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Investigating the Essence of Compensators in Engineering Systems: A Case Study of Industrial Belt Conveyor System

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A B S T R A C T

In their conventional design state, most engineering systems exhibit dynamic responses that may not be suitable for a given industrial application. For this reason, in many applications, external system called compensator is usually introduced into the operating loop of an engineering system to ensure that dynamic response performance requirements are attained. In this paper an investigation was carried out to ascertain this concept by studying the dynamic response of an industrial belt conveyor system and subsequently introducing a subsystem into its operating loop. The designed compensator in this case is an optimal algorithm called linear quadratic regulator (LQR). The entire state of the system was evaluated in MATLAB for computer based tests. The simulation tests revealed that the LQR are actually enhanced the belt conveyor dynamic response with improved rise time and settling time. This means faster response and speed during operation, which will certainly enhance operational efficiency and increased productivity.

Keywords: Conveyor, Dynamic response, Engineering system, Linear quadratic regulator, Rise time, Settling time

1. Introduction

In most engineering systems, the dynamic response to input is usually not stable and meeting certain design criteria for industrial application is not guaranteed. For instance, servo based systems are prominently common in engineering and are usually used in speed and positioning control in industry. In most cases conventional servo systems are often not able to meet certain performance requirement (Muoghalu & Achebe, 2025). In order to enhance the performance of most of these engineering systems, compensators are usually included in their operational loop to achieve increase response time, transient time, settling time and better stability. The positioning of servo base satellite yaw-axis as in Achebe and Muoghalu (2025) and Eze and Ezenugu (2024), antenna positioning (Achebe, 2018; Eze *et al*., 2024; Onyeka et al., 2018; Anyanwu et al., 2024; Muoghalu & Achebe, 2021), and hard disk drive (HDD) in Onyekwelu et al. (2023) and Eze et al. (2017) systems have been enhanced using various control methods . In power system, stability has been achieved using various control methods that compensate the associated performance limitation in maintain desired voltage level at the output terminal of generators such as in Achebe (2019), Okoye et al. (2021), and Muoghalu et al. (2020). The dynamic response of electrical discharge machine (EDM), whose pulse generator process has been simulated (Achebe, 2019) was compensated with proportional integral and derivative (PID) compensator (Eze et al., 2017). The performance characteristics of two-phase hybrid stepping motor was improved using PID (Onyeka et al., 2018). The performance of other engineering systems such as refrigeration system and robot grinding system has been using optimal control models (Ekengwu et al., 2024; Achebe and Muoghalu, 2024). Similarly as application of engineering, human heart stabilizer and room temperature control system have been compensated with various models as in Muoghalu et al. (2024) and Eze et al. (2022).

An important engineering system critical to efficient industrial process is the conveyor system and its dynamic response has been largely studied with various compensation strategies developed to enhance performance. Conveyor systems are material handling systems often employed in manufacturing industries, airports, and in shipping companies. These systems are usually automated. Conveyors are durable and reliable components used in automated distribution and warehousing. In combination with computer-controlled pallet handling equipment this allows for more efficient retail, wholesale, and manufacturing distribution. It is considered a labour saving system that allows large volumes to move rapidly through a process, allowing companies to ship or receive higher volumes with smaller storage space and with less labour expense.

In recent times, direct current (DC) motors are widely used in many belt drive systems due to precise, wide, simple and continuous control characteristics. Belt drive systems are primarily DC motors driven. A DC motor is an electrical drive that converts electrical energy into mechanical energy. Belt drive systems are primarily DC motors driven. High performance DC motor belt drives are very important in both industrial and other applications. Good dynamic speed command tracking and load regulating response is generally one of the main characteristics of high performance motor drive system (Njoku et al, 2017).

The control system component of the belt conveyor system, evaluate the difference of the controlled variable such as drive motor speed and transported material feed rate with the reference (or set point) speed which is the input of the system. The motor drives signal is produced by the control system by special control algorithms to change the drive motor speed according to the calculated deviation. This system uses intelligent system algorithm, programmable logic controller (PLC), PID and hybrid algorithm to regulate the motor speed.

