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Dynamic Modeling of a 3-DOF Articulated Robotic Manipulator Based on Independent Joint Scheme

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Authors' contributions

This work was carried out in collaboration between all authors. Author ECA designed the study, performed the simulation, analysis and wrote the first draft of the manuscript. Authors HCI and CCO managed the analyses of the study. All authors read and approved the final manuscript.

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ABSTRACT

Joint torque control of a robotic manipulator requires a close dynamic description model involving the non negligible dynamics of the subsystems making up the system. The mathematical model for joint torque control of the robotic manipulator has been identified as one of the major sources of failures of commercial robots. The manipulator is basically made up of links connected by joints, and the torque that moves the links connected to a joint is produced by the joint actuator and also in practice, the control law is fed into the actuator inputs, therefore the actuator dynamics becomes non negligible dynamics in the dynamic modeling of the manipulator for robust joint torque control. Hence, a complete dynamic model of the manipulator which involves the link dynamics plus actuator dynamics was proposed. This paper focuses on the modeling of a 3DOF articulated manipulator based on independent joint (decentralized) scheme and the determination of the viscous damping coefficient for the joint torque control model. The independent joint model provides closer mathematical description of the manipulator and also enhances robust controller design. Joint damping coefficient B, was determined through experiment based on bode plot of the open loop gain. From the results, it was concluded that joints I and II achieved the best performance when B is 0.001N.m/rad /sec and 0.01N.m/rad /sec respectively.

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Keywords: Decentralized control; robotic manipulator modeling; independent joint control; link; joint torque control; 3DOF; dynamic model; articulated robotic manipulator.

1. INTRODUCTION

Articulated robotic manipulators consist of links connected by bending or rotating joints (axes), copying the movement capability of a human arm. They are ideally suited to welding and cutting, laser applications, deep sea and medical surgery works. Kinematics is the motion geometry of the robot manipulator from the reference position to the desired position with no regard to forces or other factors that influence robot motion [1]. In practice most robot manipulators are driven by electric actuators which apply torques at the joints of the robot. The dynamics of a robotic manipulator describes how the robot moves in response to these actuator forces. In order to control the force and motion of the robotic manipulator, its actuator dynamics must be considered. In the dynamic modeling of manipulator rigid bodies (arm) the following methods were used: Lagrange-Euler, Newton Euler, D'Alembert [2]. Iqbal and Author [3] suggested that there should be an improvement in the dynamic model of the robotic manipulator by adding the complete model of the selected drives in the model. This was supported by Lewis et al. [4] who stated that to obtain a complete dynamical description of the arm plus actuators, requires adding the actuator dynamics to the arm dynamics. Melchiorri [5] declared that the actuation system has several effects on the dynamics: if motors are installed on the links, then masses and inertia are changed, and it introduces its own dynamics (electromechanical, pneumatic, hydraulic, etc) that may be non negligible. It also introduces additional nonlinear effects such as backslash, friction, and elasticity.

Alassar [6] identified two essential problems in the development of robotic manipulators: the first problem is the mathematical modeling of the manipulator and the actuators, and the second problem is the control of the manipulator. The problem of the dynamic model of the robotic manipulator was also identified in Fateh [7] to be the joint torque control problem. The inability of the commercial robots to control joint torques is a well known problem [8,9]. The general robot arm dynamic control law proposed in [10,11] was described by Fateh [7] as complex and complicated. In a manipulator driven by DC motors, the currents of the DC motors are directly controlled to implement the torque control law [12]. The DC motor driven manipulators are controlled by applying the designed controller output to the joint motor inputs and each joint feeds its output back to its controller for optimization, thereby utilizing a single input single out configuration of the decentralized control scheme. Hence, the joint dynamic model based on the decentralized control which uses multiple SISO configurations is proposed to control electrically driven manipulators. Fateh [7] stated that this method obtains simplicity, accuracy, speed and robustness to the manipulator. Most industrial robots are controlled by independent joint control strategy [13]. In [14] independent joint control law was used for robotic manipulator model by considering the actuator dynamics and the arm dynamics. In this method, the arm dynamics and the actuator dynamics are combined to form a complete manipulator dynamic model. Ovy et al. [15] applied the actuator dynamic model in their robotic arm control. Implementation of actuator dynamics in the dynamic model for joint torque control of an articulated manipulator was presented in [16,17].

