Modeling and Optimal Control of a Sport Utility Cable Suspended Robot

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Abstract: A new mechanism is presented in this paper for simulating the athlete performance and training the sportsman's exercises. This mechanism is an autonomous closed loop six degrees of freedom (DOFs) cable suspended robot which eases the implementation of some sport utilities. It cancels the necessity of presence of a sport coach for training the sportsman. Using the proposed robot, it is possible to program the robot for training the athlete limb (arm, leg and etc.) within a predefined trajectory corresponding to his special sport performance. Considering the fact that in many sports a large environmental space needs to be covered by the athlete movement, ordinary robots are not capable to be employed for this application while cable robots are applicable since a large dynamic workspace can be covered by them. Moreover, training the sportsman limb requires a precise movement of the mentioned end-effector on a predefined trajectory. This importance could not be satisfied without using a proper closed loop controlling system since variable external disturbances affects on the end-effector as a result of the weight of the sportsman limb and its dynamic movement. The validity and efficiency of the proposed mechanism in training the athletes' limb is verified by conducting experimental test on Iran University of Science and Technology (IUST) cable robot (ICaSbot).

Keywords: Automatic Sport-brancard, Cable Suspended Robot, Closed Loop Tracking Control, Rehabilitation, Sportsman Training, Studio Cam

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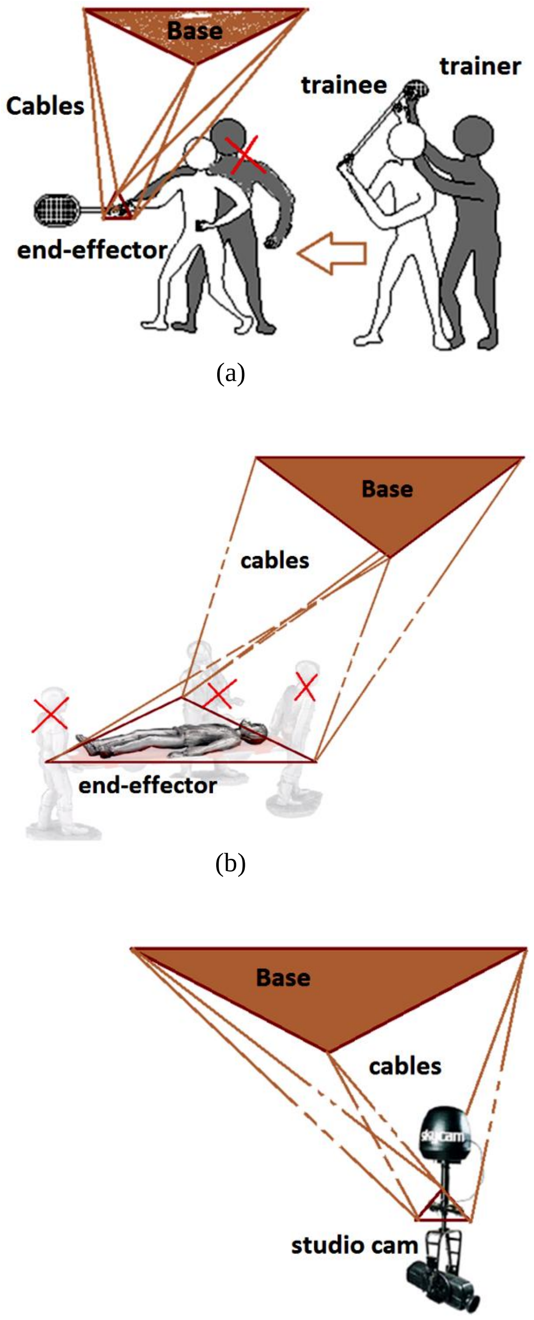
1 INTRODUCTION

Most of the sports require hard working becoming expert for a specified maneuvers in a special limb of the body. This goal cannot be covered unless bearing hours of training. An expert sport coach is required to be employed to guide the athletes and train their limbs to track a specified path and promote their performance. This procedure not only needs extraordinary cost but also some times requires extremely concentration from both sides of the athlete and coach to diagnose the mistakes and improve the movement which finally results in boring exercise hours. The lack of a robot which could be programmed in order to train the athletes' limb on a predefined path accurately for hours over and over without making a lot of cost and causing boring feels for the coach is highly observable. Guiding the studio cam which could be able to cover whole the field without the necessity of usage of helicopters is of other applications of the cable robots. It is obvious that an exact closed loop controller is required to guide both the translational and rotational angle of the end-effector. Moreover, the injured sportsman in the fields who needs to be guided to the out of the field has been a challenge for years.

Traditionally, two employers need to be employed to carry the injured athlete by the aid of a brancard toward the out of the field. Recently, some especial machines are substituted to cover the mentioned responsibility. However again the speed of these machines is considerably low which lose a lot of time. Besides, again some employers are required to place the injured sportsman on the mentioned machine which again represents the deficiencies of the traditional brancards. Here again by designing a proper robot and programming it, the injured athlete can be easily carried toward the recovery place immediately and without the necessity of employing any extra employer. These expectations can be fulfilled by the aid of the mentioned cable robot as a result of their large dynamic workspace and also their programmability.

Based on the mentioned explanations, an alternative solution can be proposed for training the athletes or carrying the injured sportsman and also managing the studio webcams based on proper robotic mechanisms which are capable to be controlled by the aid of a good closed loop controller and also are able to be programmed using an user friendly Graphical User Interface (GUI). Moreover, the possibility of training the operator before getting involved in the real practical training procedure is possible by providing a simulator which simulates the mentioned scenario for the operators. Some applications of the cable robot in sport utilities can be seen in Fig. 1.

