MECHATRONICS MOTION CONTROL DESIGN OF ELECTRIC MACHINES FOR DESIRED DEADBEAT RESPONSE SPECIFICATIONS, SUPPORTED AND VERIFIED BY NEW MATLAB BUILT-IN FUNCTION AND SIMULINK MODEL

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Abstract
To help in facing the two top challenges in developing Mechatronics motion systems, particularly, early identifying system level problems and ensuring that all design requirements are met, this paper presents Mechatronics design of electric machine and corresponding motion control in terms of desired output position or velocity for desired deadbeat response specifications, the design is facilitated using either or both proposed new MATLAB built-in function named deadbeat( ), and new Simulink model, both oriented on Mechatronics design of both electric machine and motion control systems, based on system parameters, shape and dimensions to meet desired deadbeat response with desired settling time. The introduced new MATLAB built-in function determines the coefficients that yield the optimal deadbeat response for desired output speed or angle control of a given electric machine, also calculates transfer functions (open and closed), of used motor, controller, prefilter and overall system, also, plots overall system deadbeat response and all corresponding response curves, finally, calculates main overall system deadbeat response specification, particularly $Mp$, $Ess$, $Ts$. The proposed design, model and function, can be used for various Mechatronics motion control design applications, where the proper selection of actuating machine and design of precise motion control system are of concern.

Keywords: Mechatronics system, motion control, deadbeat response, DC machine, MATLAB built-in function
1. Introduction

The term control system design refers to the process of selecting feedback gains that meet design specifications in a closed-loop control system. Motion control is a sub-field of control engineering, in which the position or velocity of a given machine are controlled using some type of actuating machine. The accurate control of motion is a fundamental concern in mechatronics applications, where placing or moving an object in the exact desired location or with desired speed with the exact possible amount of force and torque at the correct exact time, while consuming minimum electric power, at minimum cost, is essential for efficient system operation.

Because of the ease with which they can be controlled, systems of DC machines have been frequently used in many Mechatronics applications requiring a wide range of motor speeds and a precise output motor control, there are many DC machines that may be more or less appropriate to a specific type of application each has its advantages, limitations and disadvantages; the actuating machines most used in mechatronics motion control systems are PMDC motors.

Often, the goal for a motion control system is to achieve a fast response to a step command with minimal overshoot, there are many motor motion control strategies that may be more or less appropriate to a specific type of application each has its advantages and disadvantages, the designer must select the best DC machines and corresponding motion control strategy for specific application and desired overall response. Different researches on this theme, can be found including (Richard C. Dorf, 2001)( Thomas R. Kurfess, 2005)( Mohsen Shahinpoor, 1987)( Bashir M. Y. Nouri, 2005)( Chun Htoo Aung et al, 2008)( Ramjee Prased)( Ahmad A. Mahfouz et al, 2013)( Wai Phyo Aung, 2007)( Farhan A. Salem, 2013)( Farhan A. Salem, 2013)( Farhan A. Salem, 2013), most of these researches, study separate systems and applications design and control issues. To help in facing the two top challenges in developing Mechatronics motion systems, particularly, early identifying system level problems and ensuring that all design requirements are met, this paper presents Mechatronics design of electric machine and corresponding motion control in terms of desired output position or velocity for desired deadbeat response specifications, the proposed design can be used for various Mechatronics motion control design applications, where the proper selection of actuating machine and design of precise motion control system are of concern, in this paper writer is most concerned with controlling the output angular and/or linear motions and meeting the known finite settling time, of a given DC motor for specific application and satisfying all deadbeat response characteristics.

A deadbeat response is response that proceeds rapidly to the desired reference trajectory level at minimum amount of time without error and holds
at that level with minimal overshoot for step input. The ± 2 % error band at the desired level could be an acceptable range of variation from the desired response. Then, if the response enters the ±2% band at time $T_s$, it has satisfied the settling time upon entry to the band. The deadbeat control could be used in systems where the known finite settling time is required. A deadbeat response has the following characteristics, (1) Steady-state error = 0, (2) Fast response; minimum both rise time $T_R$ and settling time $T_s$, (3) 0.1% < percent overshoot <2%, (4) Percent undershoot <2% (The ± 2 % error band). Characteristics (3) and (4) require that the response remain within the ±2% band so that the entry to the band occurs at the settling time $T_s$. (Richard C. Dorf,2001). The closed-loop transfer function, $T(s)$ of the system is used to determine the coefficients (controller gains, poles and zeros), that yield the optimal deadbeat response, where $T(s)$ is compared with standard , corresponding, order and normalized transfer function . Deadbeat response is illustrated in Figure 1.

![Figure 1 Deadbeat response and performance specifications (Richard C. Dorf,2001).](image)

2. System modeling

The control of mechatronics system's motion is simplified to electric machine motion control that may or not include gear system, electric machine is powered and desired output movements will rely on how the electric motor is commanded, by using a simple controller (e.g. PIC microcontroller), and corresponding feedback element and, interfaces, the output movements (the rotation to a fixed speed or angle) can be controlled easily. Motion control system and components -A negative closed loop feedback control system with forward controller and corresponding simulink model shown in Figure 2(a)(b) are to be used.
2.1 Electric machine modeling

The actuating machines most used in mechatronics motion control systems are DC machines. The PMDC motor is an example of electromechanical systems with electrical and mechanical components. In many sources a derivation of DC motor mathematical model in different
forms in terms of different relations are introduced including (Richard C. Dorf, 2001) Thomas R. Kurfess, 2005) Mohsen Shahinpoor, 1987) (Farhan A. Salem, 2013) (Farhan A. Salem, 2013) (Farhan A. Salem, 2013) Grzegorz Sieklucki, 2012). Based on the Newton’s law combined with the Kirchoff’s law, the mathematical model of electric motor can be derived. The PMDC motor open loop transfer function without any load attached relating the input voltage, $V_{in}(s)$, to the motor shaft output angle, $\theta_m(s)$, and given by Eq. (1) and, the PMDC motor open loop transfer function relating the input voltage, $V_{in}(s)$, to the motor shaft output angular velocity, $\omega_m(s)$, given by Eq. (2):

$$G_{angle}(s) = \frac{\theta(s)}{V_{in}(s)} = \frac{K_i}{\left\{ \left( L_a J_m s^2 + (R_d J_m + b_m L_a) s^2 + (R_d b_m + K_i K_h) s \right) \right\}}$$

$$G_{speed}(s) = \frac{\omega(s)}{V_{in}(s)} = \frac{K_i}{\left\{ \left( L_a J_m s^2 + (R_d J_m + b_m L_a) s + (R_d b_m + K_i K_h) \right) \right\}}$$

Here note that the transfer function $G_{angle}(s)$ can be expressed as: $G_{angle}(s) = G_{speed}(s) \times (1/s)$. This can be obtained using MATLAB, by the following code: >> G_angle = tf(1,[1,0]) * G_speed, Where: running tf(1,[1,0]), will return (1/s). The geometry of the mechanical part determines the moment of inertia and damping, the mobile platform can be considered to be of the cuboid or cubic shape. Also, arm is considered as a rod of mass $m$, length $\ell$, (so that $m = \rho \times \ell \times s$), this rod is rotating around the axis which passes through its center and is perpendicular to the rod, correspondingly, the total equivalent inertia, $J_{equiv}$ and total equivalent damping, $b_{equiv}$ at the armature of the motor with gears attaches, can be calculated from known formulae. for robotic arm application, the moment of inertia can be found by computing the following integral:

$$\int_{-1/2}^{1/2} \rho x^2 dx = \rho \int_{-1/2}^{1/2} s^2 dx = \frac{m}{s^2} s^2 \int_{-1/2}^{1/2} x^2 dx = \frac{m}{12} s^2$$

