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MODELLING AND ANALYSIS OF DC MOTOR ACTUATOR FOR AN ELECTRIC GRIPPER

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Abstract

Robot technology has seen developments to support both the needs of industry and human life. This paper presents a brief review on the modelling and simulation of robotic grippers. The design of two fingered electric gripper, actuated by a direct current motor, is described for pick and place of spark plug. Mathematical modelling of the motor is carried out to understand and relate the control parameters. Angular velocity and torque response of the motor for a step input are verified by simulation. Controlling the direct current motor with pulse width modulation technique gives gentle variation of velocity and relatively greater torque. Further, it results in quick response of motor torque.

Keywords: DC motor, SimMechanics, Gripper, MATLAB Simulink.

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1. Introduction

Robots are usually considered to interact with the environment using an arm and a wrist. In industrial norms the robotic hand is called as a 'gripper', also known as end-effector. A robotic gripper is the physical realization of an electromechanical system to perform physical handling tasks automatically and it is designed to suit industrial application to typically grasp, carry and assemble the components. The exact function of gripper depends on its application. Grippers are classified according to their actuating methods like pneumatic, hydraulic and electrical. Nowadays, pneumatic grippers are used in the industry despite their lack of gripping force control, limited gripper force, problems due to air contamination, etc. Problems involved in the control and compliance of pneumatic systems have

Nomenclatures

a	Acceleration of gripper finger, m/s^2
b	Damping of mechanical system, kg.m.s
$G_a(s)$	open loop transfer function for position
$G_v(s)$	open loop transfer function for velocity
g	Acceleration due to gravity, m/s^2
I	motor armature current, ampere
J	Rotor moment of inertia, kg.m^2
K	back-electromotive force constant, N.m/A
L	Inductance, H
m	Mass of spark plug, kg
R	Resistance, Ω
S	Safety factor
T	motor torque, kg.m
V	Input voltage, V
V_b	back emf

Greek Symbols

θ	Shaft angle, rad
μ	Coefficient of friction
ω	angular velocity, rad/sec

Abbreviations

CAD	Computer Aided Design/Drafting
DC	Direct Current
PID	Proportional Integral Derivative
PWM	Pulse Width Modulation
RPM	Revolutions Per Minute

limited their use in advanced robotics [1]. Many techniques like bond graph method are in use, to improve the control and actuation of pneumatic grippers [2]. But still effective control of pneumatic system is not achieved. Hence, alternatives are to be found out for effective control of the gripping action. This paper focuses in particular, on the modelling and simulation of DC motor used as the actuator of a pick and place gripper.

Before practically implementing any system its performance analysis becomes extremely important to avoid further complications. This can be done by using suitable simulation software. MATLAB provides wide range of options to perform mathematical simulation and enhanced user interaction. So that actual model behaviour under applied conditions can be analysed interactively. Simulation of actuator plays an important role as we can decide the operating limits to actuate the gripper. Several papers describe the methodology for DC motor simulation. Sandesh and Nithya [3] analysed the performance of DC motor in the MATLAB Simulink environment. They proposed a robotic hand controlled by flex sensors in which DC motors were used to control each finger independently. Nicolae [4] discussed on the state-space model of the DC motor built for constant flux considering two inputs namely, supply voltage and resistive torque. The three states of the resulting model were represented by angular speed, angular displacement and current supply and any of these states can be taken as output signal. The DC motor model was simulated using MATLAB and LabVIEW, and the results obtained were analysed. Zygfryd and Glowacz [5] studied the mathematical background of DC motor in which, the commutator was approximated by a circuit with variable parameters. Model equations were solved using implicit integration method and commutation process of DC motor was investigated. Several studies have been made on the control methods used for the DC motor actuator, viz., proportional-integral, proportional-integral-derivative, PWM based on mathematical modelling of motors [6, 8-14]. By a review on various sensorless and sensor based techniques for position and speed control of brushless DC motors, it was found that sensorless control techniques can reduce overall cost of actuating devices [6].

To visualize the performance of a CAD model, the use of SimMechanics interface has been widely reported [7-9]. MATLAB Simulink with SimMechanics was used to dynamically simulate the 3D model of KUKA robot before procuring it for real life applications. The performance analysis was done by comparing the path traced by Simulink model and Inventor model [7].