Conveyors are durable and reliable components used in automated systems. The most commonly used powered conveyors are the belt conveyors because they the most versatile and least expensive. In today’s emerging economy, adaptive speed systems are the current stage in material handling system design that enables manufacturers to achieve a lower system cost of ownership with consistent operation over time. As one of the material handling system employed in industry, a belt conveyor system can use adaptive technique for improve speed and maintenance. For example, it is desired industry to operate a belt conveyor at improved variable speed and reduced maintenance cost. This required a specialized adaptive control system to regulate the speed of a belt conveyor by controlling the drives (such as D.C. motors) of the system so as to obtain maximum capacity, reduced human labour, and reduce maintenance cost. This paper seeks to design a control system that will improve the speed performance of an industrial conveyor system in Chimezirim et al. (2019).

2. Literature Review

Trufanova and Lavrenko (2016) in an article described the options for increasing traction of the belt conveyor intermediate drive. The functioning principle of intermediate linear drive with pressure rollers was described, formulas for calculating the values of traction effort was provided, also comparative graphs, which showed the efficiency of using intermediate drive in various conditions, have was given. Umoren et al. (2016) modelled a conveyor system for control application in Champion Breweries PLC. The electrical and mechanical parts were separately modelled 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. In the work by Uqaili (2016), an energy efficient conveyor system model was proposed and implemented which not only recognized and sorted the objects by sensing its colour and place these objects to its destination by using Robotic vehicle but also smartly adjusts the speed of conveyor belts by recognizing the weight of object(s). The technological advancements in process monitoring, control and industrial automation played a decisive role in increasing the industrial productivity and manufacturing at faster pace even than been dreamed. An ultimatum requirement was an accurate and precise data acquisition mechanism which could be executed through diverse sensors especially for collecting, analyzing and sorting the objects and elements. The Variable Speed Drive (VSD) based an optimal belt speed control mechanism was proposed by smartly sensing the object weight and optimally adjusting the belt speed. The proposed system optimally switches the conveyor system to on/idle/off status to minimize the energy consumption of conveyor belts. In the work, a mathematical model of the energy efficient conveyor system was also derived by considering the different dynamic parameters. When conveyor belt was fully loaded with objects, the belt moved around with its maximum potential speed, but when Online Version Only. Conveyor belt was partially or marginally loaded or unloaded; the speed of belt was adjusted accordingly. In this way, a significant amount of energy and cost of energy can be saved. It was anticipated that, the developed intelligent energy efficient conveyor system model would not only modernize the industrial manufacturing and distribution process but will significantly reduce the energy consumption and cost and would lead to increase the life time cycle of conveyor belts. Amol (2015) investigated the main objective of a research to explore the analysis of Gravity roller conveyor. The research entailed performing a detailed study of existing Gravity Roller Conveyor system and optimizes the critical part like roller, C-channel etc. by using composite material, so as to minimize the overall weight of the assembly without hampering its structural strength. A proper Finite Element Model was developed using CAD (Computer Aided Design) software Pro/E Wildfire 5. Results of Static, Modal and Transient analysis of existing design and optimized design were compared. The material used for roller and C-channel frame was a composite material such as carbon fibre. Praveenkumar et al (2015) discussed productivity improvement by using buffer conveyor system in tobacco industries. The paper implemented a comprehensive overview of design of mass flow conveyors and provided an endless chain conveyor to advance the articles of the mass flow which can be used as a variable capacity with first in first out reservoir for rod-shaped articles. The work focused on specific research problems in design and control of closed loop conveyors and provided an improved method of material handling with the aid of technical support as well as emerging technologies world- wide.