Also, the mobile robotic platform can be considered to be of the cuboids shape, with the inertia as calculated by:

$$J_{load} = \frac{bh^3}{12}$$

Where: $h$ is platform width, $h$ platform height. The total equivalent inertia, $J_{equiv}$ and total equivalent damping, $b_{equiv}$ at the armature of the motor with gears attached, equations for $J_{equiv}$ and, $b_{equiv}$ are given by:

$$b_{equiv} = b_m + b_{load} \left( \frac{N_1}{N_2} \right)^2$$

$$J_{equiv} = J_m + J_{load} \left( \frac{N_1}{N_2} \right)^2$$

$$J_{mobile} = \frac{bh^3}{12} \rightleftharpoons J_{arm} = \frac{1}{12} ml^2$$

(3)
The total equivalent inertia, $J_{equiv}$, and total equivalent damping, $b_{equiv}$ at the armature of the motor are, $J_{equiv}=0.2752 \text{ kg.m}^2$, $b_{equiv} = 0.3922 \text{ N.m.s.}$ and for used robot arm, calculating and substituting values, gives:

$$J_{Load} = (8 \times (0.4)^2)/12 = 0.1067 \text{ kg.m}^2$$

Therefore, $J_{equiv}$, to be:

$$J_{equiv} = J_m + J_{load} \times (1/1)$$

$$J_{equiv} = 0.02 + 0.107 = 0.1267 \text{ kg.m}^2$$

Obtaining the total damping, $b_{total}$, gives:

$$b_{equiv} = b_m + b_{load}(1/1)$$

$$b_{equiv, arm} = 0.03 + 0.09 = 0.12 \text{ N.sec/m}$$

### 2.2 Modeling of system dynamics

When deriving an accurate mathematical model for motion system it is important to study and analyze dynamics between system and surroundings and considering all the forces applied upon the system. Depending on system applications parameters, shape and dimensions, dynamic model can be derived, in the suggested model the load torque inertia and damping characteristics are to be defined, for specific applications, for mobile robotic applications. In (Farhan A. Salem, 2013)(Farhan A. Salem, 2013)(Grzegorz Sieklucki, 2012), an accurate derivation of all forces acting on mobile platform system, when it is running are introduced. For mobile robotic platform, considering dimensions, and for simplicity, the following most acting forces and corresponding torques, can be considered:

- **Rolling resistance force**, $F_{rolling}$: depending on the mobile platform speed and it is proportional to the vehicle platform, and is given by:

$$F_{rolling} = F_{normal\ force} \times C_r = M \times g \times C_r \times \cos(\alpha) \quad (4)$$

In terms of the vehicle linear speed Eq.(4) becomes:

$$F_{rolling} = M \times g \times (C_{r0} - C_{rl} \times \nu) \times \text{sign}(\nu)$$

The rolling resistance torque is given by:

$$T_{rolling} = (M \times g \times C_r \times \cos(\alpha)) \times r_{wheel}$$

Where : $M$ : The mass of the SMEV and cargo (Kg). $g$. $C_r$ The rolling resistance coefficients is calculated by the following expression:

$$C_r = 0.01 \left(1 + \frac{3.6 \times \nu_{robot}}{100} \right)$$

- **The hill-climbing resistance force** $F_{climb}$: while robot platform is moving up or down a hill, the weight of the robot will create a hill-climbing resistance force directed downward, this force will oppose or contribute to the motion, the component of gravity in the dimension of travel is the hill-climbing resistance force and is given by:

$$F_{climb} = M \times g \times \sin(\alpha) \quad (5)$$

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Where: \( M \): The mass of the system and cargo (Kg). \( g \): The gravity acceleration (m/s\(^2\)). \( \alpha \): Road or the hill climbing angle, road slope (Rad.). If we assume the mobile platform system is on a level surface, this force is zero, \( 0 = 0a, sin(\theta) = 0 \)

The hill-climbing resistance, slope, torque, is given by:

\[
F_{\text{climb}} = F_{\text{slope}} = (M \ast g \ast \sin(\alpha)) \ast r_{\text{wheel}}
\]  
(6)

The total *inertia force* of the mobile platform,

\[
F_{\text{inertia}} = F_{\text{slope}} = M \frac{dv}{dt}
\]

The inertia torque is given by:

\[
F_{\text{inertia}} = F_{\text{slope}} = r^2 M \frac{dv}{dt}
\]

**Aerodynamic Drag force**, \( F_{\text{aerod}} \): The force opposing the motion of the vehicle due to air drag, wind resistance, consists mainly of two components; shape drag and skin friction. The aerodynamic drag force is function of mobile platform linear velocity, \( v \) and given by:

\[
F_{\text{aerod}} = 0.5 \ast \rho \ast A \ast C_d \ast v_{\text{vehicle}}^2
\]  
(7)

Considering platform and wind speed Eq.(7) become:

\[
F_a = 0.5 \rho A C_d \left( v_{\text{robot}} + v_{\text{wind}} \right)^2 \text{sign} (v_{\text{robot}})
\]

\[
F_{\text{aerod}} = 0.5 \rho A C_d \left( v_{\text{vehicle}} + v_{\text{wind}} \right)^2 \text{sign} (v_{\text{vehicle}} + v_{\text{wind}})
\]

The aerodynamics torque is given by:

\[
T_{\text{aerod}} = \left( \frac{1}{2} \ast \rho \ast A \ast C_d \ast v_{\text{vehicle}}^2 \right) \ast r_r
\]

Where: \( C_d \): Aerodynamic drag coefficient characterizing the shape of the mobile platform

**The angular acceleration force** \( F_{\text{acc_angle}} \), is the force required by the wheels to make angular acceleration and is given by:

\[
F_{\text{acc_angle}} = J \frac{G^2}{r_{\text{wheel}}^2} \alpha
\]

The angular acceleration torque is given by:

\[
T_{\text{acc_angle}} = r_{\text{wheel}} \ast J \frac{G^2}{r_{\text{wheel}}^2} \alpha = J \frac{G^2}{r_{\text{wheel}}} \alpha
\]  
(8)

3. **Controller design for desired deadbeat response.**

The control of mechatronics system's motion is simplified to electric machines motion control that may or not include gear system, electric machine is powered and desired output movements will rely on how the electric motor is commanded. The most basic design requirements of a given electric DC machine are to rotate at desired angular speed \( \omega = \frac{d\theta}{dt} \) and/or
to achieve desired angular position, \( \theta \), at the minimum possible steady-state error \( e_{ss} \), also the machine must accelerate to its steady-state speed, \( \alpha = \frac{d^2 \theta}{dt^2} \) as soon as it turns on, this means it is desirable to have a minimum suitable settling time, \( T_s \) that will not damage the equipment (e.g. \( T_s \) in less than 2 sec), and the minimum suitable overshoot, \( M_p \) (e.g. \( M_p \) less than 5%), such suitable response can be achieved applying design for deadbeat response.

