Scientia Iranica B (2013) 20(5), 1550–1565

Sharif University of Technology
**Scientia Iranica**
*Transactions B: Mechanical Engineering*
www.scientiairanica.com


*Research Note*

# A method for simultaneous control of speed and torque of the motors of a cable suspended robot for tracking procedure

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Received 22 August 2012; received in revised form 26 February 2013; accepted 30 April 2013

**KEYWORDS**
Cable robot;
DC motor control;
Speed control;
Torque control;
PWM.

**Abstract.** In this paper, a new method is proposed for controlling the motors of ICaSbot (IUST Cable Suspended Robot), which is a modified version of crane aiming to object handling in industrial environments. In order to provide more accurate tracking, torque and speed of the motors are controlled simultaneously, using inverse kinematics and inverse dynamics of the robot. The equations of the motors are evaluated as a look-up table by conducting some special experimental tests and calibrations, while their data sheets and motor parameters are not available. The required feedforward signal of the motors are estimated by the aid of inverse dynamics of the robot, while its errors are compensated by the aid of PID controller on the speed and torque of the motor. As a result, the required (Pulse Width Modulation) PWM of the motor is exerted to produce a desired angular velocity, while a specific amount of torque is applied on the motors. Not only the voltage of the motors is controlled using the mentioned PWM, but also the current is improved using the feedback control of the torques. PID gains are optimized using Ziegler-Nichols method. By the aid of the mentioned combination of feedforward and feedback controlling terms of the motor speed and torque, the desired trajectory is tracked with the highest possible accuracy. Efficiency of the proposed method is eventually proved by comparing the experimental tests with simulation results.



## 1. Introduction

The first cable robot was designed and manufactured by Albus, and after that, a vast variety of this kind of parallel robots with different geometrical configuration were developed rapidly. This robot is a kind of parallel robot in which the end-effector is controlled using several parallel cables that are elongated by the aid of motors. The most important application of this kind of robots is object handling as a modified version of cranes, studio cams, machining, rehabilitation, etc. [1,2]. An under-constrained sample of cable robot is designed and manufactured in Iran University of Science and Technology (IUST), called ICaSbot which supports six Degrees Of Freedom (DOF), using six actuating cables and six DC motors.

The translational and rotational movement of the end-effector of this robot should be controlled by the simultaneous control of its six DC motors which are responsible for changing the length of the cables. In order to provide a proper control of the motors of robot, it is highly required to use a nonlinear controller like computed torque method as the feedforward term

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of the controlling signal of nonlinear dynamics of the robot, while a PID should be added as the feedback term of a linear controller to improve the performance of linear dynamics of the motors. To do so, the desired angular velocity of the motor should be realized while carrying a specific amount of torque. This importance is highly required to have a fast dynamic response of the end-effector of the robot for producing an accurate tracking, especially in some precise equipments like CNC machines. For the cable robot of IUST, six DC motors are used, since both speed and torque are controllable in this kind of motors, and permanent magnet type is chosen, since an acceptable proportionality can be established between the torque and motors current [3]. So, a proper controlling strategy for these motors is highly appreciated, in which our expectancy regarding control of the robot on a predefined trajectory could be satisfied.

Some research projects have been performed in this area so far. Urrea and Kernt [4] has estimated the dynamic model of a motor, and control of the motor is performed using the extracted dynamic model and simulating its dynamic behavior based on its estimated dynamic parameters. The results are verified by comparing them with simulation profiles. Ristanovic et al. [5] has done the modeling, simulation and control of an electromechanical actuator (EMA) system for Aero Fin Control (AFC) with permanent magnet brush DC motor driven by a constant current driver. Nonlinear model of the EMA-AFC system has been developed, and it is experimentally verified in actuator test bench. The model has been used as the starting point for PID position controller synthesis. The proposed method is implemented on a real analog servomotor. It can be seen that the exact dynamic model of the motor is required in the mentioned researches to control the robot. Anandaraju et al. [6] has employed a PID controller for controlling DC motors. In his method, the gains should be tuned by the aid of a proper iterative method. Genetic algorithm is a good choice for optimizing the PID gains for speed control of DC motors. Different objective functions are used for tuning the gains. Allaoua et al. [7] used adaptive neural network to control the speed of a DC motor. Fuzzy control is employed by Namazov [8] to control the position of a DC motor. He also needed the model of the DC motor, while the Fuzzy Pain Demand (FPD) parameter should be tuned in MATLAB. It is possible to control the disturbed signals and omit them with FPD, without tuning the PD parameters separately. Koksal [9] controlled the DC motor, using model-based adaptive control. The required model of the motor is estimated in this research, using a parameter identification method, based on Model-Referencing Adaptive Control (MRAC), which is one of the suitable methods of controlling the motor while the motor parameters are not available. Arez [10] employed algebraic identify, and controlled an unknown DC motor with delta method. Algebraic identification is used for high speed control and linearizing the system for controlling it based on feedback method, while the motor parameters are not available. Delta operator is an effective alternative approach like z transformer for high speed sample rate systems. One of the benefits of the high speed sample rate systems is that they can move smoothly from continues time to separate time. Hashemi et al. [11] has developed a high performance PI-based controller for an Interior Permanent Magnet Synchronous Motor (IPMSM) drive. An artificial neural network is used for online tuning of the PI controller. The Genetic Algorithm (GA) has been used in this work in order to obtain the optimized values of the controller parameters for precise speed control and different operating conditions over a wide speed range. In [11], the optimal behavior of a drive is achieved by considering two control strategies: Maximum Torque Per Ampere (MTPA) and Flux-Weakening (FW). Liu et al. [12] controls the position of a DC servo motor by the aid of PID in LabVIEW environment. The online control is realized using Data Acquisition (DAQ) card. Fuzzy controller together with PID (FPID) is used by Altayef and Qun-Xiong [13] to control the position of DC motors in LabVIEW environment. Again, DAQ card is used to control the motor in an online way. The experiment results show that Fuzzy Logic Controller (FLC) has a good performance. Yan-hong et al. [14] has optimized the gains of PID controller of servo motors. The dynamics of the robot is used to control a mobile robot by the aid of PID. In order to make the system robust, neural network equipped by observer is added to the controller. Optimizing and tuning the gains of PID is done by employing genetic algorithm. The proposed algorithm is implemented for a motor driver, and its efficiency is verified by experimental tests. Control of a geared DC motor, the data sheet and parameters of which are not available is performed by Reyes-Reyes and Astorga-Zaragoza [15], using simple neuro-control law to control the position of the motor. The proposed artificial neural network is characterized by two input synaptic weights, two output synaptic weights and one threshold; these parameters are used to define the performance of the closed loop system. Since numerical analysis is involved in controlling strategy of these researches, online control capability and speed of calculation are not as well as analytic solutions.

Therefore, it can be seen that some aspects of this topic are not completely covered yet. A proper controlling strategy compatible with robotic systems and independent of dynamic model of the motor, in which both speed and torque of the motor could be controlled simultaneously, in an online way, is not fulfilled yet. This expectation can increase the speed and accuracy of end-effector tracking.

In this paper, for the cable robot ICaSbot, six DC motors with permanent magnet are used for which a good controlling strategy can be employed for producing a suitable voltage and controlling its speed and torque on a desired profile, based on the desired trajectory of the end-effector. Controlling the speed and torque is realized by using computed torque method as the feedforward term of controlling signal, and PID as its feedback controlling signal. PID on the speed of the motor controls the voltage of the motor, and PID on the torque controls the current of the motor. PWM method is used to control the motors since it has the least loose of energy and also lets us control both speed and torque simultaneously, based on the above proposed method. In this paper, after calibration of the motors, the look-up table and thus the equations of the motors are evaluated by the aid of experimental tests conducted on each motor separately within its workspaces, which establish a relation between PWM, torque and speed of the motors by a proper curve fitting. The equations are extracted for the transient and steady states of the motors and also for both upward and downward motion of the motors separately. The advantage of this method is that not only the calculations are done analytically and in an online way, but also there is no need to have the dynamic model and parameters of the motor, and finally the speed and torque can be controlled simultaneously. The extracted equations let us estimate the required PWM of the motors, which results in a good voltage control, while current control can be fulfilled using a PID on the torque of the motors. To sum up, both feedforward and feedback terms of both motor speed and motor torque are considered to control the motors of the robot, and improve its performance. Thus, the desired speed can be provided for the motors, while a specific amount of load is exerted on it. The desired speed of the motors is estimated through inverse kinematics, and the torque of the motors is evaluated by the aid of inverse kinetics. Inverse dynamics should be solved based on the desired trajectory of the end-effector, which leads to the desired PWM of the motor. The resultant PWM will be then used as the feedforward term of controlling the signal, while a PD controller on the speed is also added to control the voltage and improve the speed of the motor, and a PD controller is added to control the current and improve the torque of the motors. The gains of the PD controller are optimized employing Ziegler-Nichols method.