One of the candidate mechanisms for covering the similar performances is parallel hexapod robot which is employed for a famous flight simulator that is represented in [1]. This simulator was designed in a way that generates the realistic feeling of takeoff, landing and in-flight turbulence. This manipulator was first presented by Stewart in 1965 and called Stewart Platform Based Manipulator. This mechanism is one of the closed loop chain parallel manipulator which has some advantages over serial mechanism.



(a)

(b)

(c)

Fig. 1 Some applications of the cable robot in sport (a. training or rehabilitation, b. brancard, c. studio cam)

Higher accuracy, bigger stiffness and higher load carrying capacity are of its main advantages. However, workspace of this kind of parallel robots is substantially smaller than that of a similar serial machine. Cable array robots are a class of light parallel manipulators with a large workspace which is a modification of cranes aiming to object handling using several actuated cables which provides the capability of control the object in all of its spatial Degrees of Freedom (DOFs). Thus it is possible to generate a path and carry the objects with a high accuracy in three translational directions and three rotational ones. They usually have a lower moving inertia compared to its rigid link counterpart. Moreover one of the most important advantages of this kind of parallel robots over its traditional parallel types is its larger dynamic workspace. This specification allows us to use it as a sportsman simulator, automatic sport brancard and studio cam since usually a large workspace needs to be covered for this kind of applications.

The flexibility of cables also allows the required training maneuvers to be performed easier. That's why, cable robot is the best choice to meet these goals while linkage robots or traditional parallel manipulators are strictly rigid with considerably limited dynamic workspace and thus they cannot be used as the mentioned purpose. This robot consists of a fixed base and a moving platform as the end-effector supporting the moving payload. This end-effector is supported by several actuated cables for which its lengths can be controlled by the aid of motors and drums and its tension can be easily estimated using the installed force measurement systems. Dealing with this mechanism SPIDAR is designed to investigate the effect of the force feedback from the environment to an operator, on task performance. This feature can provide the possibility of force control of this kind of robots [2]. As a result one of the most important applications of cable robots is rehabilitation which could be extendable for sport utilities and injured sportsman [3-5].

Some researches have been conducted so far on the applications of robots particularly in sport utilities. Two samples of simulators by which the movement of the sportsman is simulated are presented in [6, 7]; this newly-developed rowing simulator consists of a rowing boat hull equipped with multiple position sensors attached to the oar and seat. For the mentioned robotic mechanisms with the sport utility applications the employed mechanism is not cable robot and so the mentioned advantages are ignored. The cable array mechanisms have been studied in the context of sport utility applications as a virtual sports machine in [8]. The possibility of a virtual tennis is studied in [9], where equipment is developed which makes reaction forces at a grip of a tennis racket. In the developed equipment, several wires are radially stretched from the grip in order to produce force and torque vectors with six degrees of freedom. Moreover, a versatile cable robot as a haptic interface is developed for sport simulation in [10]. This robot serves as a large-scale haptic interface in a multi-modal Cave environment used for sport simulation.

In contrast to current rope robots, the configuration of the presented robot is adaptable to different simulation tasks. However in these cable based robots, the sport performance cannot be programmed autonomously since the dynamic model is not used for a closed loop controller and the designed simulator simulates the movement by the aid of a haptic interface. Promoting the cable robot to serve for autonomous applications requires developing dynamic formulations and controlling them in a closed loop way. A prototype of spatial sample of cable robot with 6 DOFs is designed and manufactured at Iran University of Science and Technology (IUST) [11]. An optimal control strategy is proposed for it [12] and its maximum load carrying capacity is evaluated [13]. Also the flexibility of this kind of robots is investigated by [14] and its required hardware installation and its GUI programming are provided [15].

Thus considering the mentioned literatures, there are some deficiencies in the mentioned studies in order to provide the required facilities to use the proposed mechanism in the mentioned sport applications. In this paper dynamics of the cable robots together with optimal control theory is employed to control the limb of the athlete which is connected to the end-effector autonomously with a high accuracy in all of spatial DOFs to generate the desired path. Since the weight of the sportsman limb and its dynamic motion can be considered as external disturbances for the end-effector, it is required to control this nonlinear dynamic plant with a proper closed loop control system. Considering the fact that the weight of the body of the injured sportsman is not ignorable compared to the dynamic load carrying capacity of the robot, it is highly required to optimize the controlling gains to provide the maximum load carrying capability.

Feedback linearization method together with LQR is used in this paper to optimal control of the mentioned cable robot. The efficiency of the proposed mechanism and its controlling strategy is proved by the aid of some simulations by which the weight of the athlete limb is carried along a predefined trajectory that is supposed to be the required sport maneuver. Finally the correctness of the proposed mechanism and its programming which is proved by the aid of simulation is verified by the aid of some experimental tests which are conducted on an under constrained prototype sample of cable robot at IUST with 6 DOFs and 6 actuating cables (ICaSbot). Therefore, it is shown that the suggested mechanism and the proposed algorithm not only can successfully train the weight of an athlete limb or handle the studio webcam within a predefined path, but also is able to carry the load of the body weight of an injured sportsman toward the borders of the field.

