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Kinematic Analysis and Motion Simulation of a 2D Cable Robot Designed for Greenhouse Applications

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ABSTRACT

The high adaptability of cable robots to complex environments has led entrance of these types of robots into the agricultural sector in recent years. Kinematic and dynamic modelling of robots is essential to develop the control algorithms and optimize their movement. In this research, the kinematic analysis of a two-dimensional laboratory cable robot, which is being developed for agricultural applications, and the results of its movement simulation in Simscape Multibody environment of MATLAB software are presented. The motions simulation of the robot in reaching a hypothetical point and traveling a certain path have been done using PID controller. Before the final evaluation, the controller used to control the robot was adjusted, so that the robot shows a suitable and acceptable performance in terms of control indicators. Finally, the time response graphs of the robot in the states of reaching a hypothetical point and traveling a linear path were determined and analyzed. The values of rise time, peak time, overshoot, and steady state error at reaching point (40, 30) were 0.8 s, 2.3 s, 10-20 %, 0 respectively. Also, the peak time and overshoot values at traveling a linear path in X direction were 2.1 s and 50%, respectively. According to the simulation results, the designed robot behaved well in reaching a hypothetical point and traveling a certain path.

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INTRODUCTION

Robots are programmable machines and do the tasks assigned them automatically. One of the new fields of the robot's application is agriculture sector and greenhouses. The increase in demand for human food along with the shortage of skilled workers has encouraged the agricultural managers to use the robots more than before (Abdi-pour & Shamsi, 2023; Masoudi, 2017). Robotic arms, wheeled robots, and drones have been most used in the agriculture and greenhouses (Masoudi et al., 2011). As shown in Table 1, in addition to many advantages, these types of robots have some limitations that make their use challenging. Therefore, a new type of robots has been proposed that move through cables instead of wheels and are called "cable robots" or "Cabots" (Bai et al., 2019; Cattani & Protonotarios, 2016). The cable robots are a group of parallel robots in which cables have replaced the common rigid arms (Qian et al., 2018). One of the most important applications of the cable robots in the agricultural sector is the construction and development of them in accordance with the working conditions (farm or greenhouse) and then the use of different final actuators for various tasks, such as crop monitoring, spraying, etc. In order to use the cable robots in the greenhouse, the necessary structures must be created. Therefore, the cable robots are not very effective in traditional greenhouses, where there are not such structures.

According to Figure 1, the cable robot has an almost simple structure. This simple structure consists of several cables that control the final actuator movement and are connected to the motor's pulleys (Cattani & Protonotarios, 2016). The cable robot moves through cables instead of wheels, and this is a big advantage compared to the other robots; because it causes high adaptability to complex agricultural environments and lack of movement restrictions. Meanwhile, the cable robots are not limited to a horizontal plane on the ground and are less affected by obstacles than the wheeled robot (Nasiri & Lotf-Avar, 2014).

Kinematic and dynamic modeling of the robots is very important for developing control algorithms and optimizing the robot movement. By having an accurate model of the robot's movement behavior, the control algorithms and optimization of the robot's movement can be designed more precisely and optimally, and as a result, improve the robot's performance. The replacement of cable instead of rigid arms in parallel cable robots makes this type of robots a suitable alternative to deal with the inherent and structural shortcomings of conventional series and parallel robots. But this issue creates new challenges (H. R. Taghirad et al., 2014). Parallel mechanisms have limitations such as the irregularity and limited working space, the presence of singular points, and complex kinematic and dynamic equations that make them difficult to control. Therefore, for proper use of this type of mechanisms, it is necessary to analyze their kinematics and dynamics (Jaafarzadeh & Mahboubkhah, 2014; Mazare et al., 2016; Pakzad & Mahboubkhah, 2017). Problems such as loosening and collision of cables with each other and the need for cables to be under tension during work make it necessary to optimize the behaviour of cable robots. Various optimization algorithms have been proposed to solve these problems (Taghirad et al., 2014).

