transforms the geometrical center to the end-effector position. In other words, the GCIFS may indicate a desired estimation for the end-effector position.

V. Simulation Results

To study the performance of the proposed algorithm, the kinematics of ARAS robot is considered. In this simulation, it is supposed that there is a 5 percent measurement error in the estimated location of the anchors due to kinematic uncertainty. Also, it is assumed that the accurate lengths of cables can be measured. Then, by using the correct lengths and applying the proposed methods, the estimated location of the end-effector is calculated. By comparing the average of the estimation errors of the proposed methods, it can be concluded that both methods have better performance than the conventional forward kinematics.

In order to investigate the accuracy and integrity of the proposed algorithms and compare the results, a desired path in the robot workspace is considered as shown in Fig. 8. The considered spiral path contains a diversity of points in the robot workspace to evaluate the accuracy of the forward kinematic solutions.

Figure 8 shows the real positions and estimated locations using different solution methods. Some representative points of this path is illustrated in the figure I and their corresponding estimations are obtained using the conventional forward kinematic method, least squares algorithm and geometrical method. Also, the 2-norm of the estimation errors are presented in this table. as it is seen in these results, both methods are improving the kinematic solution accuracies, while no preference in using either of them are seen in different examined points.

As mentioned before, the basic assumption on which the proposed methods is based is to have the accurate lengths of the cables. However, this assumption is only valid if accurate

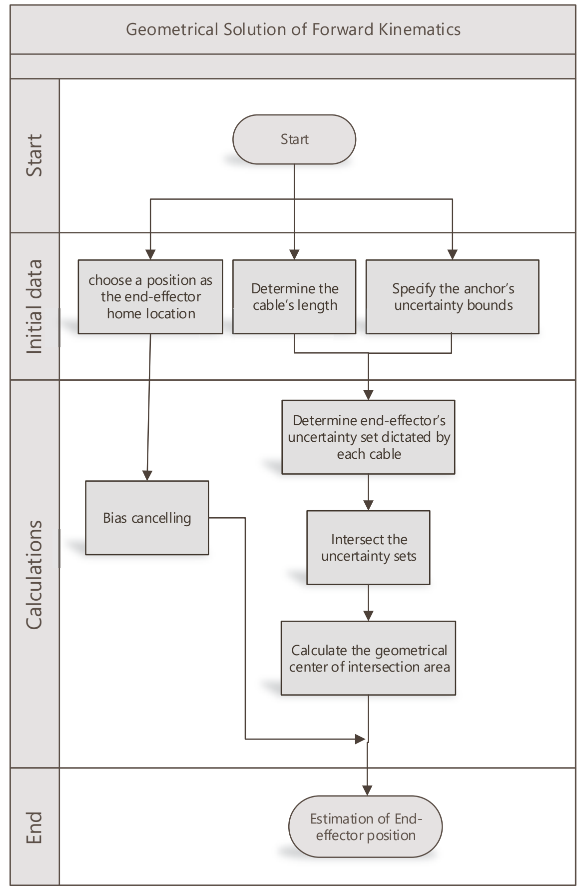

Fig. 6. The proposed flow chart of geometrical method for forward kinematics solution.

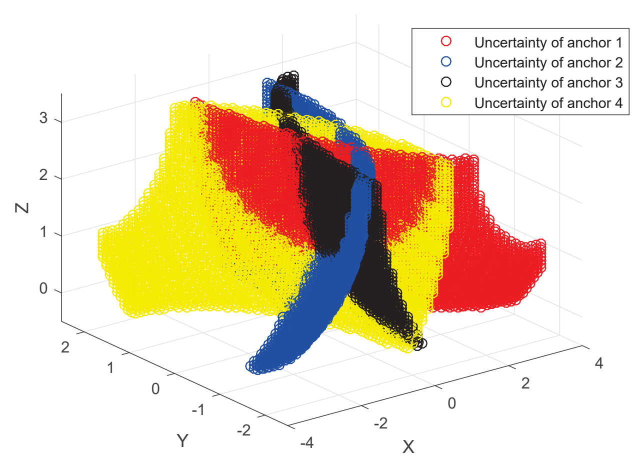

Fig. 7. Intersection of four feasible space to estimate the end-effector position.

and appropriate equipment is available, which is usually costly. Moreover, when a cable is considered as a flexible link, obtain-

