Mathematical Modeling of an Intelligent Poultry Feed Dispensing System

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ABSTRACT

Abstract The mathematical modeling of control systems and other industrial applications has helped to shape the design and performance of different systems. One of the problems faced by existing designs of poultry feed dispensing system in the tropics is feed wastage often resulting in high cost of production. Several measures that can be used to evaluate the performance of poultry flock especially broilers are growth rate, days to market, mortality, and feed efficiency. Feed is typically the most costly expense in broiler production. As a result, feed efficiency is typically the primary tool by which a flock is evaluated. This research mathematically model an intelligent poultry feed dispensing system that will dispense both solid and liquid feed which will reduce the unusual level of human involvement, feed wastage, contamination and high cost of production. The mathematical model encompasses the speed control of a DC motor which will regulate the to and fro motion of the conveyor brushes and control the flow of the solid feed. The control of the digital valves regulates the flow rate of the liquid feed in and out of the dispensing system. The mathematical model was simulated in MATLAB r2015b environment. The simulated results showed that the system under state-space is controllable and observable when the Kalman matrix test was carried out. At the end, a dynamic model for optimized balance among better yield, returns on investment and cost of operation in dispensing poultry feed was developed.

Keywords: Mathematical Modeling, Precision farming, DC Motor, State Space Model, Control Systems, & Poultry.

1. INTRODUCTION

In precision farming, the control of mechanical and electromechanical systems cannot be over emphasized. Precision Livestock Farming (PLF) requires a sensing system for outputs; a mathematical model of input and output relationships; a target and trajectory for controlled processes; and a model-based controller with actuators for process inputs [15]. Incorporating PLF to the poultry industry has contributed immensely to the development of the Nigerian economy as it serves as a major source of egg and meat which have a high nutritional value in the supply of protein to the growing population [10]. Most often, placing too much feed in the feeder trough results in feed wastage and contributes to an inferior feed conversion. But prevention of excessive loss of feed during manual feeding, small quantities of feed are added to the feeder lids by running the intelligent poultry feed dispensing system frequently, for short periods aimed at stimulating the chicks to eat more often. Also, this will encourage the chicks to feed from the intelligent feeding equipment quickly. This factor was considered in this design. With this, an environment friendly system that optimizes product quantity while minimizing cost, human intervention and the variation caused by unpredictable nature becomes necessary [6]. Figure 1 shows the diagram of the precision livestock model.
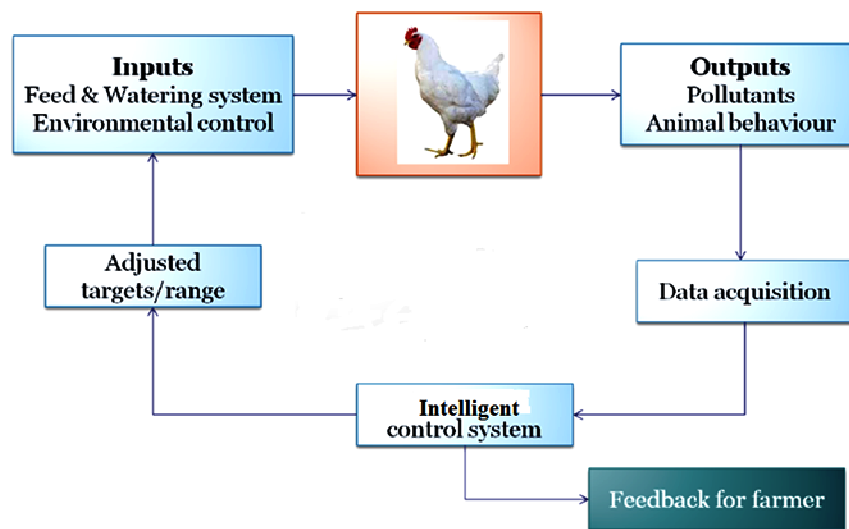

Figure 1: Precision livestock model [1]

Amongst other benefits, PLF bring about better health control as both feed usage and growth rate change will alert managers to early signs of disease problems, improved scientific understanding of nutritional, health and environmental effects on the animals as almost all important parameters will be monitored by the system and later, new measurement parameters can be added as necessary. Thus, this paper demonstrates one of the arms of PLF in the domain of mathematical modeling of input and output relationship, to reduce to the barest minimum the unusual involvement of human workers in carrying out most of the activities in poultry farms, feed wastage due to the ad libitum feeding, and contamination of feeds where the birds and farmers are directly or indirectly affected. Timed feeding of broilers has been recommended for economic reasons. Here, the birds will be fed a set amount of feed at specific intervals a day so they finish their meal and are then held without feed for about for a period of time set at the control switch.

This will have some beneficial in reducing the chance for the mechanical stimulation of feed intake that is often experienced when running the feeders throughout the day. During these times without feed birds are usually quiet, and this may improve feed utilization due to the reduced maintenance feed requirements.

The remaining section of this paper is organized into four sections. Section two presents a literature review of related works in intelligent poultry feed dispensing system. Section three presents a description and overview of the intelligent poultry feed system design and the mathematical modeling. Section four presents the simulated results using MATLAB r2015b, and the discussion of the obtained results while Section five concludes the paper.

2. REVIEW OF RELATED WORKS

In the past few years, a reasonable number of interests have been shown in the design and development of poultry feed dispensing systems. These works have explored the need to use intelligent techniques, from fuzzy logic to nature- inspired swarm intelligence, so as to obtain better results and robustness for the system. Starting from the dispensing of solid feeds, the systems have now gain the momentum of dispensing both solid and liquid feeds and have gain the merits of reducing feed wastage, manual worker involvement, and feed contamination. However, challenges and problems in the poultry farming industry keep metamorphosing into further human involvement, feed wastage and contamination.

An innovative approach is the design and development of an intelligent poultry liquid feed dispensing system using fuzzy logic control Algorithm [2]. Although the system detected the level of feed and dispensed feed if the level was low, it has a number of limitations such as the inability of the system to dispense solid feed, immobility and the absence of a mechanism to prevent contamination. Some of the limitations encountered in [3], were rigorously addressed by [1] in a mobile intelligent poultry liquid feed dispensing system using Genetic Algorithm tuned PID control technique. This system was mobile and dispensed the liquid feed in a recycling manner to avoid contamination. The results showed that the system had a better performance than the system implemented without a control technique. Notwithstanding, the major limitation of this system was the incapability to dispense poultry feeds. In addition, the GA technique used suffers from premature conversion and is not efficient in solving large optimization problems. The precision and convergence speed of advanced PSO is better than that of GA in the optimal tuning of PID controller on DC motor [9].