Garulli et al. [18] stated that when modeling physical systems for control purposes, it is necessary to provide model descriptions that capture the main features of the system behavior and are mathematically tractable at the same time. The main aim of this work is to develop a dynamic model that provides a close dynamical descriptions model, considering the electrical and mechanical dynamics of the system for robust control.

2. LITERATURE REVIEW

The dynamic model applied in [19,20] is basically the dynamical description of the mechanical arm of the manipulator. Biradar et al. [21] investigated Lagrange-Euler method and suggested a future work for an improved model that can be implemented in the controller of the manipulator, and optimized for a specific job task. In Izadbakhsh et al. [22], the Langrange model was used when considering the equation of motion of robot links. However, a complete model of the actuator was used for the robust controller design simulation in their work; they did not consider the arm dynamics in the model used in the simulation. Lewis et al. [4] stated that to obtain a complete dynamical description of the arm plus the actuator (which make up the robotic manipulator), it is required to add the actuator dynamics to the arm dynamics. According to

Helal et al. [23], actuators model are computed to merge it with the dynamic model of the robot. Conversely, the dynamic model they presented did not include the inertia of the robot link. Thus, the consideration of the manipulator link inertia into this model would give a more complete dynamical description of the robotic manipulator. In addressing the problems in robot force control as presented in [24], the actuator model is coupled to the rigid body model of the robotic manipulator. Fateh [7] modeled the robotic manipulator based on the independent joint control approach which is based on the joint actuator dynamic model and the torque due to link. Ovy et al. [15] designed an articulated robot arm for precise positioning based on joint dynamic model instead of the Lagrangian-Euler dynamic model of the arm. In order to achieve a complete dynamic model for a closer dynamic description for the robotic manipulator modeling and control therefore, the actuator dynamics plus the link dynamics must be considered and this can be achieved by the deployment of decentralized control also known as independent joint control approach.

2.1 Robotic Manipulator Kinematic Arrangements

The industrial robots are basically composed of rigid links, connected in series by joints, having one end fixed (base) and another free to move and perform useful work when properly tooled (end-effector). The structure of the robot consists of a number of links and joints, a joint will allow relative motion between two links [25]. The different arrangements of the rigid links and the type of joints applied in the design of a robotic arm gave rise to the types of arms of the manipulator. There are five types of manipulator arm configurations commonly used by industrial robotic manipulators: *cartesian, cylindrical, polar, SCARA* and *revolution.* Although there are many possible ways prismatic and revolute joints are used to construct kinematic chains, in practice only a few of these are commonly used [14]. Crowder [25] stated that the basic robot arm has three joints, this allows the tool at the end of the arm to be positioned anywhere in the robots working envelope. Even though there are a large number of robot configurations that are possible, only five configurations are commonly used in industrial robotics as summarized in Table 1.

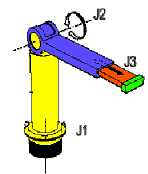
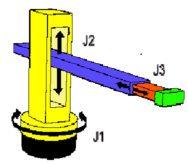
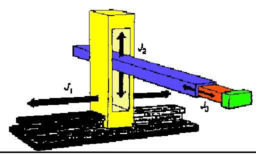
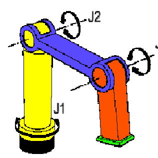
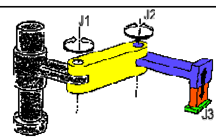
2.2 Robotic Manipulator Control Schemes

Milchiorri [26] stated that the robot performances are mainly influenced by the mechanical design and by the actuation system. He also explained that there are two types of robot control schemes: Decentralized (or independent) control schemes and Centralized control schemes. The decentralized control scheme also known as independent joint control (IJC) model has Single Input Single Output (SISO) configuration while the centralized control scheme has a Multiple Input Multiple Output (MIMO) configuration. From the review, SISO configuration (which can equally be in the form of multiple SISO) is more common and simpler than the MIMO in practice. According to Alassar [6], the basis of IJC is that the robotic manipulator is treated as a set of independent actuators working independently. This means that each link of the robotic manipulator is considered as single input single output (SISO) system with an independent controller.