2 DYNAMICS AND CONTROL SCHEME

First of all the dynamic equations of the cable robot needs to be represented. Dynamic equations of an under constrained cable robot with six DOFs and six supporting cables as depicted in Fig. 2, can be described as equation (1) [16]:

$$D(X)\ddot{X}+C(X,\dot{X})\dot{X}+g(X) \\ =-S_j^{\,T}(q(X))T;\ X=\{x_m,y_m,z_m,\varphi,\Theta,\psi\} \tag{1}$$

where X is the vector of translational and rotational DOFs of the end-effector, T is the tension vector of the cables, D is the inertia matrix of the robot, C is its Coriolis matrix, g is gravitational vector and S_j is Jacobian matrix. Also we have:

$$D=\begin{bmatrix} mI_3 & 0 \\ 0 & P^T IP \end{bmatrix};C=\begin{bmatrix} 0_3 \\ P^T\{I\dot{P}\dot{o}+(P\dot{o})\times I(Po)\} \end{bmatrix};g=\begin{bmatrix} 0 \\ 0 \\ -mg \\ 0_3 \end{bmatrix}; \\ S_j=\left[\frac{\partial q_i}{\partial x_j}\right]_{i\times j};P=\begin{bmatrix} 1 & 0 & -\sin\theta \\ 0 & \cos\psi & \sin\psi\cos\theta \\ 0 & -\sin\psi & \cos\psi\cos\theta \end{bmatrix};\dot{o}=\begin{bmatrix} \dot{\Psi} \\ \dot{\theta} \\ \dot{\varphi} \end{bmatrix} \tag{2}$$

Here q is the length of the cables, m is the load of the end-effector and I is the moment of inertia of the end-effector.

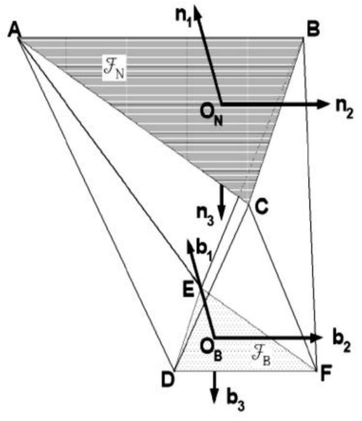


Fig. 2 Scheme of a spatial sample of cable robot

Here F_n is the fixed global coordinate attached to the fixed upper plate of the robocrane, F_b is local coordinate of the moving end-effector, A,B,C are the corners of the fixed plate and E,D,F are the corners of the moving end-effector and these points are connected using six flexible cables of time dependent length. Related state space for the mentioned spatial dynamic equations can be expressed as below [14]:

$$\begin{cases} z_1=x;z_2=\dot{x};z_3=y \\ z_4=\dot{y};z_5=z;z_6=\dot{z} \\ z_7=\psi;z_8=\dot{\psi};z_9=\theta \\ z_{10}=\dot{\theta};z_{11}=\varphi;z_{12}=\dot{\varphi} \end{cases};\begin{cases} \dot{z}_i=z_{(i+1)};if:i=odd;i=1,...,12 \\ \dot{z}_i=\dfrac{1}{D}(-C\dot{X}-g+S_j^{\,T}T)_{i/2};if:else \end{cases} \tag{3}$$

In order to prepare these nonlinear equations so that they could be ready to be used in LQR optimization method, exact feedback linearization method is applied to convert the sate spaces into linearized one. Therefore, the required cables' tension should be considered like equation (4) as the control input of the inner loop:

$$T=\{-S_j^{\,-T}(D(X)\nu+C(X,\dot{X})+g(X))\} \tag{4}$$

Where T is the tension of the cables and ν is the control input of the outer closed loop of feedback linearization which should be substituted as below to provide a controllable error equation stabilizable using LQR method:

$$\{\nu_i=\ddot{z}_{id}+K_{iD}(\dot{z}_{id}-\dot{z}_i)+K_{iP}(z_{id}-z_i) \\ \Rightarrow\{\ddot{e}_i+K_{iD}\dot{e}_i+K_{iP}e_i=0;i=1,..6 \tag{5}$$

where e is the error of the states, the index d denotes the desired value of the related parameter and K_{iP}, K_{iD} are the controlling gains of the position and velocity errors. These control procedure can be shown in the following diagram:

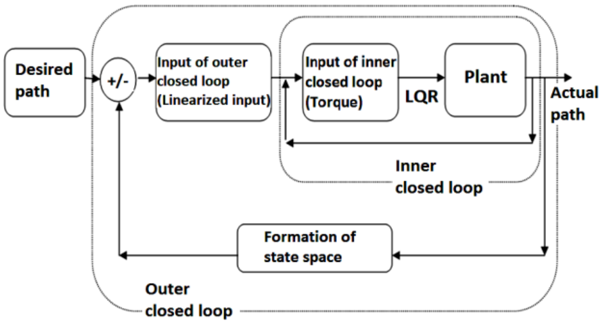


Fig. 3 Control procedure of the robot

Two main constrains of optimization of the robot subject to its payload including motor torque and tracking error are supposed to be minimized by the aid of LQR method in order to obtain the highest load capacity. Linearizing the system by the aid of feedback linearization theory has made it possible to optimize the outer control input gains by the aid of LQR method. Motor torques and end-effector errors are the terms of objective function to be minimized for the movement of the end-effector within a predefined trajectory. So the cost function can be defined as below:

$$J(x,t)=\int_t^{\infty}\begin{pmatrix} e(X,t)^T Qe(X,t) \\ +\nu(X,t)^T R\nu(X,t)\end{pmatrix}d\tau \tag{6}$$

