Design of Fuzzy Logic Tracking Controller for Industrial Conveyor System

Chimezirim O. Aliworom[1], Lazarus O.Uzoechi[2] Mathew Olubiwe[3]
[1]*M.eng Student,* [2'3]*Senior Lecturer Department of Electrical/Electronic Engineering, Federal University of Technology Owerri Imo State Nigeria*

Abstract

This work designed a tracking controller for an industrial conveyor system using fuzzy logic. Also, the work discussed the impact of Fuzzy Logic Controller on the tracking performance of the conveyor system. Simulations were carried out on a model of a conveyor system with material mass of 1.0kg. Results obtained showed an improved settling time of 0.423 seconds, the rise time of 0.235 seconds, the percentage overshoot of 0% and no steady-state error. This implies that the conveyor reaches the desired position and stops without passing. This shows that the designed Fuzzy Logic controller satisfied the performance specification.

Keywords: *Fuzzy Logic Controller, Tracking, Conveyor belt, D.C motor*

I. INTRODUCTION

In recent times, the importance of belt conveyor system, especially in industries cannot be over emphasized. Belt conveyor systems are fast becoming one of the fastest means of transporting loads/products with maximum reliability and accuracy in our industries. In many processes or manufacturing industrial environments, belt conveyor systems have been identified as reliable tools for lifting or transporting bulk materials or products (loads) from one point to another depending on the speed of handling, height of transportation, nature, quantity, size and weight of materials to be transported.

A conveyor system is a common piece of electro-mechanical handling equipment that moves materials from one location to another. Conveyors allow quick and efficient transportation for a wide variety of materials, which make them very popular in the material handling and packaging industries[1] . Most Conveyors are driven by DC electric motors. Conveyor systems are mainly designed to achieve the following: quick and precise pick-up of loads, quick and efficient transfer of load with planned time interval, transport of loads in planned quantity, safe transport without any damage, accuracy in delivering at the destination, automation with minimum human element, low initial and operational costs and simple and easy to maintain [2]

Position control is important in conveyors where materials are moved from one point to another with a waiting period for some process to take place before moving to the next point. In this conveyor type, machines and materials are usually placed at equal distance from one another.

This research is geared towards improving the tracking performance of a typical industrial Belt conveyor system. The outcome of this research work will proffer lasting solutions on ways to prevent uncontrolled conveying of loads/products in industrial processes which could result in industrial hazards or disruption of operation.

II. REVIEWS OF PREVIOUS WORKS

An insight on how to model a simple nonlinear conveyor system was provided by[3]. The paper did an overview of the conveyor belt system with fair consideration of non-linear friction. The work later derived the mathematical model of the conveyor system considering the non-linear friction on the system.

The work by[4] designed a conveyor system which includes; belt speed, belt width, motor selection, belt specification, shaft diameter, and pulley and gear box selection using standard model calculation.

The work on modelling and PID controller system synthesis for belt conveyor system using polynomial stabilization method which computationally characterizes the entire set of admissible PID gains for various control system configurations was done by[5]. The paper also showed that a correction was needed in order to find all robust PID region controllers that satisfy a given robust performance. The work also provided a selection procedure for searching the best PID gains controllers in the obtained PID gains region. The paper later applied the correct polynomial stabilization algorithm on a short D.C servo- driven belt conveyor system.

The mathematical model of a conveyor mechanism for control applications with champion breweries PLC as a case study was presented by[6]. In the work, the electrical and mechanical sections were modeled separately and then integrated to obtain one composite system. The paper designed a proportional integral derivative controller to act as a speed synchronizer in order to eliminate the problem of non-synchronization. The result of the study showed that an improvement in system response when PID speed synchronizer was coupled with the feedback loop.