In the next section, dynamics and controlling formulations of the robot and also the equations of the used DC motors are represented, and the proposed strategy of controlling the motor, based on dynamics of the robot, is explained. Afterwards, the implemented hardware and software installations are described. Motors calibration and the required experimental tests are then performed to extract the mentioned formulations of the motors. Finally the experimental test, based on the proposed methodology, is conducted, and the results are compared with simulation data of MATLAB, and its efficiency is verified and approved since a good compatibility is observed.

## 2. Formulation

### 2.1. Dynamic modeling of the robot

Dynamics of the cable robot of ICaSbot can be described as below (Figure 1) [16]:

$$D(X)\ddot{X} + C(X,\dot{X})\dot{X} + g(X) = -S_J^T(X)T,$$

$$X = (x_m, y_m, z_m, \psi, \theta, \varphi)^T, \tag{1}$$

where $X$ is the vector of translational and rotational DOFs of the end-effector, and $T$ is the tension vector of the cables. Also, we have:

$$D = \begin{bmatrix} mI_3 & 0 \\ 0 & P^T I P \end{bmatrix},$$

$$C = \begin{bmatrix} 0_3 \\ P^T \left\{ I\dot{P}\dot{o} + (P\dot{o}) \times I(Po) \right\} \end{bmatrix},$$

$$g = \begin{bmatrix} 0 \\ 0 \\ -mg \\ 0_3 \end{bmatrix}, \qquad S_J = \left[\frac{\partial q_i}{\partial x_j}\right]_{i\times j},$$

$$P = \begin{bmatrix} 1 & 0 & -\sin\theta \\ 0 & \cos\psi & \sin\psi\cos\Theta \\ 0 & -\sin\psi & \cos\psi\cos\Theta \end{bmatrix}, \qquad \dot{o} = \begin{bmatrix} \dot{\Psi} \\ \dot{\Theta} \\ \dot{\varphi} \end{bmatrix},$$

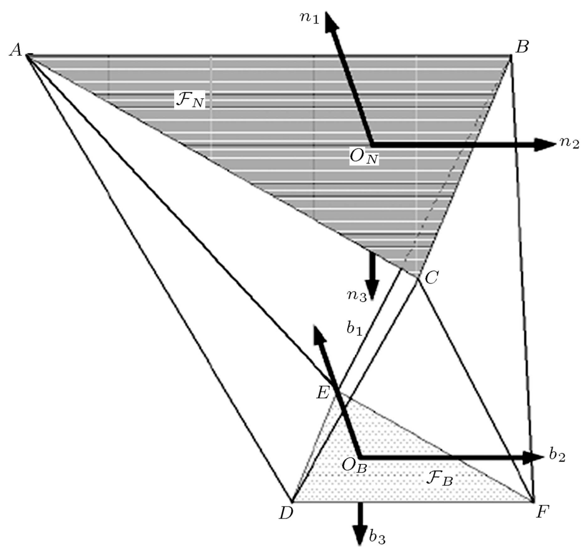


**Figure 1.** Scheme of cable robot [13].

where $D$ is the inertia matrix of the robot, $C$ is its Coriolis matrix, $g$ is gravity vector, $S_J$ is Jacobian matrix of the robot, $q$ 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.

According to [17], using feedback linearization method results in the following required cables' tension:

$$T_i = \left\{ S_J^{-1}(D(X)\nu + C(X,\dot{X}) + g(X)) \right\}_i, \quad i = 1, \cdots 6. \tag{2}$$

$\nu$ is the control input of the feedback linearization, and can be evaluated as below to create a controllable error equation:

$$\nu_i = \ddot{X}_d + K_{iD}(\dot{X}_d - \dot{X}_a) + K_{iP}(X_d - X_a), \quad i = 1, \cdots, 6, \tag{3}$$

where $K_{iD}$ and $K_{iP}$ are controlling gains of derivative and proportional errors of the end-effector, respectively, $X_d$ is the desired trajectory of the robot, and $X_a$ is its actual value. Also the required angular velocity of the motors ($\dot{\beta}$) should be evaluated using inverse kinematics of the robot. The following kinematic equation describes the relation between the cable's elongation and the pulley's rotation:

$$\left.\begin{aligned} \dot{q} = S_J \begin{bmatrix} \dot{X} \\ \omega \end{bmatrix} &= S_J \left(\dot{x}_m, \dot{y}_m, \dot{z}_m, \dot{\psi}, \dot{\theta}, \dot{\varphi}\right)^T \\ &= J \left(\dot{x}_m, \dot{y}_m, \dot{z}_m, \dot{\psi}, \dot{\theta}, \dot{\varphi}\right)^T \\ \delta q_i = r_i * \delta\beta_i & \end{aligned}\right\} \Rightarrow r_i * \dot{\beta}_i, \tag{4}$$

where $\delta_q$ is the elongation of the cables' length, and $\delta\beta$ is the variation of pulley's angle, which is a function of $X$:

$$\dot{\beta} = \frac{\partial \beta}{\partial X}\dot{X}, \qquad \ddot{\beta} = d/dt(\partial\beta/\partial X)\dot{X} + \ddot{X}(\partial\beta/\partial X), \tag{5}$$

where $X$ is the end-effector DOFs, and the angle of pulley, $\beta$, is a function of $X$. So the required cables' tension is calculated using inverse kinetic of the robot together with feedback linearization method, and the required angular velocity of the motor is evaluated using inverse kinematics of the robot. So the feedforward controlling term of the robot can be calculated using the mentioned computed torque and feedback linearization method. It is now possible to study the dynamics of the motor in order to evaluate its required PWM. The final calculated PWM will be then added to two series of PID controlling terms related to speed and torque of the motors.

### 2.2. Dynamic modeling of the motor

Dynamics of the motor which is depicted in Figure 2 can be stated as below [16]:

$$\tau_i = rT + J\ddot{\beta} + c\dot{\beta}, \qquad i = 1, \cdots 6, \tag{6}$$

where $\tau$ is the applied torque of the motor, $J$ is the rotary inertia of the motor, $r$ is the radius of the drum, $\dot{\beta}$ is its angular velocity and $c$ is the viscose damping of the motor. The desired motor torque and angular velocity were calculated in the previous section, using inverse dynamic of the motor, which results in the required torque of the motors (computed torque method + feedback linearization). So substituting Eq. (2) in Eq. (6) results in:

$$\tau_i = rS_J^{-1}(D\nu + C + g) + J\ddot{\beta} + c\dot{\beta}, \qquad i = 1, \cdots 6. \tag{7}$$

DC motors are employed to provide the desired calculated torque and angular velocity of the motors. The goal of DC motor modeling is to extract a proper formula presenting the relation between the armature voltage and its corresponding produced torque. Figure 3 shows the basic circuit diagram of a DC method is shown in Figure 4. motor. The general equations of DCPM (Direct Current Permanent Magnet) motor are presented below:

