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Modelling of BLDC Motor for Robotic Leg Joint

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**ABSTRACT**

The space robotics deals with different parameters and conditions of the planets. This robot is buildup of different type of components such as joints, links, joint controllers, different types of sensors, wheels etc. Here a four legged robot is planned in which each leg is composed of five joints. The characterization of these joints is necessary in order to study each leg and kinematics of overall configuration. Hence in this present work an attempt is made to make a mathematical model of a robotic joint which is composed of brushless DC motor, planetary gear, harmonic drive, absolute encoder and motor controller. So the model of robotic joint can be used for the kinematics and dynamic study of the robot.

**Keywords:** Robotic leg joint, Motor controllers, Brushless DC motor, Harmonic drive sensors, Absolute encoder.

**1. INTRODUCTION**

Space robotics deals with the design and development of semi-autonomous machines that have the capability to explore unknown, unstructured, dynamic and hostile environment of outer space. Space robots are preferred since they can perform tasks less expensively in an accelerated schedule with less risk and improved performance as compared to humans. They can operate for long duration and can also be sent into situations that are so risky for humans.
Generally PID controller is used for control because of its simple structure and easy implementation. One of the practical constraints mentioned in this paper [1] is the shortage of space for implementation of the board for a small mobile robot. However in practice the optimum performance cannot be obtained with the conventionally tuned PID controllers. For this purpose genetic algorithm [2] is proposed as a global optimizer to find the optimized PID gains for position control of BLDC motor. The efficiency of this method is compared with the traditional method. Simulation result shows that PID control tuned by GA provides more efficient close loop response for position control of BLDC motor. The actuation system plays a central role because the expected performance, in terms of torque, speed and control bandwidth, must not be achieved at the expense of lightness and compactness [3]. The modeling and simulation of the BLDC motor have been done using the software package MATLAB/SIMULINK after the development of the BLDC motor with sinusoidal and trapezoidal waveform of back-EMF [4]. Due to these reasons robots are been widely used for recent space explorations.

1.1. Components of Robotic Joint

The various components used in the robotic joint include the following:
- BLDC motor
- Rotor position sensors
- Motor controllers
- Planetary gear
- Harmonic drive
- Absolute encoder

1.2. Robotic Leg

A leg has five degrees of rotational freedom and each joint is actuated by a BLDC Motor [5]. The integral components of a Robotic Joint are a BLDC Motor (actuator), encoder (sensor), Controller and the associated mechanical accessories such as gears, harmonic drives which are shown in figure 1. A brushless DC motor with an integral 33:1 planetary gear head, optical encoder, and brake are used in every joint.

This actuator is then used in combination with various size harmonic drive gear [6]. Each joint also incorporates a high precision absolute encoder at the output of the actuator. In a robot, the connection of different manipulator joints is known as Robot Links and the integration of two or more link is called as Robot Joints. Hence it is clear that the BLDC motors have many advantages over brushed DC motors [7]. They are below as:
- Higher speed ranges
- Better speed versus torque characteristics
- Long operating life
- Noiseless operation
- Higher dynamic response

Commulation in BLDC motor is usually electronic commutation based on hall position sensors, where in Brushed DC motor Brushes are used. Maintenance of BLDC motor is less required due to the absence of brushes, and has a long operating life. But Brushed DC motor requires periodic maintenance and shorter operating life. Efficiency is high in BLDC motor as compared to the Brushed one [8]. In BLDC motor electrical noise generated is low but the Brushed one will generate noise due to arcs in the Brushes. They have concerned with PID control of rigid robots equipped with brushless DC (BLDC) motors [9]. Here they showed that a PID controller is sufficient to achieve local stability whereas an adaptive PD controller will provide the global convergence. Also presented a theoretical justification for the torque control or current control strategy commonly used in practice to control BLDC motors.
1.3. Motor Controllers

In this work the motor and controllers modelled and characterized using MATLAB software. The aim of this is to make a complete model of the BLDC motor and to design an optimal controller for its position control [10]. Generally PID controller is used for control because of its simple structure and easy implementation. However in practice often to get the optimum performance with the conventionally tuned PID controllers. For this purpose genetic algorithm is proposed as a global optimizer to find the optimized PID gains for position control of BLDC motor [11]. The efficiency of this method is compared with the traditional method. Simulation result shows that PID control tuned by GA [12] provides more efficient close loop response for position control of BLDC motor. The modelling control and simulation of the BLDC motor have been done using the software package MATLAB/SIMULINK [13].