Another challenging innovative approach is the design of a mobile intelligent poultry solid and liquid feed dispensing system which used fuzzy logic control technique [10]. This system can sense the feed and water level and dispenses them when the levels were low. A limitation of this system was that fuzzy logic is not suitable for highly complex systems as it requires a lot of data and expertise to develop fuzzy rules and membership functions. Finally, in [12], a mobile intelligent poultry feed dispensing system was developed using PSO tuned PID control technique. The need to design a simplified and an intelligent system with an effective memory capability to changes in an environment and fewer parameters to control the PID compared to GA prompted the development of mobile intelligent poultry feed dispensing system using PSO tuned PID control technique. The system was capable of dispensing both solid and liquid feed and also showed better performance than the system implemented without a control technique. One of the significant problems encountered with this system is the low efficiency in carrying out the specified task, which can be made better with the application of a suitable hybrid intelligent control technique.

One salient issue that is involved with these previously designed and developed systems is that they lack the ability to detect when the feeds are exhausted and when there is any form of contamination. This problem will be addressed by the introduction of an alarm system that will detect when the solid and liquid feed troughs are empty. The mobility of the system did not really addressed challenges of feed wastage and human involvement. Therefore, it will be better to keep the system fixed with better extension made on the feed conveyors.

3. SYSTEM OVERVIEW

This section presents a detailed description of the system design and the modeling that governs the effective performance of the system. Figure 2 displays the conceptualized system and every component parts that make up the main system as a whole unit. This system is carefully modeled to cater for the feeding need of broilers in the sense that the solid and liquid feeds are well partitioned to avoid bird flocking and uneven distribution. The need for mobility has been eliminated by the introduction of extended feed pipes for appropriate feed distribution.

The mechanical unit is composed of a DC motor used to initiate the rotation of the belt drive, which in turn controls the to and fro movement of the brushes or feed conveyor inside the solid feed pipe. The liquid feed is dispensed by controlling the opening and closing of the digital valves at each outlet point. The liquid output flow rate is monitored by the control unit. Both the solid and liquid feeds are emptied into different troughs to check the feed conversion ratio of the birds and to control the flock crowding habit of the birds. Figure 3 depicts the side view of the system.
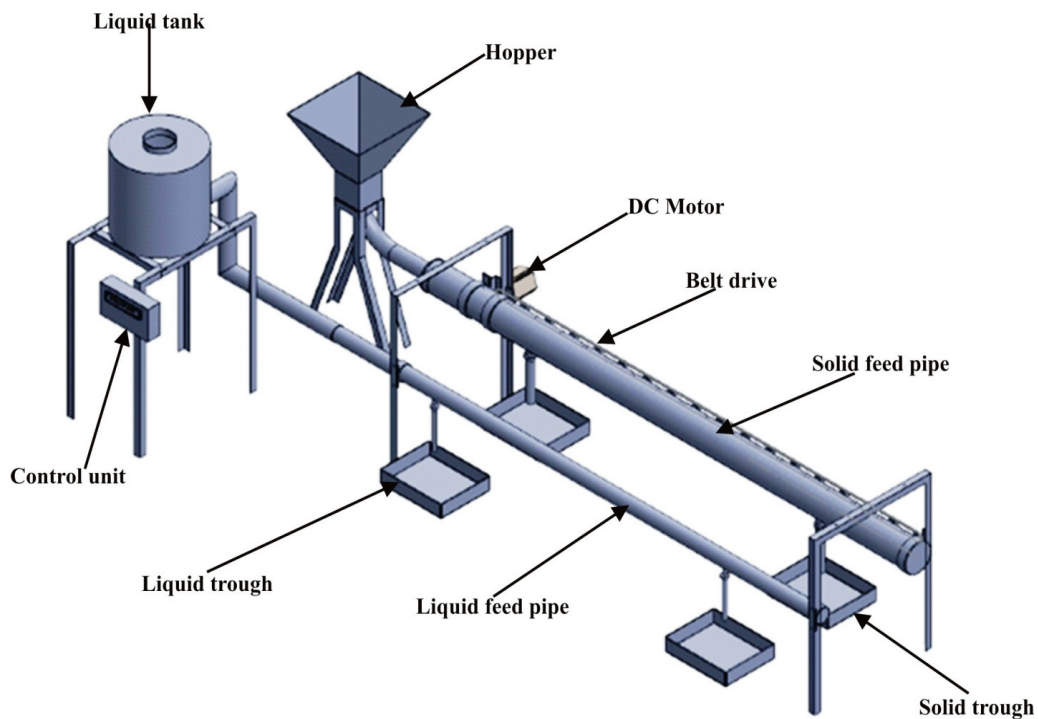

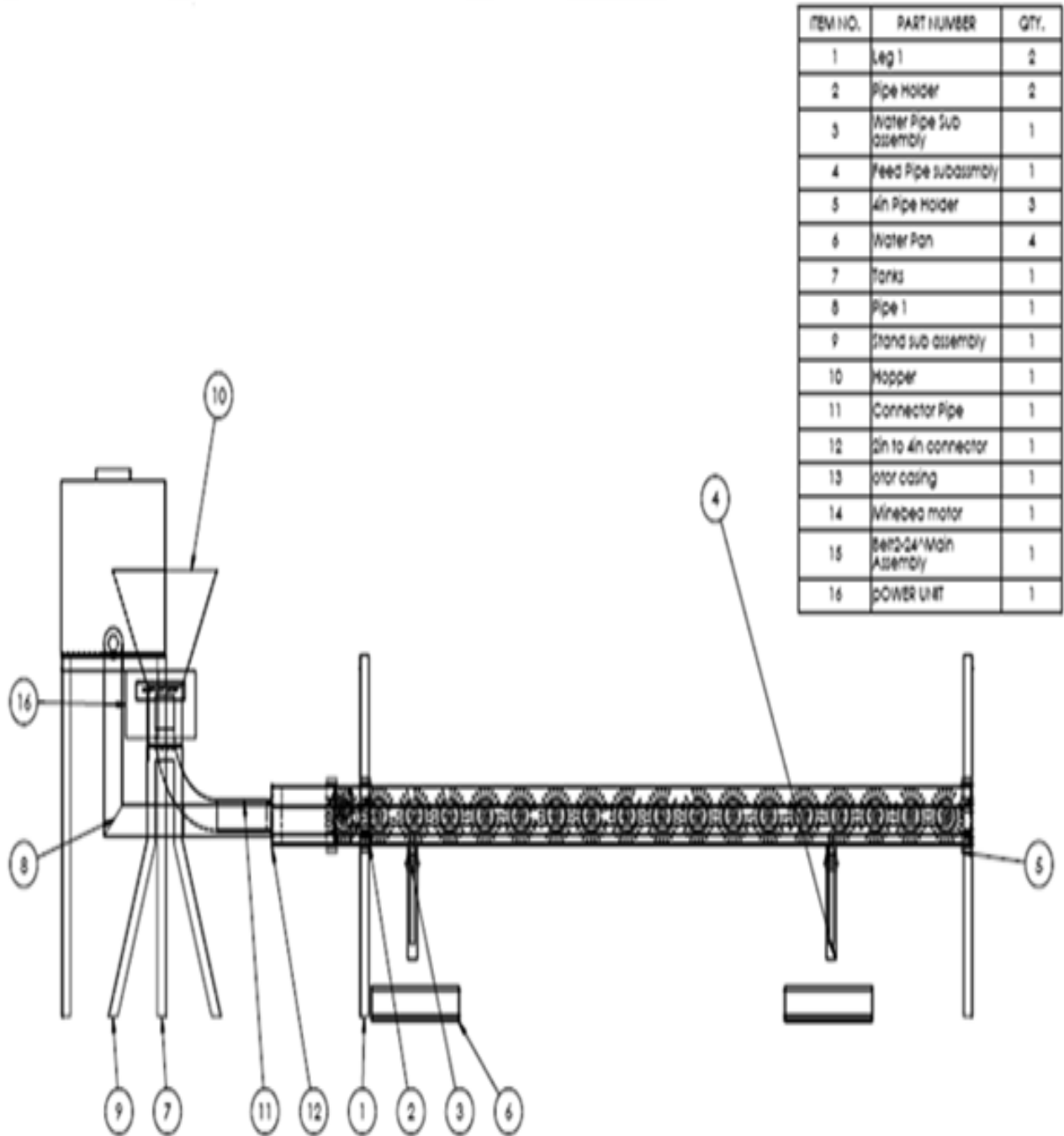**Figure 2: Concept of the main intelligent poultry feed dispensing system assembly**