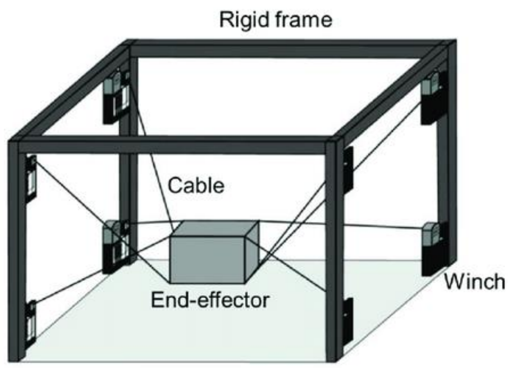


Figure 1. Schematic of a cable robot (Jin et al., 2018)

The special structure of the parallel plane cable robots with two degrees of freedom makes them only have translational motion and no rotational motion. This feature, apart from being important in some applications, allows the use of suitable kinematic indicators based on the Jacobian matrix to analyze the accuracy and other characteristics of the parallel robot (Mirnajafizadeh & Haj Abbasi, 2013). Low inertia of the cable robots is an advantage for the application of moving light objects. In agricultural environments, they can be effective for light tasks such as crop monitoring, data collection and sampling, and even irrigation and spraying operations. These types of applications generally require high accuracy, speed and acceleration, so the kinematic and dynamic performance of the robot is very important. Also, in parallel robots, the working space is limited and the singular points inside it make the working space even more limited. Therefore, in the process of designing the robot, the robot functional behavior in the work space is studied by focusing on the two fields of kinematics and dynamics (Ghanbari et al., 2021).

In most of the previous researches, the kinematics and dynamics of the built robots have been analyzed. A parallel robot with three translational degrees of freedom was designed and built in the research of Mazare et al. (2016). Basic features including inverse and direct kinematics analysis, singularity and workspace analysis, and speed analysis were investigated. By a numerical algorithm, the design parameters were extracted to access the desired workspace. In the study of Ghanbari et al. (2021), in order to analyze the kinematics of a parallel robot with four degrees of freedom, using the geometric method, constraint equations were extracted and then Jacobian matrices were determined by speed analysis. The robot working space was obtained by taking into account the constraint equations and joints limitations as a point-by-point search of the space. By studying the inverse and direct Jacobian matrices, the status and type of singularities in the working space were determined. Also, the dynamic equations of the robot were extracted using the Euler-Lagrange method, and the results of solving kinematic and dynamic problems were validated with the output of the mechanism simulation in Adams software.

Despite the advantages that cable robots have for agricultural operators, their use has its own challenges. Some of the most important challenges are (Helmi et al., 2023):

- In the analysis of cable robots, obtaining the relations of inverse kinematics is simple but direct kinematics is complex.

- The analysis of the workspace is very complicated, because of needing to the cables tension.

- Due to elasticity in the cables, the final actuator position will be accompanied by a slight deviation, which affects the mechanism accuracy.

The main purpose of this research was to introduce the kinematics of two-dimensional cable robot movement designed for greenhouse applications and to simulate its working and movement performance in Simscape Multibody environment of MATLAB software.

Table 1. Comparison of widely used robots in agriculture (Cattani and Protonotarios, 2016; Gay et al., 2008)

Type of robot	Advantages	Limitations	Applications
Robotic arms (Manipulators)	High speed, high work coverage compared to the occupied space	Expensive initial installation and complex operation mechanism	Greenhouses
Wheeled robots (Mobile robots)	Fast movement, easy control, turning in place and getting around in narrow spaces	Require a local infrastructure to accurately estimate the location of the robot, rely on batteries, be able to move only in a 2D horizontal plane	Greenhouses and farms
Flying robots (drones)	Ease of use, high maneuverability	Limited capacity of sensor installation and transportation, limited flight time, and work limitation in some weather conditions	Farms
Cable robots (Cabots)	Adaptability to different work environments, accessibility to different parts of the farm	Need different final operators to do different things	Greenhouses and farms

MATERIALS AND METHODS

The studied cable robot

The cable robot analyzed in this research is a completely bounded plane cable robot with three degrees of freedom and four cables, which has been designed in the Agro-Mechatronics Laboratory, Shahid Chamran University of Ahvaz, Iran, for greenhouse applications. The working space of the robot is 38×62 cm^2. In this robot, four steel columns are used as the chassis. A shaft with a pulley is located at the top of each column, and an electrical motor (12 VDC, 480 rpm) with gearbox and a roller mounted on its axis is located at the bottom of each column. If location of the cable exit from the drive system be not fixed and the coordinates of this point be variable, it is not possible to perform calculations to find the position of the final actuator, so these points must be bounded first. For this reason, to move the final actuator of the robot, instead of directly connecting of the cable from the motor axis roller to the final actuator, the cable first goes from the roller to the pulley and then connects to the final actuator of the robot (Aqli, 2011). The final actuator is pulled by four DC motors and four cables and thus placed in the desired location. By installing an imaging camera on the final actuator, this type of robot can be used for product monitoring in greenhouses. The 3D model of the cable robot designed in CATIA V5 software and the actual image of the built robot are shown in Figure 2.