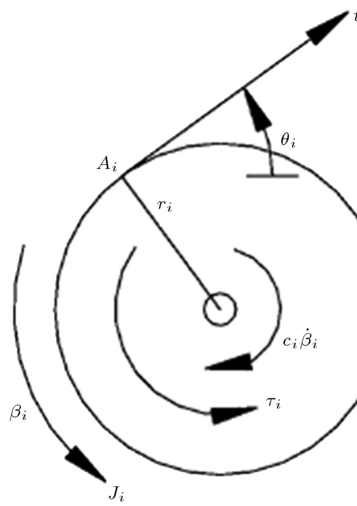


**Figure 2.** Scheme of the motor [13].

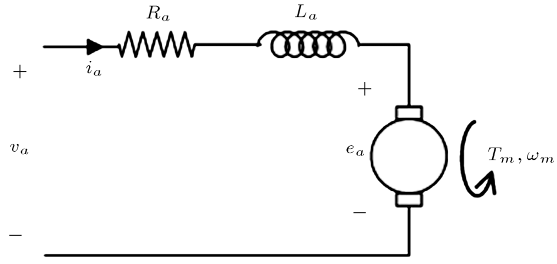


**Figure 3.** Circuit diagram of a DC motor [15].

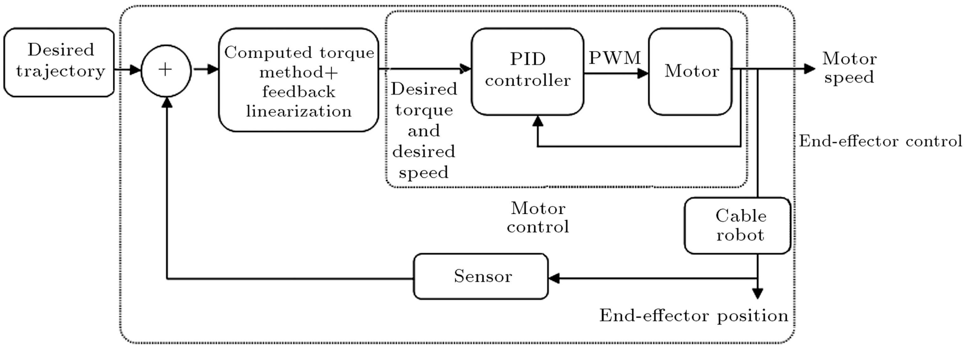


**Figure 4.** Flowchart of the proposed controlling strategy of the robot.

$$v_a = R_a i_a + L_a \left(\frac{di_a}{dt}\right) + e_a, \quad (8)$$

$$e_a = K_m \omega_m, \quad (9)$$

$$\tau_m = K_m i_a, \quad (10)$$

where $v_a$ is the armature voltage, $R_a$ is the resistance of the armature wire, $L_a$ is the armature inductance, $i_a$ is the armature current, $e_a$ is the reverse current, $K_m$ is the constant of the motor torque, $\tau_m$ is the produced torque and $\omega_m$ is the free running angular velocity of the DC motor [18]. So, the required voltage of the motor can be computed based on the desired torque, and speed of the motor, using Eq. (8) in which $e_a$ is substituted by Eq. (9) and $i_a$ is substituted by Eq. (10). Finally this voltage can be implemented on the motor, using PWM method which has the least loose of energy.

$$\text{PWM} = v_a / v_{\max}, \quad (11)$$

where $v_{\max}$ is the maximum voltage of the motor, however, this is possible if and only if the exact model and parameters of the motor would be available, and it is obvious that in many conditions these parameters are not available. So, a look up table is provided for which a curve is fitted, and the relation between PWM, torque and speed of the motor is extracted for controlling the end-effector within its desired trajectory.

It can be seen in Section 4 that this relation is constructed as below between these parameters:

$$\text{PWM} = d\dot{\beta}^3 + e\dot{\beta}^2 + f\dot{\beta} + a\tau + b, \quad (12)$$

where $a$, $b$, $e$, $f$ and $d$ are constants which should be evaluated by the aid of experimental tests and will be explained in the rest of the paper, and finally PWM is the required pulse width modulation of the DC motor. The methodology of evaluating this equation is explained in Section 4. The overall strategy of controlling the end-effector of the robot based on this proposed

## 3. Hardware and software setups

An under-constrained cable robot is designed and manufactured in Iran University of Science and Technology (IUST), called ICaSbot, which supports six DOFs including three translational and three rotational movements of the end-effector by the aid of six active cables and six DC motors. A scheme of the mentioned robot can be seen in Figure 5(a) [19]. The experimental tests are conducted on this robot in order to verify the efficiency of the proposed controlling strategy of the motors. A hardware setup is designed and manufactured, and also a supporting software package is programmed for conducting the required experimental tests and evaluating the required parameters of the motors' equations. The hardware setup is presented in Sections 3. 1, 2 & 3 and the related supporting softwares are presented in Section 3.4.

### *3.1. Designed hardware setup*

Six motors are selected for the robot whose specifications are listed in Table 1. Each motor is connected to an encoder by a 3 cm diameter circular 2shaft which has a high resolution precision of 4*600 pulses per rev. The cable which transfers the load weight is passed over a pulley and wrapped around a shaft. As Table 1 shows, this 12 Volt and 17 watt geared motor runs with 150

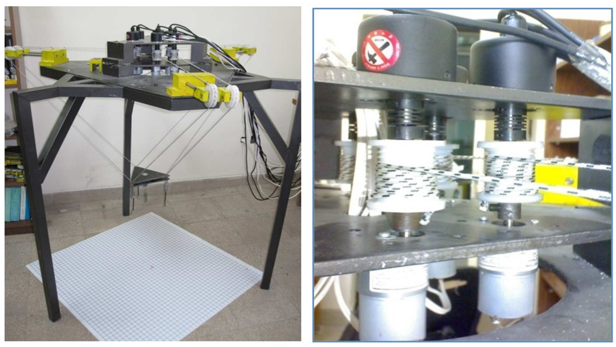

**Figure 5.** (Left) The ICaSbot robot. (Right) The assembled system, from top to down: 1- Encoder 2- Shaft 3-Motor.

**Table 1.** The specifications of the selected motor (left) and encoder (right).

| Motor's specification | Value |
|---|---|
| Mark | Retarding gear motor |
| Model | 1.61.070.304 Buhler |
| Reference voltage | 12 v |
| No load speed | 150 rpm |
| Stall torque | 1.7 N.m |
| No load current | 0.3 A |
| Stall current | 1.2 A |
| Reduction ratio | 1:175 |
| Weight | 220 g |

| Encoder's specification | Value |
|---|---|
| Mark | Autonics |
| Model | E50S8-600-3-T-24 |
| Resolution | 600 |
| Output phase | $A$, $B$, $Z$ |
| Control output | Totem pole |
| Power supply | 12-24 v |
| Max allowable revolution | 5000 rpm |

rpm (in free running condition). Other specifications of the motor and encoder are listed in Table 1. Also, six loadcells are employed to evaluate the actual torque of each motor, and improve it in a PD controller of motor current. The assembled system of encoder, shaft and motor is shown in Figure 5.

### 3.2. Printed Circuit Board (PCB) of motor's drivers

In this test, PWM method is used for regulating the input voltage. In PWM method, the desired pulse width is amplified by a motor driver IC, L298. The PCB converts the command (modulating) signal to a pulse-width modulated output. The lower limit of PWM is 0 V and the upper one is 12 V. Generally, the larger command signal produces the wider pulse. The mentioned PCB and its layout are shown in Figure 6.

### 3.3. Printed Circuit Board (PCB) of encoders

The encoders used in this hardware setup have high resolution precision of $4 * 600$ pulses per rev; two output signals of encoders have a 90 degree phase shift. It is possible to connect the encoders to the data card reader directly without using any intermediate PCB, and estimate the angular velocity and the motion direction, using the phase shift between the two output signals; however, it is preferred here to use a designed intermediate PCB in order to increase the precision and reduce the amount of mathematical calculation.

The designed PCB increases the reading precision from 600 to 2400 pulses per rev, and the output signal received by data cart reader is a square shape signal which varies between 0 and 1 V. The received signals can be read by the aid of a proper software package. The PCB reads rotary encoder's output and its layout are shown in Figure 7. The PCBs, data card reader's ports and the power supply are installed in hardware setup box. A view of the hardware setup box is shown in Figure 8.

### 3.4. Software setup

A Graphical User Interface (GUI) software setup which reads the encoders' output signals, using data card reader, is programmed in the LabVIEW environment. A panel of the GUI-software setup is shown in Figure 9.

Using this software setup, the user is able to generate the plan of robot's trajectory and run the robot to move within the desired path. It is also possible to run each motor separately with a desired speed by producing its related PWM. The software setup sends the command signal to each motor, and determines the pulse width and voltage level of PWM signal. It also reads the output signals of encoders and calculates the position, orientation, linear velocity and angular velocity of the end-effector. It also plots the motion diagram, position and angular velocity of each motor in a real-time way. In Figure 9, a panel of the software is shown in which the desired and actual positions of six motors are being plotted simultaneously in a real-time way.

## 4. Experimental tests

### 4.1. Extracting the equations of the motors

In order to extract the equations of the motors, the profile of Speed-PWM is firstly obtained for two different weights, for both upward and downward motions of the motor. Not only these profiles are evaluated for steady state response of the motor (after overcoming the initial inertia and friction of the motor), but also they are obtained for transient state of the motor motion (first 0.2 seconds when the motor starts its motion from static condition). The reason of this selection is that the controlling step of the motor is 0.2 seconds, and so every 0.2 seconds, a new set-point is considered for the motor. So if the motor is going to start its motion from static condition, it follows the dynamic response of the second profiles, while the first profiles are the pattern of the motor behavior during its dynamic rotation period.

