

Kinematics and Jacobian analysis of a three DOF sufficiently actuated largescale cable-driven robot with insufficient actuated structure

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Abstract

A novel cable-driven mechanism with three spatial translational motions and a central prismatic actuator to keep the cables under tension and increase the workplace volume is investigated. Having high accuracy in its workspace, the robot has potential for large-scale robotic manipulations, machining of large parts, and material handling. Kinematic and Jacobian analysis are performed after developing the loop chain equations. Then the motion is numerically analyzed to study the relations between the winches' revolute angles and the position of the end-effector for a sample welding path.

Keywords

Cable Robot, Parallel Platform, Singularity Analysis, Actuation Insufficiency, Jacobian Analysis

1. Introduction

Although simple in form, cable robots are extensively exploited today for multiple purposes, including handling. Multiple fixed- or moving-winches are also employed to move the end effector through the connection cables. These type of robots are usually utilized for carrying objects such as video cameras, hooks, or other types of grippers.

One of the most important usages of robotic systems is in power transmission maintenance, and their monitoring by mobile sensing (Jiang *et. al.* , 2004). Sensitivity improvement and thus system reliability enhancement are just two of their advantages. Their applications include live maintenance of high-voltage transmission lines, thereby removing human workers from dangerous and highly specialized operations. They can also work in hazardous environments like radioactive locations in nuclear plants and access tight spaces such as cable viaducts and cooling pipes, and help in the precise positioning of measurement equipment. Robotics and information technology are implemented within electrical networks to make their power systems more efficient and form a small grid. (Rashid *et. al.* 2018).

Robots can be widely used in energy applications. Jeon *et. al.* (2012) introduced a blade-cleaning robot for the maintenance of wind power blades. These types of maintenance devices require a continuous supply of green-source energy, and due to the special shape of the blades, must have a mechanism that can conform to it and still be efficient.

Meng *et al.* (2018) performed the conceptual design, kinematic analysis, and workspace identification of a four DOF parallel robot. They used a line-graph method and specified the performance of the robot. Yang *et al.* (2011) proposed a 7-DOF dexterous robotic arm with an anthropomorphic design consisting of shoulder, elbow, and wrist modules, all cable driven. They performed displacement, tension-closure, and workspace analysis, and optimized the system to mimic humans as much as possible. In another work, Abdolshah *et al.* (2015) studied a linear quadratic (LQ) optimal controller with position and velocity feedback for a 3-DOF planar cable-driven parallel robot (Feriba-3). Liu *et al.* (2016) developed a human-scale artificial ankle joint actuated by a cable pulley transmission and performed a multi-body dynamic performance evaluation in ADAMS to investigate the usage of the mechanism in humanoid robots.

In a related work, Bamdad (2013) developed a general model for a cable-suspended manipulator and solved the cable vibrations analytically. A closed form solution is obtained for the dynamic response to flexibility, and optimal torques are generated considering actuator limitations. In addition, Wei *et al.* (2012) used Linear Programming and a geometric method to calculate the velocity output and force output of manipulators, especially heavy duty ones, in different situations. As an example, the force capacity space of a heavy-load excavating mechanism is calculated and is represented as a multi-dimensional polytope. Zhang *et al.* (2012) built the dual-robot coordination system for coordinating the welding of complex curved seams, the robots holding the workpiece and the torch, respectively. A three point calibration method is presented, and a non master/slave scheme is chosen for the motion planning to calculate the work space trajectories through the constrained relationship matrices automatically. As depicted, the welding process meets the requirements of downhand welding, the joint displacement curves are smooth and continuous, and no joint velocities are out of the working scope. Yuan *et al.* (2016) have introduced an automatic robot taping system consisting of a robot manipulator, a rotating platform, a 3D-scanner, and specially designed taping end-effectors. Considering different classes of geometries, a collision avoidance algorithm is introduced and various surface coverage strategies are discussed.