ITEM NO.	PART NUMBER	QTY.
1	Leg 1	2
2	Pipe Holder	2
3	Water Pipe Sub assembly	1
4	Feed Pipe subassmbly	1
5	4in Pipe Holder	3
6	Water Pan	4
7	Tanks	1
8	Pipe 1	1
9	Stand sub assembly	1
10	Hopper	1
11	Connector Pipe	1
12	2in to 4in connector	1
13	otor casing	1
14	Minebea motor	1
15	Belt2Q4^Main Assembly	1
16	pOWER UNIT	1

Figure 3: Side view of the main intelligent poultry feed dispensing system

The electrical unit is the main source of power supply to the DC motor and the controller unit of the system. This comprises of a 12V DC battery which can be regulated to power the electronic components. This unit is also composed of other electronic subcomponents. Figure 4 and 5 shows the model flowchart and block diagram respectively.
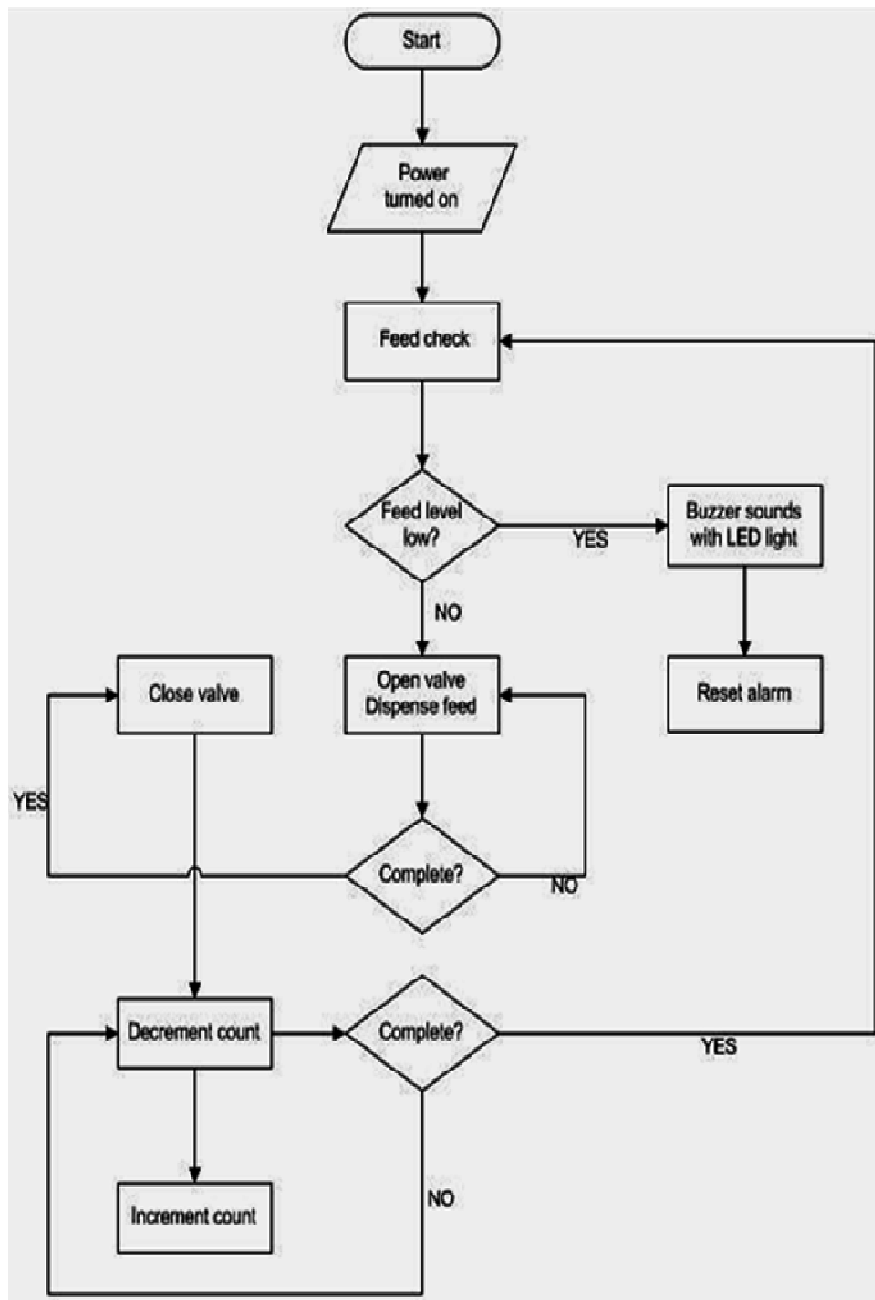