Figure 2. 3D computer model and built prototype of the studied cable robot

Kinematic analysis of the cable robot

One of the important and basic analyzes about the robots is their kinematic analysis. In the kinematics analysis of robots, the movement geometry of robot different components and their relationship are investigated without considering the forces that cause the movement. This topic itself is divided into two parts: direct kinematic analysis and inverse kinematic analysis. Obtaining the inverse kinematic relation in cable robots is easier than obtaining the direct kinematic relation. In the other words, finding a direct kinematic relationship for the cable robots is considered an open problem (Rajabi Moghadam, 2020).

Inverse kinematics of the cable robot

The purpose of the inverse kinematic relationships of a cable robot is to obtain the variables of robot's joints (the length of cables), by giving them the coordinates of the final actuator. In the other words, the cables length could be obtained as a function of the robot's final actuator location. The two-dimensional view of the studied cable robot is shown in Figure 3. The variables of L1 to L4 are lengths of the four cables that are connected to the robot final actuator. A1 to A4 are where the cables are connected to the robot chassis, and B1 to B4 are where the cables are connected to the final actuator. According to the geometric rules, the length of each cable can be calculated from equations 1 to 4:

$$L_1^2 = (x_c - m/2)^2 + (y_c - n/2)^2 \quad (1)$$

$$L_2^2 = (W - x_c - m/2)^2 + (y_c - n/2)^2 \quad (2)$$

$$L_3^2 = (x_c - m/2)^2 + (T - y_c - n/2)^2 \quad (3)$$

$$L_4^2 = (W - x_c - m/2)^2 + (T - y_c - n/2)^2 \quad (4)$$

Where, x_c and y_c are the middle point coordinates of the final actuator, W is the width of robot chassis (38 cm), T is the length of robot chassis (62 cm), m is the length of final actuator platform, and n is the width of final actuator platform.

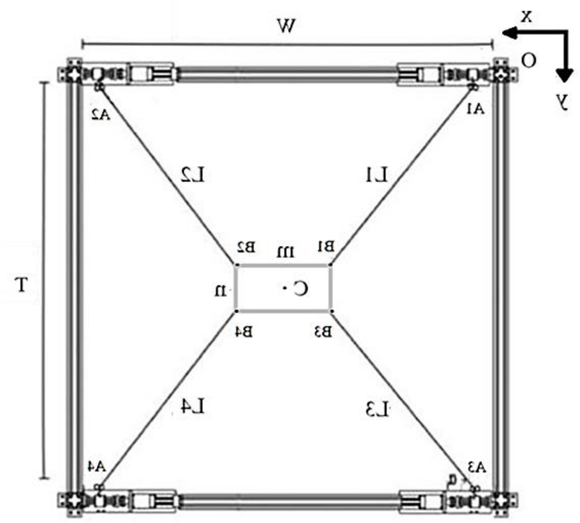


Figure 3. Schematic of the two-dimensional plane cable robot (Amiri Ahooyi et al., 2017)

Direct kinematics of the cable robot

The direct kinematics are the relations that, when the joint variables of the robot (the cables length) are given, the location of the final actuator (coordinates of point C) can be obtained. In the other words, it means determining the coordinates of final actuator of the robot as a function of the length of the cables. In cable robots, like most parallel robots, finding this relationship is difficult and complicated. From the review of the previous researches, it can be concluded that there is no single answer to solve the problem of direct kinematics of parallel robots (H. R. Taghirad et al., 2014; Vafapour et al., 2021). Genetic algorithm is one of the proposed solutions to solve this problem. In this method, the problem becomes an optimization model. Another solution to the direct kinematics problem is the use of artificial neural networks. In this method, first the neural network is trained with the help of inverse kinematics, and in the next step, by doing the reverse of this task, an attempt is made to solve the problem of direct kinematics. Although the initial efforts did not have a favorable result (H. R. Taghirad et al., 2014). Since the equations provided for the inverse kinematics of the cable robot are in the form of nonlinear equations, it is concluded that there is no analytical solution for the direct kinematics equations of this robot, and numerical methods and software assistance can be used if needed (Rajabi Moghadam, 2020).