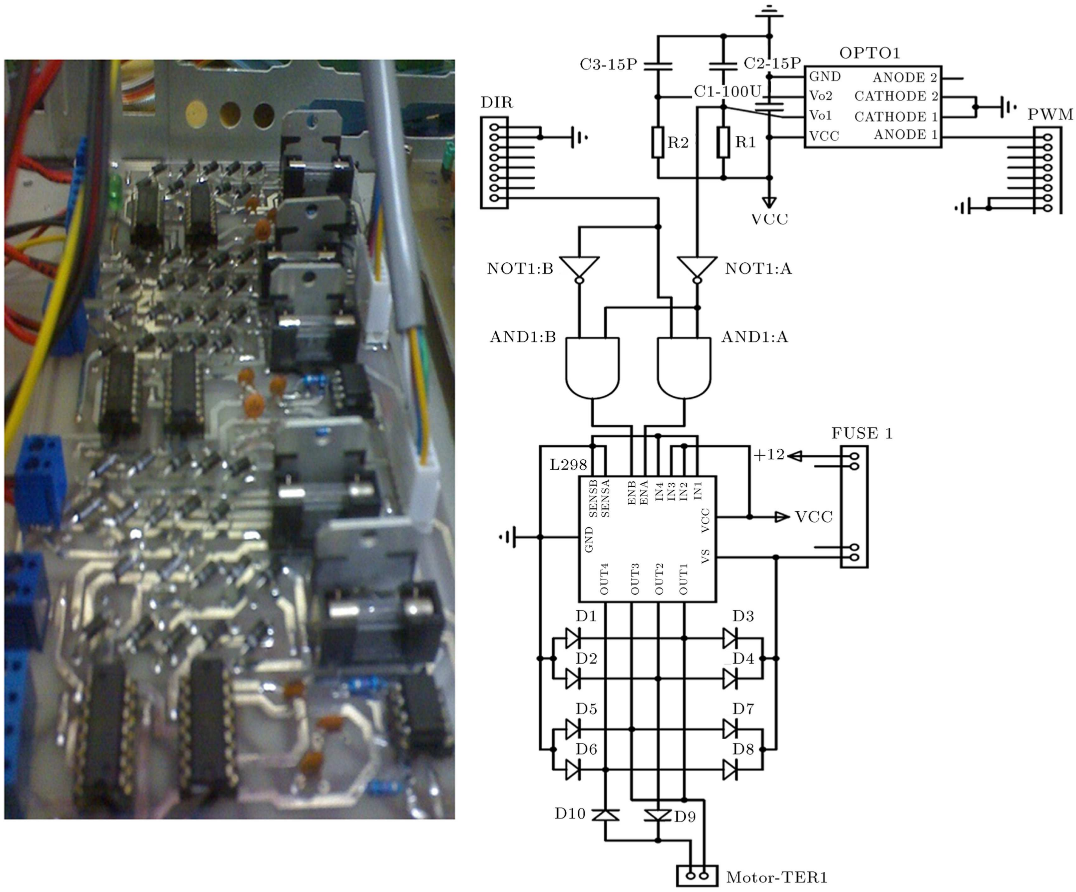


**Figure 6.** Printed Circuit Board (PCB) regulates the motor's angular velocity (left) and its layout (right).

In Figure 10, the profile of the motor is plotted for the first 0.2 seconds of motion for upward direction while Figure 11 is related to the steady state condition. The horizontal axis is the angular velocity of the motor based on RPM, while the vertical axis is the percentage of PWM. In each figure, two profiles are plotted for which the first is related to the load of 200 gr. and the second is related to the load of 460 gr. Also, the curve which is fitted on them can be seen in the profiles for which the procedure of their derivation is described in the next section. The profiles are shown for the first two motors, and the rests are not plotted since they are similar. In these figures, $y$ is the required PWM of the motors and $x$ is the motor speed.

The reason of choosing two different weights is that two unknown variables will be appeared in the equation of the motors, which should be evaluated using two equations. Finally the reason of conducting the tests for two upward and downward directions is attributed to the fact that the motors have different dynamic behavior in upward and downward directions, because of the difference of breaking force produced by the gearbox as a result of gravity for different voltages. The weights 200 gr. and 460 gr. are chosen to perform the interpolation and finding out the unknown variables of the motor equation, since the maximum and minimum workspace loads of each motor corresponding to the weight of the end-effector are within the mentioned range. The cables of the robot which bear the load are suspended through some drums which are eventually controlled by the aid of motors' rotation. Although the mentioned method is dependent on the workspace of the robot and the resolution of the conducted calibration tests, its advantage is that there is no need to extract the model of the motor, and also it provides a high accurate response of the motor (since both of speed and torque are included) with low processing calculation (since there is no need to solve the dynamics of the motor in a real-tem way), which is suitable for online applications of robot procedure.

So, the torque of the motor can be calculated based on the tension of the cables through the following formula:

$$\tau = rmg. \tag{13}$$

In this equation, $r$ is the radius of the drum, $m$ is the mass of the weight and $g$ is the gravitational acceleration. According to the mentioned equation, the torque of the motor is calculated for two loads.