In order to predict the pose accuracy of precise robots in the design stage, and/or reducing the calibration time of existing robots, Jáuregui *et al.* (2013) presented two novel methods for estimating the accuracy of parallel robots. Propagation of errors is considered as the first method. Secondly, each actuator is assumed to have a constant error at any stroke. Quaglia *et al.* (2015) proposed a dynamic based method in the design of balancing devices for articulated robots in industry. Two aspects have been considered: optimizing the position of the balancing system, and designing the balancing parameters. Pneumatic, hydro-pneumatic, and mechanical springs, investigated for the requirements of torque compensation are all shown able to perfectly balance statically in all configurations.

Lens *et al.* (2012) presented a lightweight BioRob manipulator for safe physical human-robot interaction and analyzed it using a worst-case collision scenario. A safety evaluation method was proposed considering the potential energy stored. The results enable safe operation even at high velocities.

Quaglia *et al.* (2013) statically balanced a 2-DOF anthropomorphic robot. Two solutions were employed: pneumatic and hydro-pneumatic. As a result, the workspace and payload capabilities were shown to have improved.

Having eliminated the complex components, Modak *et al.* (2016) introduced an innovative low-cost configuration stair-climbing mechanism that can be implemented as a staircase-climbing wheelchair or staircase-climbing trolley for material transfer systems.

To reduce the pressure exerted on the entrance point in a patient's abdominal wall during minimally invasive surgery, Stoica *et al.* (2013) have used an analytical approach to introduce a parallel robot that can also handle

both a laparoscope and an active instrument for different surgical procedures. The inverse and direct geometric and kinematic models are derived. The necessary workspace and also different types of singularities are discussed.

It is typical for cable robots to be actuated by a set of cables mounted both at the top and bottom of a moving platform. As mentioned before, since cables can only exert tensile forces, they have to be kept in tension condition during operation of the robot. The set of cables under the moving platform are used to keep the upper cables under tension within the workspace of the moving platform. However, in this case, the work space of the robot is limited to only the space formed by the planes passing through the points at which winches are mounted.

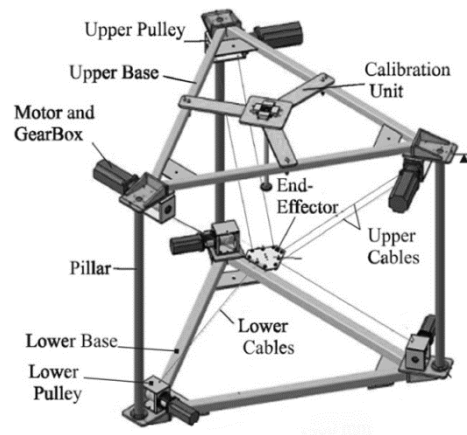


Fig. 1. Cable arrangement in conventional cable robots
Alikhani *et al.* (2009)

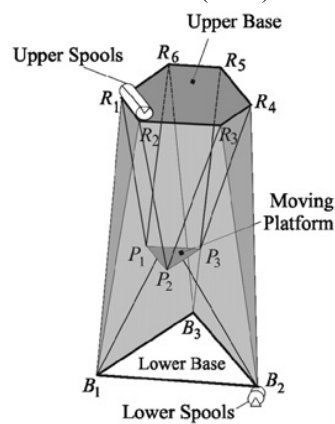


Fig. 2. Workspace volume in conventional cable robots
Alikhani *et al.* (2009)

In this paper a novel mechanism is used to keep upper cables under tension and extend the workspace of the robot. First kinematics analysis is developed. Afterwards, Jacobian analysis is performed to determine the relation between input and output parameters.

2. Mechanism

The robot consists of a fixed platform and a moving platform. The former is fixed on the stationary base and the latter can perform three translational motions in the space beneath.

Rigid links are replaced by cables to decrease the inertia of the robot. The main drawback of this substitution is that cables can only be used for exerting tensile forces. Thus, they always have to be kept under tension.

The common method for providing the required tension condition in cables is that two sets of cables are used. The first set is located above the moving platform and connects the moving platform to the upper section of the fixed base. The second set is located below the moving platform and is connected to the lower section of the fixed base as shown in Fig. (1).