One of the important factors in gripper design is to decide the number of fingers to be used to hold the object for a particular application. Number of fingers to be used totally depends upon the object to be grasped and gripping force requirement, considering weight of object to be grasped. A five finger robotic gripper design behaving like a human hand was proposed with a DC servo and PID controller to control the kinematic motion of each finger [8]. Further, in a three finger gripper design, both gross motion and fine motion of the fingers was demonstrated using a DC motor actuator with proportional-differential controller [9].

Park and Kim [15] designed a gripper with vacuum pad end effector. It had three fingers with two degree of freedom each, and rotary potentiometers attached to joints to measure angle state of each joint. The form closure concept has been considered in the design of a three finger gripper to grasp the cylindrical shaped objects [16]. On the other hand, the force closure concept was considered in the design of a pneumatic actuated two finger gripper for pick and drop action [17]. Moreover, the use of replaceable finger insert was suggested, to improve part handling. Majid and Kalivitis [18] proposed an autonomous friction gripper for pick and place application, equipped with range of sensors to avoid the collision. The gripping force was controlled using force sensing resistor. Karokh [19] used RobotStudio for simulation of a pick and place robot with electromagnetic gripper for sheet metal parts, to be transported from laser notching machine to manufacturing cells. Grippers with two degrees of freedom are used to permit rotation of the object while being grasped. Practically, most of the grippers used for grasping objects having regular geometry, are two fingered type. A two finger parallel gripper driven by a cam-follower mechanism was found to provide better control of gripping strength and stroke [20].

Along with the developments in the robotic gripper design, research is also carried out in the development and simulation of entire robotic arm. Modelling and simulation of robots could be achieved using either of the following models: the geometrical model (positions, postures), the kinematic model and the dynamic model. Different robot postures for the same trajectory can be compared to obtain the kinematic and dynamic parameters by simulation using SolidWorks and

MATLAB/Simulink [21]. Analysis of the kinematics and trajectory of AL5B robotic arm was also performed using a virtual reality interface developed with MATLAB Simulink. [22]. Modelling of the humanoid robot arm with a PID controller was performed using MATLAB SimMechanics, to produce a grasping time of less than one second for cylindrical objects [14].

2. Method

A two finger gripper is considered to be apt for spark plug pick and place application. Design parameters such as gripper force, linkage to actuator (DC motor) and friction at gripping area are considered for the gripper design. The gripping area on the finger is decided by the uniform grasping area available in the object, i.e., spark plug. A DC motor actuator suited to this application is chosen based on gripper force and torque requirements. The mathematical background of DC motor is studied in order to understand and relate the control parameters of the actuator and the gripper. A Simulink model of DC motor is developed and the model reliability is confirmed with a reference model [11] using standard values of motor constants. The performance of DC motor actuator, for pick and place of spark plug, is then analysed by observing the torque and angular velocity response with time. A circuit diagram is developed in Simulink for PWM control of the DC motor actuator. The simulation results obtained with and without PWM control are compared.

3. Modelling of DC Motor Actuated Gripper

3.1. Architecture of gripper

Grippers are designed with special characteristics according to application. For a spark plug pick and place application, the two finger scissor type of gripper has been designed with SolidWorks software. A DC motor actuator is fixed to the input link of gripper by a peg. This converts the rotary motion of DC motor into the to and fro motion of the push rod of gripper which finally results in opening and closing of gripper fingers.

This design is similar in many aspects to the parallel plane or level finger mechanism described by Yunming and Zarrugh [23]. The level finger mechanism, as shown in Fig. 1, is simple in design, less in weight and gives a nonlinear finger/actuator relationship. Both the fingers are of equal length, pivoted at the base such that under actuation, they move on a circular arc. As in Fig. 1, the angle θ, which defines the finger position, changes with the force F, applied by the actuator. In terms of gripper ratio, defined as the ratio of payload to gripper weight, the electric gripper and pneumatic gripper are found to be equivalent. Though hydraulic power source gives better performance, the electric gripper is preferred due to simplicity in implementing position and force control [23].