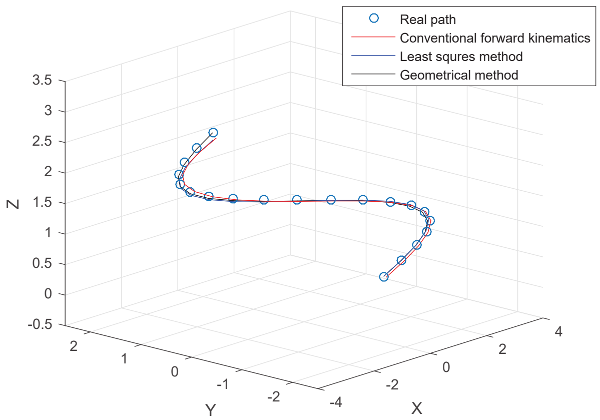

Fig. 8. The performance comparison of proposed forward kinematics solutions in tracking a desired path.

TABLE I
COMPARING THE PERFORMANCE OF THE CONVENTIONAL METHOD WITH THE OTHER PROPOSED ALGORITHMS.

	Real position	**Conventional method**	$\|\|e\|\|$	**LS method**	$\|\|e\|\|$	**Geometrical method**	$\|\|e\|\|$
1	$\begin{bmatrix}1.912\\-1.170\\-2.280\end{bmatrix}$	$\begin{bmatrix}1.940\\-1.185\\-2.292\end{bmatrix}$	0.034	$\begin{bmatrix}1.914\\-1.157\\-2.274\end{bmatrix}$	**0.014**	$\begin{bmatrix}1.911\\-1.144\\-2.293\end{bmatrix}$	0.028
2	$\begin{bmatrix}2.906\\-0.870\\-2.080\end{bmatrix}$	$\begin{bmatrix}2.936\\-0.874\\-2.086\end{bmatrix}$	0.032	$\begin{bmatrix}2.908\\-0.850\\-2.067\end{bmatrix}$	**0.024**	$\begin{bmatrix}2.904\\-0.830\\-2.098\end{bmatrix}$	0.044
3	$\begin{bmatrix}2.789\\-0.570\\-1.880\end{bmatrix}$	$\begin{bmatrix}2.816\\-0.577\\-1.886\end{bmatrix}$	0.029	$\begin{bmatrix}2.789\\-0.551\\-1.869\end{bmatrix}$	**0.021**	$\begin{bmatrix}2.788\\-0.531\\-1.898\end{bmatrix}$	0.042
4	$\begin{bmatrix}1.607\\-0.270\\-1.680\end{bmatrix}$	$\begin{bmatrix}1.626\\-0.294\\-1.695\end{bmatrix}$	0.034	$\begin{bmatrix}1.603\\-0.260\\-1.683\end{bmatrix}$	**0.011**	$\begin{bmatrix}1.604\\-0.249\\-1.694\end{bmatrix}$	0.026
5	$\begin{bmatrix}-0.188\\0.030\\-1.480\end{bmatrix}$	$\begin{bmatrix}-0.181\\-0.019\\-1.496\end{bmatrix}$	0.052	$\begin{bmatrix}-0.198\\0.026\\-1.502\end{bmatrix}$	0.024	$\begin{bmatrix}-0.192\\0.028\\-1.496\end{bmatrix}$	**0.017**
6	$\begin{bmatrix}-1.912\\0.330\\-1.280\end{bmatrix}$	$\begin{bmatrix}-1.916\\0.257\\-1.278\end{bmatrix}$	0.073	$\begin{bmatrix}-1.927\\0.313\\-1.317\end{bmatrix}$	0.043	$\begin{bmatrix}-1.917\\0.326\\-1.304\end{bmatrix}$	**0.025**
7	$\begin{bmatrix}-2.906\\0.630\\-1.080\end{bmatrix}$	$\begin{bmatrix}2.917\\0.543\\-1.055\end{bmatrix}$	0.091	$\begin{bmatrix}-2.924\\0.605\\-1.130\end{bmatrix}$	0.059	$\begin{bmatrix}-2.914\\0.629\\-1.108\end{bmatrix}$	**0.029**
8	$\begin{bmatrix}-2.789\\0.930\\-0.880\end{bmatrix}$	$\begin{bmatrix}-2.803\\0.843\\-0.864\end{bmatrix}$	0.089	$\begin{bmatrix}-2.810\\0.906\\-0.950\end{bmatrix}$	0.077	$\begin{bmatrix}-2.800\\0.931\\-0.911\end{bmatrix}$	**0.033**
9	$\begin{bmatrix}-1.607\\1.230\\-0.680\end{bmatrix}$	$\begin{bmatrix}-1.618\\1.157\\-0.718\end{bmatrix}$	0.083	$\begin{bmatrix}-1.627\\1.215\\-0.776\end{bmatrix}$	0.010	$\begin{bmatrix}-1.615\\1.233\\-0.695\end{bmatrix}$	**0.017**
Average of error			**0.062**		**0.041**		**0.029**

ing its accurate length using only the encoders is impossible. Therefore, the forward kinematic solution for the deployable robot in presence of cable length uncertainty is still an open problem and further research should be done to address this problem.