Figure 4: Flowchart of the intelligent poultry feed dispensing system
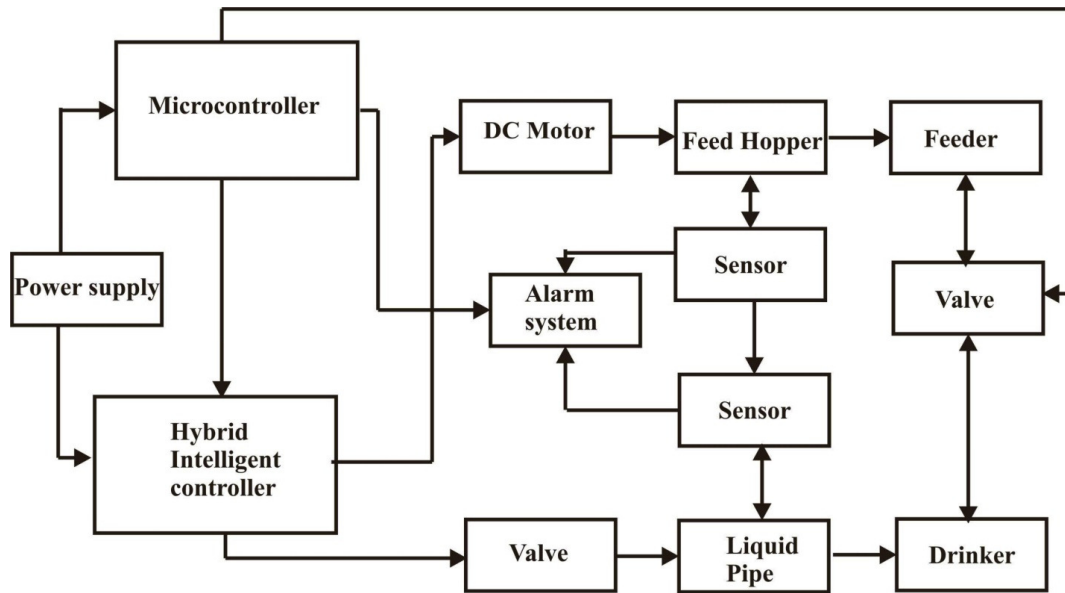
Figure 5: Block diagram of the intelligent poultry feed dispensing system

3.1 Mathematical Modeling of the System

The two main subsystems are the liquid feed pipe and the solid feed hopper. Although modeling of the liquid pipe would depend on the rate of flow of the liquid from the pipe through the valve, the action of dispensing the solid feed will be in corollary to the forward and backward motion of DC motor.

3.1.1 Mathematical Modeling of the Solid Feed Subsystem

The DC motor which is the main driver of the belt drive and rollers is depicted in Figure 6. Here the torque generated by the motor is proportional to the product of the armature and field current, increasing linearly with field current through the field voltage.
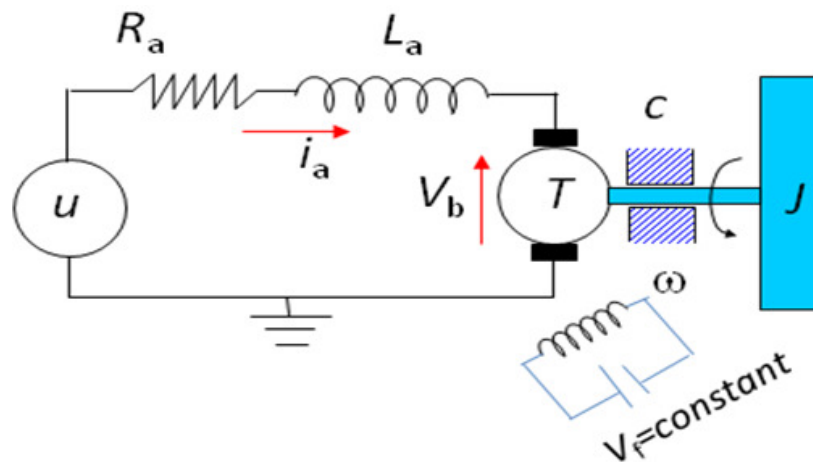

Figure 6: Model diagram of the DC motor

The following parameters were used to model the solid feed subsystem:

V_a = armature voltage
V_b = back emf
R_a = armature winding resistance,
L_a = armature winding inductance,
i_a = armature winding current,
K_b = back emf constant,
K_t = motor torque constant,
J = moment of inertia of the motor,
ω = angular Velocity
T = Torque developed by the motor
C=viscous-friction coefficients of the motor.

Taking u as the reference input and ω as the feedback, the difference is fed to the motor armature. Therefore for the electrical part, this becomes:

$$V_a(t) = u(t) - \omega(t)$$

$$L_a \frac{di_a}{dt} = V_a(t) - R_a i_a(t) - K_b \omega(t) \tag{1}$$

$$L_a \frac{di_a}{dt} = V_a(t) - R_a i_a(t) - V_b(t)$$

$$\frac{di_a}{dt} = \frac{1}{L_a} V_a(t) - \frac{R_a}{L_a} i_a(t) - \frac{K_b}{L_a} \omega(t) \tag{2}$$

Considering the electromechanical part of the of the DC motor and belt drive,
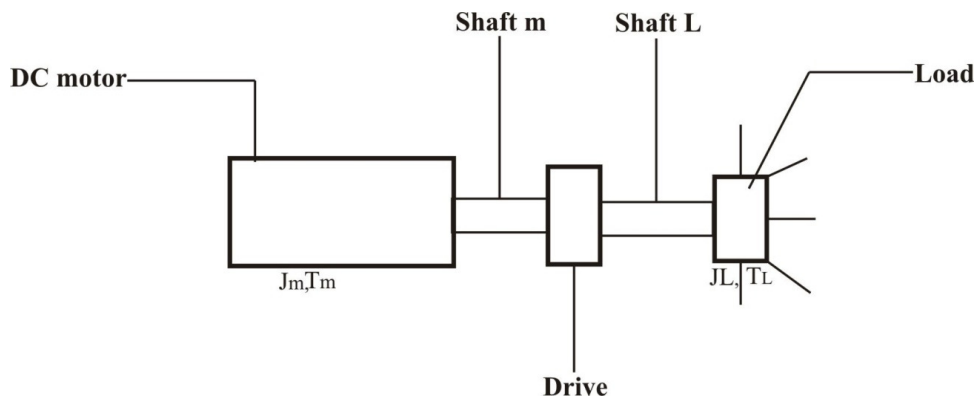

Figure 7: Electromechanical model of the motor and load

$$J_m \frac{d\omega_m}{dt} + c_m \omega_m(t) + T_f = T_m(t)$$

$$J_L \frac{d\omega_L}{dt} + c_L \omega_L(t) + T_f = T_L(t)$$

To obtain the overall nonlinear model of the system, the combination of the nonlinear friction effect becomes:

$$\frac{d\omega_L}{dt} = \frac{K_t}{J} i_a(t) - \frac{c}{J} \omega_L(t) - \frac{1}{J} T_L(t) - \frac{1}{J} T_f$$

Considering the torque friction, $T_f = 0$

$$\frac{d\omega_L}{dt} = \frac{K_t}{J} i_a(t) - \frac{c}{J} \omega_L(t) - \frac{1}{J} T_L(t) \qquad (3)$$

Putting into consideration the elasticity constant of the belt K_x, the total pulling force F_x, displacement of the belt $x(t)$, the total load on the belt is assumed to be L. Figure 8 displays the subsection of the driver and driven parts which made up the conveyor system.