Where *e* is the error of position and velocity of the end-effector, *Q* is the gain matrix of accuracy and *R* is the gain matrix of control input. Solving this cost function for a closed loop state space, results in the following Riccati equation where its stability is assured by the aid of Lyapunov equation [13]:

$$SA+A^TS+Q-SBR^{-1}B^TS=0 \tag{7}$$

where *A* and *B* are the state space matrix of the closed loop system. Solving the mentioned Riccati equation for *S* results in the following optimal control input which should be substituted in the equation (4). Here τ is the torque of the motors, Jc is the inertia matrix of the motor, *c* is its viscous friction matrix and $\dot{\beta}$ is the angular velocity of the motors.

$$\begin{aligned}&\nu^*=-R^{-1}B^TSe(X,t)\\ &T_i=\{J^{-1}(D(X)\nu+C(X,\dot{X})+g(X))\}_i\\ &\Rightarrow \tau_i=rS^{-1}(D\nu+C+g)+Jc\ddot{\beta}+c\dot{\beta};i=1,..6\end{aligned} \tag{8}$$

Table 1 The properties of the simulated cable robot

Name	Symbol	Value	Unit
Moment of inertia of the triangle end-effector	I	$Ixx=Iyy=0.0018$ $Izz=0.0036$	$kg.m^2$
Half of the base and end-effector triangle	a,b	0.59,0.085	m
Error gain matrix	Q	$diag[100]$	
Input gain matrix	R	$diag[0.1]$	
Radius of the motor	r	$diag[0.015]$	m
Damping Coefficient	c	$diag[0.01]$	$N.m/rad$
Rotary inertia of the	Jc	$diag[0.0008]$	$kg.m^2$
Mass of the end-effector	m	1.09	kg
Mass of the sportsman	m_l	0.5	kg

3 SIMULATION RESULST

In order to show the efficiency of the proposed methodology for carrying a load as an uncertainty within a predefined trajectory, a circular shape trajectory is considered as the desired path of sportsman training. Required motor torque and actual tracking of the end-effector in presence of parametric uncertainty is obtained and the results of the proposed closed loop optimal controller and the simple open loop case are compared. The specifications of the simulated spatial cable robot which is considerded as the mentioned trainer or automatic brancard are expressed in Table 1. The mentioned spatial system has the following state space equation:

$$\begin{Bmatrix}\dot{e}(z_1)\\ \dot{e}(z_2)\\ \ldots\ldots.\\ \dot{e}(z_{12})\end{Bmatrix}=\begin{bmatrix}010000000000\\ 000000000000\\ 001000000000\\ \ldots\ldots\ldots\\ 000000000000\end{bmatrix}\begin{Bmatrix}e(z_1)\\ e(z_2)\\ \ldots\ldots.\\ e(z_{12})\end{Bmatrix}+ \begin{bmatrix}000000\\ 100000\\ 000000\\ \ldots\ldots.\\ 000001\end{bmatrix}\begin{Bmatrix}\delta\nu_1\\ \delta\nu_2\\ \delta\nu_3\\ \delta\nu_4\\ \delta\nu_5\\ \delta\nu_6\end{Bmatrix} \tag{9}$$

It results in the following optimal control command:

$$\delta\nu=\begin{bmatrix}-31 & -32 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & -31 & -32 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & -31 & -32 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & -31 & -32 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -31 & -32 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -31 & -32\end{bmatrix} \times\begin{Bmatrix}e(z_1)\\ e(z_2)\\ \ldots\ldots..\\ e(z_{12})\end{Bmatrix}=\begin{Bmatrix}-31e(z_1)-32e(z_2)\\ -31e(z_3)-32e(z_4)\\ -31e(z_5)-32e(z_6)\\ -31e(z_7)-32e(z_8)\\ -31e(z_9)-32e(z_{10})\\ -31e(z_{11})-32e(z_{12})\end{Bmatrix} \tag{10}$$

The payload is increased by 0.5 kg as an uncertainty which is the weight of the sportsman limb or studio camera. The results of the open loop robot in which the system input is just feed forward commands is compared with the optimal closed loop system in order to verify the efficiency of the designed optimal controller. Comparison of the applied motors' torque for the two systems is shown in Fig. 4.