In Fig. (2), the workspace of the moving platform is limited to the space formed by the planes passing through the locations of winches. However, it is obvious that for points located near the boundary planes the robot will approach singularity.

The alternative proposed design eliminates the lower cables; however, to compensate for the tension provided by these cables a novel method is used.

An additional limb consisting of two links connected by a prismatic joint connects the top of the moving platform to the fixed base. The prismatic joint can be actuated by using a screw-ball mechanism or a hydraulic cylinder. Since the added limb is attached to both the fixed and moving platforms, it should be able to rotate about any arbitrary coordinate axis; thus two spherical joint are used to connect the new limb to the fixed and moving platform; that is, two universal joints are used at the ends of this limb.

3. Kinematics analysis

Herein, the procedure by which the length of the hydraulic cylinder is determined is discussed.

3.1 General loop-closure equation

Fig. (3) shows the kinematical construction of the robot. In order to write the loop-closure equation as the base equation for kinematical analysis, we first attached a frame to the fixed base such that the positive direction of the “y” axis is from point P located at the center of the fixed platform to point A_1 . The positive direction of the other axis is shown in Fig. (3).

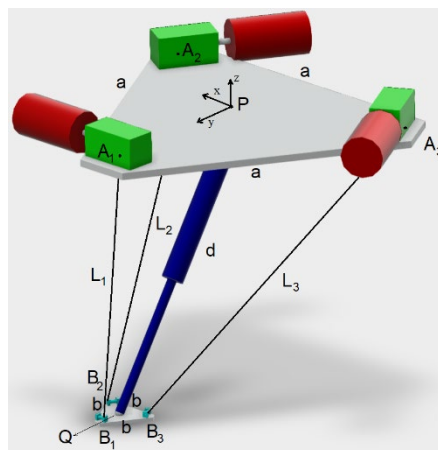


Fig. 3. Schematic design of the cable robot

Each cable is shown by vector \mathbf{L}_i and its length is designated by L_i which is a function of the initial length l_i and the revolute angle of the winches θ_i and is computed using Eq. (1).

$$L_i = l_i + r\theta_i \quad i = 1, 2, 3 \quad (1)$$

in which r is the radius of the cable pulley's of the winches. However, for the initial conditions of the moving platform located at the calibration location, the initial lengths of all the cables are equal.

Now, the loop-closure equation can be written for the robot. The three loop-closure equations can be derived by using the vector addition of successive position vectors. The loop-closure equations can be written as:

$$\mathbf{PQ} + \mathbf{QB}_i - \mathbf{PA}_i = \mathbf{L}_i \quad i = 1, 2, 3 \quad (2)$$

3.2 Forward Kinematics

In the forward kinematic analysis of this robot, the angles of the revolutions for motorized winches are known, and the final position of the moving platform has to be determined. Knowing the revolution angles for the winches, the length of the cables can be computed from Eq. (1). Afterwards, by substituting the lengths in Eq. (2), three equations are obtained. These equations are strictly nonlinear; thus, a Maple™ code is developed to find the numerical solutions for the forward kinematics. In order to ensure the robustness of the derived solution, numerical results obtained from Maple™ code are evaluated by experimental results.

Regarding Eq. (2), the position vector of the mass center of the moving platform designated by \mathbf{PQ} is a vector as follows:

$$\mathbf{PQ} = [Q_x, Q_y, Q_z]^T \quad (3)$$

The position vectors of the vertices of the moving platform with respect to the moving platform mass center Q are designated by \mathbf{QB}_i and have fixed magnitudes, as follows:

$$\begin{aligned} \mathbf{QB}_1 &= [0, \frac{\sqrt{3}}{3}b, 0]^T \\ \mathbf{QB}_2 &= [\frac{1}{2}b, -\frac{\sqrt{3}}{6}b, 0]^T \\ \mathbf{QB}_3 &= [-\frac{1}{2}b, -\frac{\sqrt{3}}{6}b, 0]^T \end{aligned} \quad (4)$$