$$F_x = L = T$$

$$x = r\theta$$

$$\frac{Lx^2}{dt^2} + K_x x = T$$

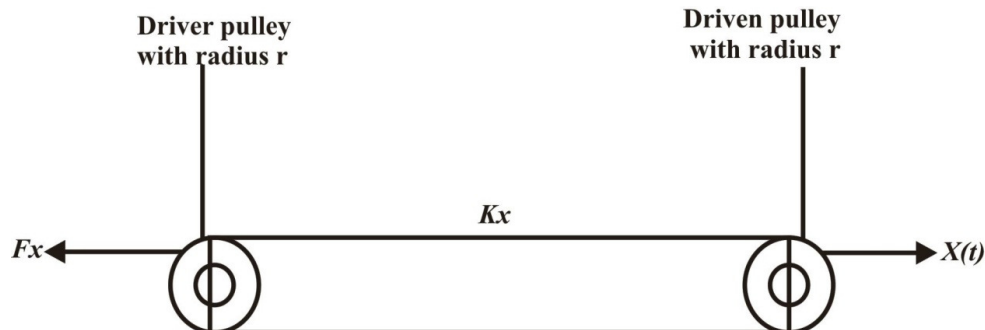$$\frac{Lr\theta^2}{dt^2} + K_x r\theta = T \qquad (4)$$

Figure 8: Feed conveyor system

Taking the Laplace transform of the equation 2 and 3, and assuming zero initial conditions:

$$sI(s) = \frac{1}{L}V(s) - \frac{R}{L}I(s) - \frac{K_b}{L}\Omega(s)$$

$$V(s) = LsI(s) + RI(s) + K_b\Omega(s)$$

$$(Js + C)\Omega(s) = K_t I(s)$$

$$\Omega(s) = \frac{K_t I(s)}{Js + C} \tag{5}$$

$$V(s) = \frac{JLs^2 + (CL + JR)s + CR + K_b K_t}{(Js + C)} \tag{6}$$

Combining the transformed equations together gives the transfer function:

$$\frac{\Omega(s)}{V(s)} = \frac{K_t}{JL} \cdot \frac{1}{s^2 + \left(\frac{C}{J} + \frac{R}{L}\right)s + \left(\frac{CR + K_b K_t}{JL}\right)} \tag{7}$$

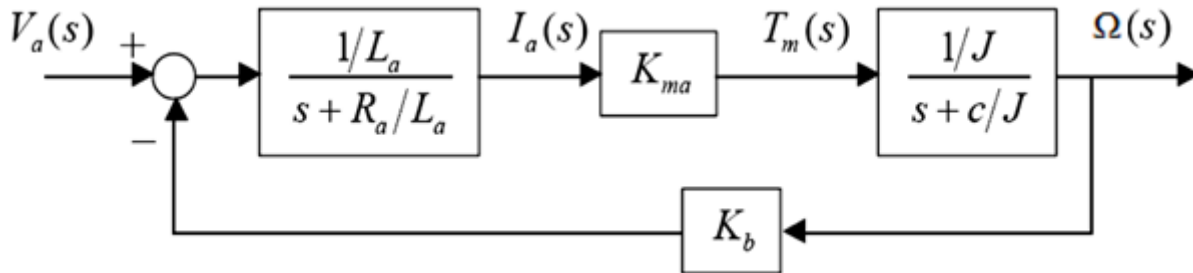
Figure 9: Closed loop of the feeder subsystem transfer function

Given the values of the main parameters:
R_a = armature winding resistance = 7.56 Ω
L_a = armature winding inductance = 0.055 H
K_b = back emf constant = 3.38 $V/rad\ sec$
K_t = motor torque constant = 3.38 Nm/Amp
J = moment of inertia of the motor = 0.068 kg/m^2
C = viscous-friction coefficients of the motor = 0.035 $Nm/rad\ sec$

From equation 7, the transfer function becomes:

$$G(s) = \frac{\Omega(s)}{V(s)} = \frac{3.38}{0.00473s^2 + 0.6521s + 11.69} \tag{8}$$

3.1.2 State Space Model of the Poultry Feed Dispensing System

From the mathematical representation of equation 6 and 7, the state space model of the hybrid intelligent poultry feed dispensing system was obtained to determine the system output for any given input, and improve the system efficiency and performance by applying appropriate control technique that will meet the need of the system model. The general form of a state space model for Linear Time Invariant (LTI) system is given by:

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{9}$$
$$y(t) = Cx(t) + Du(t) \tag{10}$$

Where x is a column vector of dimension n called state vector,
u is the input of the system,
y is the output of the system,
A is system matrix,
B is input matrix,
C is Output matrix,
D is feedback matrix.

Equations 6 and 7 make up the state space equations.

$$x_1 = i_a(t) \ and \ x_2 = \omega(t)$$

$$\dot{x}_2 = \frac{di_a}{dt} \ and \ \dot{x}_2 = \frac{d\omega}{dt}$$

$$A = \begin{bmatrix} -\frac{R_a}{L_a} & -\frac{K_b}{L_a} \\ \frac{K_t}{J} & -\frac{c}{J} \end{bmatrix}; \ B = \begin{bmatrix} \frac{1}{L_a} \\ -\frac{1}{J} \end{bmatrix}; \ C = \begin{bmatrix} 1 & 0 \end{bmatrix}; \ D = 0$$

Therefore the resultant state space matrices become

$$\begin{bmatrix} \frac{di_a}{dt} \\ \frac{d\omega}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_a}{L_a} & -\frac{K_b}{L_a} \\ \frac{K_t}{J} & -\frac{c}{J} \end{bmatrix} \begin{bmatrix} i_a(t) \\ \omega(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L_a} \\ -\frac{1}{J} \end{bmatrix} \begin{bmatrix} u(t) \\ T_L(t) \end{bmatrix}$$

$$\begin{bmatrix} \frac{di_a}{dt} \\ \frac{d\omega}{dt} \end{bmatrix} = \begin{bmatrix} -13.75 & -61.45 \\ 49.71 & -0.51 \end{bmatrix} \begin{bmatrix} i_a(t) \\ \omega(t) \end{bmatrix} + \begin{bmatrix} 18.81 \\ -14.71 \end{bmatrix} \begin{bmatrix} u(t) \\ T_L(t) \end{bmatrix}$$

$$y(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

3.1.3 Mathematical Modeling of the Liquid Feed Subsystem

The flow rate of the liquid feed in and out of the conveyor was taken into consideration. A cylindrical shape container was used. Hence, the cross sectional area of the cylinder was considered. The resistance to the rate of flow of the liquid out of the pipe was also considered in this model.
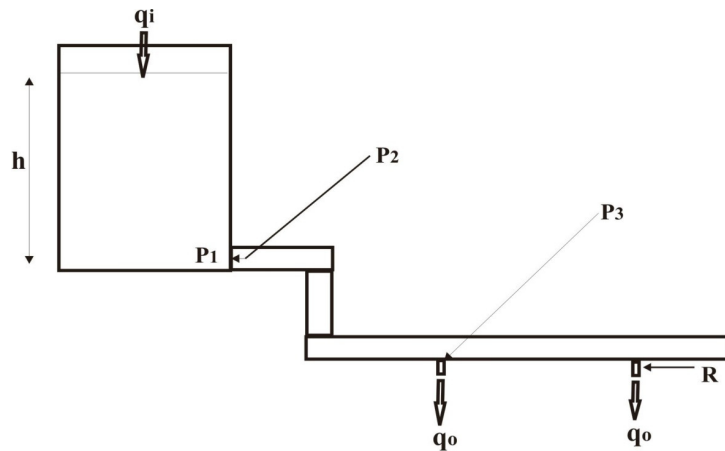