A controller is a device introduced in the system to modify the error signal and to produce a control signal [14]. The controller modifies the transient response of the system. The controllers used in the robotic joint to control the current, velocity and position are PI controller and PID controller.

2. MODELLING OF BLDC MOTOR

The analysis is carried out by means of the equations (2.1), (2.2), (2.3), (2.4), (2.5), (2.6), (2.7), (2.8), (2.9), (2.10) and (2.11).

The voltage equation of BLDC motor is given by

\[ V = L \frac{di}{dt} + iR + E_b \]  

(2.1)

where, \( E_b = K_t \frac{d\theta}{dt} \)

Armature side

\[ L \frac{di}{dt} + iR = V - K_t \frac{d\theta}{dt} \]  

(2.2)

Load side

\[ iK_t - r \frac{d\theta}{dt} = J \frac{d^2\theta}{dt^2} \]  

(2.3)

Taking transfer function of the equations (2.2) and (2.3)

\[ LsI(s) + RI(s) = V(s) - K_t s\theta(s) \]  

(2.4)

\[ Js^2\theta(s) + rs\theta(s) = K_t I(s) \]  

(2.5)

From equation (2.4) \( I(s) \) can be obtained as

\[ I(s) = \frac{V(s) - K_t s\theta(s)}{R + Ls} \]  

(2.6)

Substitute \( I(s) \) in equation (2.5)

\[ Js^2\theta(s) + rs\theta(s) = \frac{K_t [V(s) - K_t s\theta(s)]}{R + Ls} \]  

(2.7)

\[ \theta(s) [Js^2 + rs][R + s] = V(s) K_t - K_t^2 s\theta(s) \]

\[ V(s) K_t = \theta(s) [Js^2 + rs][R + Ls] + K_t^2 s\theta(s) \]

\[ V(s) = \frac{\theta(s) [Js^2 + rs][R + Ls] + K_t^2 s\theta(s)}{K_t} \]  

(2.8)

From equation (2.8)

\[ \frac{\theta(s)}{V(s)} \]  

is calculated

\[ \frac{\theta(s)}{V(s)} = \frac{K_t}{[Js^2 + rs][R + Ls] + K_t^2 s} \]

(2.9)

Let \( S\theta(s) = \omega(s) \)

\[ \frac{\omega(s)}{V(s)} = \frac{K_t}{[Js + r][R + Ls] + K_t^2} \]  

(2.10)

Consider

\( G(s) = \frac{\omega(s)}{V(s)} \)

where \( \omega(s) \) is the velocity

\[ G(s) = \frac{K_t}{LJs^2 + (JR + L)s + Jr + K_t^2} \]  

(2.11)

where,

\( K_t \rightarrow \) Torque constant \((mNm/A)\)
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L → Terminal inductance phase to phase (mH)

J → Rotor inertia (Kgm²)

R → Terminal resistance phase to phase (Ω)

r → Frictional coefficient of motor and load (Nm/(rad/sec))

In order to achieve the transient response Maxon motor and Maxon controller parameters are used. It is shown in table 1 and table 2 below.

3. RESULTS AND DISCUSSION

The various simulated result of BLDC motor without gear and also its current and velocity controllers are shown below:

3.1. Design and Performance of Maxon BLDC Motor

Electrical part

\[ R = 0.527 \Omega \]
\[ L = 0.0503 \text{mH} \]

Interface between Electrical and Mechanical parts

\[ K_e = K_{e0} = 14 \frac{\text{Nm}}{\text{A}} \] \hspace{1cm} (3.1)

Mechanical part

Moment of inertia,

\[ I = I_{motor} + I_{load} = 5000 + 5.54 = 5005.54 \text{gcm}^2 = 5005.54 \times 10^{-7} \text{Kgm}^2 \] \hspace{1cm} (3.2)

Frictional coefficient of motor and load,

\[ r = \frac{K_t}{n_0} I_o = \frac{14 \times 10^{-8}}{16200} \times 206 \times 10^{-3} = 1.7802 \times 10^{-7} \] \hspace{1cm} (3.3)

The equations (3.1), (3.2) and (3.3) are shown above. The input to the BLDC motor is the voltage at the motor winding and the outputs are current and velocity [15].