Independent joint control scheme is widely adopted in most industrial manipulator controller because of its simplicity [27]. According to Richter [28], to derive the independent joint control model, it is assumed that the DC motor is connected to a gear reduction of ratio r : 1 and moment of inertia J_g. The reduced-speed shaft drives a rotational inertia J_l, which represents the link driven by the motorized joint. The motion of the other links should influence the DC motor as well. For the independent joint model, however, the influences of the other links are treated as disturbances and then the controller is designed to be robust (tolerant) against them [28]. When applying the independent joint scheme, Melchiorri [26] stated that each joint of the robotic manipulator is considered independently, and the term d $(= {}^{\tau_l}/_{r})$ is considered as an external disturbance. These considerations can be applied with proficiency when there is no direct coupling between the actuator and the joint.

Fig. 1 illustrates the independent control scheme where the actuator and link dynamics are considered. Where J_a, J_g and J_l are respectively, the actuator, gear, and load inertias. Bm is the coefficient of motor friction and includes the friction in the brushes and gears. τ_l is the link torque, r is the gear ratio. Considering a DC motor actuator, the independent joint model of the robotic manipulator is derived in [14,26]. Fig. 2 shows the block diagram of a robotic manipulator and Fig. 3 represents a third order system from input voltage V(s) to output position θ_m.

Table 1. Configurations commonly used in industrial robots [25]

Polar		The linear extending arm is capable of being rotated around the horizontal and vertical axes.
Cylindrical		The linear extending arm can be moved vertically up and down around a rotating column.
Cartesian and Gantry:		Three orthogonal sliding or prismatic joints.
Jointed Arm or Articulated		Three joints arranged in an anthropomorphic configuration.
Selective Compliance Assembly Robotic Arm, SCARA		Two rotary axes and a linear joint.

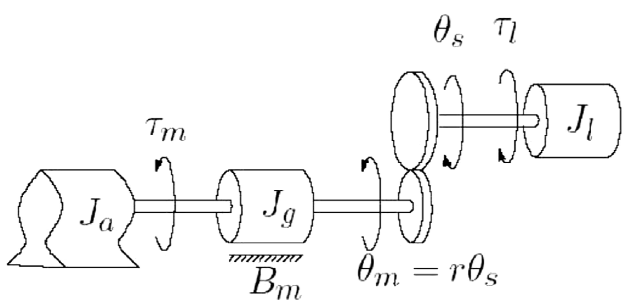


Fig. 1. Lumped model of single link with actuator/gear train [14,26]

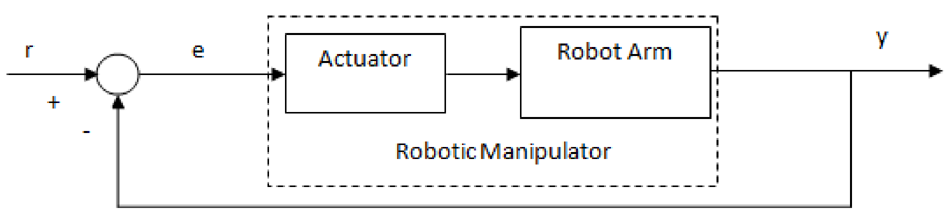


Fig. 2. Robotic manipulator block diagram (SISO)

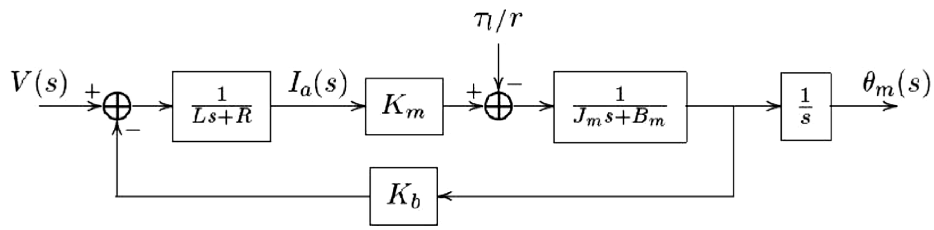


Fig. 3. Block diagram of actuator model with link [14,26]