3. Method

The essence of this paper is to significantly improve the performance of an industrial conveyor system include: determining a suitable mathematical models for the conveyor systems, performing controllability test on the model, designing a linear quadratic regulator, MATLAB/Simulink simulation of the closed-loop control system and result validation. The transfer function of the conveyor system is given by Chimezirim et al. (2019):

$$G_P(s) = \frac{\theta(s)}{V_{app(s)}} = \frac{K_m}{s(Js+b)(Ls+R)+(M_T r s^2+kr)(Ls+R)+k_m k_b s} \tag{1}$$

The parameters in Eq. (1) are defined as: $J = 1.2 \times 10^{-6}\text{kg}m^2$, $K_m = 13.3 \times 10^{-1} NM/A$, $K_m = 13.3 \times 10^{-1} NM/A$, $K_b = 13.33 \times 10^{-1} Volt/rad$, $R = 2.17\Omega, L = 1.17 \times 10^{-2}\text{H}$, $B = 2.5 \times 10^{-3} Nms$, M_m=1.0kg, M_b=0.2kg, r=17.4mm=0.0174m, $M_T = 1.2\,\text{Kg}$, $= 4.5 \times 10^{-2} N/M$. With these values substituted in Eq. (1), the numerical expression of transfer function is determined as in Eq. (2). The closed loop configuration of the belt conveyor system is shown in Fig. 1. The determined closed loop transfer function considering the system being implemented without a compensator is given in Eq. (3).

$$\mathrm{G_P(s)} = \frac{1.33}{0.0002443s^3+0.04534s^2+1.774s+0.001699} \tag{2}$$

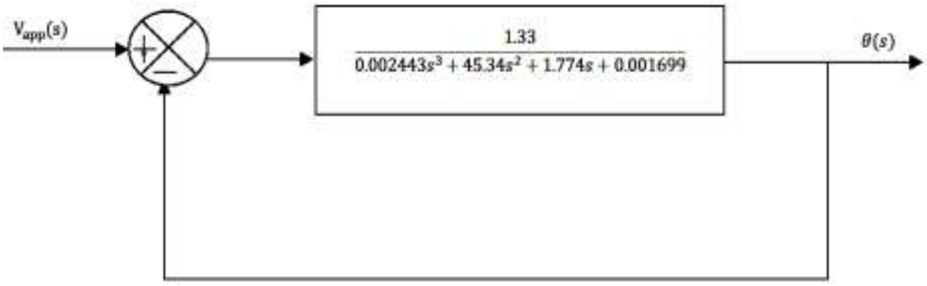

Fig. 1 – Closed loop model of belt conveyor system

$$\frac{\theta(s)}{V_{app(s)}} = \frac{1.33}{0.0002443s^3+0.04534s^2+1.774s+1.332} \tag{3}$$

The state space model for the system is established as follows:

$$0.00024443\theta s^3 + 0.045340\theta s^2 + 1.7740\theta s + 0.0016990\theta = \ 1.33u(s) \tag{4}$$

$$\theta s^3 + 185.590\theta s^2 + 7261.560\theta s + 6.950\theta = 5444.12\, V_{app}(s) \tag{5}$$

By making $\theta = x_1$

$$\dddot{x}_1 + 185.59\ddot{x}_1 + 7261.56\,\dot{x}_1 + 6.95x_1 = 5444.12u \tag{6}$$

$$\dot{x}_1 = \ x_2 \tag{7}$$

$$\dot{x}_2 = x_3 \tag{8}$$

$$\dot{x}_3 = -6.95x_1 - 7261.56x_2 - 185.59x_3 \ + 5444.12u \tag{9}$$

Combining Eq.(6), (7), and (8) yields the state-space matrix expression given by:

$$\begin{bmatrix}\dot{x}_1\\\dot{x}_2\\\dot{x}_3\end{bmatrix} = \begin{bmatrix}0 & 1 & 0\\0 & 0 & 1\\-6.95 & -7261.56 & -185.59\end{bmatrix}\begin{bmatrix}x_1\\x_2\\x_3\end{bmatrix} + \begin{bmatrix}0\\0\\5444.12\end{bmatrix}u \tag{10}$$

$$y = \ [1 \quad 0 \quad 0]\begin{bmatrix}x_1\\x_2\\x_3\end{bmatrix}$$

The controllability and the observability tests were performed because it is necessary to ascertain these two system properties when designing optimal control systems. The mathematical expressions for controllability and observability matrices are given by Ekengwu et al. (2022):