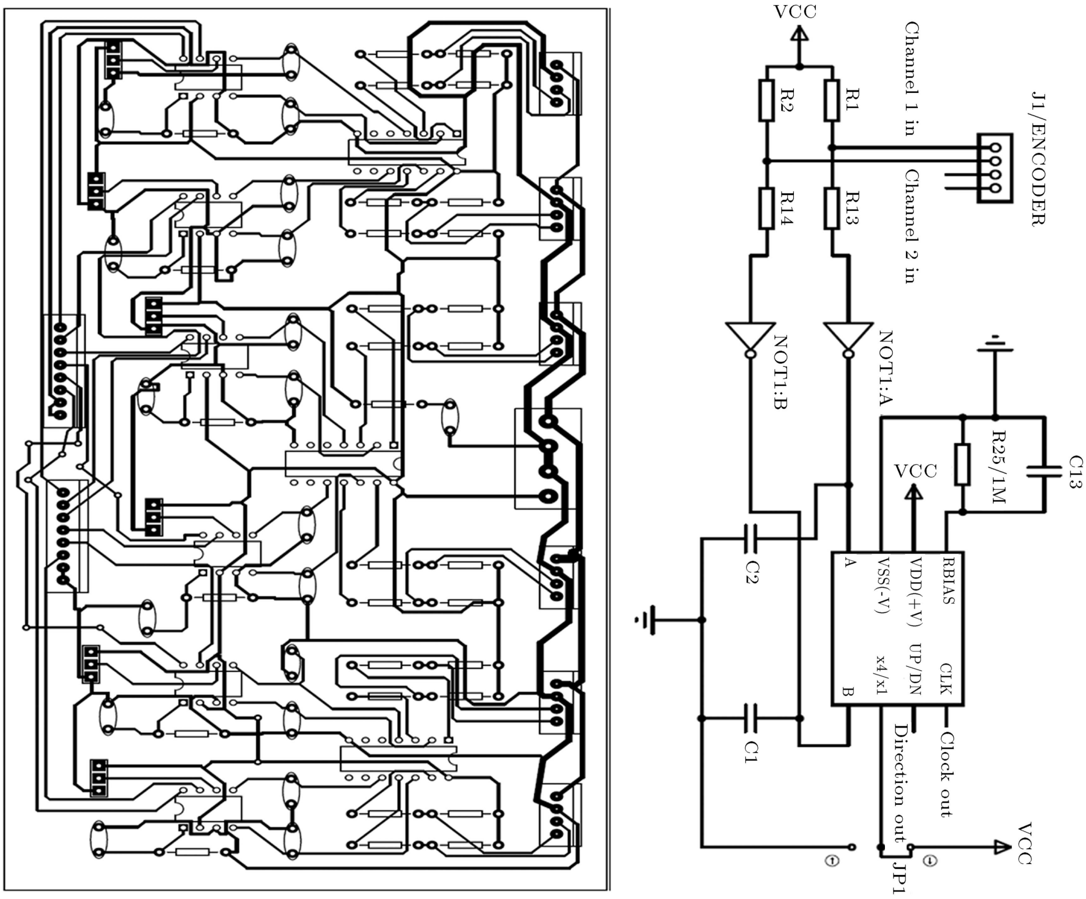


**Figure 7.** Circuit diagram of the PCB reads rotary encoder's output (left) and its layout (right).

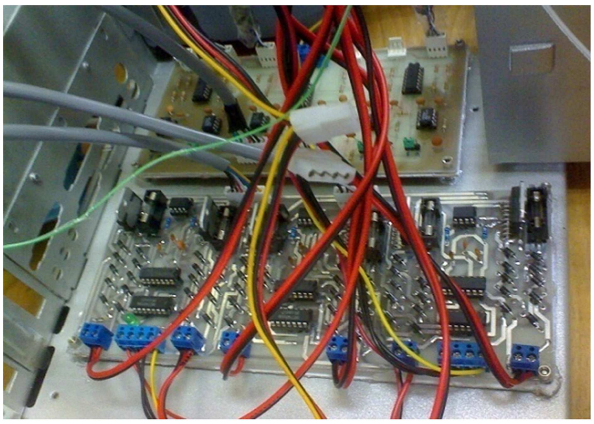

**Figure 8.** A view of the hardware setup box of the ICaSbot: the PCB reads rotary encoder's output (up) and the PCB regulates the motor's angular velocity (down).

For carrying 200 gr. load, the motor torque is 0.0294 (N.m), and for the 460 gr. load it is 0.0676 (N.m).

For conducting the upward motion test of the motor, the percentage of PWM of the motors is gradually increased from zero to 100, up to the threshold of the motor rotation. This value of PWM forms the first point of the profiles. The rest of the points are also provided by recording the angular velocity of the motor related to each percentage of PWM. Finally, six profiles for upward motion and six profiles for downward motion of the motors are derived, based on the mentioned procedure. These profiles are shown for the first two motors in Figures 10 and 11, and similar trends exist also for the rest of the motors.

### *4.2. Curve fitting and extracting the finalized equations*

Based on the gained profiles of previous section, it is obvious that the relation between PWM and motor speed is not perfectly linear. Since the trend is more like a polynomial, a curve of order three is fitted on the gained profiles. Also, these profiles are extracted within our workspace, which is under 50 rpm.

Two different weights within the workspace range of the robot are chosen to conduct the tests in order to perform a precise interpolation and evaluate the equations. Also, since the response of the motors for their upward and downward directions is different, these tests are repeated for both directions. The following curve is employed to be fitted on the PWM-speed profiles:

$$\mathrm{PWM} = d\dot{\beta}^3 + e\dot{\beta}^2 + f\dot{\beta} + c. \tag{14}$$

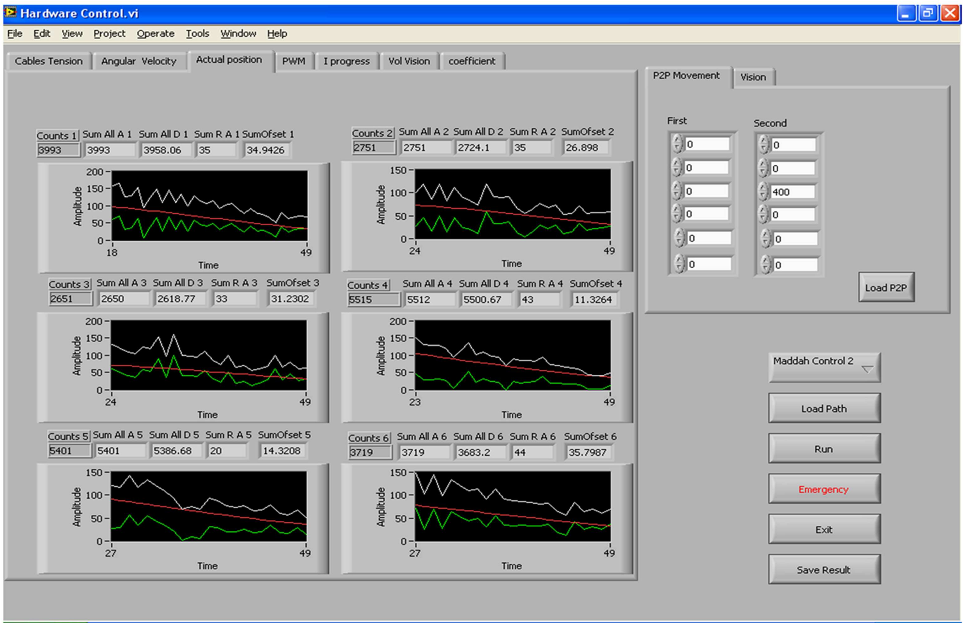


**Figure 9.** The Graphical User Interface (GUI) software setup programmed in LabVIEW environment.

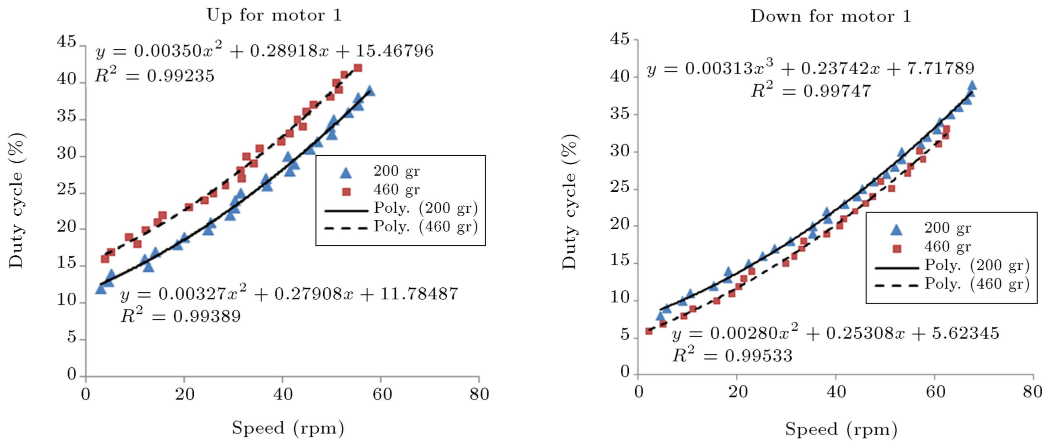


**Figure 10.** The extracted profiles of the 1st motor related to the loads of 200 and 460 g. conducted in upward direction (left) and downward direction (right) for the first 0.2 seconds (the transient state).

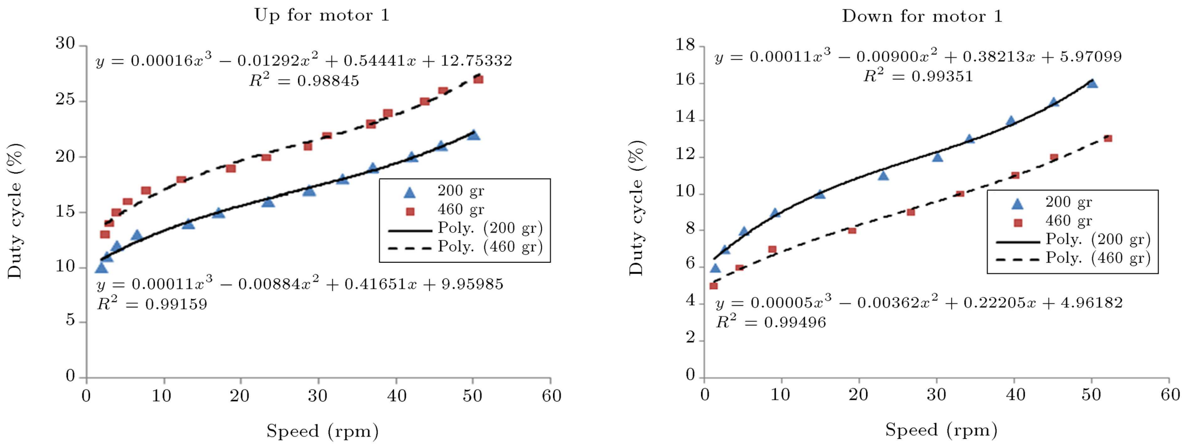


**Figure 11.** The extracted profiles of the 1st motor related to the loads of 200 and 460 g. conducted in upward direction (left) and downward direction (right) for ultimate velocity condition (the steady state condition).