The position vectors of the vertices of the fixed platform with respect to the coordinate system fixed at P are designated by \mathbf{PA}_i and have fixed magnitudes and directions as follows:

$$\begin{aligned} \mathbf{PA}_1 &= [0, \frac{\sqrt{3}}{3}a, 0]^T \\ \mathbf{PA}_2 &= [\frac{1}{2}a, -\frac{\sqrt{3}}{6}a, 0]^T \\ \mathbf{PA}_3 &= [-\frac{1}{2}a, -\frac{\sqrt{3}}{6}a, 0]^T \end{aligned} \quad (5)$$

Now the loop-closure equation is rewritten for each loop, resulting in three vector equations. On the other hand, there are three unknowns, which are the coordinates of point Q of the moving platform. Hence, there is a system of three unknowns and three equations that must be solved simultaneously in order for the position of the moving platform to be determined.

3.3 Inverse Kinematics

In inverse kinematics analysis of this robot, the position of the moving platform is known as PQ and the components of the L_i need to be determined. Afterwards, the magnitude of L_i can be computed, and finally, by using Eq. (1) and substitution of the $|L_i|$ revolute angles for each winch can be determined as follows:

$$\theta_i = \frac{L_i - l_i}{r} \quad i = 1, 2, 3 \quad (6)$$

4. Jacobian analysis

For Jacobian analysis of this robot, firstly the loop closure equations should be derived as in Eq. (1). Afterwards, the time differentiation of both sides must be computed. The most important issue about the time differentiation is that the time differentiation of each L_i has two components. The first component is due to changes in the length of the cable, which changes when the winches revolve. The second one is due to the rotation of L_i with respect to the coordinate system fixed at point P. However, the time differentiation of the vectors PA_i and QB_i are zero, since their magnitudes are constant. Moreover, due to the translational motion of the moving platform, they experience no change in their orientations. On the other hand, the time differentiation of PQ has two components, one of which is due to changes in the length of the prismatic actuator, \dot{d} , and the other is due to the rotation of the prismatic actuator.

From a computational viewpoint, both components of the time differentiation of PQ depict the velocity of point Q, which is equal to the absolute velocity of the moving platform.

The main result that \dot{d} is not computed directly and explicitly is that the central limb does not transmit any torque and it only provides the required compressive force for keeping the cables under tension condition. Thus, the time rate of change of its length is a function of the time differential of the length of other cables.

$$PA_i + A_iB_i = PQ + QB_i \quad (7)$$

$$\frac{d}{dt}PA_i + \frac{d}{dt}A_iB_i = \frac{d}{dt}PQ + \frac{d}{dt}QB_i$$

$$\dot{L}_i \mathbf{s}_i + \boldsymbol{\omega}_i \times L_i \mathbf{s}_i = \mathbf{V}_Q \quad i = 1, 2, 3 \quad (8)$$

in which \mathbf{s}_i is the unit vector in the direction of the i th link. In order to eliminate the angular velocity of each cable, both sides of the above equation have to be dot multiplied by \mathbf{s}_i :

$$\dot{L}_i \mathbf{s}_i \cdot \mathbf{s}_i + \boldsymbol{\omega}_i \cdot (\mathbf{s}_i \times L_i \mathbf{s}_i) = \mathbf{s}_i \cdot \mathbf{V}_Q \quad i = 1, 2, 3 \quad (9)$$

Two Jacobians can be defined in the above formula. The first one is the coefficient of the moving platform velocity vector V_Q and the other one is the coefficient of the scalar \dot{L}_i :

$$J_q = I$$

$$J_x = \begin{bmatrix} s_{1x}, s_{1y}, s_{1z} \\ s_{2x}, s_{2y}, s_{2z} \\ s_{3x}, s_{3y}, s_{3z} \end{bmatrix} \quad (10)$$

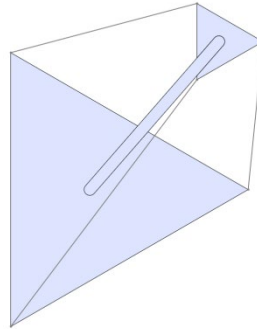


Fig. 4. Schematic depiction forward kinematics singularity (case I: both platforms on a single plane)

5. Singularity analysis

5.1 Inverse Kinematic Singularities

Since $J_q = I$ is an identity matrix, there exists no inverse kinematic singularity within the workspace of the robot. However, inverse kinematic singularities can occur at the boundaries of the workspace where the central limb is in its fully stretched or retracted positions.