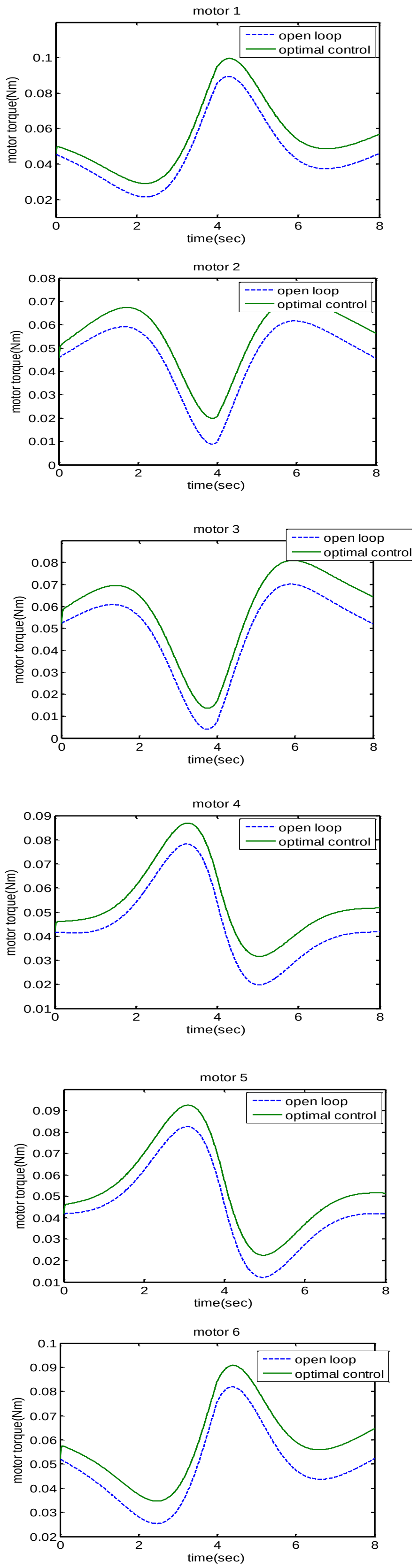


Fig. 4 Comparison of the applied motor torques for two systems

Based on these motors' torque, the comparison of trajectory for the predefined circular path with 10 cm diameter (for which the center is at the origin of the cartesian coordinate and its altitude is 0.45 m) and its related error comparisons for each degree of freedom are shown as in Fig. 5.

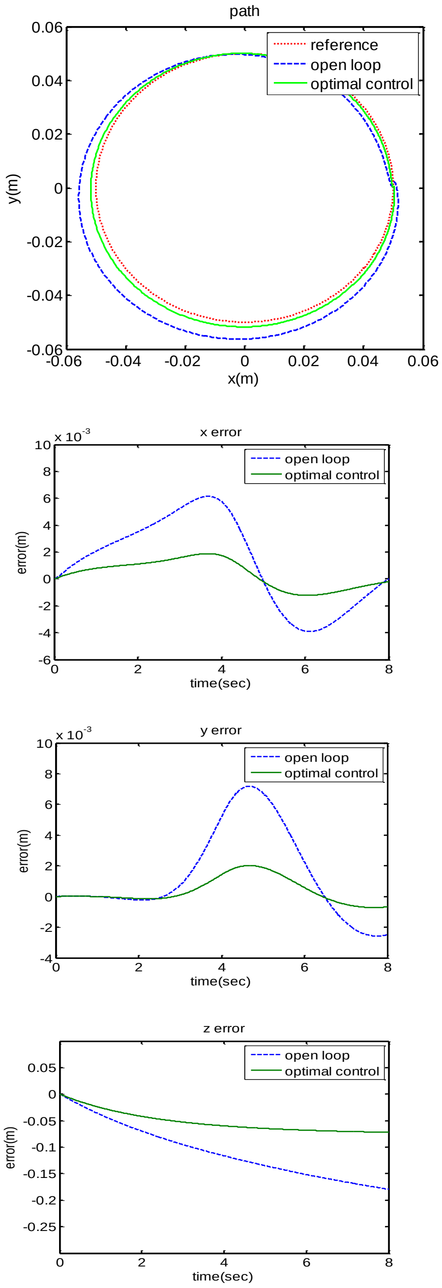


Fig. 5 Comparison of trajectory for a predefined circular path and its related error comparisons for each DOF

It can be seen that the designed controller has successfully carried the weight of the sportsman limb or athlete injured body as a parametric uncertainty. It is obvious that the optimal closed loop controller tries to decrease the amount of tracking error by increasing the required motors' torque within its allowable range and so prevents the end-effector of being deviated from allowable error bounds. This performance results in higher load carrying capability for the robot (more than 20% improvement).

4 EXPERIMENTAL SETUP

The under constrained cable robot of Iran University of Science and Technology (IUST) called ICaSbot with six DOFs and six actuating cables is a closed loop prototype of cable robot. The experimental tests are conducted on this robot in order to provide a comparison study between the simulation results and experimental tests and show the efficiency of the proposed algorithm ([11], Fig. 6, Table 2).

Fig. 6 Overall scheme of the ICaSbot (left), Motors, encoders, drums and cables of the robot

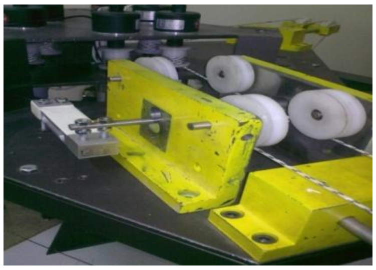


Fig. 7 Load cell as the used tension sensing device

Pulse width Modulation (PWM) method is used to control the motors based on feed forward terms of inverse dynamics and feedback terms of PD controller [17]:

$$PWM = PWM_f(\tau, \dot{\beta}) + K_{dm}(\dot{\beta}_d - \dot{\beta}) + K_{pm}(\beta_d - \beta) \quad (11)$$

where PWM_f is the feed forward term of PWM which is calculated through the inverse dynamics of the robot together with feedback linearization method and is a function of torque and speed of the motor. *Kdm, Kpm* are PD controlling gains of the speed and angle of the motors respectively. The speed of the motors is evaluated using encoders. Moreover, Loadcell is employed to monitor the actual kinetic response of cables' tension [18] which is exerted on the robot as a result of athlete weight and its dynamic movement (Fig. 7), where the specification of each load cell is listed in Table 3.