VI. Conclusions

In this paper, in order to expand the applications of the cable driven parallel robots, the idea of a deployable design is considered, and inverse and forward kinematic solution for such robots are investigated. It is shown that parameter uncertainties in the deployable cable robots can highly affect the kinematic equations. An analysis on parameter sensitivity of the DSCR was presented and the importance of the parameters in forward kinematic solution is categorized. By recognizing effective parameters and by using the redundancy property of the actuators, two methods for the DSCR forward kinematic solution is presented. The first proposed method uses a least squares solution on a extracted linear regression model, while the second method is based on geometrical interpretation of uncertainty model. The accuracy and integrity of the proposed methods are evaluated and compared on a path, and the improvement in terms of accuracies are reported. It is seen that both methods are improving the kinematic solution accuracies and may be used in further online implementations.

References

[1] Brett L Jordan, Maxim A Batalin, and William J Kaiser. Nims rd: A rapidly deployable cable based robot. In *Proceedings 2007 IEEE International Conference on Robotics and Automation*, pages 144–150. IEEE, 2007.

[2] Per Henrik Borgstrom, Brett L Jordan, Bengt J Borgstrom, Michael J Stealey, Gaurav S Sukhatme, Maxim A Batalin, and William J Kaiser. Nims-pl: a cable-driven robot with self-calibration capabilities. *IEEE Transactions on Robotics*, 25(5):1005–1015, 2009.

[3] Paul Bosscher, Robert L Williams, and Melissa Tummino. A concept for rapidly-deployable cable robot search and rescue systems. In *ASME 2005 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pages 589–598. American Society of Mechanical Engineers, 2005.

[4] J.P. Merlet. Marionet, a family of modular wire-driven parallel robots. *Advances in Robot Kinematics: Motion in Man and Machine*, pages 53–61, 2010.

[5] Gloria J Wiens. Parameter sensitivity in system identification of parallel mechanisms. In *ASME 2002 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pages 721–730. American Society of Mechanical Engineers, 2002.

[6] M Saeed Varziri and Leila Notash. Kinematic calibration of a wire-actuated parallel robot. *Mechanism and Machine Theory*, 42(8):960–976, 2007.

[7] Roger Boudreau and Noyan Turkkan. Solving the forward kinematics of parallel manipulators with a genetic algorithm. *Journal of Field Robotics*, 13(2):111–125, 1996.

[8] Valentin Schmidt, Bertram Müller, and Andreas Pott. Solving the forward kinematics of cable-driven parallel robots with neural networks and interval arithmetic. In *Computational Kinematics*, pages 103–110. Springer, 2014.

[9] Jean-Pierre Merlet. On the real-time calculation of the forward kinematics of suspended cable-driven parallel robots. In *14th IFToMM World Congress on the Theory of Machines and Mechanisms*, 2015.

[10] Bin Zi, Huafeng Ding, Xia Wu, and Andres Kecskemethy. Error modeling and sensitivity analysis of a hybrid-driven based cable parallel manipulator. *Precision Engineering*, 38(1):197–211, 2014.

[11] Genliang Chen, Hao Wang, and Zhongqin Lin. Determination of the identifiable parameters in robot calibration based on the poe formula. *IEEE Transactions on Robotics*, 30(5):1066–1077, 2014.

[12] MH Saadatzi, M. Tale Masouleh, HD Taghirad, C. Gosselin, and M. Teshnehlab. multi-objective scale independent optimization of 3-rpr parallel mechanisms. *Proceedings of the IFToMM*, 2011.

[13] Seyed Ahmad Khalilpour, Azadeh Zarif Loloei, Hamid D Taghirad, and Mehdi Tale Masouleh. Feasible kinematic sensitivity in cable robots based on interval analysis. In *Cable-Driven Parallel Robots*, pages 233–249. Springer, 2013.

[14] S. A. Khalilpour, A. Zarif Loloei, M. Tale Masouleh, and HD Taghirad. Kinematic performance indices analyzed on four planar cable robots via interval analysis.