### 3.1 Design for deadbeat response

To be able to control a motion process in DC motor system, the precise output of system (speed or position) needs to be measurable. Feedback comparison of the desired and actual output is then a natural step in implementing a motion control system. This comparison generates an error signal that may be used to correct the system motion, thus yielding repeatable and accurate results. The applied controller's gains, poles and zeros are responsible for achieving the optimal desired system response, e.g. deadbeat response. In controller design for deadbeat response approach, the controller's coefficients, \((\text{controller gains, poles and zeros})\), depend on the physical parameters of the system. To determine the optimal coefficients, that yield the optimal deadbeat response, the system's overall equivalent closed-loop transfer function, \( T(s) \) is compared with standard, of corresponding order, and normalized transfer function, (particularly the characteristic equations are compared). In this approach, to determine the coefficients, that yield the optimal deadbeat response, the \textit{standard} transfer function is normalized; and is to be used as the system's overall and desired closed-loop transfer function. The coefficients of the normalized \textit{standard} transfer function are then assigned the values necessary to meet deadbeat response requirements. These coefficients were selected to achieve deadbeat response and minimize settling time \( T_s \) and rise time, \( T_R \) to 100% of the desired command; the coefficients of the \textit{normalized} standard transfer function are recorded in Table 1(Richard C. Dorf, 2001). For example; The desired Standard \textit{third} order closed-loop transfer function for achieving desired deadbeat response specifications can be rewritten to have the form:

\[
T(s) = \frac{\omega_n^3}{s^3 + \alpha \omega_n s^2 + \beta \omega_n s^3 + \omega_n^3} \tag{9}
\]

Dividing the numerator and denominator by \( \omega_n^3 \), and letting \( \tilde{s} = s / \omega_n \), substituting, gives:

\[
T(s) = \frac{\omega_n^3 / \omega_n^3}{\omega_n^3 / \omega_n^3 + \alpha \omega_n / \omega_n + \beta \omega_n / \omega_n + \omega_n^3 / \omega_n^3} = \frac{1}{\tilde{s}^3 + \alpha \tilde{s}^2 + \beta \tilde{s} + 1}
\]
For a higher-order system, the same method is used to derive the normalized equation (Richard C. Dorf, 2001). The desired Standard second order closed-loop transfer function for achieving desired deadbeat response specifications is given by:

\[ T(s) = \frac{\omega_n^2}{s^2 + \alpha \omega_n s + \omega_n^2} \]  

(10)

Let's assume that, it is required, for a given third, order plant, to design a control system to have deadbeat characteristics response to step input and meeting desired settling time of 0.5 sec., the design can be accomplished as follows: From table 1, substituting coefficients values, for third order system, that is \( \alpha = 1.9 \), \( \beta = 2.20 \), gives:

\[ T(s) = \frac{\omega_n^3}{s^3 + 1.9 \omega_n s^2 + 2.20 \omega_n^2 s + \omega_n^3} \]

Then, we calculate and chose undamped natural frequency, \( \omega_n \), based on the desired settling time or rise time: for desired settling time of 0.5 second, the normalized settling time (from table 1) is given by:

\[ \omega_n T_s = 4.04 \quad \Rightarrow \quad \omega_n = \frac{4.04}{T_s} = \frac{4.04}{0.5} = 8.08 \approx 8.0 \text{rad/sec} \]

Now, the complete closed-loop transfer function with all variables (coefficients defined) is known, and given by:

\[ T(s) = \frac{512}{s^3 + 15.2 s^2 + 121.6s + 512} \]  

(11)

Also, from table 1, the step response of this system has a deadbeat response with an overshoot of 1.65%, undershoot of 1.36% and a settling time of 0.5 second. Finally, to find the applied appropriate controller and its optimal coefficients; gains, poles and zeros, we compare transfer function given by Eq (15) with system's overall equivalent closed loop transfer function. The following nominal values for the various parameters for two different eclectic motor are to be used and tested:

- **First motor**: \( V_{in} = 12 \) Volts; \( J_m = 0.02 \) kg·m²; \( b_m = 0.03 \); \( K_t = 0.023 \) N·m/A; \( K_b = 0.023 \) V·s/rad; \( R_a = 1 \) Ohm; \( L_a = 0.23 \) Henry; \( T_{Load} \).
- **Second motor**: \( V_{in} = 12 \) Volts; Motor torque constant, \( K_t = 1.188 \) Nm/A; Armature Resistance, \( R_a = 0.1557 \) Ohms (\( \Omega \)); Armature Inductance, \( L_a = 0.82 \) MH; Geared-Motor Inertia: \( J_m = 0.271 \) kg·m², Geared-Motor Viscous damping \( b_m = 0.271 \) N·m·s; Motor back EMF constant, \( K_b = 1.185 \) rad/s/V.

To test and verify all of the proposed design, calculation, built in function and simulink model of actuating machine, the design will be applied to two different mechatronics motion control applications; mobile robot and single joint robot arm, to achieve desired deadbeat response with desired settling time, the disturbance in the form of load torque is to be defined and calculated and defined. The mobile platform, has the following nominal
dimensions and parameters values; wheel radius, \( r = 0.075 \, m \), platform height, \( h = 0.920 \, m \), platform width, \( b = 0.580 \, m \), the distance between wheels centers = 0.4 m. The desired suitable linear output speed, for domestic, mobile robot, is to move with 0.5 meter per second, that is \( \omega = \frac{V}{r} = \frac{0.5}{0.075} = 6.6667 \, \text{rad/s}. \) Tachometer constant, and the corresponding sensor, tachometer, for maximum applied input voltage of \( V = 12 \), \( K_{Iac} = \frac{12}{6.6667} = 1.8 \, (\text{rad/sec}) \). The robot arm system to be designed, has the following nominal values; arm mass, \( M = 8 \, \text{Kg} \), arm length, \( L = 0.4 \, m \), and viscous damping constant, \( b = 0.09 \, \text{N.sec/m.} \) so that a voltage range of 0 to 12 volts corresponds linearly of an Robot arm output angle range of 0 to 180, that is to move the robot arm to the desired output angular position, \( \theta_L \), corresponding to the applied input voltage , \( V_{in} \), for simplicity, gear ratio, \( n=1,10 \).

Table 1 The coefficients of the normalized standard transfer function

<table>
<thead>
<tr>
<th>System order</th>
<th>Optimal coefficients</th>
<th>Percent Overshoot</th>
<th>Percent Undershoot</th>
<th>Rise,90%</th>
<th>Rise,100%</th>
<th>Settling</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a )</td>
<td>( \beta )</td>
<td>( \gamma )</td>
<td>( \delta )</td>
<td>( \epsilon )</td>
<td>( \alpha % )</td>
<td>( \beta % )</td>
</tr>
<tr>
<td>2nd</td>
<td>1.82</td>
<td></td>
<td></td>
<td></td>
<td>0.10%</td>
<td>0.00%</td>
</tr>
<tr>
<td>3rd</td>
<td>1.90</td>
<td>2.20</td>
<td></td>
<td></td>
<td>1.65%</td>
<td>1.36%</td>
</tr>
<tr>
<td>4th</td>
<td>2.20</td>
<td>3.50</td>
<td>2.80</td>
<td></td>
<td>0.89%</td>
<td>0.95%</td>
</tr>
<tr>
<td>5th</td>
<td>2.70</td>
<td>4.90</td>
<td>5.40</td>
<td>3.40</td>
<td>1.29%</td>
<td>0.37%</td>
</tr>
<tr>
<td>6th</td>
<td>3.15</td>
<td>6.50</td>
<td>7.55</td>
<td>7.55</td>
<td>4.05</td>
<td>1.63%</td>
</tr>
</tbody>
</table>

3.2 Proportional -Integral (PI) controller

PI controller is widely used in variable speed applications and current regulation of electric motors, because of its simplicity and ease of design. PI controller transfer function is given by:

\[
G_{pi}(s) = K_P + \frac{K_I}{s} = \frac{K_P(s + \frac{K_I}{K_P})}{s} = K_P(s + Z_o) \quad (12)
\]

Where, \( Z_o \): Zero of the PI-controller, \( K_P \): The proportional gain, \( K_{P1} \): The proportional coefficient; \( T_1 \): time constant. This transfer function, shows that, PI controller represents a pole located at the origin and a stable zero placed near the pole, at \( Z_o = - \frac{K_I}{K_P} \), resulting in drastically eliminating steady state error due to the fact that the feedback control system type is increased by one. The PI pole and zero will affect the response, mainly the PI zero, \( Z_o = - \frac{K_I}{K_P} \), will significantly and inversely effect the response and should be cancelled by prefilter given by Eq. (15).