A 3D model of the proposed two fingered gripper mechanism is shown in Fig. 2(a) for the pick and place of a spark plug shown in Fig. 2(b). Linkages shown in Fig. 2(a) constrain the movement of the two fingers such that, the revolution of DC motor attached to the input link corresponds to one cycle of gripper action, i.e., opening or closing of the gripper. Dimensions are to be decided by taking into consideration, factors such as space constraint, material cost, weight constraint, etc. Calculation of force at the gripper is done by standard gripper force formula,

$$F = [m(g + a)\mu]S \tag{1}$$

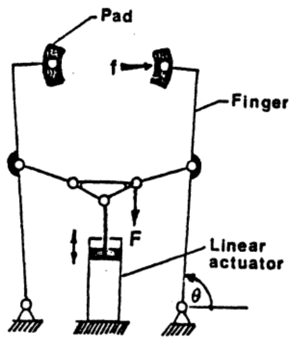
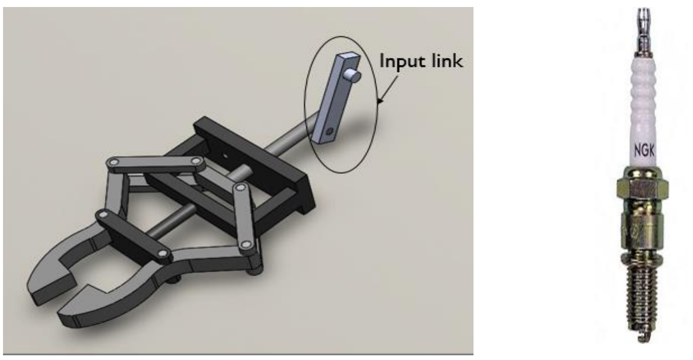


Fig. 1. Level finger mechanism [23].



(a) 3D model of gripper mechanism. **(b) Spark plug.**

Fig. 2. Two fingered gripper for the pick and place of a spark plug.

The gripping force calculated for lifting the spark plug of mass 0.05 kg is 11.11 N. The torque at the input link, assuming a crank radius of 20 mm is 0.22 Nm. The specifications of DC motor suited for this application are hence, 30 rpm no load speed, 12 V input, 0.22 Nm torque, 0.18 kg weight. Assuming that the gripper linkages transmit the torque and displacement given at the input link without any loss, we proceed to simulate the performance of DC motor actuator in order to get a preview of the gripper performance. This helps to determine the cycle time for a pick and place operation.

3.2. Mathematical model of DC motor

DC motor can be represented diagrammatically as shown in Fig. 3.

The motor torque, $T = K . I$ (2)

Back emf, V_b is related to angular velocity by,

$$V_b = K\omega = K\frac{d\theta}{dt} \quad (3)$$

From Fig. 3, by applying Newton's law and Kirchhoff's law we can write,

$$J\frac{d^2\theta}{dt^2} + b\frac{d\theta}{dt} = KI \quad (4)$$

$$L\frac{dI}{dt} + RI = V - K\frac{d\theta}{dt} \quad (5)$$

Using Laplace transform,

$$[Js^2 + bs]\theta(s) = KI(s) \quad (6)$$

$$LsI(s) + RI(s) = V(s) - Ks\theta(s) \quad (7)$$

Where, s is the Laplace operator. From Eqs. (6) and (7), we get

$$[Js^2 + bs]\theta(s) = K\left[\frac{V(s) - Ks\theta(s)}{R + Ls}\right] \quad (8)$$

By using above equations we can represent DC motor in a block diagram as shown in Fig 4. Using the block diagram in Fig. 4, it can be seen that, the open loop transfer function $G_a(s)$ and $G_v(s)$ for the DC motor relating the input voltage and output position and velocity respectively are,

$$G_a(s) = \frac{\theta(s)}{V(s)} = \frac{K}{s[(R + Ls)(Js + b) + K^2]} \quad (9)$$

$$G_v(s) = \frac{\omega(s)}{V(s)} = \frac{K}{[(R + Ls)(Js + b) + K^2]} \quad (10)$$

Therefore, given the input-output relations, the right choice of power input and DC motor constants (and hence the motor specifications) is necessary to achieve the required torque and speed characteristics, identified in section 3.1.

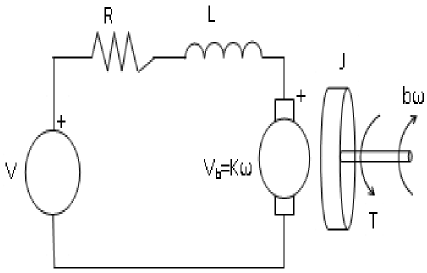


Fig. 3. Components of DC motor.