3. METHODOLOGY

The mathematical models for the robotic manipulator are very important for the development of the system. To achieve robust joint torque control, the robotic manipulator analysis must involve the source of the joint torque. The development of mathematical model for joint torque control of the manipulator must involve a complete dynamical description of the entire system comprising of the links and the actuators. Therefore, a complete dynamic model comprising of the link dynamics and actuator dynamics was proposed in this work for joint torque control of the manipulator. Independent joint control strategy was adopted in order to separately model the joint torques to enable precise robust controller design for every joint of the manipulator. Fig. 4 shows the kinematics of a two-link 3DOF planar arm.

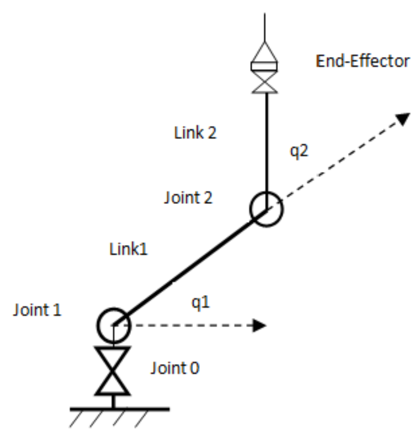


Fig. 4. Kinematics of a two-link 3DOF planar arm

3.1 Robot Arm Dynamic Model

The dynamics of an *n-DOF* robot manipulator is governed by the following equation [29]:

$$M(q)\ddot{q} + N(q,\dot{q}) = \tau \quad (1)$$

Where τ is actuation torque, M (q) is a symmetric and positive define inertia matrix, N is the vector of nonlinearity term.

$N(q,\dot{q}) = C(q,\dot{q})\dot{q} + g(q)$, therefore:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau \quad (2)$$

Where q is the joint variable vector, M(q) is the completed inertia matrix, $C(q,\dot{q})$ is the centripetal and Coriolis torque vector, G(q) is the gravitational torque vector. Due to the complexity of this method of robotic manipulator dynamics analysis, Lin et al. [30] assumed that g(q) = 0. However, Kim et al. [31] and Liu et al. [32] did not adopt such assumption. From the review, there are too many differences in the assumptions in most works where equation 2 was applied.

3.2 Joint Actuator Model

The articulated manipulator is driven by electric actuator and the dynamic equation of a manipulator driven by DC motors [7,14] is formulated as follows:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = K_t i \quad (3)$$

where i is the armature current vector, and K_t is the diagonal matrix of motor torque constant. The actuator nominal model is derived from the motor internal structure.

$$\tau_m = K_t i \quad (4)$$

Sum of torques at the motor gear is equal to zero, that is:

$$J_m \frac{d^2\theta m}{dt^2} + B_m \frac{d\theta m}{dt} = K_t i \quad (5)$$

Taking the Laplace transform of equation 5 yields;

$$J_m \omega_m s(s) + B_m \omega_m(s) = K_t I(s) \quad (6)$$

The electrical circuit of the actuator provides the following equation [13]:

$$V_{in} = Ri + L_a \frac{di}{dt} + K_e \frac{d\theta_m}{dt} \quad (7)$$

Taking the Laplace transform of equation 7

$$V_{in}(s) = RI(s) + L_a sI(s) + K_e \omega(s) \quad (8)$$

Where ω is the angular velocity

Resolving the equations with the help of the actuator block diagram in Fig. 3 and solving for the relationship between voltage input V_{in} and the position of the shaft θ_m in the closed loop system yields the actuator dynamic model as derived in [6,15]. When the motor is not connected to the robotic manipulator joint mechanism (i.e. T_l=0), its dynamic model does not include the inertia due to the linkage or load. Combining the mechanical and electrical subsystem dynamics of the motor, therefore actuator dynamic model becomes:

$$\begin{cases} Js\dot{\theta}_m + B\dot{\theta}_m = K_t I \\ V_{in} = RI + L_a sI + K_e \dot{\theta}_m \end{cases} \quad (9)$$

The model for the variable $\theta_m(s)$ becomes:

$$\theta_m(s) = (L_a J_m s^3 + (R_a J_m + B_m L_a)s^2 + (R_a B_m + K_t K_e)s)^{-1} K_t V_{in}(s)) \quad (10)$$

Where, J_m is the motor inertia, R_a is the actuator resistance, L_a is the actuator inductance, K_t is the torque constant, K_e is the back emf constant, B_m is the frictional damping coefficient of motor, $\omega_m = \dot{\theta}_m$ is the velocity of the motor.