The investigation of how belt drives provided freedom to the position of motor relative to the load and how this phenomenon enabled the reduction of the robot arm inertia was carried out by [7]. It also facilitated quick response when employed in robotics. Unfortunately, the flexible dynamics deteriorated the positioning accuracy. Therefore, there exists a trade-off between the simplicity of the control strategy to reject time varying disturbance caused by flexibility of the belt and precision in performance. Resonance of the system further led to vibrations and poor accuracy in positioning. In the paper, accurate positioning of a belt driven mechanism using a feed-forward compensator under maximum acceleration and velocity constraints was proposed. The proposed method plans the desired trajectory and modified it to compensate delay dynamics and vibration. Being an off-line method, the proposed method could be easily and effectively adapted to the existing systems without any modification of the hardware setup. The effectiveness of the proposed method was proven by experiments carried out with an actual belt driven system. The accuracy of the simulation study based on numerical methods was also verified with the analytical solutions derived.

The paper by [8]studied the use of belt for high precision applications that became appropriate because of the rapid development in motor and drive technology as well as the implementation of timing belts in servo systems. Modeling of a linear belt-drive system and designing its position control were examined in the research work. Friction phenomena and position dependent elasticity of the belt were analyzed. Computer simulated results showed that the developed model was adequate. The PID control for accurate tracking control and accurate position control was designed and applied to the real test setup. Both the simulation and the experimental results demonstrated that specifications. The designed controller met the specified performance specifications.

The work by [9] developed a controller scheme for a sorting machine which was made up of conveyor belt and a skid both attached to a D.C motor and a photo detector. The sorting machine in the work was required to sort sticks of different lengths into a predestined bucket while keeping statistics on how many sticks are sorted and also keep track of how many odd sticks (too long or too short) are passing through the machine and where they went. The work used two controllers for the conveyor belt and skid; the skid controller was designed with PD controller whereas the conveyor belt was designed with PI controller. Furthermore, the study developed a physical model of two D.C motors, designed two controllers in MATLAB using frequency response method and implemented it on real time system. The system designed in the work was able to sort sticks reliably up to a speed of 1.0m/s with a minimum gap of 2.0mm.

An article on the methodology and verification for implementation of a rule-based fuzzy logic controller applied to a closed loop DC motor speed control was presented by[1]. The designed Fuzzy Logic Controller's performance was compared against with that of a PI controller.

The work by[6] Presented a mathematical modeling of a conveyor mechanism for control application with Champion Breweries PLC as a case study. The electrical and mechanical sections were modeled separately and then integrated to obtain on composite system. Due to the lack of synchronization of the conveyor line speed and the speed of action of the Empty Bottle Inspection (EBI), and the Full Bottle Inspection (FBI) units at the Champion Breweries, there existed the problem of residue left-over in bottles, cracked bottles on the conveyor line and the non-detection of incorrect liquor level in bottles. Therefore, a proportional Integral Derivative (PID) Controller was designed to act as a speed synchronizer in order to eliminate the above problems.

The advantages of using fuzzy logic controller over some others include: inherent approximate capability, high degree of tolerance, smooth operation, reduce the effect of non-linearity fast adaption and learning ability.

III . METHODOLOGY

Firstly, the mathematical model of the conveyor system was obtained, further the fuzzy logic controller was designed and the transfer function obtained from mathematical model simulated with the designed fuzzy logic controller.

A. Belt Conveyor System Modeling Assumptions

The following assumptions were made in the course of presenting a suitable mathematical model of the belt conveyor system:

i) Friction in rotor of motor is very small but cannot be neglected ($B \neq 0$)
ii) The dynamic energy consumption associated with start-up and stop of the belt conveyor is not considered
iii) the drive motor provides a higher dynamic speed with small time delay
iv) Connection between motor shaft, and gear drive is rigid and short
v) Connection between gear drive shaft, and driving pulley is finite stiffness

The conveyor is coupled directly to the motor pulley or roller

B. Belt Conveyor Systems Mathematical Models

The mathematical models suitable for optimization of a typical belt conveyor systems are presented in this section. The typical dynamic model of a conveyor system can be represented by the three components in figure 1. The three components comprise of the electrical, the mechanical and the belt conveyor torque components. The input to the system is armature voltage V_s (t) in volts and the output is the angular speed $\omega(t)$ of the drive motor shaft, directly connected to the drive pulley of the belt conveyor.