3.3 Proportional -Derivative - PD controller:

The transfer function of PD-controller is given by :

\[
G_{pd}(s) = K_P + K_D s
\]

Rearranging, we have the following form:
\[ G_{pd}(s) = K_p + K_ds = K_d \left( s + \frac{K_p}{K_d} \right) = K_d \left( s + Z_{pd} \right) \] (13)

The PD-controller is equivalent to the addition of a simple zero at:

\[ Z_{pd} = \frac{K_p}{K_d} \]. The addition of zeros to the open-loop has the effect of pulling the root locus to the left, or farther from the imaginary axis, resulting in improving the transient response.

### 3.4 Systems design with prefilter

Prefilter is defined as a transfer function \( G_p(s) \) that filters the input signal \( R(s) \) prior to calculating the error signal. Adding a control system to plant, will result in the addition of poles and/or zeros, that will effect the response, mainly the added zero, will significantly inversely effect the response and should be cancelled by prefilter, therefore the required prefilter transfer function to cancel the zero is given by Eq.(14). In general. The prefilter is added for systems with lead networks or PI compensators. A prefilter for a system with a lag network, mainly, is not, since we expect the effect of the zero to be insignificant.

### 3.5 PI controller with deadbeat response design:

With PI controller with deadbeat response design, the order of overall closed-loop transfer function, \( T(s) \), will be increased by one and contain a new added PI-controller zero at \( Z_{pi}=\frac{K_p}{K_p} \). this zero will significantly and inversely affect the response of the closed-loop system, \( T(s) \), and should be eliminated while maintaining the proportional gain \( K_p \), of the closed-loop system, this can be achieved by a prefilter. Therefore the required prefilter transfer function to cancel the zero is given by Eq.(15):

### 3.6 PD controller with deadbeat response design:

For systems with PD compensators, a prefilter is used to eliminate any undesired effects of the term \( s + z \) introduced in the closed-loop transfer function, the required prefilter transfer function is given by Eq.(16):

\[ G_{prefilter}(s) = \frac{Z_o}{(s + Z_o)} \] (14)

\[ G_{PI \_Prefilter}(s) = \frac{Z_{pi}}{(s + Z_{pi})} \] (15)

\[ G_{PD \_Prefilter}(s) = \frac{Z_{pd}}{(s + Z_{pd})} \] (16)
3.7 Position and velocity feedback sensors modeling; Potentiometer and Tachometer modeling.

To calculate the error, we need to convert the actual output (arm position, or mobile speed) into voltage, \( V \), then compare this voltage with the input voltage \( V_{in} \), the difference is the error signal in volts.

**Potentiometer** is a sensor used to measure the actual output position, \( \theta_L \), convert into corresponding volt, \( V_p \) and then feeding back this value, the Potentiometer output is proportional to the actual position, \( \theta_L \), this can be accomplished as follows: the output voltage of potentiometer is given by:
\[
V_p = \theta_L * K_{pot}
\]
Where: \( \theta_L \) :The actual position, \( K_{pot} \) the potentiometer constant; it is equal to the ratio of the voltage change to the corresponding angle change, depending on maximum desired output angle, the potentiometer can be chosen. For our case, input volt range \( V_{in} = 0:12 \), and output angle range \( \theta = 0:180 \) degrees, substituting, we have:
\[
K_{pot} = \frac{(\text{Voltage change})}{(\text{Degree change})} = \frac{12 - 0}{180 - 0} = 0.0667 \text{ V/degree}
\]

Potentiometer constant \( K_{pot} = 0.0667 \text{ V/degree} \). This value (0.0667), means that each one input volt corresponds to 180/12 = 15 output angle in radians, to obtain a desired output angular position of 180, we need to apply 12 volts, to obtain an angular position of 90 we need to apply (90*0.0667 = 6.0030 Volts).

**Tachometer** is most used sensor to measure the actual output angular speed, \( \omega_L \). Dynamics of tachometer can be represented using the following equation:
\[
V_{out}(t) = K_{tac} * \frac{d \theta(t)}{dt} = V_{out}(t) = K_{tac} * \omega
\]
The transfer function of the tachometer is given by:
\[
V_{out}(s) / \omega(s) = K_{tac}
\]
A suitable linear output speed of e.g. of domestic mobile robot is to move with 0.5 m/s, that is:
\[
\omega = \frac{V}{r} = \frac{0.5}{0.075} = 6.6667 \text{ rad/s},
\]
Tachometer constant, \( K_{tac} = 12 / 6.6667 = 1.8 \)

3.8 Design for PD controller with desired deadbeat response specifications in terms of desired output angular position.

Considering that system dynamics and disturbance torques depends on application shape and dimensions (robot arm, conveyer), the mechanical DC motor part, will have the form:
\[
K_t * i_a = T_a + T_a + T_{load} + T_f
\]
The coulomb friction can be found at steady state, to be:
\[
K_t * i_a - b* \omega = T_f
\]
In the following calculation the disturbance torque, T, is all torques including coulomb friction, and given by (T = T_{load} + T_f). Applying PD controller with deadbeat response, the open-loop transfer function of the PMDC, is given by:

\[ G_{open}(s) = \frac{K_t}{(L_a s + R_a)(J_m s^2 + b_m s) + (L_a s + R_a)(T) + K_b K_t} \]

Manipulating for forward and closed loop transfer functions, including disturbance torques, sensor and gear ratio, gives:

\[
G_{open}(s) = \frac{K_t}{(L_a s + R_a)(J_m s^2 + b_m s) + (L_a s + R_a)(T) + K_b K_t} \\
G_{open}(s) = \frac{nK_{pot} K_t}{L_a J_m s^3 + (R_a J_m + b_a L_a) s^2 + (R_a b_m + L_a T) s + (R_a T + K_b K_t)} \\
G_{forward}(s) = \frac{nK_{pot} K_t K_D s + nK_{pot} K_t K_p}{L_a J_m s^3 + (R_a J_m + b_a L_a) s^2 + (R_a b_m + L_a T + nK_{pot} K_D K_t) s + (R_a T + K_b K_t)} \\
G_{closed}(s) = \frac{nK_{pot} K_t K_D s + nK_{pot} K_t K_p}{L_a J_m s^3 + (R_a J_m + b_a L_a) s^2 + (R_a b_m + L_a T + nK_{pot} K_D K_t) s + (R_a T + K_b K_t) + nK_{pot} K_t K_p} \\
T(s) = \frac{\omega_a^3}{s^3 + \alpha \omega_a s^2 + \beta \omega_a^2 s + \omega_a^5} \\
\beta \omega_a^2 = \frac{(R_a b_m + L_a T + nK_{pot} K_D K_t)}{L_a J_m} \Rightarrow K_D = \frac{\beta \omega_a^2 L_a J_m - (R_a b_m + L_a T)}{nK_{pot} K_t} \\
\omega_a^3 = \frac{(R_a T + K_b K_t + nK_{pot} K_t K_p)}{L_a J_m} \Rightarrow K_p = \frac{\omega_a^3 L_a J_m - (R_a T + K_b K_t)}{nK_{pot} K_t}
\]