3.3 Robotic Manipulator Joint Dynamic Model

According to Fateh [7], there are some problems in implementing the control law presented in equation 2. This control law is not complete since some terms such as frictional torques have been omitted for simplicity and reducing the computing time, and some terms are not precise. Therefore, applying this control law cannot provide a perfect linear and decoupled system, and due to inaccuracy in model, errors will be produced. Moreover, implementing the control law requires feedbacks of all joint positions and their derivatives. Also, the control strategy is complex since the system is highly coupled and multi-input/multi-output. The tracking error increases as velocity increases. He also stated that the dynamic model involving the actuator dynamics is preferred to equation 2 in the robotic manipulator design. This is because all feedbacks belong to the actuator (motor). Also, manipulator model is not required to form the control law. As a result, the control law is simple, fast, and more accurate in comparison with the equation 2. The control law requires only a feedback of actuator current and position. Moreover, the electrical signals can be measured more convenient and more precise than mechanical signals. This control law can be used for tracking control of a high-speed robot since this approach is free of manipulator model. The actuator dynamic equation is used for precise control of each degree of freedom of a robotic arm as applied in [16].

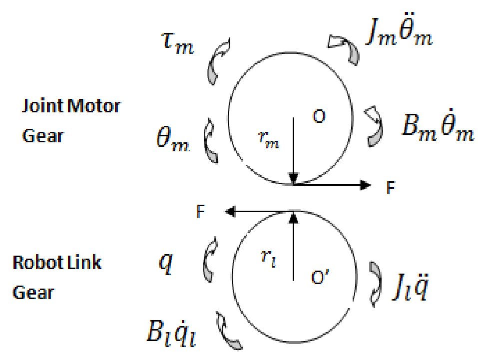


Fig. 5. Mechanical subsystems of the motor and link gears

The mechanical subsystems of the actuator and the robot arm are connected at the actuator and link gears as shown in Fig. 5. The coupling of the actuator dynamics and link dynamics at the gears in each independent joint is achieved as follows.

The sum of torques at the motor gear gives:

$$\sum torques\ at\ the\ motor\ gear = J_m \ddot{\theta}_m$$

$$\tau - B_m\dot{\theta}_m - r_m F = J_m\ddot{\theta}_m$$
$$J_m\ddot{\theta}_m + B_m\dot{\theta}_m + r_m F = \tau \quad (11)$$

The sum of torques at the robot arm gear gives:

$$\sum torques\ at\ the\ link\ gear = J_l\ddot{q}$$
$$r_l F - B_l\dot{q} = J_l\ddot{q}$$
$$J_l\ddot{q} + B_l\dot{q} = r_l F \quad (12)$$

$$F = (J_l\ddot{q} + B_l\dot{q})/r_l \quad (13)$$

Substituting equation 13 into equation 11 yields;

$$J_m\ddot{\theta}_m + B_m\dot{\theta}_m + \frac{r_m}{rl}(J_l\ddot{q} + B_l\dot{q}) = \tau \quad (14)$$

The gear kinematics for the motor gear and link gear is as follows

$$\frac{r_m}{r_l} = \frac{N_m}{N_l} = \frac{\dot{q}}{\dot{\theta}_m} = \frac{q}{\theta_m} \quad (15)$$

Where r_m is the radius of motor gear, r_l is the radius of link gear, N_m is the number of teeth of the motor gear, N_l is the number of teeth of the link gear, F is the contact force, J_l is the link inertia, B_l is the link damping coefficient.