The schematic diagram of a belt-drive conveyor system is presented in figure 1

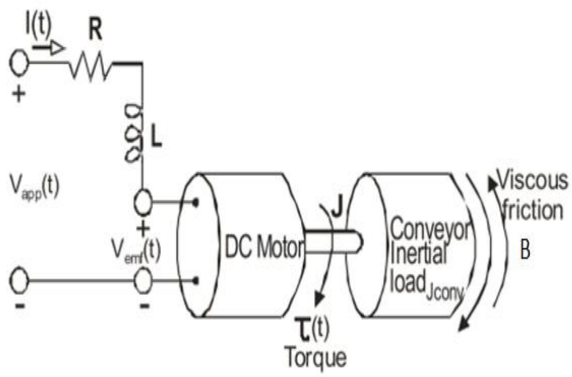

Figure 1: Diagram of Belt Conveyor System

Where R is the resistance of motor circuit, L is the self-inductance of the motor armature, τ is the torque produced at the shaft of the of the motor, V_b is the back induced electromotive force, J is the total inertia of the belt conveyor, $\omega(t)$ the angular speed of the motor shaft and b is the viscous friction.

1. Electrical Components

The electrical component of the belt conveyor system ensures that the appropriate input voltage is allowed into the system for accurate tracking.

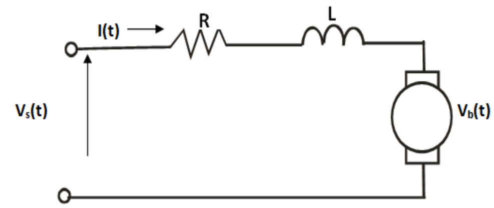

Figure showing electrical components of the conveyor.

Figure 2 shows the representation of the electrical component. A changing voltage signal connected to the input of the system gives a good torque and speed characteristics of the drive DC Motors.

The voltage across the resistor is represented according to Ohm's law can be written as

$$V_{ra} = Ri(t) \quad (1)$$

Similarly, the voltage across the inductor which is proportional to the change in current through the coils with respect to time is given as

$$V_{la} = L\frac{di(t)}{dt} \quad (2)$$

Therefore, the control equation of the DC drive motor electrical component can be derived using Kirchhoff's voltage as the follows:

$$V_s(t) = Ri(t) + L\frac{di(t)}{dt} + V_b(t) \quad (3)$$

Where

R = Resistance.

L = Inductance.

$V_{s(t)}$ = Applied or input voltage.

V_b = The back electromotive force (emf).

$i(t)$ = the current.

The back Electromotive Force (emf) can be expressed as

$$V_b(t) = K_b\omega(t) \quad (4)$$

Where:
K_b = Back emf constant
$\omega(t)$ = angular speed of the motor shaft.
Substituting equation 4 into 3

$$V_s(t) = Ri(t) + L\frac{di(t)}{dt} + K_b\omega(t) \quad (5)$$

$$V_s(t) = Ri(t) + L\frac{di(t)}{dt} + K_b\frac{d\theta}{dt}(t) \quad (6)$$

$$V_s(t) - K_b\frac{d\theta}{dt}(t) = Ri(t) + L\frac{di(t)}{dt} \quad (7)$$

Taking Laplace transform of equation above we have;

$$V_s(s) - K_b s\theta(s) = RI(s)LIS(s) \quad (8)$$

$$\mathrm{I(s)} = \frac{V_{s(s)} - K_b s\theta(s)}{R(s)LS(s)} \quad (9)$$

Equation 6 represents the input voltage of the belt conveyor system which determines the overall performance of the mechanical component.

2. Mechanical Component

The mechanical component of the belt conveyor system converts the electrical energy from the electrical component of the belt conveyor to mechanical energy. This component involves the motor torque, the damper, load or shaft inertia, angular position of the output shaft etc. The mechanical component can be represented by figure 3.