Figure 10: Model diagram of the liquid feed

The following are the parameters for the liquid feed subsystem as shown in Figure 10:

q_i = Flow rate of liquid into the trough (m^3/s)

q_o = Flow rate of liquid out of the pipe (m^3/s)

L = Length of the liquid pipe (m)

h = Fluid level in the liquid trough (m)

A_T = Cross-sectional area of the water trough (m^2)

A_p = Cross-sectional area of the pipe (m^2)

p = Pressure in the system (Nm)

V = Volume of the liquid inside the pipe (m^3)

R = Flow resistance (Ω)

C_v = Valve constant $(m^3 pa^{-1}s^{-1})$

The liquid balance in the steady-state, that is, the state where state variables are steady and do not change is generally expressed in the word form as

Flow rate into the system	=	Flow rate out of the system

Introducing the dynamic liquid balance inside the trough which involves changes with respect to time in the form of the accumulation, mathematically, this becomes:

$$q_i = q_0 + \frac{dv}{dt} \qquad\qquad (11)$$

The volume V of a container is generally given as:

$$V = A_T h \qquad\qquad (12)$$

Therefore the volumetric flow rate becomes:

$$\frac{dV}{dt} = A_T \frac{dh}{dt}$$

Taking into consideration the flow rate through the orifice:

$$q_i = q_o$$

Hence equation 8 could be rewritten as:
$$q_i = q_o + A_T \frac{dh}{dt} \qquad\qquad (13)$$

But discharge rate q_0 is equal to rate of out flow
$$q_0 = \frac{1}{R}\Delta p = \frac{1}{R}(p_1 - p_2)$$
$$q_i = \frac{1}{R}(p_1 - p_2) + A_T \frac{dh}{dt} \qquad\qquad (14)$$

Change in pressure inside the pipe:
$$\Delta p = \frac{\rho L}{A_p} \cdot q_0$$
$$p_2 - p_3 = \frac{\rho L}{A_p} \cdot q_0 \qquad\qquad (15)$$
$$q_i = \frac{1}{R}\frac{\rho L}{A_p} \cdot q_0$$

Differentiating with respect to time,
$$\frac{dq_i}{dt} = \frac{1}{R}\frac{\rho L}{A_p}\cdot\frac{dq_o}{dt}$$
$$\frac{dq_i}{dt} = \frac{1}{R}\frac{\rho L}{A_p}\cdot\frac{dq_0}{dt} + A_T \frac{dh}{dt} \qquad\qquad (16)$$

from the steady state approach,
$$\frac{dh}{dt} = \frac{1}{C_v \rho g}\cdot\frac{dq_i}{dt} \qquad\qquad (17)$$
$$\frac{\rho L}{A_p R}\frac{dq_o}{dt} = \left[\frac{C_v \rho g - A_T}{C_v \rho g}\right]\frac{dq_i}{dt}$$

Taking the Laplace transform, the equation becomes:

$$\frac{\rho L}{A_p R} Q_o(s) = \left[\frac{C_v \rho g - A_T}{C_v \rho g}\right] Q_i(s)$$

$$\frac{Q_o(s)}{Q_i(s)} = \frac{A_P R(C_v \rho g - A_T)}{C_v \rho^2 g L}$$

$$H(s) = \frac{Q_o(s)}{Q_i(s)} = \frac{A_P R(C_v \rho g - A_T)}{C_v \rho^2 g L} \qquad (18)$$

$$Y(s) = G(s) + H(s)$$

$$Y(s) = \frac{K_t}{JL} \cdot \frac{1}{s^2 + \left(\frac{C}{J} + \frac{R}{L}\right)s + \left(\frac{CR + K_b K_t}{JL}\right)} + \frac{A_P R(C_v \rho g - A_T)}{C_v \rho^2 g L} \qquad (19)$$
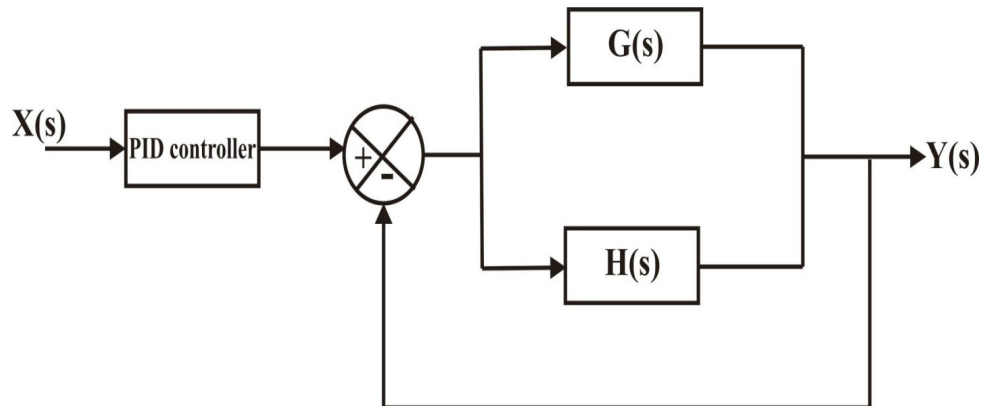

Figure 12: Block representation of the poultry feed dispensing system

4. SIMULATED RESULTS AND DISCUSSION

Using MATLAB r2015b, the simulated results of the DC motor for both the open loop and close loop response is displayed. With the introduction of the PID controller and lead compensator, time domain specification of percentage overshoot was reduced by the derivative action, and the steady-state error was eliminated by the integral part. This also brings about a much improved settling time. Figure 17 and 18 shows the root locus plots without controller and with controller respectively.
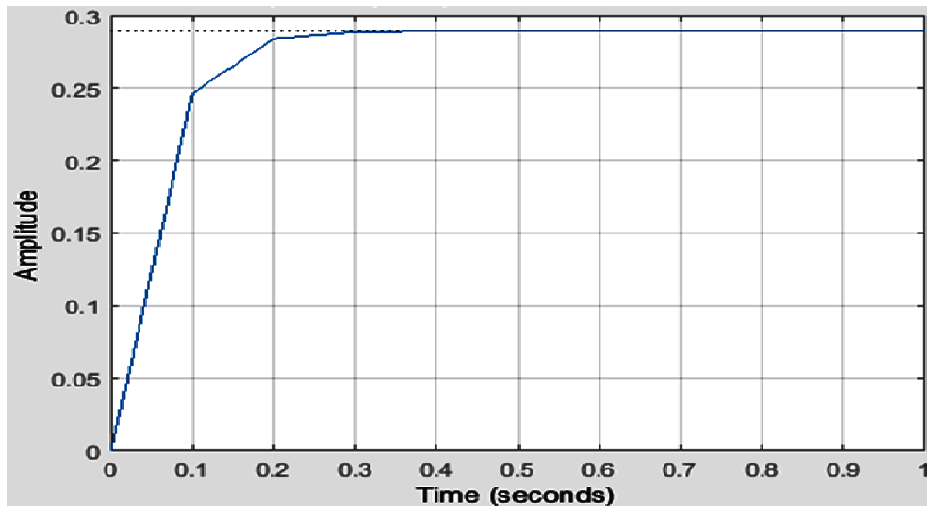