Therefore, the angular position of the link is derived from the motor position and the gear ratio of motor and link gears as:

$$\theta_m = \left(\frac{r_l}{r_m}\right) q \quad (16)$$

$$\dot{\theta}_m = \left(\frac{r_l}{r_m}\right) \dot{q} \quad (17)$$

$$\ddot{\theta}_m = \left(\frac{r_l}{r_m}\right) \ddot{q} \quad (18)$$

Substituting equations 16, 17 and 18 into equation 14, yields:

$$\left(\frac{r_l}{r_m}J_m + \frac{r_m}{r_l}J_l\right)\ddot{q} + \left(\frac{r_l}{r_m}B_m + \frac{r_m}{r_l}B_l\right)\dot{q} = \tau \quad (19)$$

Combining the mechanical and electrical subsystems of the actuator and arm dynamics yields:

$$\begin{cases} \left(\frac{r_l}{r_m}J_m + \frac{r_m}{r_l}J_l\right)\ddot{q} + \left(\frac{r_l}{r_m}B_m + \frac{r_m}{r_l}B_l\right)\dot{q} = K_t I \\ V_{in} = RI + L_a sI + \frac{r_l}{r_m}K_e\,\dot{q} \end{cases} \quad (20)$$

The transfer function model of the joint dynamic model becomes:

$$G = \left(s\left[\left(\left(\frac{r_l}{r_m}J_m + \frac{r_m}{r_l}J_l\right)s + \left(\frac{r_l}{r_m}B_m + \frac{r_m}{r_l}B_l\right)\right)(L_a s + R) + K_e K_t\right]\right)^{-1} \mathrm{K}_t \quad (21)$$

Hence, the joint I and II dynamic models becomes:

$$G_1 = \left(s\left[\left(\left(\frac{r_{l1}}{r_{m1}}J_{m1} + \frac{r_{m1}}{r_{l1}}J_{l1} + J_{l2}\right)s + \left(\frac{r_{l1}}{r_{m1}}B_{m1} + \frac{r_{m1}}{r_{l1}}B_{l1}\right)\right)(L_{a1}s + R_1) + K_{e1}K_{t1}\right]\right)^{-1} \mathrm{K}_{t1}$$

$$G_2 = \left(s\left[\left(\left(\frac{r_{l2}}{r_{m2}}J_{m2} + \frac{r_{m2}}{r_{l2}}J_{l2}\right)s + \left(\frac{r_{l2}}{r_{m2}}B_{m2} + \frac{r_{m2}}{r_{l2}}B_{l2}\right)\right)(L_{a2}s + R_2) + K_{e2}K_{t2}\right]\right)^{-1} \mathrm{K}_{t2}$$

The dynamic model for joint torque control relating angular position of the link and the voltage input into the actuator becomes:

$$q = \left(s\left[\left(\left(\frac{r_l}{r_m}J_m + \frac{r_m}{r_l}J_l\right)s + \left(\frac{r_l}{r_m}B_m + \frac{r_m}{r_l}B_l\right)\right)(L_a s + R) + K_e K_t\right]\right)^{-1} \mathrm{K}_t V(s) \quad (22)$$

The multiple SISO model for the articulated robotic manipulator dynamic description becomes:

$$q_1 = \left(s\left[\left(\left(\frac{r_{l1}}{r_{m1}}J_{m1} + \frac{r_{m1}}{r_{l1}}J_{l1} + J_{l2}\right)s + \left(\frac{r_{l1}}{r_{m1}}B_{m1} + \frac{r_{m1}}{r_{l1}}B_{l1}\right)\right)(L_{a1}s + R_1) + K_{e1}K_{t1}\right]\right)^{-1} \mathrm{K}_{t1}V(s)$$

$$q_2 = \left(s\left[\left(\left(\frac{r_{l2}}{r_{m2}}J_{m2} + \frac{r_{m2}}{r_{l2}}J_{l2}\right)s + \left(\frac{r_{l2}}{r_{m2}}B_{m2} + \frac{r_{m2}}{r_{l2}}B_{l2}\right)\right)(L_{a2}s + R_2) + K_{e2}K_{t2}\right]\right)^{-1} \mathrm{K}_{t2}V(s)$$

In order to determine the effective viscous damping coefficient at the joints, the following design specifications must be met.