5.2 Forward Kinematic Singularities

For forward kinematic singularity analysis, the determinant of the forward kinematics Jacobian J_x should be set to zero. Thus we would have:

$$Det(J_x) = 0$$

$$s_{1x}s_{2y}s_{3z} + s_{1y}s_{2z}s_{3x} + s_{1z}s_{2x}s_{3y} - (s_{1z}s_{2y}s_{2x} + s_{1y}s_{2x}s_{3z} + s_{1x}s_{2z}s_{3y}) = 0 \quad (11)$$

Afterwards, the concluding equation should be solved to determine the positions at which a singularity occurs. However, the analysis is performed for two straightforward scenarios.

5.2.1 Case I

Regarding Eq. (11), the Z-component of s_i appears in all terms of the determinant of J_x . If s_i does not have any component in Z direction, then Eq. (11) would be satisfied. That is equivalent to the robot cables being stretched in the plane of XY. In such cases the moving platform can perform infinitesimal motions while the

winches and prismatic actuator are fully locked. The schematic orientation of the robot for this singularity is depicted in Fig. (4).

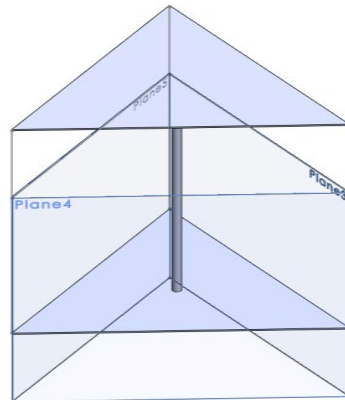


Fig. 5. Depiction of singular workspace (case II)

5.2.1 Case II

In Eq. (11) when s_i does not have components in the directions of X and Y , the equation would be satisfied. This case occurs when the triangle formed by the winches is identical to the moving platform and has a length of edge equal to those of the moving platform, that is $a = b$.

However, this condition is required but not sufficient. In order for the robot to become singular, s_i should be normal to the plane of XY . In this case, the workspace in which a singularity occurs is a prism the upper base of which is located at the plane of the moving platform while the prismatic actuator is fully retracted. The lower base of that prism lies on the plane of the moving platform while the prismatic actuator is fully stretched. The singularity workspace in this case is depicted in Fig. (5).

6. Numerical analysis of motion

A numerical analysis is conducted to study the relations between the revolute angles of the winches, the length of the prismatic actuator, and the position of the end-effector.

The analysis is conducted for a suggested workspace trajectory determined as a welding path, depicted in Fig. (6). The path is expressed in parametric form as a function of the time parameter t . Parametric coordinates of the end-effector as functions of time are as follows:

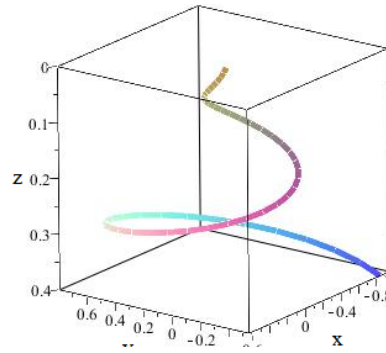


Fig. 6. Welding path for the end-effector

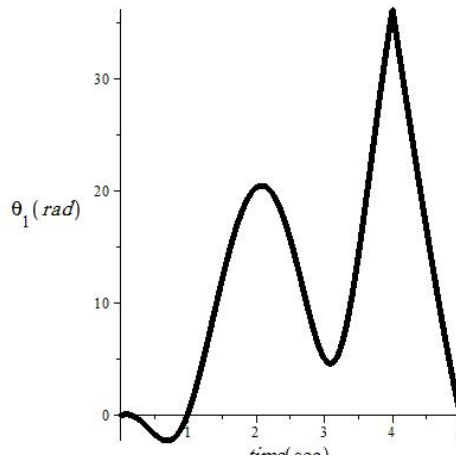


Fig. 7. Changes of θ_1 with respect to time

$$\begin{cases} x(t) = 0.25 \cdot t \cdot \cos(2.5 \cdot t) \\ y(t) = 0.25 \cdot t \cdot \sin(2.5 \cdot t) \\ z(t) = 0.1 \cdot t \end{cases} \quad 0 \leq t \leq 4 \quad (12)$$