For design consideration, and based on required design accuracy we can use the simplified second order model, assuming L_a = 0, and manipulating for closed loop with PD controller, gives:
\[ G_{\text{angle}}(s) = \frac{\theta(s)}{V_{\text{in}}(s)} = \frac{K_i}{\left[L_p J_m s^3 + (R_c J_m + b_m L_m) s^2 + (R_p h_m + K_p K_m) s\right]} \]

\[ G_{\text{angle}}(s) = \frac{R_s J_m}{s \left( R_s J_m s^2 + (R_p h_m + K_p K_m) s\right)} \]

\[ G_{\text{angle}}(s) = \frac{\theta(s)}{V_{\text{in}}(s)} = \frac{nK_i}{s \left( (R_s J_m) s^2 + (R_p h_m + K_p K_m) s\right)} \]

\[ G_{\text{forward}}(s) = \frac{\theta(s)}{V_{\text{in}}(s)} = \frac{K_i K_p + K_m K_p s}{s \left( (R_s J_m) s + (R_p h_m + K_p K_m) s\right)} \]

\[ G_{\text{closed}}(s) = \frac{\theta(s)}{V_{\text{in}}(s)} = \frac{nK_i K_p + nK_i K_m s}{s \left( (R_s J_m) s + (R_p h_m + K_p K_m) s\right)} \]

Comparing with standard normalized second order system and manipulating, for \( K_D \) and \( K_R \), given by Eq.(10)

\[ nK_i K_p + nK_i K_m s \]

\[ G_{\text{closed}}(s) = \frac{\theta(s)}{V_{\text{in}}(s)} = \frac{nK_i K_p + nK_i K_m s}{s \left( (R_s J_{\text{equiv}}) s^2 + (R_p h_{\text{equiv}} + K_i K_p + nK_i K_D) s\right) + nK_i K_P K_D} \]

\[ \alpha \omega_n = \frac{R_p h_{\text{equiv}} + K_i K_p + nK_i K_D}{R_s J_{\text{equiv}}} \]

\[ K_D = \frac{\alpha \omega_n R_s J_{\text{equiv}} - (R_p h_{\text{equiv}} + K_i K_p)}{nK_i K_P} \]

\[ K_D = \frac{R_s J_{\text{equiv}}}{nK_i K_P} \]

\[ Z_{PD} = \frac{K_D}{K_i} \]

From Table 1, substituting coefficients values, for second order system, that is \( \alpha = 1.82 \), \( T_s = \omega_n / 4.82 \), the prefilter transfer function is obtained

### 3.9 Design for PI controller with desired deadbeat response specifications in terms of desired output linear speed.

Based on equations that describes DC motor, system dynamics and sensor modeling, the open loop transfer function, relating the armature input terminal voltage, \( V_{\text{in}}(s) \) to the output terminal voltage of the tachometer \( V_{\text{tach}}(s) \), with load and corresponding torques applied and considered, will be given by Eq.(17):

\[ G_{\text{open}}(s) = \frac{2K_{\text{tach}} * K_i}{2b_{\text{equiv}} L_s s^2 + r^3 M L_s s + 2b_{\text{equiv}} R_s s + r^3 M R_s s + C_i L_s s + 2J_{\text{equiv}} L_s s + 2K_K R_s + C_R a + 2J_{\text{equiv}} R_a} \]

(17)

Applying PI controller with deadbeat response design, for desired output speed, the system's closed-loop transfer function, \( T(s) \), is given by Eq.(18):

\[ T(s) = \frac{2K_{\text{tach}} * K_i}{2b_{\text{equiv}} L_s s^2 + r^3 M L_s s + 2b_{\text{equiv}} R_s s + r^3 M R_s s + C_i L_s s + 2J_{\text{equiv}} L_s s + 2K_K R_s + C_R a + 2J_{\text{equiv}} R_a} \]
\[ G_{\text{cloud}}(s) = \frac{2K_{\text{ach}} * K_p}{(2b_{\text{equiv}} + r^2M) L_a} \frac{(s + Z_{pt})}{(s + (C_r + 2J_{\text{equiv}}) R_a + 2K_{K_e} + K_{\text{ach}} K_p)} \]

The prefilter transfer function is given by Eq.(15). Applying deadbeat design approach to determine the optimal coefficients, (controller gains, poles and zeros), that yield the optimal deadbeat response, by comparing Eq. (18), with Eq(10) gives:

- \[ K_p = \frac{[\beta \omega_n^2 L_a (2b_{\text{equiv}} + r^2M)] - [(C_r + 2J_{\text{equiv}}) R_a + 2K_{K_e} + K_{\text{ach}}]}{2K_{K_e} K_{\text{ach}}} \]
- \[ K_l = \frac{\omega_n^2 L_a (2b_{\text{equiv}} + r^2M)}{2K_{K_e} K_{\text{ach}}} \]
- \[ Z_{pt} = \frac{K_l}{K_p} = \frac{\omega_n^2 L_a (2b_{\text{equiv}} + r^2M)}{[\beta \omega_n^2 L_a (2b_{\text{equiv}} + r^2M)] - [(C_r + 2J_{\text{equiv}}) R_a + 2K_{K_e} + K_{\text{ach}}]} \]

From Table 1, the required coefficients are: \( \alpha = 1.9, \beta = 2.2 \) and \( \omega_n, T_s = 4.04, T_s = 4.04/\omega_n \)

4. Simulation

The simulink model of DC motor system for desired deadbeat response using PI or PD, is shown in Figure .3, in presented model three most suitable controllers for DC motor output control are applied; PID, PI and PD, where three forms of simulink PID model are used, as well as separate PI and PD models are used, two prefilter blocks are added with PI zero and with PD zero, also disturbance torques are included. This model can be switched from one controller to another, from filter to another, from controlling output speed or position and from input type to another, by the use of manual switches. The presented model is also supported with visual readings of steady state final values. This model can be used as separate tool, as well as supporting model for design for deadbeat response testing and verification. To use this model, load of attached system (application) and used DC motor parameters, must be first defined in MATLAB, directly or using MATLAB m.file, also using calculated optimal values that yields the desired deadbeat response, obtained using the new built-in function. Running this model will return angular and linear speed/time, angular and linear position/time, torque/time, current/time, control signal/time response curves also visual readings of steady state final values, after running the simulink model for a given motor parameters and desired deadbeat response, the next code can be used to plot all response plots.
load PMDC1, load PMDC2, load PMDC3, load PMDC4, load PMDC5, load PMDC6

subplot(3,2,1); plot(DC_angle), ylabel('\Theta, Rad'), xlabel(''), title('Angular position Rad'), grid,
subplot(3,2,2); plot(angular_speed), ylabel('Angular speed, \omega Rad/s'), xlabel(''), title('Angular speed Rad/Time, '), grid,
subplot(3,2,3); plot(DC_linear_speed), ylabel(''), title('Linear speed M/s'), grid,
subplot(3,2,6); plot(torque), ylabel('Motor Torque, Nm'), xlabel(''), title('Motor Torque Nm/Time'), grid,
subplot(3,2,5); plot(controller_signal), ylabel('controller signal (mA)'), grid,
subplot(3,2,4); plot(Current), ylabel('Current Amp/s'), xlabel(''), title('Current Amp/s'), grid,

Figure 3 Simulink model for motion control design for desired deadbeat response specifications.