- Peak gain>>0 (i.e., peak gain must be very much greater than zero)
- Both Gain Margin (GM) and Phase Margin (PM) must exist
- PM should be greater than GM

The arm parameters are as follows: mass of link 1 (m1) =1kg, mass of link 1 (m2)=0.06kg, length of link 1 (L1) = 1m, length of link 1 (L2) = 0.9m, taking $r_m = r_l$. Table 2 shows a summary of joint I and II design parameters.

Table 2. The parameters of joints I and II

Parameters	Joint I	Joint II
Inertia (J)	0.001 Kg-m^2	0.0003 Kg-m^2
Resistance (R)	2.5Ω	3.5Ω
Inductance (La)	0.004H	0.001H
Current (i)	1A	1A
Torque constant (km)	0.1N.m/A	0.05N.m/A
Electromotive force constant (Ke)	0.1V.s/rad	0.05V.s/rad

4. RESULTS AND DISCUSSION

Figs. 5 and 6 show the Bode plots of the open loop gain of the robotic manipulator joints I and II without a controller. Tables 3 and 4 were generated from the MATLAB bode plots of Fig. 5 and Fig. 6.

From the joint I experimental results in Fig. 6 and Table 3, PM does not exist when B=10 N.m/rad/sec, and it was less than GM when B=0.00001N.m/rad/sec. However, when B=0.1 N.m/rad/sec, 0.01N.m/rad/sec and 0.001 N.m/rad/sec the system satisfied the design specifications but when B=0.001N.m/rad/sec, the system achieved highest peak gain of 418dB compared with when B=0.1 and 0.01N.m/rad/sec.

Table 3. Damping coefficient experiment results for joint I

B (N.m/rad/sec)	GM (dB)	PM (Degree)	Peak gain (dB)
10	128	-	352
0.1	65.5	89.8	392
0.01	46.9	78.5	409
0.001	37.9	42.3	418
0.00001	35.9	34.6	420

Table 4. Damping coefficient experiment results for joint II

B (N.m/rad/sec)	GM (dB)	PM (Degree)	Peak gain (dB)
10	148	-	343
0.1	88.6	90	383
0.01	68.5	87.8	402
0.001	52.5	44.3	418
0.00001	45	19.7	426