In this equation, $f$, $e$ and $d$ are the gains of motor speed in the mentioned polynomial function, and $c$ is a linear function of the applied torque of the motor, which can be stated as:

$$c = a\tau + b. \quad (15)$$

Substituting Eq. (15) in Eq. (14) results in Eq. (12). In order to find out the values of $a$ and $b$ in Eq. (15), two different weights are suspended through the motor for both directions, and the weight of 200 gr. is considered as the reference load, since it is the load which is produced by the aid of the weight of the sole end-effector on each cable. Two equations, as below, will be produced:

$$c_1 = 0.0294 * a + b, \quad (16)$$

$$c_2 = 0.068 * a + b. \quad (17)$$

In these equations, the value of $c_1$ is the constant of the fitted curve for the load of 200 gr. for upward motion of the motor, and $c_2$ is the same value for the weight of 460 gr. The values of these constants are contrariwise for the downward motion of the motor. So, as it can be seen from the figures, the profiles related to the weight of 460 gr. is upper than the one which is extracted for the weight of 200 gr. for upward motion, while this sequence is contrariwise for the downward motion of the motor as it was expected (The speed of downward motion of the motor is obviously faster for the heavier load as a result of a unique PWM and vice versa). Also, the value of $a$ in these equations are the torque of the motors, and it is related to the weight of 200 gr. for the first equation and 460 gr. for the second one.

Eventually, twelve equations can be extracted for upward and downward motions of the motor during both transient state (first 0.2 seconds) and steady state responses of the motor. Twelve equations related to transient state are listed in Table 2, and the ones related to steady state are listed in Table 3.

The relation between torque and speed for a DC motors is roughly linear, and its linear equation can be used for control procedure. Moreover, the relation between speed and current is also linear (Figure 12). However, this relation is not perfectly linear, and considering it a linear function causes some inaccuracy in the tracking procedure. In this paper, we have established the exact profile between torque-speed and PWM by the aid of experimental tests. As can be seen in Figure 13, this relation is not perfectly linear and it can be expressed as a polynomial function of order three. Thus, more accuracy can be provided by the aid of this profile. The reason of this nonlinearity can be justified by using PWM rather than voltage.

### *4.3. Tuning the PID gains*

After evaluating the required PWM of the motors based on the computed torque method and feedback

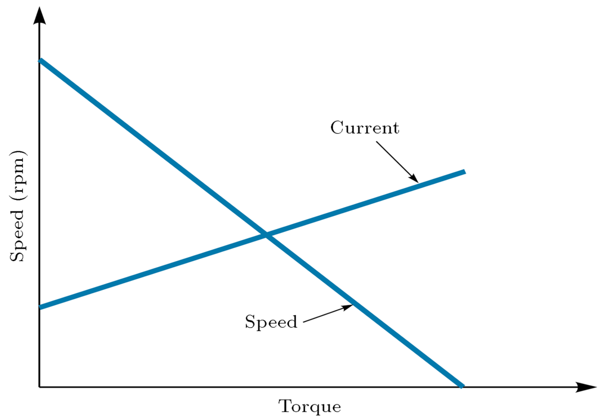


**Figure 12.** The speed-torque relation of motor [6].

**Table 2.** The obtained equations of motors in transient state.

| Direction | Motor number | Obtained equations |
|---|---|---|
| **Upward** | 1 | $\text{PWM} = 0.00327\dot{\beta}^2 + 0.27908\dot{\beta} + 108.55\tau + 8.59$ |
| | 2 | $\text{PWM} = 0.00344\dot{\beta}^2 + 0.30371\dot{\beta} + 108.81\tau + 8.13$ |
| | 3 | $\text{PWM} = 0.00357\dot{\beta}^2 + 0.27498\dot{\beta} + 113.21\tau + 8.16$ |
| | 4 | $\text{PWM} = 0.00384\dot{\beta}^2 + 0.28683\dot{\beta} + 101.55\tau + 8.38$ |
| | 5 | $\text{PWM} = 0.00278\dot{\beta}^2 + 0.32256\dot{\beta} + 111.13\tau + 8.08$ |
| | 6 | $\text{PWM} = 0.00412\dot{\beta}^2 + 0.22306\dot{\beta} + 125.65\tau + 7.78$ |
| **Downward** | 1 | $\text{PWM} = 0.00313\dot{\beta}^2 + 0.23742\dot{\beta} - 49.74\tau + 9.17$ |
| | 2 | $\text{PWM} = 0.00450\dot{\beta}^2 + 0.16908\dot{\beta} - 41.45\tau + 10.07$ |
| | 3 | $\text{PWM} = 0.00387\dot{\beta}^2 + 0.21694\dot{\beta} - 56.99\tau + 9.8$ |
| | 4 | $\text{PWM} = 0.00439\dot{\beta}^2 + 0.23088\dot{\beta} - 47.15\tau + 9.17$ |
| | 5 | $\text{PWM} = 0.00349\dot{\beta}^2 + 0.25659\dot{\beta} - 43.78\tau + 9.53$ |
| | 6 | $\text{PWM} = 0.00366\dot{\beta}^2 + 0.21438\dot{\beta} - 43.52\tau + 8.7$ |

**Table 3.** The obtained equations of motors in Steady state.

| Direction | Motor number | Obtained Equation |
|---|---|---|
| Upward | 1 | $\text{PWM} = 0.00011\dot{\beta}^3 - 0.00884\dot{\beta}^2 + 0.41651\dot{\beta} + 103.62\tau + 6.9$ |
| | 2 | $\text{PWM} = 0.00013\dot{\beta}^3 - 0.00978\dot{\beta}^2 + 0.41734\dot{\beta} + 116.58\tau + 6.75$ |
| | 3 | $\text{PWM} = 0.00029\dot{\beta}^3 - 0.01975\dot{\beta}^2 + 0.73202\dot{\beta} + 103.62\tau + 9.63$ |
| | 4 | $\text{PWM} = 0.00011\dot{\beta}^3 - 0.00777\dot{\beta}^2 + 0.36483\dot{\beta} + 110.1\tau + 6.72$ |
| | 5 | $\text{PWM} = 0.00014\dot{\beta}^3 - 0.01197\dot{\beta}^2 + 0.48955\dot{\beta} + 129.53\tau + 5.63$ |
| | 6 | $\text{PWM} = 0.00012\dot{\beta}^3 - 0.00978\dot{\beta}^2 + 0.42073\dot{\beta} + 108.8\tau + 6$ |
| Downward | 1 | $\text{PWM} = 0.00011\dot{\beta}^3 - 0.00900\dot{\beta}^2 + 0.38213\dot{\beta} - 64.76\tau + 7.87$ |
| | 2 | $\text{PWM} = 0.00008\dot{\beta}^3 - 0.00619\dot{\beta}^2 + 0.28112\dot{\beta} - 51.81\tau + 8.34$ |
| | 3 | $\text{PWM} = 0.00006\dot{\beta}^3 - 0.00509\dot{\beta}^2 + 0.28136\dot{\beta} - 64.76\tau + 8.04$ |
| | 4 | $\text{PWM} = 0.00008\dot{\beta}^3 - 0.00582\dot{\beta}^2 + 0.30402\dot{\beta} - 83.16\tau + 8.55$ |
| | 5 | $\text{PWM} = 0.00011\dot{\beta}^3 - 0.00902\dot{\beta}^2 + 0.37596\dot{\beta} - 51.81\tau + 7.66$ |
| | 6 | $\text{PWM} = 0.00006\dot{\beta}^3 - 0.00420\dot{\beta}^2 + 0.24346\dot{\beta} - 57\tau + 7.47$ |

**Table 4.** Optimum gains obtained using Ziegler-Nichols method.

| Optimum gains | Ultimate sensitivity method | Transient response method | Final employed gain |
|---|---|---|---|
| $kp$ | 0.035 | 0.03 | 0.035 |
| $ki$ | 0.02 | 0.025 | 0.02 |
| $kd$ | 0.004 | 0.006 | 0.004 |