Table 2 Geometrical properties and motor specification of the robot

Body	
Height	120 cm
Variable side length of base triangle	100-120 cm
Weight	350 Kg
End Effector	
Side length of base	17 cm
Thickness	8 mm
Weight	1100 g

Motor	
Mark	DC gear motor
Model	Buehler 1.61.070
Reference voltage	12 v
No load speed	103 rpm
Max torque	910 mN.m
Rated current	1.4 A
Reduction ratio	1:25.2
Weight	220 g

Table 3 Specification of force sensor

Model	Single Point 1661
Material	Aluminum Alloy
Surface	anodized treatment
Size	$250 \times 350\text{mm}^2$
Capacity	5kg
Excitation Voltage	$5-10\text{Vdc}$
Output sensitivity	$2.0 \pm 0.1\text{mv / v}$

A combination of laser and camera is employed in order to record and feedback the actual position of the end-effector [19]. The lasers are responsible of recording the altitude of the end-effector together with its angles while the camera is used to monitor its planar movement (Fig. 8).

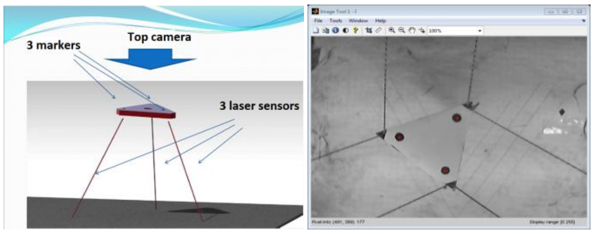
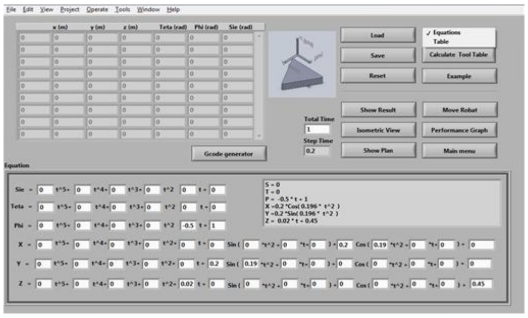


Fig. 8 Strategy of recording all of the end-effectors DOFs by coupling the camera and laser data

"Advantech-PCI-1711L" card is applied for reading the analogue data of loadcell and laser sensors, while "Advantech-PCI-1780" card is applied for reading the digital data of motor and encoder sensor (Fig. 9).

Fig. 9 Data card, external electronic board and the cable



Total Time 1

Step Time 0.2

Sie = 0 t^5+ 0 t^4+ 0 t^3+ 0 t^2 0 t+ 0

Teta = 0 t^5+ 0 t^4+ 0 t^3+ 0 t^2 0 t+ 0

Phi = 0 t^5+ 0 t^4+ 0 t^3+ 0 t^2 -0.5 t+ 1

X = 0 t^5+ 0 t^4+ 0 t^3+ 0 t^2+ 0 t+ 0 Sin(0 *t^2+ 0 *t+ 0)+ 0.2 Cos(0.19 *t^2+ 0 *t+ 0)+ 0

Y = 0 t^5+ 0 t^4+ 0 t^3+ 0 t^2+ 0 t+ 0.2 Sin(0.19 *t^2+ 0 *t+ 0)+ 0 Cos(0 *t^2+ 0 *t+ 0)+ 0

Z = 0 t^5+ 0 t^4+ 0 t^3+ 0 t^2+ 0.02 t+ 0 Sin(0 *t^2+ 0 *t+ 0)+ 0 Cos(0 *t^2+ 0 *t+ 0)+ 0.45

```
S = 0
T = 0
P = -0.5 * t + 1
X =0.2 *Cos( 0.196 * t^2 )
Y =0.2 *Sin( 0.196 * t^2 )
Z = 0.02 * t + 0.45
```

Fig. 10 A view of graphical environment to generate robot path

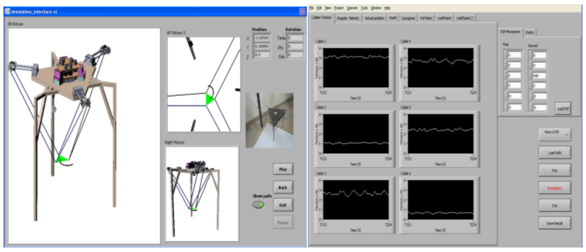


Fig. 11 Online graphical display window of cable tension for each sensor output

Finally, a GUI is designed in LabVIEW in order to generate and record the desired path of the sportsman training, control the end-effector of studio camera or brancard and monitor the required data [15]. A scheme of the designed interface is shown in Fig. 10 and Fig. 11. Controlling commands as a desired trajectory are sent to the hardware by the aid of a window like Fig. 10 and its results are monitored in an online way in a window like Fig. 11. Generally the overall scheme of controlling the robot in a close loop way is depicted in the following flowchart. It consists of an inner loop to control the motors' speed each 0.01 seconds and an outer loop which controls the position of the end-effector or sportsman limb each 0.2 second.

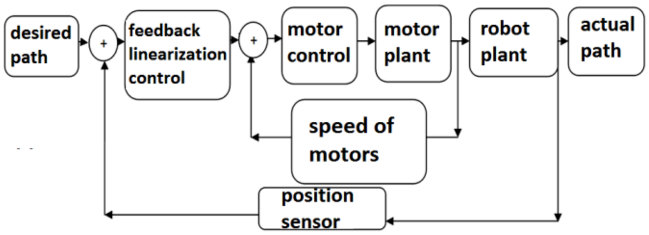


Fig. 12 Controlling strategy of the cable robot of ICaSbot in a training process

5 EXPERIMENTAL VERIFICATION

An experimental test is conducted on the mentioned ICaSbot cable robot to validate the simulation results and prove the efficiency of the proposed mechanism and its controlling strategy for guiding the athlete limb on a predefined trajectory. It is supposed here that the training process should be performed on a semicircle with 10 cm radius as the desired trajectory in z=90 cm while its origin is located at x=0 cm, y=0. A load about 1 kg is placed on the end-effector as the weight of the limb. Recorded position of the center of the end-effector by the aid of the designed GUI can be seen in Fig. 13.