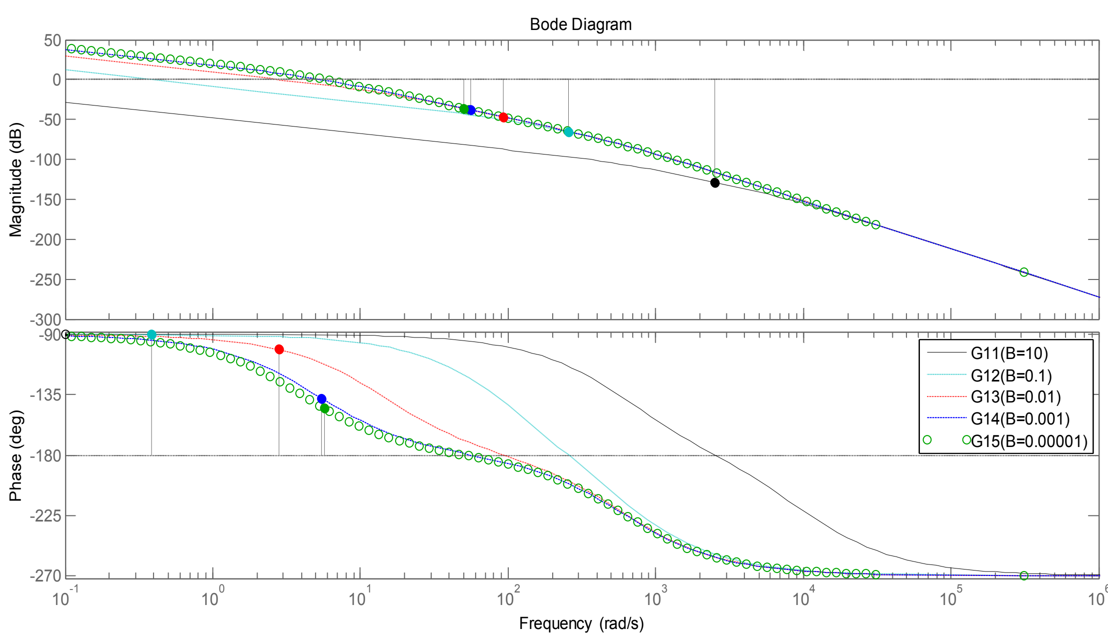


Fig. 6. Joint I damping coefficient results

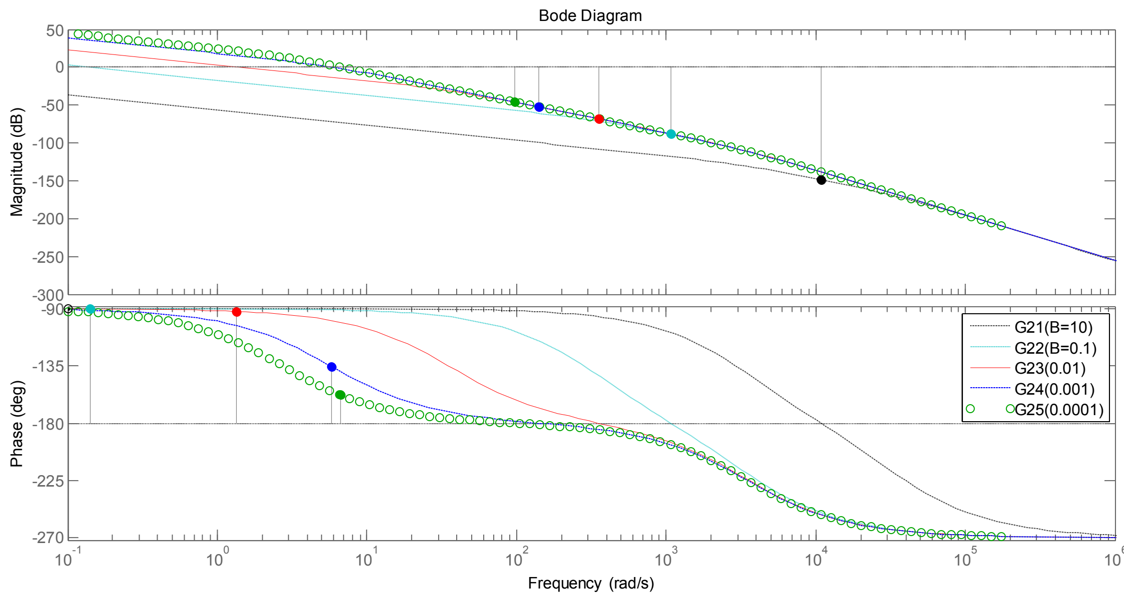


Fig. 7. Joint II damping coefficient results

From the joint II experimental results in Fig. 7 and Table 4, PM does not exist when B=10 N.m/rad/sec, and it was less than GM when B=0.001N.m/rad/sec and 0.00001N.m/rad/sec. On the other hand, when B=0.1N.m/rad/sec and 0.01N.m/rad/sec the system satisfied the design specifications, however when B=0.01N.m/rad/sec, the system achieved highest peak gain of 402dB compared with when B=0.1 N.m/rad/sec.

5. CONCLUSION

The dynamic model for the joint torque control of the 3DOF articulated manipulator was achieved based on the independent joint approach. This method is simple and more complete, and also it involves a more and better dynamic description of the manipulator comprising of the electrical and mechanical dynamics of the joint actuator and the mechanical dynamics of the links. Therefore, the control law can be applied to the inputs of the controller which makes it more preferable to be employed in practice for controller design than using only the robot arm model. The damping coefficient for the joint torque model was determined based on the stability characteristics of the system on bode plots. The influences of the nonlinearities, unmodeled and neglected dynamics in the model are treated as disturbances and the controller is designed to be robust against them. This approach is therefore recommended for robust control of robotic manipulators under uncertainties.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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