Simulation of the robot movement in Simscape Multibody environment

Simulink is one of the tools for modeling, simulation and analysis of systems in engineering and due to its accuracy and high performance, it is widely used and trusted in industry and research. Simscape multibody environment of Simulink is special for robotics and robot analysis. Simscape helps engineers to model and analyze mechanical systems, especially robots. The first thing analyzed in the simulated system is the inverse kinematics of the robot. It means that by giving the position of the robot final operator, the cable length for each column can be calculated and displayed. By doing this, correctness of the inverse kinematics equations of the robot is checked and the theoretical results can be compared with the simulation results.

In this research, Simscape simulation environment was used. In this simulation, the behavior of the robot was investigated for different inputs (various points and paths). As shown in Figure 4, the robot chassis which consists of four columns and also the final actuator (robot platform) were modeled with real sizes. Then by giving the X and Y points in the MATLAB software environment, or by giving the path, various outputs were checked. Then the calculated cable length was converted to the required angle of each motor and applied to the DC encoder motors. A PID controller, which is one of the most widely used industrial controllers, was used to control the robot. After that, by forming the control loop, the required angle for each motor and the angles that reached by each motor in practice were improved using PID controller; and the time response diagram was drawn for each motor. In the last step, the desired position of the robot (desired X and Y) and the actual position of the robot (actual X and Y) were compared with each other and the time response diagram was drawn for it.