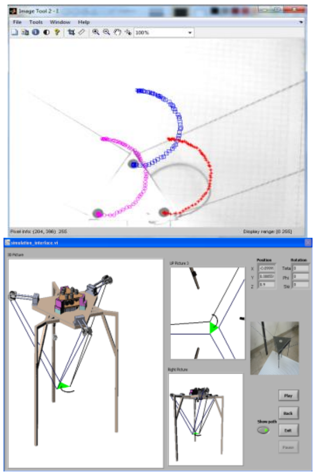


Fig. 13 Recording the trajectory by the aid of designed GUI

Moreover, comparison of the tracked trajectory for simulation and experiment is shown in Fig. 14. An acceptable compatibility of the simulation and experimental results prove the efficiency of the proposed algorithm for carrying the sportsman limb or injured athlete on a predefined trajectory. The little difference and vibration of experimental profile around the simulation result is due to motor friction, its clearance and other un-modeled uncertainties.

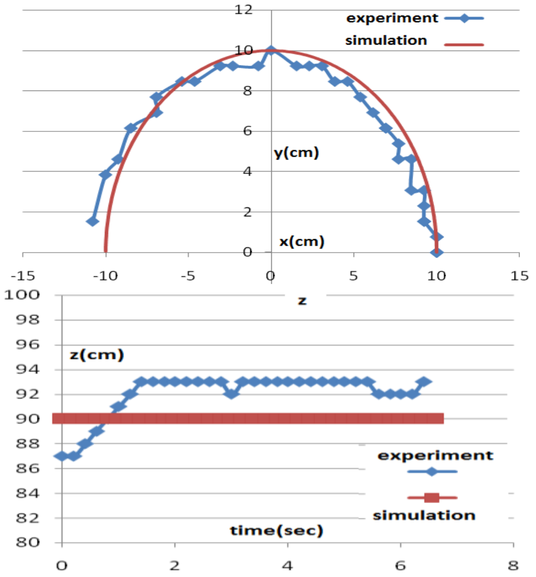
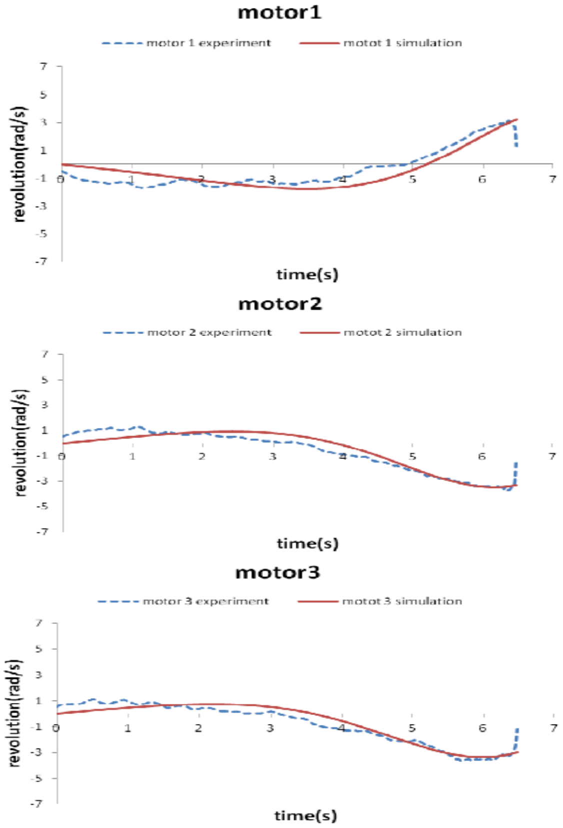