The model of the BLDC motor has the armature and load shown in Figure A1. The input given to the motor is voltage and output obtained is the speed which is measured in rpm. To overcome the limitations and to combine a motor system with a precise and high dynamic regulation, it will be necessary to control the motor movement as well as the load movement. Figure A2 represent the waveforms of speed with respect to time.

Current waveform with respect to time obtained for BLDC motor is shown in Figure A3. The current value initially rises to the starting current of about 45.5A and it falls to the nominal current value of about 3.82A.

The speed waveform with respect to time obtained for BLDC motor is shown in Figure A4. The no load speed of about 16000 rpm is obtained at the output.

The input voltage given to the motor is 24V and the output speed obtained by the
no load speed of about 16200rpm which can be shown in Figure A5.

3.2. Current Regulation

During a movement within a drive system, forces or torques must be controlled. Therefore, current regulation structure offers current-based control.

The current regulation is done by including the BLDC motor along with the PI controllers which is shown in Figure A6. The input current set value given to the motor is about 3.1A.

The current waveform with respect to time for BLDC motor is shown in Figure A7. The output current here is of about 1.3A. The steady state output is achieved by tuning the parameters in the PI controller.

The speed varied linearly with respect to time for 5 seconds can be seen in Figure A8. For 5 seconds the speed is obtained about 1720rpm.

The input current set 1.31A is applied in to the motor and the output current obtained of about 1.3A which can be seen in Figure A9.

3.3. Velocity Regulation

The objective of velocity regulation is to maintain the velocity of the motor shaft at a given constant desired reference. In contrast, the goal of velocity control is to accurately track a time-varying desired velocity. The design of stable velocity controllers is important in industrial robots, since they use motor drives provided with an inner velocity feedback loop as the core of the control system.

However, in order to achieve a desired performance, the physical limitations of the motor should be taken into account. The velocity feed forward factor and acceleration feed forward factor are included in the velocity regulation. Figure A10 represent the simulink model of Maxon BLDC motor with Velocity Regulation.

The current waveform for the velocity regulation with respect to time for BLDC motor is shown in Figure A11. The transient response is obtained in a very short interval of time and the current value of about 3.57A.

The steady state speed value is obtained of about 6.2rpm which is represented in Figure A12. This is achieved by tuning the parameters \( K_p \) and \( K_i \).

4. CONCLUSION

The brushless DC Motor has been modelled considering the actual motor parameters and the characteristics have been studied. A velocity controller has also been designed and simulated. Control of BLDC motors shall be further refined by Genetic Algorithm method. Current design employs only one encoder at the end of the gear set. Another encoder shall be used directly at the motor shaft output which can improve the transient response and performance.

REFERENCES


APPENDIX A
Figure A1. Simulink model of Maxon BLDC motor (323218)

Figure A2. Waveforms with respect to time
Figure A3. Current vs Time characteristics

Figure A4. Speed vs Time characteristics

Figure A5. Voltage and Speed waveform of BLDC motor

Figure A6. Simulink Model of Maxon BLDC motor with Current Regulation
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Figure A7. Current vs Time characteristics

Figure A8. Speed vs Time characteristics

Figure A9. Current waveforms with respect to time
Figure A10. Simulink Model of Maxon BLDC motor with Velocity Regulation

Figure A11. Current vs Time characteristics

Figure A12. Speed vs Time characteristics

APPENDIX B

BLDC motor parameters
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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Nominal voltage (V)</td>
<td>24</td>
</tr>
<tr>
<td>No load speed (rpm)</td>
<td>16200</td>
</tr>
<tr>
<td>Starting current (A)</td>
<td>45.5</td>
</tr>
<tr>
<td>Nominal current (A)</td>
<td>3.82</td>
</tr>
<tr>
<td>Terminal resistance (Ω)</td>
<td>0.527</td>
</tr>
<tr>
<td>Terminal inductance (mH)</td>
<td>0.0503</td>
</tr>
<tr>
<td>Rotor inertia (gcm²)</td>
<td>5.54</td>
</tr>
</tbody>
</table>