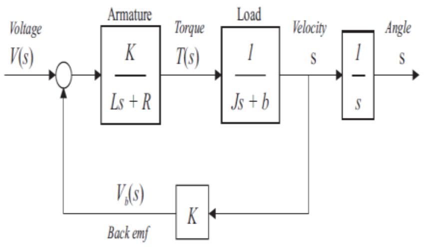


Fig. 4. Block Diagram representation of DC motor [11].

3.3. Simulink model of DC motor

Modelling of DC motor in MATLAB Simulink is performed as shown in Fig. 5. The same motor constants as in reference [11] are employed for our simulation. This Simulink model of DC motor is subsequently used for developing the PWM speed control system.

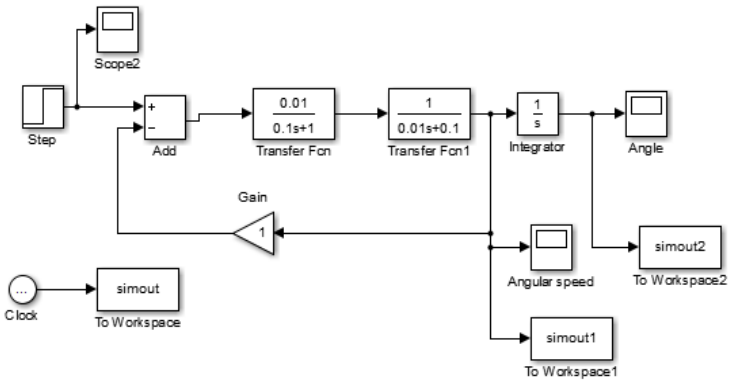


Fig. 5. Block diagram representation of DC motor in Simulink.

3.4. PWM controller for DC motor actuator

The torque speed characteristics of DC motors and other features such as constant power output, rapid acceleration or deceleration, and adjustable speed control made them very useful for industrial applications [24]. Figure 6, showing the typical torque speed characteristics of DC motors, indicates that the no-load speed and the stall torque are proportional to the load (voltage) applied across the motor. Thus, by varying the voltage across the motor, its torque is controlled. Pulse width modulation can be used to vary the voltage applied to the motor and it has been found to be a better approach to control DC motor. An important advantage of PWM circuits when controlling DC motors is that they maintain uniform torque over the entire speed range. When using a linear control (rheostat based), the DC motor jerks forward as it draws enough power to overcome inertia. But in PWM control, the pulses always contain the total circuit voltage and the pulse duration is only changes. So even at low speeds, the motor receives high enough voltage to overcome inertia [25].

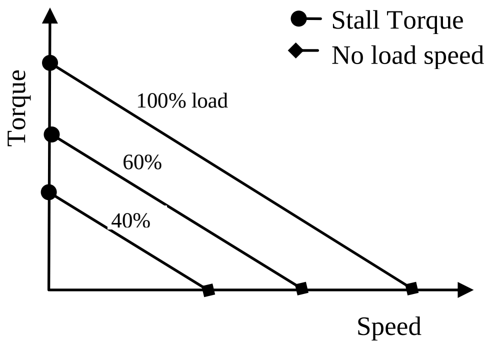


Fig. 6. Typical torque-speed characteristics of DC motor.

The PWM controller circuit for DC motor in MATLAB Simulink is shown in Fig. 7 and motor behavior is analysed by giving required input parameters. The average voltage applied to the motor is proportional to the PWM duty cycle. Better performance of gripper is obtained by varying the duty cycle of PWM controller.