5. MATLAB built-in function script

The equations derived, was used to design a new MATLAB built-in function with specific purpose, that is design and verification for desired deadbeat response specification, particularly for desired settling time. The presented built-in function is named deadbeat(a), the input argument a, can have the value of 1 or 2; where 1 for electric motor system output speed control with PI-controller design for deadbeat response with desired settling time. The input argument 2 for electric motor system output angle control with PD-controller design for deadbeat response with desired settling time. Using this new built-in function user is to define the used DC motor parameters, gear ratio, application system shape, dimensions, and corresponding torque disturbance, by running the function it will return and plot each of the following; the open loop motor transfer in terms of output
speed and position, the closed loop transfer in terms of selected output speed or position for specific application, corresponding response deadbeat response curves, determines the coefficients (gains pole and zero) that yield the optimal deadbeat response for desired output speed or angle control, as well as performance specifications in terms of Mp, Ess, Ts, final output value. The built-in function script is written below:

The coefficients (gains pole and zero), from running built in function is to be used to be defined in MATLAB workspace to run the simulink model for design verification.

```matlab
function deadbeat(a)
% DEADBEAT Determines the coefficients that yield the optimal
% deadbeat response for desired output speed or angle control of a given PMDC motor with gears attached.
% Also calculate transfer functions ( open and closed),
% of motor used, controller, as well as mobile robot
% system, Prefilter.
% Also plots system and corresponding deadbeat response plots.
% deadbeat(1) used for output speed control ( e.g. MOBILE robot,
% system and controller design) Determines the Coefficients that yield the optimal proportional-
% Integral (PI) controller with P deadbeat response,
% for a given MOBILE robot system and plots deadbeat response.
% deadbeat(2) used for output position and controller design for
% given PMDC with gears e.g. for single joint robotic arm
% system and controller design Determines the coefficients that yield the optimal Proportional- Derivative (PD) controller for a
given PMDC motor system and plots corresponding deadbeat response.

clc, close all, format short
disp( ' ')
disp( '================================================================')
disp( ' Please define PMDC parameters ')
disp( '================================================================')
Jm = input(' Enter Motor armature moment of inertia (Jm) :')
bm = input(' Enter damping constant of the motor system (bm):')
Kb = input(' Enter ElectroMotive Force constant (Kb):')
Kt = input(' Enter Torque constant (Kt):')
Ra = input(' Enter electric resistance of the motor armature ,ohms, (Ra):')
La = input(' Enter electric inductance of the motor armature ,Henry,(La) :')
n = input(' Enter gear ratio ,(n) : ')
disp( ' ')
num1 = 1;
den1 = [La, Ra];
um2 = 1;
den2 = [Jm ,bm];
A = conv([La, Ra], [Jm ,bm]);
```
TF1 = tf(Kt*n, A);
% Obtaining open and closed loop transfer functions of DC motor system and step response
Gv = feedback(TF1,Kt);
Gv1 = zpk(Gv)
disp('DC motor open loop transfer function in terms of:Speed/Volt: ')
Gv = feedback(TF1,Kt);
Gv1 = zpk(Gv)
disp('DC motor OPEN loop transfer function in terms of:Angle/Volt: ')
Ga = tf(1,[1,0])*Gv;
Ga1 = zpk(Ga)

Figure ure, subplot(2,1,1), step(V*Ga), title(' (ANGLE) Step response of used DC motor open loop transfer function '), xlabel(' Time '), ylabel(' DC motor output angle \theta ')

subplot(2,1,2), step(V*Gv), title(' (ANGULAR SPEED) Step response of used DC motor open loop transfer function'), xlabel(' Time '), ylabel(' DC motor output speed \omega ')

if a==1;

disp(' Design for PM


disp(' PI with desired deadbeat reponse, e.g. mobile robot output speed design and control :')
disp(' Define plant parameters ( e.g. mobile robot')
disp(' ') mobile_robot_height = input(' Enter system's Height, in meters : ');
mobile_robot_width = input(' Enter system's Width, in meters : ');
b_load = input(' Enter Load damping constant : '); J_load = input(' Enter Load inertia reflected to the motor armature shaft : ');
wheel_radius = input(' Enter wheel radius, in meters : ');
desired_linear_speed = input(' Enter desired output linear speed: ');
m = input(' Enter system's total mass : ');
friction = input(' Enter rolling friction coefficient : ');
V = input(' Enter applied input voltage Vin : ');
inclination_angle = input(' Enter inclination angle, if exist : ');
% for example: Jtotal_mobile_robot = (mobile_robot_width*
(mobile_robot_height)^3)/12;
Jtotal = Jm + J_load/(n)^2;
btot = bm + b_load/(n)^2;
desired_angular_speed = (linear_speed)/r;
Ktach = Vin/ desired_angular_speed ;%tachometer constant
disp(' ') Ts = input(' Enter desired settling time in seconds, Ts : ');
disp(' ')

% mobile robot open loop TF
num_mobile = [Kt*n];  den_mobile = [La*Jtotal , (Ra*Jtotal+btotal*La) , (Ra*btotal+Kt*Kb)];
mobile_open_tf = tf(num_mobile, den_mobile);
\[
\alpha = 1.9; \beta = 2.2; \omega_n = 4.04/T_s; \\
K_p = ((\beta \omega_n^2 \lambda_a (r^2 M + b_{total}) - (R_a (Cr + 2 J_{total}) + K_t K_d)) / (2 K_t K_{tach})); \\
K_i = \omega_n^3 \lambda_a \alpha (r^2 M + b_{total}) / (2 K_t K_{tach}); \\
Z_{PI} = K_i / K_p; \ num_{PI} = K_p \times [1 \ Z_{PI}]; \ den_{PI} = [1 \ 0]; \\
PI_{tf} = tf(num_{PI}, den_{PI}); \ num_{filter1} = Z_{PI}; \ den_{filter1} = [1 \ Z_{PI}]; \\
G_{fill} = tf(num_{filter1}, den_{filter1}); \ T_{mobile PI} = \text{series}(PI_{tf}, mobile\_open\_tf); \ T_{mobile PI\_closed} = \text{feedback}(T_{mobile PI}, K_{tach}); \\
T_{mobile\_deadbeat\_PI\_closed\_prefilter} = \text{series}(T_{mobile PI\_closed}, G_{fill}); \\
cc = zpk(T_{mobile\_deadbeat\_PI\_closed\_prefilter}); \\
\]