For numerical analysis, the first step is to discretize the path along which the end-effector travels. For discretization of the path, a time step of 0.001 second is set as the increment. The values for the coordinates of the end-effector are computed for every time step. Afterwards, for all time steps, loop closure equations are written and expanded in scalar form for all the cables. Then, the lengths of the cables are computed from the three scalar components of the loop closure equation. Finally the revolute angle corresponding to each time step is computed by using Eq. (6). The changes of the revolute angles of winches with respect to time are depicted in Fig. (7) through Fig. (9).

On the other hand, since the length of the prismatic actuator is equal to the magnitude of the position vector of the end-effector, by using the discretized value for the coordinate of the end-effector, the length of the prismatic actuator can be computed as depicted in Fig. (10).

As depicted in the figures showing the changes of the revolute angles and the prismatic actuator's length, there is a negative slope in the last second of the motion. This occurs because the robot is assumed to return to its original position when reaches the end point of the curved welding path.

7. Conclusion

This paper has presented the kinematical analysis of a 3-DOF cable robot. We also performed Jacobian analysis in order to find the forward and inverse kinematic Jacobian matrices. Afterwards, singularity analysis was done for two special cases, and singular workspaces were found. Finally, a numerical analysis was done to study the changes of the winches' revolute angles with respect to time for a special given welding path.