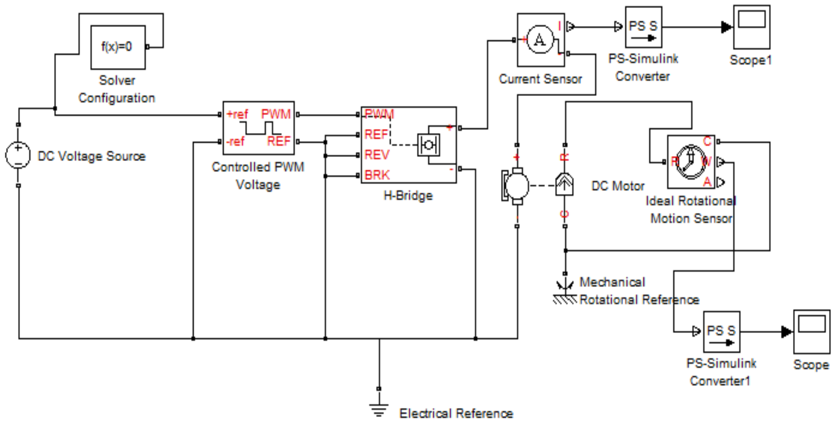


Fig. 7. Simulink model of DC motor with PWM controller.

4. Results and Discussion

From the mathematical model of DC motor, we note that the motor constants, K, L, R, J and b are influencing the torque, velocity and displacement of the rotor and hence the gripper. The values of DC motor constants are adopted from reference [11] for studying the motor behaviour. They are as follows: J= 0.01 kg.m^2, b= 0.1 Nms, K= 0.01 Nm/A, R= 1Ω, L=0.5H. Robort [11] obtained the velocity and displacement against time response for a step input using the MATLAB Control Systems Toolbox and is shown in Fig. 8. The polynomial terms in the transfer function equations (9) and (10) were also given as input.

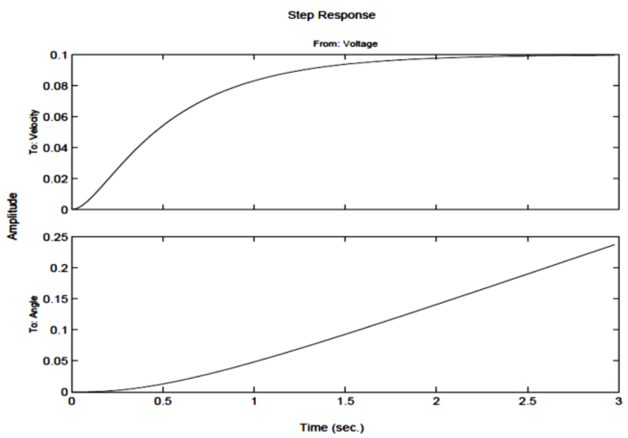
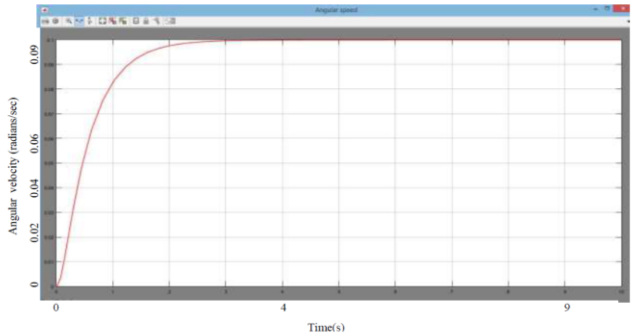
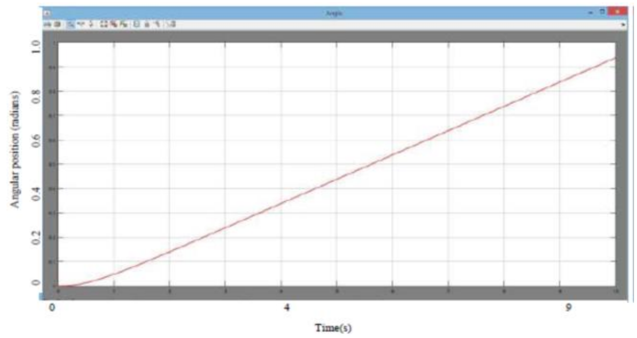


Fig. 8. Behavior of DC motor modelled using MATLAB Control System Toolbox [11].