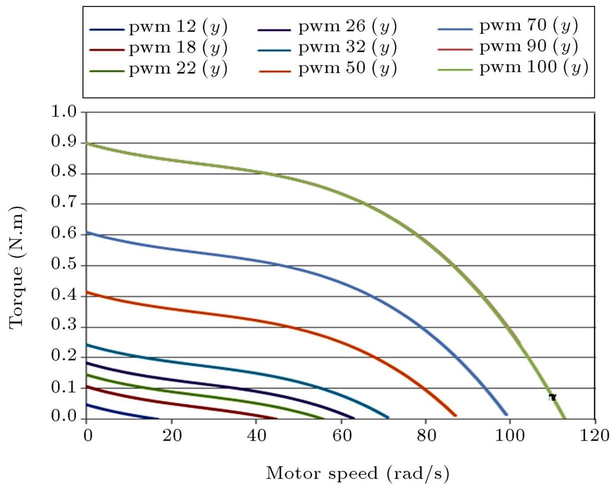


**Figure 13.** The angular velocity-torque relation of motor for different PWM signal.

linearization as the feedforward term of controlling signal, it is required to improve it, using a PID controller. First, the voltage is controlled using motor speed feedback:

$$\text{PWM} = \text{PWM}_f + kd(\beta'_d - \beta'_a) + kp(\beta_d - \beta_a) + ki\int(\beta_d - \beta_a), \tag{18}$$

where $\text{PWM}_f$ is the feedforward term of the controlling signal, which is evaluated by the aid of Eq. (12), $\beta_d$ is the desired angular velocity of the motors computed through the inverse kinematics of the robot, $\beta_a$ is the actual value of the same term and $kp$, $kd$ and $ki$ are the gains of feedback controller of motor speed, which should be properly optimized. There are a lot of approaches for tuning and optimizing the gains of a PID controller [20-22]. Some of them are depended on the dynamic model of the system and some are independent. Ziegler-Nichols, Cohen-Coon and Chien-Hrones-Reswick are of the most famous approaches [20].

In this research, Ziegler-Nichols is used in order to tune the PID gains of the motors. This method is based on two algorithms including transient response method and ultimate sensitivity method. The optimum gains are obtained using both mentioned algorithms in this paper. The results are considerably similar, and they are listed in the Table 4. These values are employed for the installed PID of the robot motors.

In the mentioned controlling strategy for the motor, just the feedback of the motor speed is used to improve the feedforward term of PWM. Since, based on this algorithm, there is no control on the current or torque of the robot's motor, the mentioned controlling loop can be even strengthened using the feedback terms of actual torque of the motor. Since the desired torque of the motors can be calculated using the inverse dynamics by the aid of Eq. (7) and the actual torque of the motor can be estimated using the employed loadcells in the robot, it is possible to increase the accuracy of the designed controller by using the controlling feedback of the motor torque. Considering the fact that both speed and torque of the motors are included in the feedforward term, by the aid of the mentioned strategy, not only the voltage and speed of the motor can be improved using the feedback of the motor speed (encoders), but also the current and torque of the robot can be modified using the feedback of the motor torque (Loadcell). So, the following formula is used as the finalized required PWM of the motors:

$$\begin{aligned} \mathrm{PWM} =& \mathrm{PWM}_f + kd(\beta_d' - \beta_a') + kp(\beta_d - \beta_a) \\ &+ ki \int (\beta_d - \beta_a) + kd2(\tau_d' - \tau_a') \\ &+ kp2(\tau_d - \tau_a) + ki2 \int (\tau_d - \tau_a), \end{aligned} \tag{19}$$

where $kd2$, $kp2$ and $ki2$ are the PID controlling gains related to the torque, and $\tau_d$, $\tau_a$ are the desired and actual torque of the motors, respectively.

## 5. Results

### 5.1. Experimental Verification

In order to verify the correctness of experimental installation and validate the efficiency of the proposed controlling method, the results of experimental test conducted on the ICaSbot, in which the motors are controlled by the aid of the proposed algorithm, is compared with simulation results of MATLAB. A parabolic trajectory with the following equation is chosen for the mentioned comparison:

$$\begin{aligned} &X = (5/5.69 \times t) \times 0.01, && Y = 0, \\ &Z = ((5/5.69 \times t)^2 + 85) \times 0.01, && 0 \leq t \leq 5.69. \end{aligned} \tag{20}$$

Comparison of experimental tracking with simulation path is plotted in Figure 14. In this profile, the performance of a robot is compared between the traditional approach of motor control (using just the encoder feedback) and the new proposed approach in which the feedforward and feedback terms of the motor torque is also considered. It can be seen that a perfect compatibility can be observed between simulation and experimental results as a result of the designed motor controller. Also, it is obvious that the performance of the proposed method is considerably increased compared to the traditional method of controlling a DC motor, and the error is decreased more than 50%.

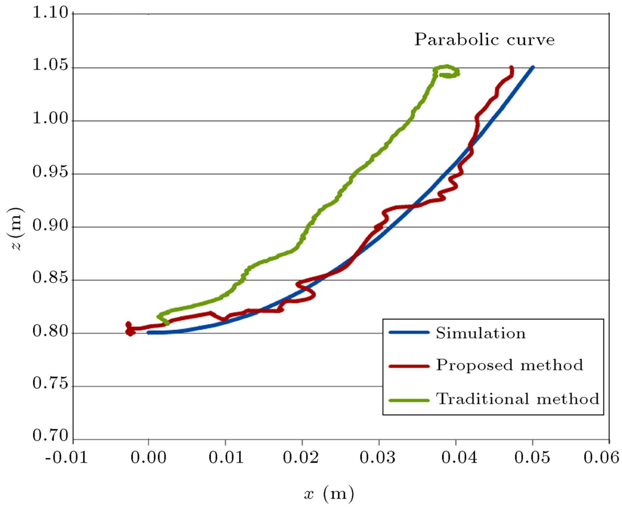


**Figure 14.** Tracked parabolic path by the robot ($X$-$Z$ plan) and its comparison between simulation and experiment with and without torque consideration.

Comparison of angular velocity of the motors between simulation and experimental results are shown in Figure 15 for the six motors. Again, here the profiles are compared for two mentioned approaches. Not only an acceptable compatibility can be observed between experiment and simulation, but also it can be concluded that the proposed method provides a smoother response of the motor. The reason is contributed to the fact that in traditional approach of controlling the motor, just the feedback of the motors are used which results in more fluctuated response of the motor speed, while using the feedforward and also feedback terms of motor torque helps the controller to smooth down these unwanted fluctuations.

Since the actual torque of the motors is required in this approach, they should be monitored by the aid of loadcells. Comparison of the tension of the motors between simulation and experimental data is also shown in Figure 16 for the six motors.

Again, a good compatibility can be observed between simulation and experimental results, which shows the efficiency of the proposed controller. The little vibrating behavior of the experiment profile around the simulation path can be justified by the motor friction, clearance and also the resolution and accuracy of the encoders. Generally, it can be seen that the deviations of the experimental angular velocity of the motors compared to the desired simulation path, by the aid of the proposed controller and so the integral of the area under the motors speed profiles, are roughly equal for simulation and experiment, which provides a similar summation of rotating angle of the motors. Error of the motor speed compared to its desired value, which is extracted through the inverse kinematics, is depicted in Figure 17 for the six motors.