Figure 13: Open loop response without controller
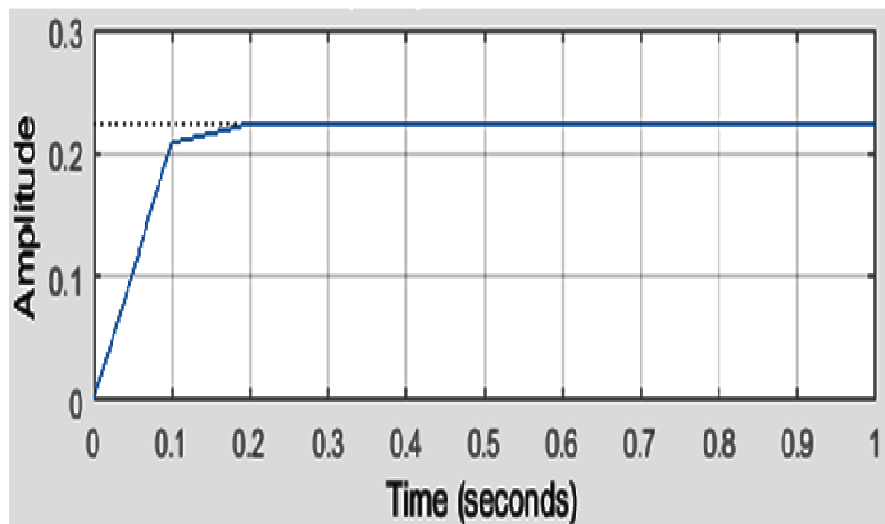

Figure 14: Closed loop response without controller

Figure 13 and 14 show the response for the continuous time transfer function. For both the open and closed loop, it can be observed that the system response is slow without the controller. But the aim is to obtain a dynamic system model better than the existing ones where the response is faster, steady state error is eliminated, rise and settling time is quickly achieved, and the percentage overshoot is truncated to a desired minimum. This brought the need to apply the PID controller and the lead compensator. Figure 15 and 16 show the simulated response for the PID controller and the lead compensator respectively.

This is to meet the desired settling time and overshoot. Although the system brought out a good response with a reduced overshoot and better settling time, it was still a little below the desired response and efficiency. The lead compensator eliminated the oscillatory action and gave a good response, but the time taken by the output to get to the expected percentage of the final value and the settling time were high for the open loop. On the contrary to the response of the open loop with the lead compensator, the closed loop gave a better response with a well reduced overshoot and much desired rise time and settling time. This is depicted in figure 17.
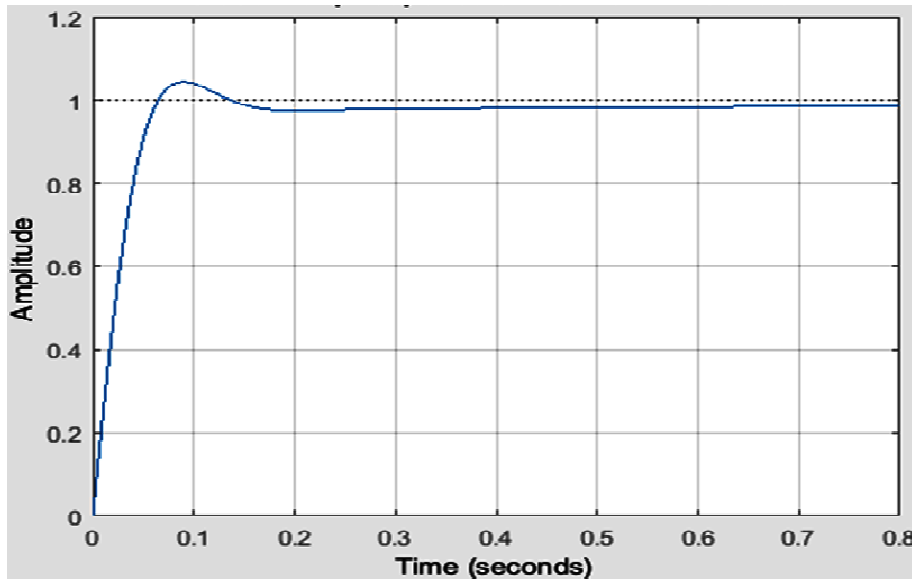

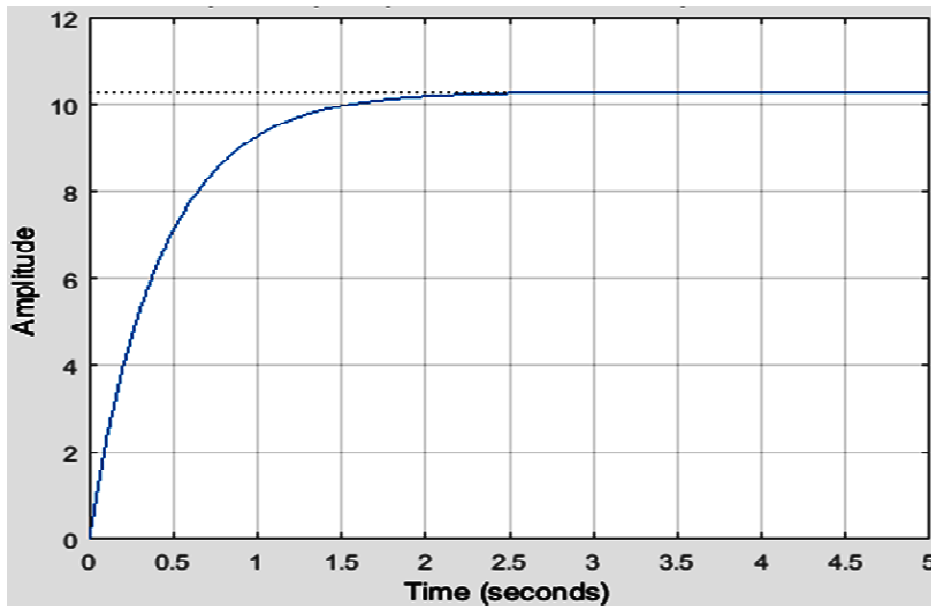Figure 15: Closed loop response of DC motor with PID controller