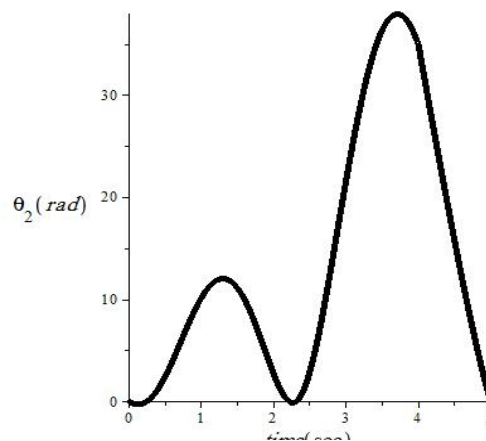


Fig. 8. Changes of θ_2 with respect to time

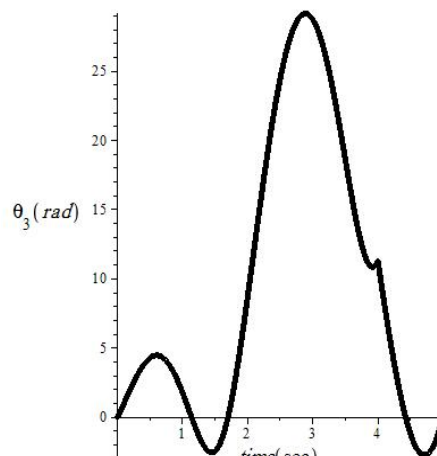


Fig. 9. Changes of θ_3 with respect to time

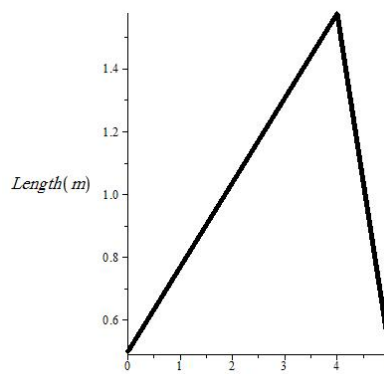


Fig. 10. Changes of prismatic actuator's length with respect to time

8. References

- Abdolshah S, Barjuei ES. Linear quadratic optimal controller for cable-driven parallel robots. *Frontiers of Mechanical Engineering*. 2015 Dec 1;10(4):344-51.
- Alikhani A, Behzadipour S, Sadough Vanini SA, Alasty A. Workspace analysis of a three DOF cable-driven mechanism. *ASME Journal of Mechanisms and Robotics* 2009; 1(4):041005.1–7.
- Bamdad M. Analytical dynamic solution of a flexible cable-suspended manipulator. *Frontiers of Mechanical Engineering*. 2013 Dec 1;8(4):350-9.
- Jáuregui JC, Hernández EE, Ceccarelli M, López-Cajún C, García A. Kinematic calibration of precise 6-DOF Stewart platform-type positioning systems for radio telescope applications. *Frontiers of Mechanical Engineering*. 2013 Sep 1;8(3):252-60.
- Jeon M, Kim, B, Park S, Hong D, Maintenance robot for wind power blade cleaning. In *29th International Symposium of Automation and Robotics in Construction, ISARC2012*. December 2012, Eindhoven, Netherlands.
- Jiang, B. and Mamishev, A., Robotic monitoring of power systems. *IEEE Transactions on Power Delivery*, 2004, 19(3):912-918.
- Lens T, Von Stryk O. Investigation of safety in human-robot-interaction for a series elastic, tendon-driven robot arm. *In IROS 2012* Oct 7 (pp. 4309-4314).
- Liu H, Ceccarelli M, Huang Q. Design and simulation of a cable-pulley-based transmission for artificial ankle joints. *Frontiers of Mechanical Engineering*. 2016 Jun 1;11(2):170-83.
- Meng Q, Xie F, Liu XJ. Conceptual design and kinematic analysis of a novel parallel robot for high-speed pick-and-place operations. *Frontiers of Mechanical Engineering*. 2018 Jun 1;13(2):211-24.
- Modak GS, Bhoomkar MM. Innovative stair climber using associated wheels. *Frontiers of Mechanical Engineering*. 2016 Sep 1;11(3):299-310.
- Nayyerloo M, Chen X, Wang W, Chase JG. Cable-climbing robots for power transmission lines inspection. In *Mobile Robots-State of the Art in Land, Sea, Air, and Collaborative Missions*. IntechOpen. 2009.
- Quaglia G, Yin Z. A balancing mechanism for an anthropomorphic robot. *Advanced Materials Research*. 2013 (Vol. 774, pp. 1397-1403). Trans Tech Publications.
- Quaglia G, Yin Z. Static balancing of planar articulated robots. *Frontiers of Mechanical Engineering*. 2015 Dec 1;10(4):326-43.
- Rashid R, Ganee N. Robotic Monitoring of Power Systems. *Published in International Journal of Trend in Scientific Research and Development*, ISSN: 2456-6470, 2(5), August 2018, pp.740-744.
- Stoica A, Pislă D, Andras S, Gherman B, Gyurka BZ, Plitea N. Kinematic, workspace and singularity analysis of a new parallel robot used in minimally invasive surgery. *Frontiers of Mechanical Engineering*. 2013 Mar 1;8(1):70-9.
- Yang G, Mustafa SK, Yeo SH, Lin W, Lim WB. Kinematic design of an anthropomimetic 7-DOF cable-driven robotic arm. *Frontiers of Mechanical Engineering*. 2011 Mar 1;6(1):45-60.
- Yuan Q, Chen IM, Lembono TS, Landén SN, Malmgren V. Strategy for robot motion and path planning in robot tapping. *Frontiers of Mechanical Engineering*. 2016 Jun 1;11(2):195-203.
- Wei B, Gao F. A method to calculate working capacity space of multi-DOF manipulator and the application in excavating mechanism. *Frontiers of Mechanical Engineering*. 2012 Jun 1;7(2):109-19.
- Zhang T, Ouyang F. Offline motion planning and simulation of two-robot welding coordination. *Frontiers of Mechanical Engineering*. 2012 Mar 1;7(1):81-92.