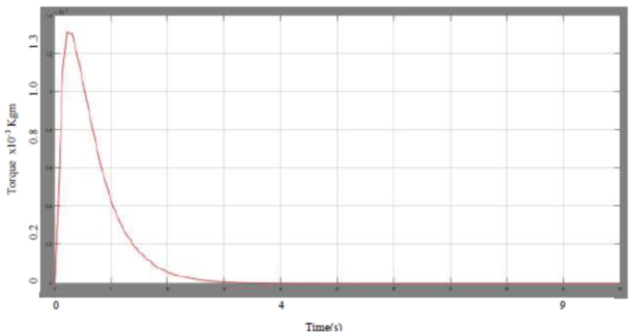
The step response of Simulink model of DC motor, shown in Fig. 9, is seen to be comparable to that of Fig. 8 (solved through Control System Toolbox), considering the same simulation parameters, viz., J, R, K, L, b. The angular speed and position variation with time for step input of 1 V is shown in Fig. 9(a) and (b). This confirms the suitability of the Simulink model of DC motor. Figure 9(c) shows the torque variation under the same conditions. From Fig. 9 (a) the angular velocity under stated conditions is seen to reach a steady state value of 0.09 rad/sec in 3.5 seconds and Fig. 9(c) shows that the torque reaches a maximum value of 1.3×10^{-3} kg.m in 0.5 seconds.



(a) Angular velocity variation for a unit step input of 1V.



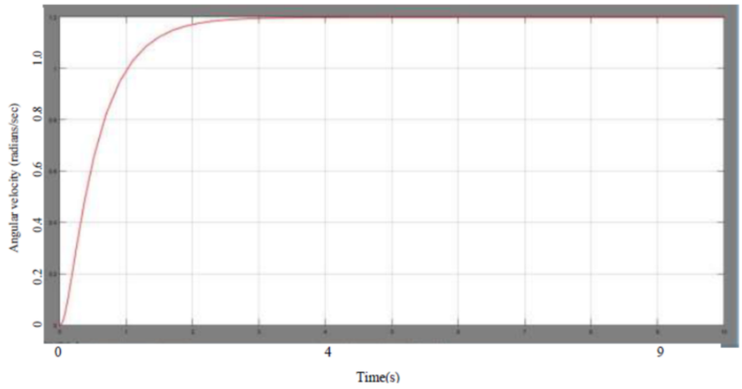
(b) Angular position variation for a unit step input of 1V.



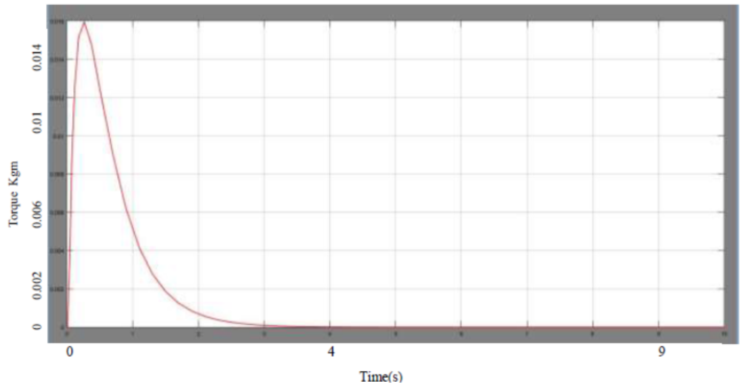
(c) Torque variation for a unit step input of 1V.

Fig. 9. Step response of DC motor in Simulink.

DC motor performance is next simulated for the proposed gripper requirements of 0.02 kg.m torque and 12 V input. Figures 10(a) and (b) show the angular velocity and torque response for 12 V step input. It is seen that the angular velocity attains a steady value of 1.2 rad/sec in 2.5 seconds and maximum torque of 0.016 kg.m is obtained at less than 0.5 seconds.



(a) Angular velocity variation with time.

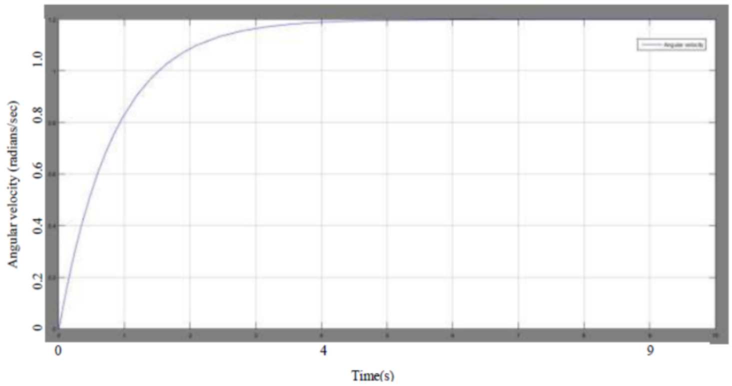


(b) Torque variation with time.