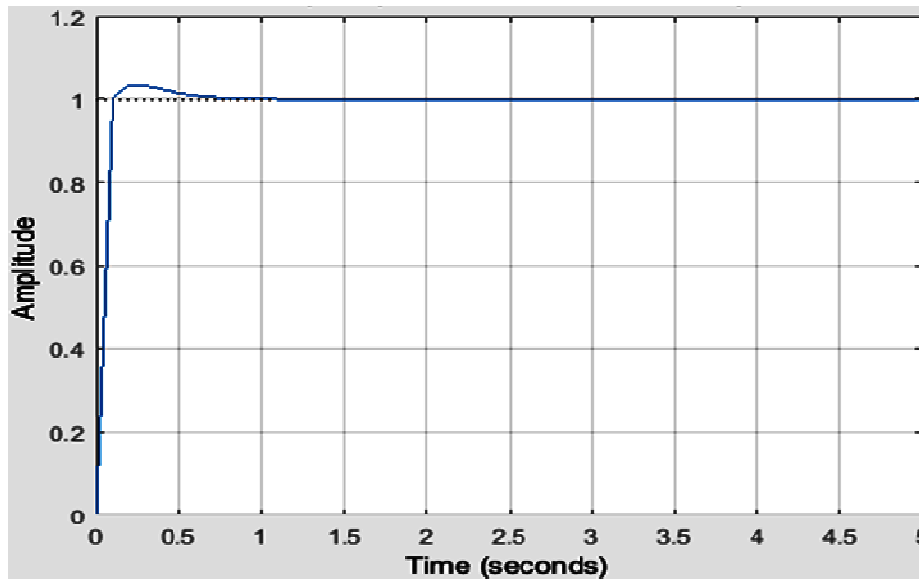**Figure 16: Open loop response with lead compensator**

Figure 17: Closed loop response with lead compensator

The root locus plots brought about a better understanding of the precise or specific location of the roots which then helped to obtain better values of gain that made the dynamic system model produce better response.

This sophisticated approach contrary to the trial and error Ziegler-Nichol method of PID tuning, helped to check under-damped, over-damped and critically damped response of the system. Figure 18 and 19 show the MATLAB graphical representation of the root locus plots.
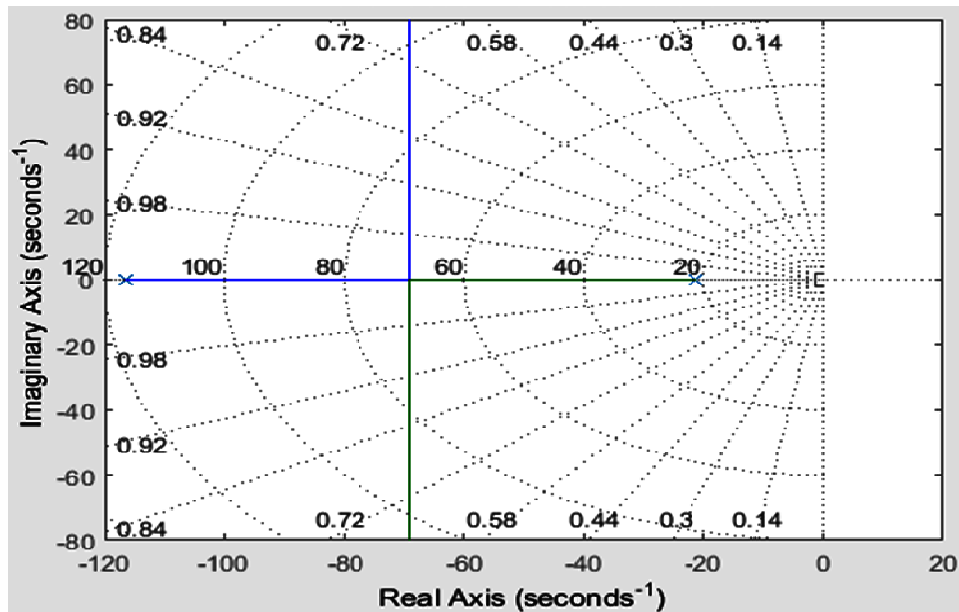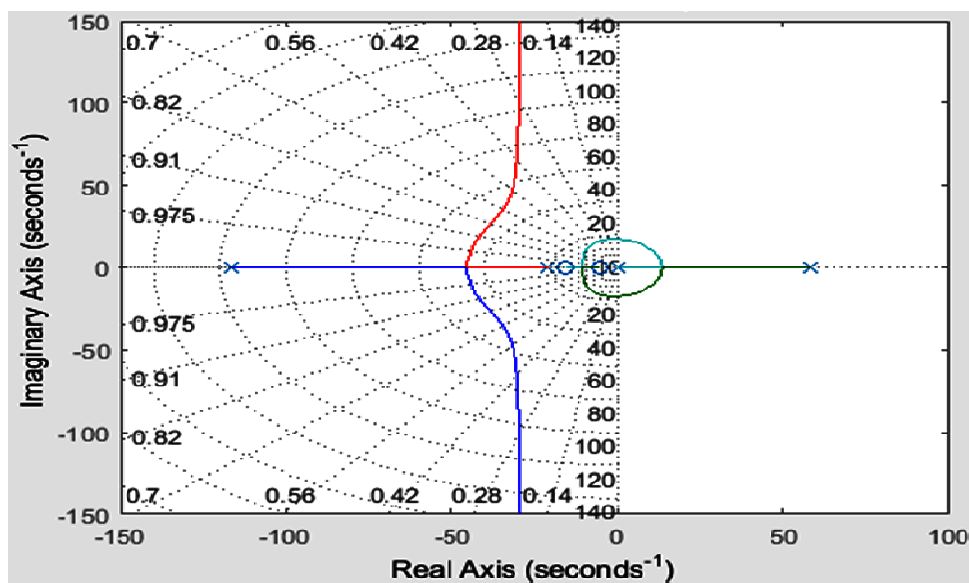

Figure 18: Root locus without controller

Figure 19: Root locus with lead compensator

5. CONCLUSION AND RECOMMENDATION

This paper shows the mathematical modeling of an intelligent poultry feed dispensing system. The dynamic system model will help to solve the problems of unusual human involvement, wastage of feeds, contamination, and flock crowding; bringing about an optimized balance between cost of operation and feed cost thereby maximizing profit index. It will also enhance production of good quality chicken and eggs devoid of the usual contamination especially from liquid wasted stains. In the poultry breeder industry, it will be a handy equipment to reduce embryo mortality often resulting from infections falling contamination especially from liquid feed spillage and frequent human interactions. The state space representation helps to address the limitations of the classical concept of transfer function to produce a time domain solution which is the same as single first order differential equation.

This easily brings in the effect of an initial condition. The performance of the control system is improved upon by the introduction of the lead compensator, thereby minimizing or reducing the unwanted frequency response, bringing about the stability of the model with an improved overshoot. What the controller could not achieved in terms of the system stability, adding zero to the system through the controller helps to attain stability. It was necessary to verify from the outset whether a solution exist to the control problem.

This prompted the test for controllability and observability using the Kalman test. Although the mathematical modeling of the hybrid intelligent poultry feed dispensing system tends to address some salient issues in previous works, there are still other improvements that can be incorporated into the system. The load on the DC motor can be minimized by fixing lighter feed conveyors for better efficiency. The system can also be improved by developing a management application that will generate data which can assist the farmers in making the appropriate decision for better planning.

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