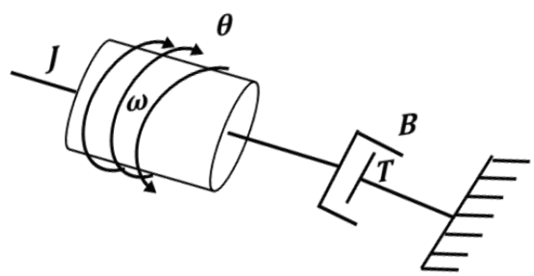

Figure 3: Mechanical Component of Belt Conveyor System

The parameters considered in figure 3 are denoted as follows:

J = load or shaft inertia.
ω = the angular speed of the shaft.
B=the viscous friction
T = the motor torque.
θ = angular position of the output shaft. .
Most conveyor systems require a constant level of torque at different operating speeds. According to Newton's law, the product of the inertial load and the derivative of angular rate equal the sum of all the torques about the motor shaft. This implies that the resultant torque on motor shaft is equal to zero (energy conservation)

$$T - T'_\omega - T_\omega - T_c = 0 \quad (10)$$

Where T is the electromagnetic torque, T'_ω is the torque due to rotational acceleration of the rotor, T_ω is torque associated with velocity of rotor, and T_c is the torque of the belt conveyor system. The current through the armature winding is proportional to the electromagnetic torque as shown in Equation 11.

$$T = K_m i(t) \quad (11)$$

K_m is a torque constant that depends on the flux density of the fixed magnets, the reluctance of the iron core, and the number of turns in the armature windings. T'_ω can be expressed as:

$$T'_\omega = \frac{Jd\omega(t)}{dt} = J\frac{d^2\theta}{dt^2} \quad (12)$$

The torque produced as a result of rotor velocity is given as:

$$T_\omega = B\omega(t) = B\frac{d\theta}{dt} \quad (13)$$

The damping coefficient or viscous friction associated with the rotating members of the motor is represented by b.
The torque balance equation of the mechanical component is given by

$$T - J\frac{d^2\theta}{dt^2} - B\frac{d\theta}{dt} - T_c = 0 \quad (14)$$

In Equation 14 the motor torque T can be expressed as the product of the current and the torque constant.

$$T = K_m i(t) \quad (15)$$

Substituting equation 15 into 14 gives

$$K_m i(t) - J\frac{d^2\theta}{dt^2} - B\frac{d\theta}{dt} - T_c = 0 \quad (16)$$

Consider a simple mechanical system consisting of a mass M and belt elasticity constant K. Where f(t) is the external force, T_c is total pulling force and x(t) is the displacement of the mass as shown in Fig 4 below.

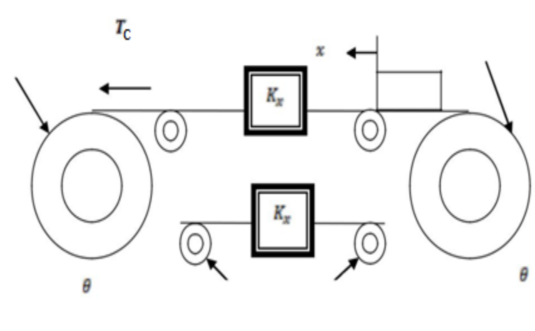

Fig.4 Conveyor belt system diagram ([3]

Three forces (and inertia) influence the motion of the mass, namely the applied force and the spring force as shown in the free-body diagram below, assuming finite damping.

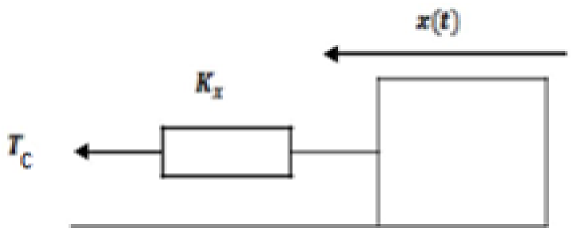

Fig.5: Belt and load Mass, Stiffness and Displacement (Mapoka et al, 2013)

F= T_c= load torque

$T_c = M_T \frac{d^2x}{dt^2} + kx$ (17)