Biographies

Kambiz Ghaemi Osgouie is an assistant professor of Mechanical Engineering at University of Tehran, Iran. He earned his BSc, MSc, and PhD in 1999, 2002, 2009, respectively, all from School of Mechanical Engineering at Sharif University of Technology, Tehran, Iran. He has conducted research and published conference and journal papers in the fields of Robotics, Artificial Intelligence, Design and Analysis of Novel Mechanisms, and Control. His educational and research interest topics mainly lie at Kinematics and Dynamics of Parallel and Redundant Robots. He has multiple publications on the applications of Optimal Control in Multi Arm Robots. He is also interested in various applications of Mechatronics specially those related to Biological and/or Sustainable systems; including Robots with special applications in Occupational Therapy, Electricity Generating Roof Gardens using PMFCs, Wave Power Harvesting Mechanisms, Adaptable Configuration Robots, a Novel Linear Electromotor, and a Novel Jumping Mechanism. He is very interested in the teaching/learning processes of Mechanical Engineering. He has worked as an engineer in the design and automation of multiple sections of car production plants of Iran Khordro Company, Tehran, for years.

Assal Haqiqat Pars is a member of Green Planet Lio company and has also been a graduate researcher at University of Tehran for three years, working with Dr. Ghaemi Osgouie in robotics fields. She holds a Bachelor of Science degree in Mechatronic Engineering from Sharif University of Technology International Campus at Kish Island and a Master of Science degree in Mechatronic Engineering from Science and Research branch of Islamic Azad University of Tehran, received in 2012 and 2017, respectively. She has worked on the optimal path following for planar redundant robots using Pontryagin's optimal control on her master's thesis. She has also worked on multiple industrial projects; modeling of a hydraulic-mechanical excavator, automation of a biscuit production line. She served as a member of Energy Sakhteman Company as a mechanical engineer for two years and has contributed to three construction projects in the cities of Rasht, Ahvaz and Khorramshahr.

Ali Elkamel is a Professor in the Department of Chemical Engineering and is cross-appointed to the Systems Design Engineering department at the University of Waterloo. He is a member of the Canadian Society for Chemical Engineering, the American Institute of Chemical Engineers, the Canadian Operational Research Society, and the Institute for Operations Research and Management Sciences (INFORMS). Along with his students, Professor Elkamel has successfully developed region-wide cost effective carbon dioxide strategies that will help to find solutions for carbon dioxide capture, additional treatment, transportation and storage. In 2013, they were able to apply their optimization of networks monitoring air quality solution to an existing network of refinery stacks, which improved the ability to protect environmental resources and human health. His lab, in conjunction with Virox Technologies Inc. and Professors Duever and Reilly, has also designed a green product disinfectant that received the Design for the Environment Champion Status Award. He holds more than 200 refereed journal publications, international proceedings, and conference presentations. His publications have been featured in the Journal of Physical Chemistry, Advances in Environmental Research, and the Journal of Dispersion Science and Technology among many others. He has also written 4 books, including "Environmentally Conscious Fossil Energy Production."

Azadeh Maroufmashat is a postdoctoral fellow in Chemical Engineering, University of Waterloo. She obtained her B.Sc. degree in Mechanical Engineering in 2007 and her M.Sc. and Ph.D. in energy system engineering in 2010, and 2015, respectively, all from Sharif University of Technology, Tehran, Iran. During her PhD, she was a visiting scholar at the University Waterloo. Now she is working on projects related to the modeling and optimization of various energy conversion and storage systems at University Waterloo as a postdoctoral fellow. Her research interests lie at the intersection of energy system modeling, optimization and policy recommendations and her research contributions have been in the optimal integration of sustainable energy generation and storage technologies with the current energy system. She has investigated the technical, environmental, and economic aspects of urban energy system modeling (a micro-grid application), and power-to-gas as a feasible energy storage technology and a low-carbon sustainable energy alternative for transportation and for the hydrogen economy. Her future research will address climate change issues in large scale energy system modeling. She has a number of advising experiences; as examples of successful mentorship, teams that she co-advised were the Grand prize winners (2016) and honorable mentions (2018) of the Hydrogen student design contest, held by the Department of Energy (DOE) of the United States.