It can be seen that the mean value of the error of

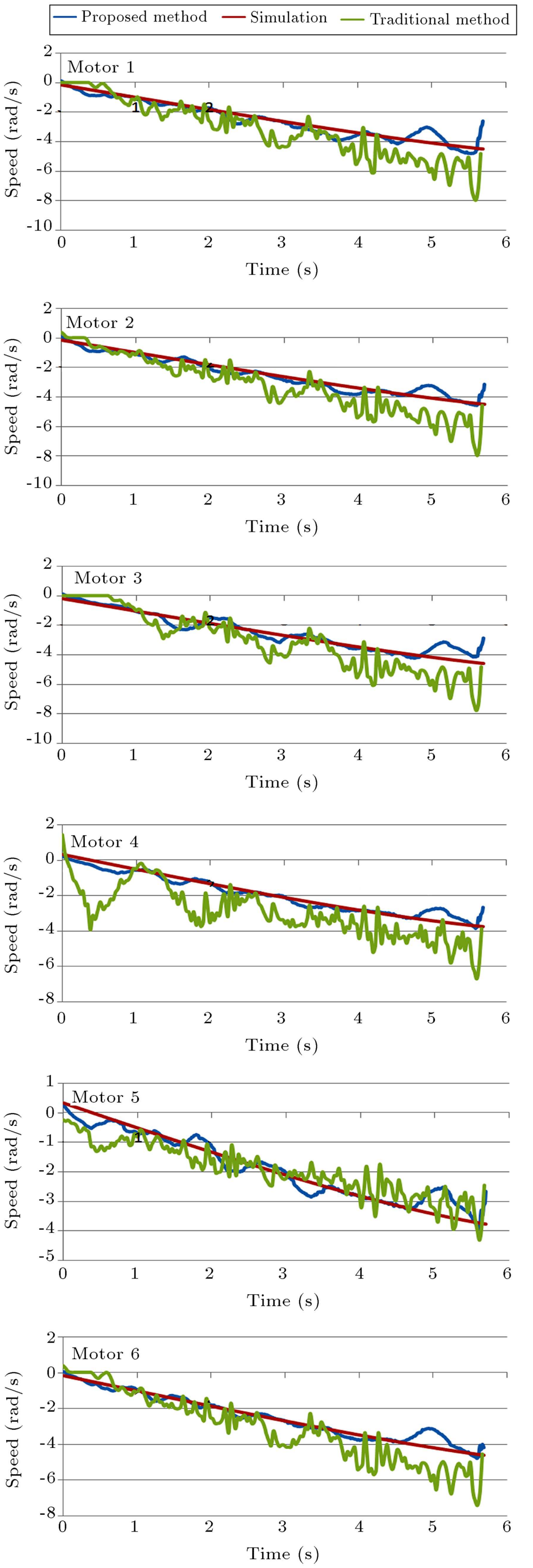


**Figure 15.** Angular velocities of the six motors for tracking the parabolic path and its comparison between simulation and experiment with and without torque consideration.

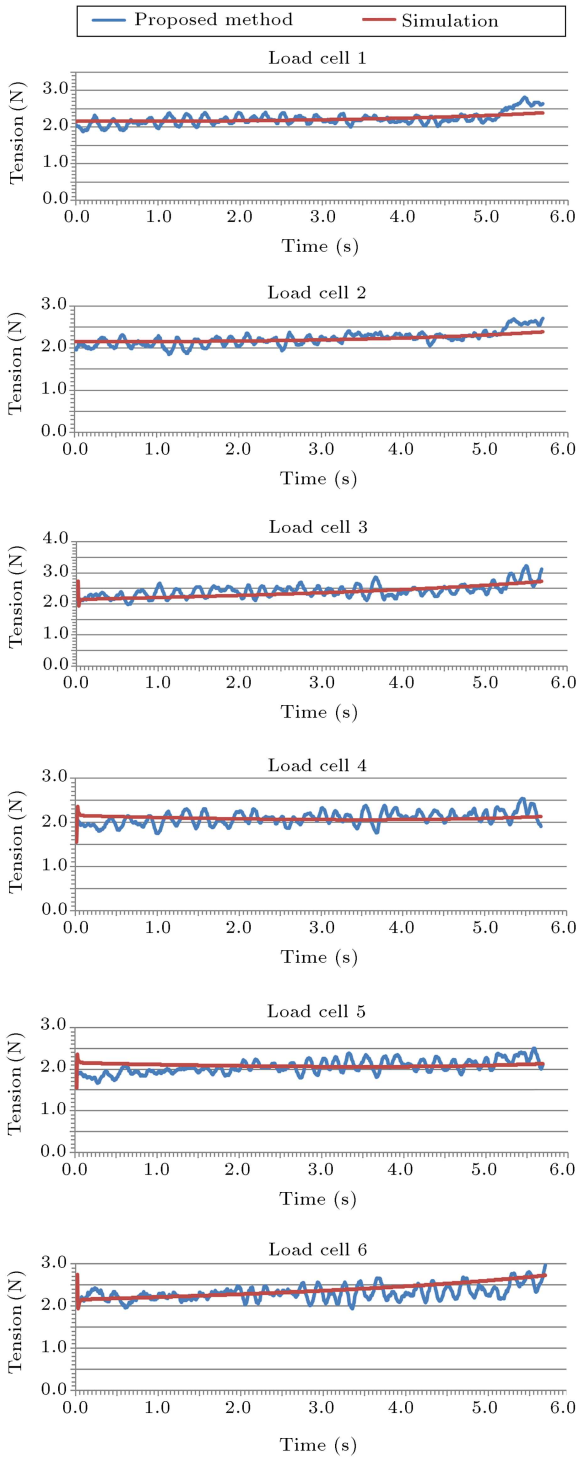


**Figure 16.** Comparison of the experimental torque of the six motors for tracking the parabolic path with simulation.

the motors' speed is less than 0.7 rad/s which is a good record and proves the efficiency of the implemented controller. Also again, here the error related to the proposed controlling methodology is decreased considerably compared to the traditional control algorithm of DC motor. The offset and vibrations are mostly related to the gearbox clearance, high inertia and friction of

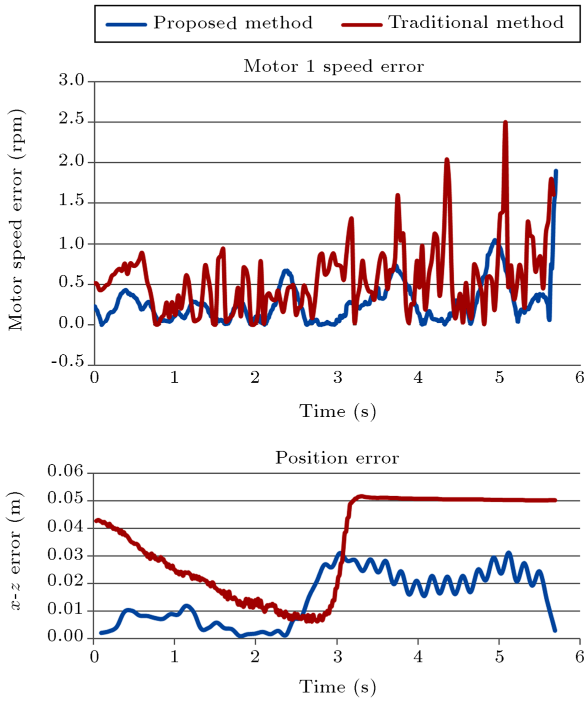


**Figure 17.** The error of motor speed and position in parabolic path tracking.

the motors and the resolution of the encoders. The order of the errors are increased a little bit at the end of the tracking procedure, which is related to the braking procedure of the motors in the last moments of tracking in experimental tests, which is not modeled in the simulation (according to the equation of the predefined trajectory). Moreover, the normal error of the proposed strategy is decreased more than 50% (3 cm error for traditional method versus 1 cm for the proposed method).

## 6. Conclusion

In this paper, the required PWM of the DC motors of a cable suspended robot was evaluated for online controlling of the end-effector in a predefined trajectory in a way that both the desired angular velocity and desired torque of the motor can be provided, and eventually results in an accurate tracking. A novel and accurate method for simultaneous control of speed and torque of the motor is proposed, which is not dependent on the model of the motor. These equations were extracted experimentally as a function between PWM, torque and the speed of the motors, while the data sheet and parameters of the motors were not available. Both the transient and steady state equations were estimated separately for both upward and downward motions of the motor. It was seen that the extracted formulation of the motors have a considerable compatibility up to 90% with the points of look-up table of the motor. The advantage of the presented method over look- up table is its higher analyzing speed, its online capability and its independency to motor parameters and datasheet.

This simultaneous control of torque and speed of the motor is provided using inverse dynamics of the robot together with feedback linearization method. The first loop of PID controls the voltage of the motor and improves its speed, while the second one controls the current of the motor and improves its torque. Thus, not only both the speed and torque of the motor are considered in the feedforward term of motor control, both of them are also improved using PD controller. It was also investigated that using inverse dynamics of the motor, as the feedforward controlling term of the motor results in faster response of the dynamic of the motor, which realizes more accurate tracking for robotic applications. Good compatibility between the tracked trajectory of the end-effector for the simulation and experimental results approved the efficiency of the proposed joint space controlling strategy of the motors. For all of the comparative profiles consisting of the path, motor speed and its related error, the performance of the proposed controlling strategy of a DC motor in a robot is considerably increased (more than 50%), which proves the efficiency of the proposed method. Also using the feedback and feedforward terms of the motor torque have decreased the fluctuations related to the motor speed, which is highly appreciated. A delay was observed between experimental and simulation profiles, which can be referred to as the high inertia and friction of the motors, which are not modeled in the simulation. Also, the vibrating response of the motor speed compared to the smooth simulation results is due to the clearance and flexibility of the motor and robot structure which are not modeled in the simulation. It was seen that the integral area under both experimental and simulation profiles of the motor speed profiles is roughly similar as a result of good compensation of the proposed controller.

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