Figure
\[\text{ure}, subplot(2,2,1),\text{step}(V \times r \times T_{mobile\_deadbeat\_PI\_closed\_prefilter}), \text{ylabel('System linear speed \( \nu \)')}, \text{xlabel(' Time ')}, \text{title('Output linear speed, WITH prefilter')}, \text{grid} \]
\[\text{figure} \text{ure}, \text{subplot}(2,2,3), \text{step}(V \times r \times T_{mobile\_PI\_closed}); \text{ylabel('System linear speed \( \nu \)')}, \text{xlabel(' Time ')}, \text{title('Output linear speed, WITHOUT prefilter')}, \text{grid} \]
\[\text{subplot}(2,2,2), \text{step}(V \times T_{mobile\_deadbeat\_PI\_closed\_prefilter}); \text{ylabel('System angular speed \( \omega \)')}, \text{xlabel(' Time ')}, \text{title('Output angular speed, WITH prefilter')}, \text{grid} \]
\[\text{subplot}(2,2,4), \text{step}(V \times r \times G_{v}); \text{ylabel('DC motor speed \( \nu \)')}, \text{xlabel(' Time ')}, \text{title('DC motor open loop tf linear speed: ')} \]
\[\text{steady} = \text{dcgain}(V \times r \times T_{mobile\_deadbeat\_PI\_closed\_prefilter}); \text{Ess} = \text{steady} - \text{desired linear speed}; \text{t} = 0:0.01:100; \text{[ww,yy]} = \text{step}(V \times r \times T_{mobile\_deadbeat\_PI\_closed\_prefilter}); \text{MM} = \text{max}(\text{ww}) ; \text{Mp} = \text{MM} - \text{desired linear speed}; \]
\[\text{home} \]
\[\text{disp('------------------------------------------------------')} \]
\[\text{disp('               System Performance specifications :   ')} \]
\[\text{disp('------------------------------------------------------')} \]
\[\%\text{fprintf(' Kp =\%g , Kd=\%g ,ZPD=\%g \( \nu \),Kp,Kd,ZPD);} \]
\[\%\text{fprintf(' Final steady state output value =\%g \( \nu \),steady);} \]
\[\%\text{fprintf(' Steady state error Ess=\%g \( \nu \),Essl);} \]
\[\%\text{fprintf(' Percent overshoot, Mp=\%g \( \nu \),Mp);} \]
\[\%\text{fprintf(' Tachometer constant, Ktach =\%g \( \nu \),Ktach );} \]
\[\%\text{fprintf(' Angular speed, Omega =\%g \( \nu \),desired_angular_speed );} \]
\[\text{disp('------------------------------------------------------')} \]
\[\text{disp(' Gains and zero of: PI controller & prefilter :')} \]
\[\%\text{fprintf(' Kp =\%g , Ki=\%g ,ZPI=\%g \( \nu \),Kp,Ki,ZPI);} \]
\[\%\text{fprintf(' Kp =\%g \( \nu \),Kp);} \]
\[\%\text{fprintf(' Ki =\%g \( \nu \),Ki);} \]
\[\%\text{fprintf(' ZPI =\%g \( \nu \),ZPI);} \]
\[\text{disp('------------------------------------------------------')} \]
\[\text{disp(' PI Controller transfer function ')} \]
\[\text{WWW}\text{W}=zpk(PI_{tf}) \]
\[\text{disp('------------------------------------------------------')} \]
\[\text{disp(' Prefilter transfer function ')} \]
\[G_{fill} = tf(num_{filter1}, den_{filter1}); \text{WWW}\text{W}=zpk(G_{fill}) \]
\[\text{disp('------------------------------------------------------')} \]
\[\text{disp(' Closed loop transfer function, PI WITHOUT prefilter ')} \]
\[\text{WWW}\text{W}=zpk(T_{mobile PI\_closed}) \]
disp('------------------------------------------------------)
disp('   Closed loop transfer function, PI WITH prefilt er')
W=zpk( T_mobile_deadbeat_PI_closed_prefilter)
disp('------------------------------------------------------)
elseif a==2
   home
disp('')
disp('------------------------------------------------------)
disp('   Designing for output angular displacement with deadbeat response')
disp('')
disp('   e.g. Robotic arm angular displacement :')
disp('------------------------------------------------------)

M=input(' Enter Load mass , M=');
Jequiv= input(' Enter Load inertia , Jload=');
b_load= input(' Enter Load damping factor , b_load =');
n= input(' Enter gear ratio, n = ');
V = input(' Enter applied input voltage, Vin :')
V_max = input(' Enter maximum allowed voltage , V max :');
Angle_max = input(' Enter desired maximum allowed output angle : ');
T_load= input(' Enter Load torque : ');
% for example f ro robot arm: Jequiv=((M* Length^2)/12)+Jm;
Kpot=V_max /angle_max;  \% pot constnt
bequiv= bm + b_load;
Jequiv= Jm + J_load;
T=T_load;  \% + angular speed
num_arm_open = [Kt*n*(180/pi)];
den_arm_open=[La*Jequiv (Ra*Jequiv+La*bequiv)
(Ra*bequiv+Kt*Kb) 0];
disp('');
home
disp('')
disp('------------------------------------------------------)

G_close_arm= feedback(Ga_arm_open,(Kpot/n));
Q=zpk(G_close_arm)
disp('------------------------------------------------------)
disp(' Closed loop transfer function in terms of output Linear Position, : ')
G_close_arm_linear= feedback(Ga_arm_open1,(Kpot/n));
Q=zpk(G_close_arm_linear)
disp('------------------------------------------------------)
disp(' Response curves plotted ')
disp('------------------------------------------------------)
Ts= input(' Enter desired settling time in seconds, Ts : ');
disp('------------------------------------------------------)
alph=1.90 ,bita= 2.20;  omega_n=Ts/4.04
Kd1=(bita*omega_n*La*Jequiv -(Ra*La + La*T))/(n*Kpot*Kt);
Kp1= omega_n^3*La*Jequiv -(Ra*T+Kb*Kt)/(n*Kpot*Kt);
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Kp=abs(Kp1);
Kd=abs(Kd1);
ZPD=(Kp/Kd)/(1.510);
ZPI=ZPD;
G_PD=Kd*[ 1  ZPD];
prefilter_num=[ZPD];
prefilter_den=[1  ZPD];
G_prefilter=tf(prefilter_num,prefilter_den);
um_arm_PD =G_PD* [Kt*n];
den_arm_PD=[La*Jequiv  (Ra*Jequiv+La*bequiv) ,(Ra*bequiv+Kt*Kb)
0];
G_arm_PD_tf= tf(num_arm_PD, den_arm_PD);
G_arm_PD_dead_closed= feedback(G_arm_PD_tf, Kpot);
G_arm_PD_dead_overall=series(G_prefilter, G_arm_PD_dead_closed);
G_arm_PD_dead_overal2=series(G_prefilter, G_arm_PD_dead_closed)*(r);
steady=dcgain(V*G_arm_PD_dead_overall);
Ess= angle_max-steady;
home
disp( '========================================================'
' PD controller & Deadbeat prefilter gains and zero are
' %fprintf(' Kp =%g , Kd=%g ,ZPD=%g
,Kp,Kd,ZPD);
fprintf(' Kp  =%g
',Kp);
fprintf(' Kd  =%g
',Kd);
fprintf(' ZPD =%g
,ZPD);
[ ww, yy]=step(V*G_arm_PD_dead_overall);MM=max(ww);Mp=MM-angle_max;
disp( '========================================================'
' Performance specifications are :
' disp( '-----------------------------------------------
' %fprintf(' Kp =%g , Kd=%g ,ZPD=%g
,Kp,Kd,ZPD);
fprintf(' Final steady state output value =%g 
',steady);
fprintf(' Steady state error, Ess =%g
,Ess);
fprintf(' Percent overshoot, Mp =%g
,Mp);
fprintf(' Potentiometer constant, Kpot =%g
,Kpot );
fprintf(' Desired output angle, Theta =%g
,Angle_max);
disp( '========================================================'
' PD transfer function, G = Kd(s + Kp/Kd)= Kd(s
zpd),is
given by :
') fprintf( ' \[t\[t\[t\]
') fprintf( ' Gpd(s)=%g(s+%g)
,Kd,ZPD)
disp( '========================================================'
' Prefilter transfer function :
') disp( '-----------------------------------------------
') G_prefilter=tf(prefilter_num,prefilter_den);
QQ=zpk(G_prefilter)
 disp( '========================================================'
' Overall closed loop transfer function in terms of output
Angular displacement :
') G_arm_PD_dead_overall=series(G_prefilter, G_arm_PD_dead_closed);
QQQ=zpk(G_arm_PD_dead_overall)
Figure ure, subplot(2,2,1),
step(V*G_arm_PD_dead_overall),ylabel('Mobile speed \omega'),xlabel('Time '), title('Angular displacement, PD with deadbeat'), grid
subplot(2,2,2),step(V*G_arm_PD_dead_overall2),ylabel('Mobile speed 
u'),xlabel('Time '), title('linear displacement, PD with deadbeat'), grid
subplot(2,2,3), step(V*Ga_arm_open);ylabel('Arm position, \theta Rad '),xlabel(' Time '), title('OPEN loop Angular displacement '), grid
subplot(2,2,4), step(V*G_close_arm);ylabel('Arm position, \theta Rad '),xlabel(' Time '), title('CLOSED loop Angular displacement '), grid
disp(' ' ================-------------------------------------')
else
    error (' Enter 1 for Speed control and 2 for Position control ')
end