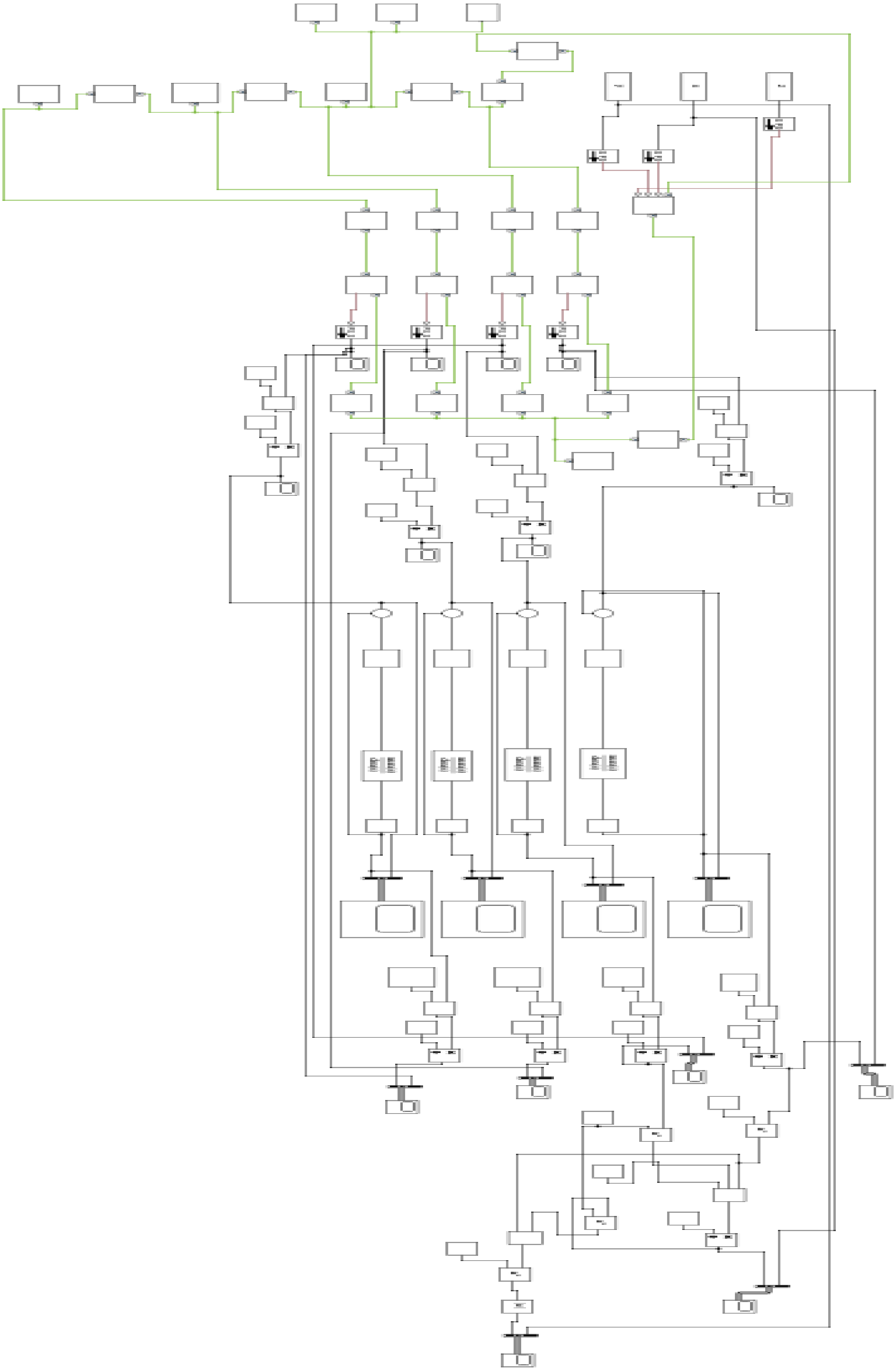


Figure 4. Inverse kinematics simulation of the cable robot in Simscape environment

Finally, the direct kinematics of the robot was simulated. In this simulation, by specifying the length of each cable, the position of the robot final actuator was obtained and displayed. The direct kinematic simulation diagram of the robot is shown in Figure 5.

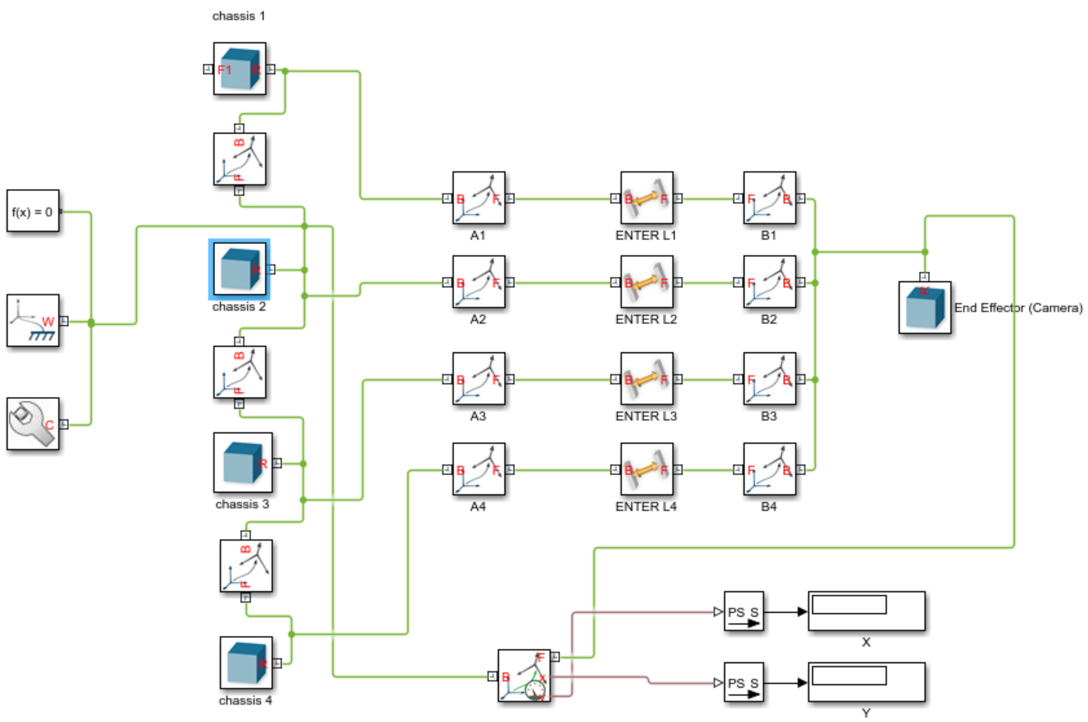


Figure 5. Direct kinematics simulation of the cable robot in Simscape environment

Results And Discussion

To analyze the simulated cable robot behavior, the robot movement in reaching a hypothetical point as well as traveling along a specific path was investigated and its time response diagram was drawn. Before the final test, the controller was adjusted (tuned) in MATLAB software, so that the robot would show appropriate and acceptable performance in terms of control indicators. The only variable in simulation process was the robot speed in three values, low (80 from 255), medium (160 from 255), and high (240 from 255).