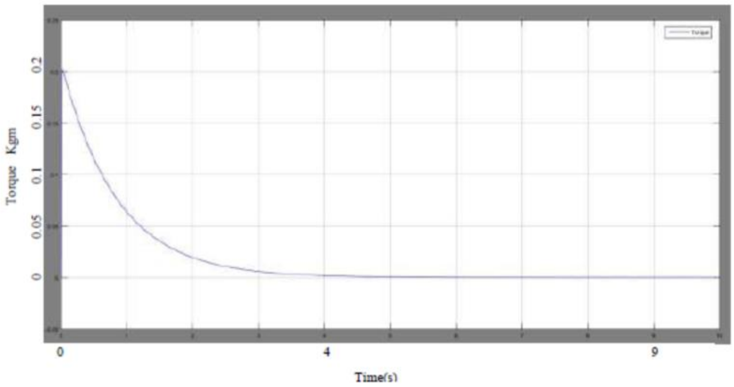
Fig. 10. DC motor performance for 12 V step input in Simulink.

Next, the performance of the DC motor is analysed for precise control of the gripper using a PWM controller. PWM controlled voltage with duty cycle of 50% and pulse duration of 12.2 ms is given to the H bridge device which is used to drive the motor. A current sensor is added in the circuit to analyze the current behaviour of DC motor. The speed characteristic of motor is obtained by using rotational motion sensor in MATLAB. Output of rotational motion sensor is given to the PS-Simulink block which converts the output into RPM.

The graphs obtained from the Simulink model of PWM controlled motor is shown in Fig. 11(a) and (b) for angular velocity and torque variation with time respectively. In this case the angular velocity gradually reaches the steady value of 1.2 rad/sec in 4 seconds and a maximum torque in excess of 0.02 kg.m is obtained instantly at the start of motor. This demonstrates the quick response of holding torque of the electric gripper. As discussed in section 3.1, the load torque requirement of 0.2 Nm or even higher is therefore achievable. PWM control is seen to provide a shorter response time to get maximum torque and a smoother transition to maximum angular velocity.



(a) Angular velocity output.



(b) Torque output.

Fig. 11. PWM controlled DC motor output for 12V supply in Simulink.

5. Conclusions

The design and modelling of an electric gripper actuated by a DC motor has been described for spark plug pick and place application. MATLAB and SolidWorks offer a simple means of simulation for such complex devices. Some concluding observations are noted as follows.

- The mathematical model of DC motor brings out the relation between the input/out parameters and the motor constants and helps in selecting the right motor for an application.
- The modelling of DC motor in MATLAB Simulink has been reviewed and its performance is analysed for step input under applied condition. The torque and

angular velocity response of the actuator are well into the expected range of operation of electric gripper for pick and place of spark plug.

- PWM control of DC motor actuator produces a quick response of holding torque of gripper fingers. Better control of gripping action is obtained by varying the duty cycle of PWM controller.