Fig. 14 Comparison of the trajectory for simulation and experiment



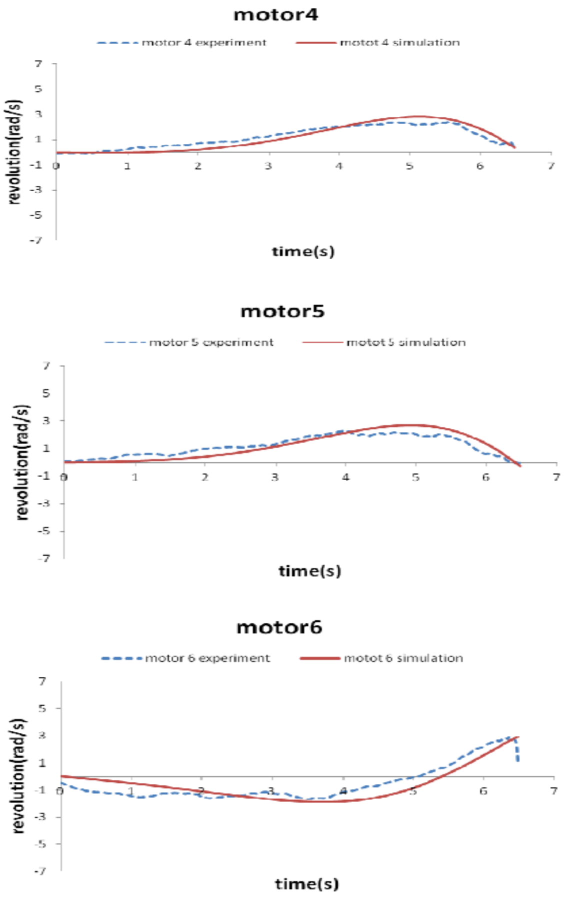


Fig. 15 Motors' speed for simulation and experimental test

Comparison of the motor speed between simulation and experiment is also plotted in Fig. 15. Again it can be seen that the trend of profiles are exactly the same and the vibrating response of experimental curve can be reffered to the above mentioned uncertainties and aslo the resolution of the encoders. Finally the comparison of the cables' tension as the kinetic response of the robot can be seen in Fig. 16. This tension together with the speed of the motors can be used as an evaluation of the actual torque which should be exerted on the motors in order to carry the training subject, studio camera or brancard on its desired path.

Putting away the phenomenon of vibrating behaviour of the experimental curves which is the result of the mentioned uncertainties and the resolution of the load cells, it is obvious that the compatibility of simulation and experiment in the response of kinetics of the robot is also good which indicates the correctness of the proposed modelling, simulation process and experimental installation and finally proves the efficiency of this mechanism in performing the mentioned sport mission.

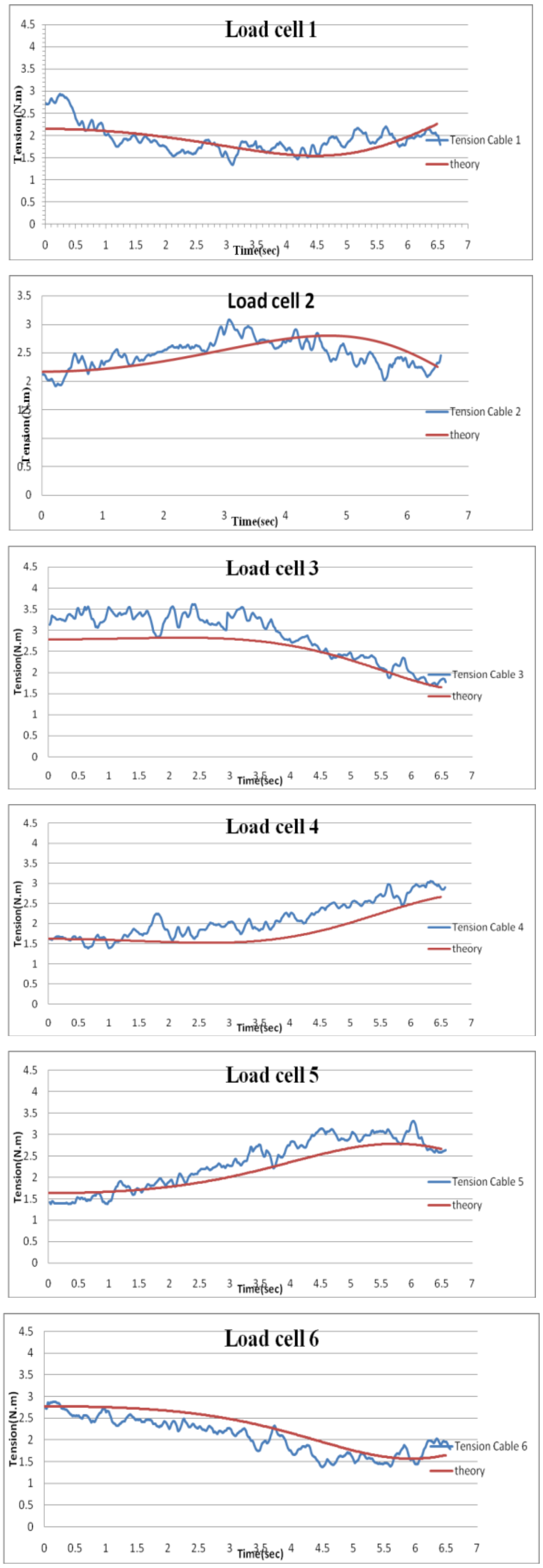


Fig. 16 cables' tension for simulation and experimental test

7 CONCLUSION

A new mechanism was presented in this paper as a sportsman trainer, automatic brancard and studio camera manager called cable robot. It was modelled and autonomously controlled using closed loop optimal control in order to handle the sport object with the highest accuracy. It was shown that this expectancy may be met due to the fact that the end-effector can cover a large dynamic workspace and is able to guide the sportsman limb or brancard or studio camera with an optimal closed loop controller within a predefined path. Simulation was performed for a predefined circular trajectory. It was observed that the proposed closed loop cable robot may successfully carry the injured athlete, manage the studio camera or train the sportsman limb on a predefined trajectory by the aid of producing a proper motor controlling torque. It was observed that this control is a mixture of inverse dynamics of the robot as the feed forward controlling term and feedback linearization as its feedback controlling term.

Finally the required torque was optimized using LQR to provide the possibility of carrying the maximum load (about 20% improvement was observed). The efficiency of the proposed mechanism and its related controller for the mentioned sport applications were also verified experimentally by conducting some tests on a prototype of cable robot (ICaSbot) manufactured in IUST. Although some deviation and vibrating response was observed through the profile of the experimental results, which is the result of flexibility and other un-modelled uncertainties of the system, the good compatibility of the kinetics and kinematics of the robot between simulation and experiment confirmed the efficiency of the proposed mechanism for the mentioned sport mission.

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