Where x is linear displacement

$M_T = M_b + M_m$ (18)

M_b= mass of belt

M_m=mass of material

But x=rθ

$T_c = M_T r \frac{d\theta}{dt}^2 + kr\theta$ (19)

Equation 17 becomes

$K_m i(t) - J\frac{d^2\theta}{dt^2} - b\frac{d\theta}{dt}(t) - M_T r\frac{d\theta}{dt}(t) - kr\theta(t) = 0$
(20)

Therefore

$K_m i(t) = J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt}(t) + M_T r\frac{d\theta}{dt} + kr\theta$ (21)

Taking laplace transform we have

$K_m I(s) = Js^2\theta(s) + Bs\theta(s) + M_T rs^2\theta(s) + kr\theta(s)$
(22)

Substituting I= $\frac{V_{app\ (s)} - K_b s\theta(s)}{R(s)LS(s)}$

into equation 22

We have $K_m \frac{V_{app\ (s)} - K_b s\theta(s)}{R(s)LS(s)} = Js^2\theta(s) + Bs\theta(s) + M_T s^2 r\theta(s) + kr\theta(s)$
(23)

Therefore the overall transfer function is:

$G_P(s) = \frac{\theta(s)}{V_{app\ (s)}} = \frac{K_m}{s(Js+b)(Ls+R) + (M_T rs^2 + kr)(Ls+R) + k_m k_b s}$
(24)

The figure below is the block diagram representation of the conveyor system model

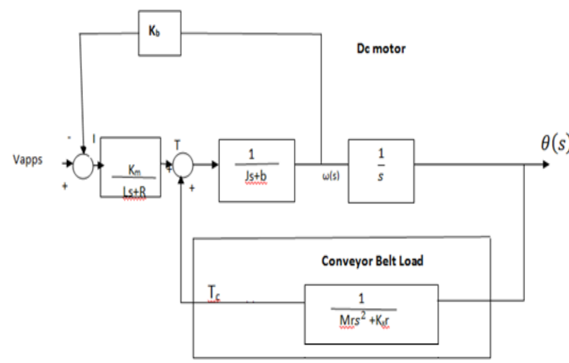

Fig 6 Block diagram of the conveyor model

The parameters of conveyor system are as follows:

J=1.2 $\times$ 10 − 6kgm[2]

K_m=13.3 × 10−[1]NM/A

K_b=13.3 × 10−[1]volt/rad

R=2.17Ω

L=1.17 × 10−[2]H

B=2.5 × 10−[3]Nms

M_m=1kg

M_b=0.2kg

r=17.4mm=0.0174m

M_T = 1.2Kg

K=4.5 × 10−[2]N/M

Substituting the values above into Equation 24 we have

$G_P(s) = \frac{\theta(s)}{V_{app\ (s)}} = \frac{1.33}{0.0002443s^3 + 45.34s^2 + 1.774s + 0.001699}$
(25)

The unit step response parameters required for an optimized belt conveyor system tracking control include the following:

a) Percentage overshoots less than 10%.

b) Settling time less than 6.5 seconds.

c) Rise time of less than 2 seconds.

d) Steady-state error less than 0.2%.

3.3 Fuzzy **Logic Controller Design**

Fuzzy logic is an easy approach to control engineering problems which involves a simple rule based “IF A and B then C” method. Figure 11 shows the components of a fuzzy logic controller.

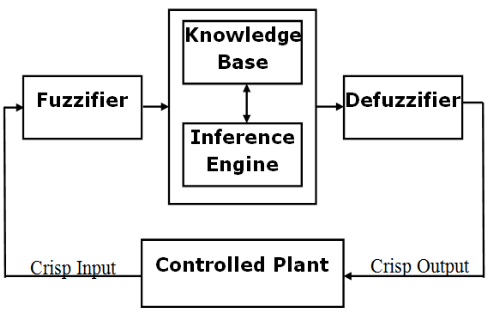

Figure 11: Components of a Fuzzy Logic Controller

The specific components a fuzzy logic controller consists of Fuzzifier, Defuzzifier, Knowledge base and Inference Engine (Decision making unit). The representation of the parameters involved in fuzzy logic is known as linguistic variables. The linguistic variables used in this research include: NB=Negative Big, NM=Negative Medium, NS=Negative Small, ZE=Zero Error, PS= Positive Small, PM= Positive Medium and PB= Positive Big.