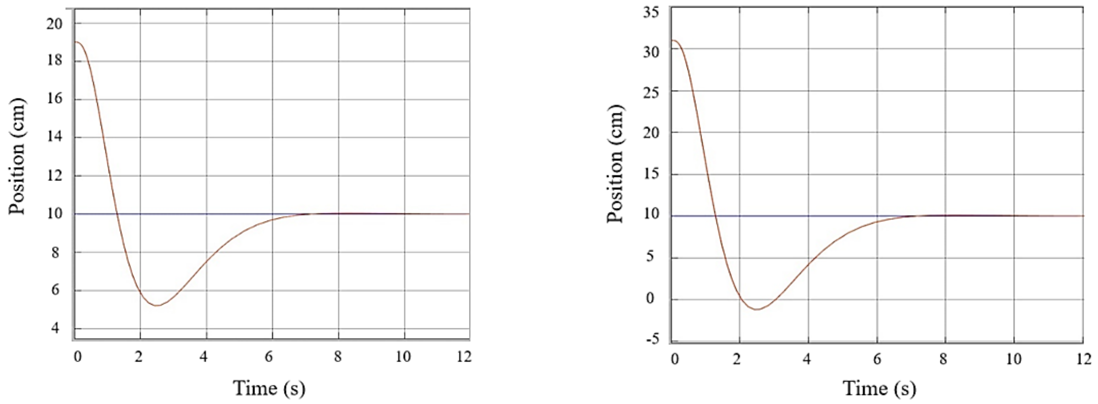
The robot performance in reaching a defined point

As shown in Table 2, increasing each parameter of the PID controller has its own effect on the system response. In the Tune environment of MATLAB software, it is possible to view the shape of response instantly by setting the control parameters and to choose the acceptable response. To investigate the robot behavior in reaching a hypothetical point of the working space (with X and Y coordinates), the point was defined as the robot destination point in the Simscape environment. Time response diagrams of the robot in reaching the destination point, for two of the 12 selected points, are shown for X and Y coordinates in Figures 6 and 7, separately.

Table 2. Effect of PID controller parameters on the robot response

Control parameter	Functional parameter			
	Rise time (T_r)	Settling time (T_s)	Overshoot (OS)	Steady state error (SSE)
P	Decrease	A few changes	Increase	Decrease
I	Decrease	Increase	Increase	Deletes
D	A few changes	Decrease	Decrease	A few changes

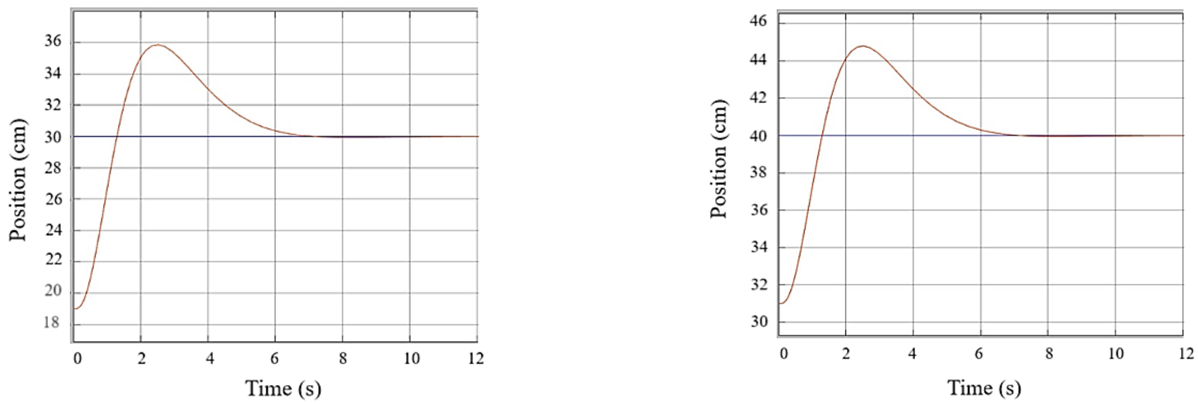
According to Figure 6, the rise time of the response was about 1.2 seconds, which indicates the appropriate speed of the system response, and the peak time was about 2.2 seconds. But the amount of overshoot was a little high. However, tuning the controller and changing each of the control parameters had its own effect on the response. Besides, another reason for this overshoot was the calculations used in the Simulink software to obtain the robot direct kinematics, and it showed itself in the response. Therefore, in practice, the amount of this overshoot will be much less. It can be seen that finally the response value was close to the desired value and the steady state error was equal to zero. This shows the appropriateness of using PID controller in the system control. Also, due to the open problem of direct kinematics of cable robots, the calculations performed in Simulink to obtain the direct kinematics of the robot caused the initial value of the response to be non-zero. Since, the initial value was greater than the final value of the system response, it caused the graph peak point be occurred in below.