References

1. Caldwell, D.G.; Medrano-Cerda, G.A.; and Goodwin, M.J. (1993). Braided pneumatic actuator control of a multi-jointed manipulator. *IEEE International Conference on Systems Man and Cybernetics*, Le Touquet, France, 423-428.
2. Sakurai, Y.; Haneishi, Y.; Tanaka, K.; Nakada, T.; and Kohda, T. (2008). Simulation of dynamic characteristics of air gripper by a new Bond-Graph method. *JFPS International Symposium on Fluid Power*, Toyama, Japan, 747-752.
3. Sandesh R.S.; and Nithya,V. (2014). Novel approach to control of robotic hand using flex sensors. *International Journal of Robotics and Automation*, 3(4), 234 -244.
4. Nicolae, P. (2005). Modelling and simulation of the DC motor using Matlab and LabVIEW. *International Journal of Engineering*, 21(1), 49-549.
5. Zygfryd, G.; and Glowacz, W. (2007). Mathematical odel of DC motor for analysis of commutation processes. *Electrical Power Quality and Utilisation Journal*, 13(2), 65-68.
6. Gamazo, R.; Carlos, J.; Ernesto. V.S.; and Jaime. G.G. (2010). Position and speed control of brushless DC motors using sensorless techniques and application trends. *Sensors*, 10(7), 6901-6947.
7. Udai, A.D.; Rajeevlochana, C.G.; and Saha, S.K. (2011). Dynamic simulation of a KUKA KR5 industrial robot using MATLAB Sim Mechanics. *National Conference on Machines and Mechanisms*, Chennai, India, 1-8.
8. Widhiada, W.; Nindhia, T.G.T.; and Budiarsa, N. (2015). Robust control for the motion of five fingered robot gripper. *International Journal of Mechanical Engineering and Robotics Research*, 4(3), 226-232.
9. Widhiada, W.; Douglas, S.S.; Jenkinson, I.D.; and Gomm, J.B. (2011). Design and control of three fingers motion for dexterous assembly of compliant elements. *International Journal of Engineering, Science and Technology*, 3(6), 18-34.
10. Salem, F.A. (2014). Modelling, simulation and control issues for a robot arm; Education and Research III. *International Journal Intelligent Systems and Applications*, 6(4), 26-39.
11. Robort, B.; and Stefano, S. (1999). Matlab Simulink for modelling and control, Delft University of Technology, Netherlands.
12. Al-Mashakbeh, A.S.O. (2009). Proportional Integral and Derivative control of brushless DC motor. *European Journal of Scientific Research*, 35(2), 198-203.

13. Vikas, K; Bhuvanesh, K.; and Arvind, S. (2013). PID controller of speed and torque of servo motor using MATLAB. *International Journal on Recent and Innovation Trends in Computing and Communication*, 1(9), 726-729.
14. Jamaludin, J.; Hairuddin, H.; and Sumaiya, M. (2014). Modelling and simulation of a humanoid robot arm. *International Conference on Multidisciplinary Trends in Academic Research (GTAR),*16-18.
15. Park, K.T.; and Kim, D.H. (2012). Robotic handling gripper using three fingers. *IEEE International Conference on Ubiquitous Robots and Ambient Intelligence (URAI)*, Daejeon, South Korea, 588-592.
16. Samavati, F.C.; Feizollahi, A.; Sabetian, P.; and Moosavian,S.A.A. (2011). Design, fabrication and control of a three-finger robotic gripper. *IEEE International Conference on Robot, Vision and Signal Processing*, Kaohsiung, Taiwan, 280-283.
17. Khadeeruddin, M.; Prasad, T.V.S.R.K.; and Raffi, M. (2013). Design and analysis of two jaw parallel pneumatic gripper. *International Journal of Computational Engineering Research*, 3(12), 41-45.
18. Majid, T.R.; and Kalivitis, P. (2011). Development of an autonomous friction gripper for industrial robots. *World Academy of Science, Engineering and Technology, International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering*, 5(10), 1993-1998.
19. Karokh, M. (2010). Design of a gripper tool for robotic picking and placing., *ISRN UTH-INGUTB-EX /24-SE*.
20. Silva, C.A.; Gonzalez, P.M.; and Aguilera, C.L.A. (2011). Implementation of the Slide-O-Cam mechanism in the design of a robot gripper. *World Congress in Mechanism and Machine Science*, Guanajuato, Mexico, A12_503.
21. Gouasmi, M.; Ouali, M; Fernini, B.; and Meghatria, M. (2012). Kinematic modelling and simulation of a 2-R robot using SolidWorks and verification by MATLAB/Simulink. *International Journal of Advanced Robotic Systems*, 9(6), 1-13.
22. Qassem, M.R.A.; Abuhadrous, I.; and Elayd, H. (2010). Modeling and Simulation of 5 DOF educational robot arm. *IEEE International Conference on Advanced Computer Control*, Shenyang, China, 569-574.
23. Yunming, L; and Zarrugh, M.A. (1983). Kinematic and force control of robotic grippers. *Technical Report RSD-TR-6-83*, University of Michigan, USA.
24. Siddhapura, K.R.; and Raval, D.B. (2014). *A Text Book of Electrrical Machines*. New Delhi: Vikas Publishing House Pvt. Ltd.
25. Braga, N.C. (2002). *Robotics, mechatronics and artificial intelligence: experimental citcuit blocks for designers* (1st ed.). New Delhi: Newnes Publishers.