Table: 1: Fuzzy Rules Table

e/∆e	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NS	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PS
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NS	NVS	ZE	PS	PM	PB	PB
PM	NVS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PS	PB	PB	PB	PB

A fuzzy logic control flow chart is shown in figure 12.

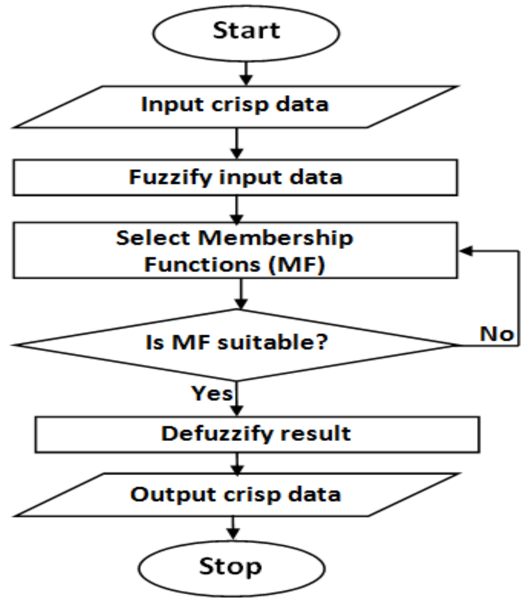

Figure 12: Fuzzy Logic Control Flowchart

The Fuzzy Logic Controller (FLC) above is integrated in a belt conveyor system as presented in figure 13.

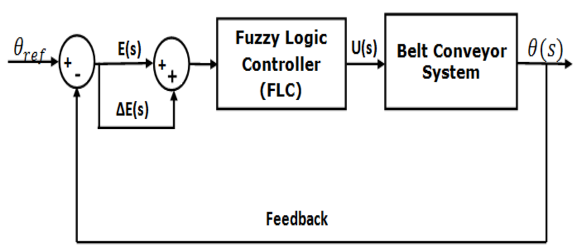

Figure 13: Block Diagram of Belt Conveyor System with FLC

The membership function used for fuzzy simulation is as shown below

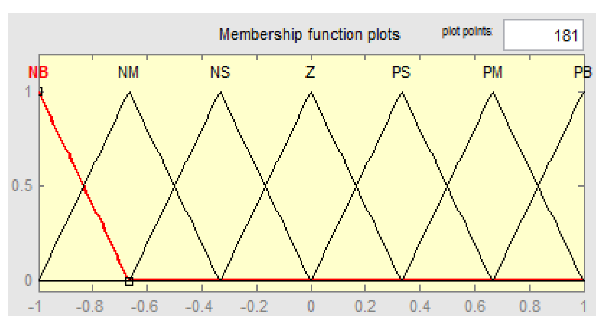

Fig. 14: Membership functions for inputs (’e’ and’ec’) and output

The Simulink model of figure 13 is presented in figure 15.

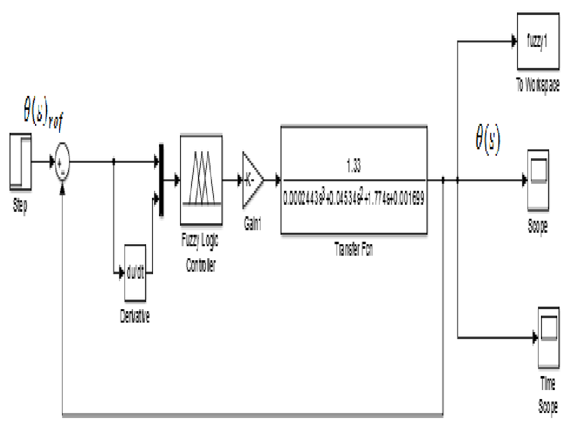

Figure 15: Simulink Model of Belt Conveyor System with FLC

Figure 15 was simulated in Simulink using the membership function defined by table 1. Minmax fuzzification method and Centre of Gravity diffuzification method were used.