6. Testing and analysis

6.1 Testing and analysis of PI controller with desired deadbeat response specifications in terms of desired output linear speed

Running the new built-in function for input argument 1, deadbeat(1), that is design of PI controller with deadbeat response, for desired output linear speed of 0.5 m/s, and settling time of 4 seconds and correspondingly defining used DC motor application's and sensor's parameters, dimensions and load torques, built-in function will return the below data including the coefficients that yield the optimal PI controller with desired deadbeat response, also system, controller, and prefilter transfer functions, as well as corresponding response curves of open loop motor system response (Figure 4(a)) and designed system deadbeat response (Figure 4(b)), with and without prefilter. the resulted response curves show achieving the desired fast deadbeat response with desired settling time of 4.1 seconds, also the following performance specifications; Final steady state output value =0.5 m/s, Steady state error, Ess=-5.55112e-017, Percent overshoot, Mp=-0.00158942, Angular speed, Omega =-6.66667, Kp =0.194489, Ki =-0.217222, ZPI =-1.11689, Tachometer constant, Ktach =1.8

To verify the design, we can use the simulink model, by defining the obtained coefficients Kp, Ki, ZPI, in MATLAB workspace, switching simulink model to PI controller and correspondingly switching sensor to speed measuring, and running simulation will result in response curves shown in Figure 4(c), the resulted response linear speed/time, angle/time, current/time and torque/time curves show achieving the desired fast deadbeat response with desired settling time of 4 seconds. Here notice that the simulink model includes the coulomb friction.

Running the new built-in function for desired output linear speed of 0.5 m/s, for PI design with deadbeat response, but for desired settling time of 1 seconds, will result in response curves shown in Figure 5(a), the resulted curves show achieving the desired fast deadbeat response with desired settling time of 4.1 seconds the desired response is achieved and Final steady state output value =0.5, Steady state error Ess=-5.55112e-017, Percent
overshoot, $M_p = -0.00148821$, Tachometer constant, $K_{tach} = 1.8$, Angular speed, $\Omega_m = 6.66667$, $K_p = 6.90286$, $K_i = 13.9022$, $ZPI = 2.01398$.

Now, defining the obtained coefficients $K_p$, $K_i$, $ZPI$, in MATLAB workspace, switching simulink model to PI controller and correspondingly switching sensor to speed measuring, and running it, will return response curves shown in Figure 5(b), curves show the identity and correctness of calculations using both built-in function and simulink model.

Design for PMDC output angular and linear SPEED PI with desired deadbeat response, e.g. mobile robot output speed design and control:

Please define PMDC parameters

DC motor open loop transfer function in terms of: Speed/Volt:
Zero/pole/gain:

$$\frac{50}{(s+3.861)(s+1.987)}$$

DC motor OPEN loop transfer function in terms of: Angle/Volt:
Zero/pole/gain:

$$\frac{50}{s(s+3.861)(s+1.987)}$$

Define plant parameters (e.g. mobile robot:

Enter desired settling time in seconds, $Ts$ : 4

System Performance specifications:

Final steady state output value = 0.5
Steady state error $E_{ss} = -5.55112e-017$
Percent overshoot, $M_p = -0.00158942$
Tachometer constant, $K_{tach} = 1.8$
Angular speed, $\Omega_m = 6.66667$

Gains and zero of: PI controller & prefilter:

$K_p = 0.194489$
$K_i = 0.217222$
$ZPI = 1.1168$

PI Controller transfer function
Zero/pole/gain:
0.19449 (s+1.117)
---------------------------------
s
Prefilter transfer function
Zero/pole/gain:

\[ \frac{1.1169}{s+1.117} \]

Closed loop transfer function, PI WITHOUT prefilter
Zero/pole/gain:

\[ \frac{9.545 (s+1.117)}{(s+1.011) (s^2 + 4.853s + 18.98)} \]

Closed loop transfer function, PI WITH prefilter
Zero/pole/gain:

\[ \frac{10.6607 (s+1.117)}{(s+1.117) (s+1.011) (s^2 + 4.853s + 18.98)} \]

\[ \begin{array}{c}
\text{DC motor output angle (°)}
\end{array} \]

(ANGLE) Step response of used DC motor open loop transfer function

\[ \begin{array}{c}
\text{DC motor output speed (°/s)}
\end{array} \]

(ANGULAR SPEED) Step response of used DC motor open loop transfer function

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure4a.png}
\caption{(a) Using built-in function: response curves of open loop motor system}
\end{figure}
**Figure 4(a)** Using built-in function: designed system deadbeat response with desired $T_s=4$ s, linear and angular speed, with and without prefilter.

**Figure 4 (c)** Using simulink model: designed system deadbeat response with desired $T_s=1$ s, linear and angular speed, with and without prefilter, also current and torque and controller signal.
**Figure 5(a)** Built-in function: designed system deadbeat response with desired $T_s=3$ s, linear and angular speed, with and without prefilter.

**Figure 5(b)** Using simulink model: designed system deadbeat response with desired $T_s=1$ s, linear and angular speed, with and without prefilter, also current and torque and controller signal.
6.2 Testing and analysis of PD controller with desired deadbeat response specifications in terms of desired output position

Running the new built-in function for input argument 2, deadbeat(2), that is design of PD controller with deadbeat response, for desired output angle of 90, and settling time of 2 seconds and correspondingly defining used DC motor application's and sensor's parameters, dimensions and load torques, built-in function will return response curves of open loop motor system response and designed system deadbeat response (Figure 6(a)), the resulted response curves show achieving the desired fast deadbeat response with desired settling time of 1.8 (error of 0.2) seconds, also the following performance specifications; Final steady state output value = 90, Steady state error, Ess = -2.84217e-014, Percent overshoot, Mp = -0.334091, Angular displacement, theta = 90, Kp = 32.6243, Kd = 14.5295, ZPD = 2.24539, Tachometer constant, Ktach = 0.1333. To verify the design, using the simulink model, define the obtained coefficients Kp, Kd, ZPD, in MATLAB workspace, switching simulink model to PD controller and correspondingly switching sensor to angle measuring, and running simulation will result in response curves shown in Figure 6(b).

![Graphs](image)

**Figure 6 (a)** Built-in function: designed system deadbeat response with desired \( T_s = 3 \) s, linear and angular speed, with and without prefilter.
Figure 6(b) Using Simulink model: designed system deadbeat response with desired $T_s=2$ s, linear and angular speed, also current and torque and controller signal.

Conclusion

Mechatronics design of most used electric DC machine and corresponding motion control in terms of desired output position or velocity for desired deadbeat response specifications is proposed, the design is facilitated using either or both proposed new MATLAB built-in function named deadbeat($\theta$), and new Simulink model, both oriented on Mechatronics design of both electric machine and motion control systems. The introduced new MATLAB built-in function determines the coefficients that yield the optimal deadbeat response for desired output speed or angle control of a given electric machine, also calculates transfer functions (open and closed), of used motor, controller, prefilter and overall system, also, plots overall system deadbeat response and all corresponding response curves and deadbeat response specification, particularly $M_p$, $E_s$, $T_s$.

The proposed models and the supporting new MATLAB built-in function were tested for different electric DC machines and for different applications, the results show the applicability and accuracy of the proposed designs in Mechatronics motion control applications for achieving desired deadbeat specification, resulting in simplification and acceleration of Mechatronics motion control system design process. The proposed design, model and function, can be used for various Mechatronics motion control
design applications, where the proper selection of actuating machine and design of precise motion control system are of concern.

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