(a) (b)

Figure 6. The robot time response in reaching the point with coordinates (10, 10), a) X coordinates, b) Y coordinates

In Figure 7, the rise time of the response was about 0.8 seconds, which indicates the appropriate speed of the system response. The peak time was about 2.3 seconds, and the overshoot value was between 10 and 20%, the acceptable amount of overshoot was about 20%. The final response value was close to the desired value and the steady state error was equal to zero. This shows the appropriateness of using PID controller in the system control. As mentioned, due to the calculations involved in obtaining the robot direct kinematics, the response did not start from zero. For the rest points, one of the above two states occurred and the steady state error was almost equal to zero.



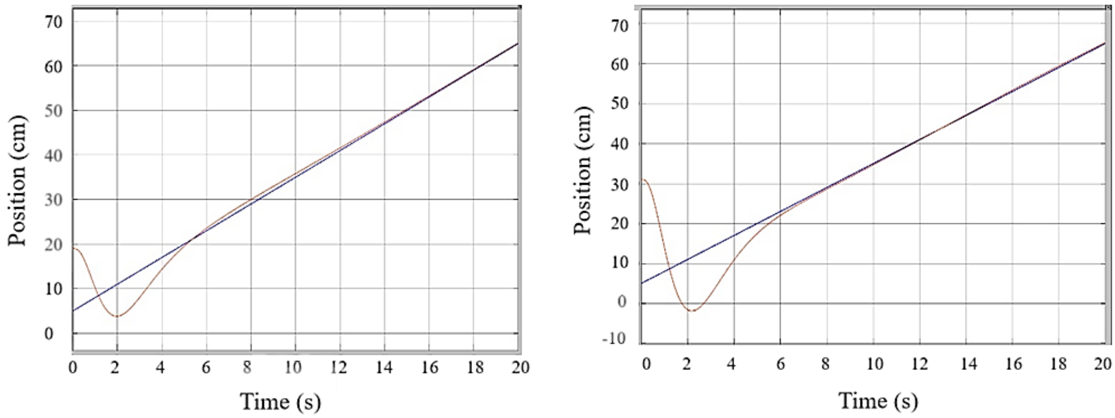
(a) (b)

Figure 7. The robot time response in reaching the point with coordinates (30, 40), a) X coordinates, b) Y coordinates

coordinate. As mentioned before, the effect of calculations used in the Simulink software to obtain the robot direct kinematics are shown in this section. Therefore, in practice, the amount of overshoot will be much less. The final response value was close to the desired value and the steady state error was almost equal to zero, which shows the appropriateness of using the PID controller in the robot control.

The robot performance in traveling a linear path

In the second test, a linear path for the robot movement was defined in Simscape environment. The path traveled by the robot in two X and Y directions can be seen in Figure 8. The time to reach the peak, was about 2.1 second, and the overshoot value was about 50% for the X coordinate and more than this value for the Y coordinate.



(a) (b)

Figure 8. The robot response along a linear path, a) X coordinates, b) Y coordinates

CONCLUSIONS

In this research, the designed laboratory two-dimensional cable robot was analyzed and simulated. Theory topics of the robot direct and inverse kinematics were discussed, and then the relations were analyzed in the Simscape Multibody of MATLAB software and their correctness was confirmed. In the robot control, a PID controller was used to check the robot movement in reaching a desired point and along a specific path. According to the results, the robot behaved well in both cases of reaching a hypothetical point and traveling a certain path.

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Data availability: The datasets generated and used during this study are available from corresponding author on reasonable request.

Conflict of interest declarations: The authors declare that they have no conflict of interest.

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