IV. RESULTS AND DISCUSSION

A. Step Response of Conveyor Model without a Controller

The initial performance of the belt conveyor control system without a controller was investigated by simulating equation 25 (Transfer Function) using Matlab/Simulink software. The unit step response plot of the result is shown in figure 16 The settling time of over 4000 seconds, the rise time of over 2000s seconds, a steady-state error less than 5% were obtained and the plot is under-damped with very little overshoot.

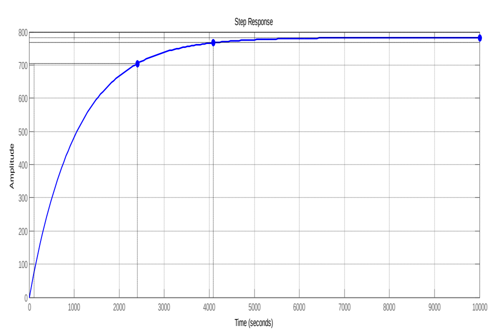

Figure 16: Initial Unit Step response of Conveyor Transfer Function, G(s).

Figure 16 present the step response of conveyor system model without a well tuned controller. The unit step response plot has a high settling time of over 4000 seconds which indicates poor timing and adaptability to additional load on the conveyor belt. The rise time of over seconds imply that the system takes a longer time to regain its steady state or normal conveying speed when a new load is introduced to the belt. A steady-state error of approximately 6% shows that the system stability is marginal.

B. Conveyor System Model with Fuzzy Logic Controller

The belt conveyor control system model with a fuzzy logic controller shown in figure 15 was simulated using Matlab/Simulink modelling enviroment. The unit step response plot obtained from the simulation is presented in figure 17.

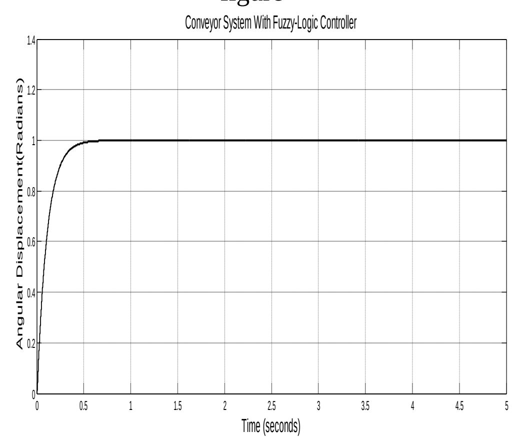

Figure 17: Unit Step Response of Conveyor Control System with FLC

The control parameters obtained from Figure 17 include: a settling time of 0.423 seconds, the rise time of 0.235 seconds, the percentage overshoot of 0% and no steady-state error. The settling time, rise time and percentage overshoot indicates a faster and better performance of the system. This shows the optimization effect of the fuzzy logic controller on the conveyor system. The steady-state error which is less than 0% shows improved system stability. The 0% overshoot means that conveyor does not exceed the input displacement and hence position. This shows that the conveyor was able to deliver its load to the desired destination without exceeding the position.

V. CONCLUSION

This research has so far presented an improvement on the performance of an industrial belt conveyor system. The suitable mathematical model of a belt conveyor system has been successfully obtained and simulated based on the unit step response input. A more accurate rule-based Fuzzy Logic Controller (FLC) has also been designed and integrated to the model.

The simulation results of the belt conveyor system integrated with the FLC Controller improved fastness and accuracy in the system response. The simulation results showed that FLC integrated to the overall belt conveyor control system gives a better performance compared to the previous system. Based on the analysis it was demonstrated that the settling time, percentage overshoot, steady state error and rise time were greatly improved by the new belt conveyor control model and controller achieved in this research.

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