$$C_{con} = \ [B \, : \, AB \, : \, A^2B \colon \ldots A^{n-1}B] \tag{12}$$

$$O_{Obs} = \ [C \, : \, CA \, : \, AC^2 \colon \ldots CA^{n-1}]^T \tag{13}$$

Solving (12) and (13) gives:

$$\mathrm{A} \ = \begin{bmatrix}0 & 1 & 0\\0 & 0 & 1\\-6.95 & -7261.56 & -185.59\end{bmatrix}, B = \begin{bmatrix}0\\0\\5444.12\end{bmatrix},\ \mathrm{AB} \ = \begin{bmatrix}0 & 1 & 0\\0 & 0 & 1\\-6.95 & -7261.56 & -185.59\end{bmatrix}\begin{bmatrix}0\\0\\5444.12\end{bmatrix} = \begin{bmatrix}0\\5444.12\\-1010400\end{bmatrix}$$

$$\mathrm{A}^2 \ = \begin{bmatrix}0 & 1 & 0\\0 & 0 & 1\\-6.95 & -7261.56 & -185.59\end{bmatrix}\begin{bmatrix}0 & 1 & 0\\0 & 0 & 1\\-6.95 & -7261.56 & -185.59\end{bmatrix} = = \begin{bmatrix}0 & 0 & 1\\-6.95 & -7261.56 & -185.59\\1289.85 & 1347665.97 & 27182.09\end{bmatrix}$$

$$\mathrm{A^2B} = \begin{bmatrix}0 & 0 & 1\\-6.95 & -7261.56 & -185.59\\1289.85 & 1347665.97 & 27182.09\end{bmatrix}\begin{bmatrix}0\\0\\5444.12\end{bmatrix} == \begin{bmatrix}5444.12\\-1010400\\147982559.81\end{bmatrix}$$

$$\mathrm{C} = [1 \quad 0 \quad 0],\ \mathrm{CA} = [0 \quad 1 \quad 0], \mathrm{CA^2} = [0 \quad 0 \quad 1],$$

$$C_{con} == \begin{bmatrix}0 & 0 & 5444.12\\0 & 5444.12 & -1010400\\5444.12 & -1010400 & 147982559.81\end{bmatrix}$$

$$O_{Obs} = \begin{bmatrix}1 & 0 & 0\\0 & 1 & 1\\0 & 0 & 1\end{bmatrix}$$

The determinants of the controllability and the observability matrices are not zero. Hence, they are of rank 3 and the system is controllable and observable. The optimal controller (LQR) was designed by computer computation of the MATLAB syntax$[\mathrm{K, S, P}] = \mathrm{lqr(A, B, Q, R)}$. The Simulink model of the system is shown in Fig. 2.

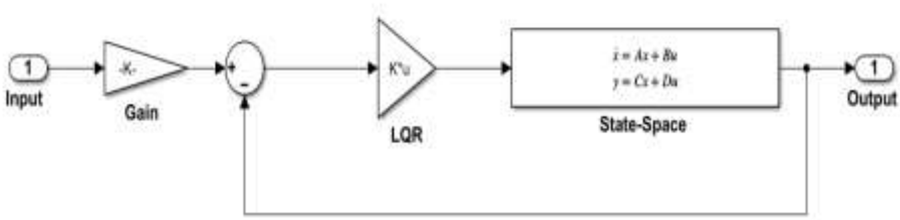

Fig. 2 – Simulink model of design optimal controller for conveyor

4. Results

The step responses of the belt conveyor system for various design conditions are shown in Fig. 3 to 5. The system was simulated using MATLAB R2022b. The performance of the system for each design state was evaluated in terms of MATLAB stepinfo analysis of system dynamic response. The numerical values of the performance parameters, which are rise time, transient time, settling time, settling minimum, settling maximum, overshoot, undershoot, peak, and peak time are listed in Table 1.

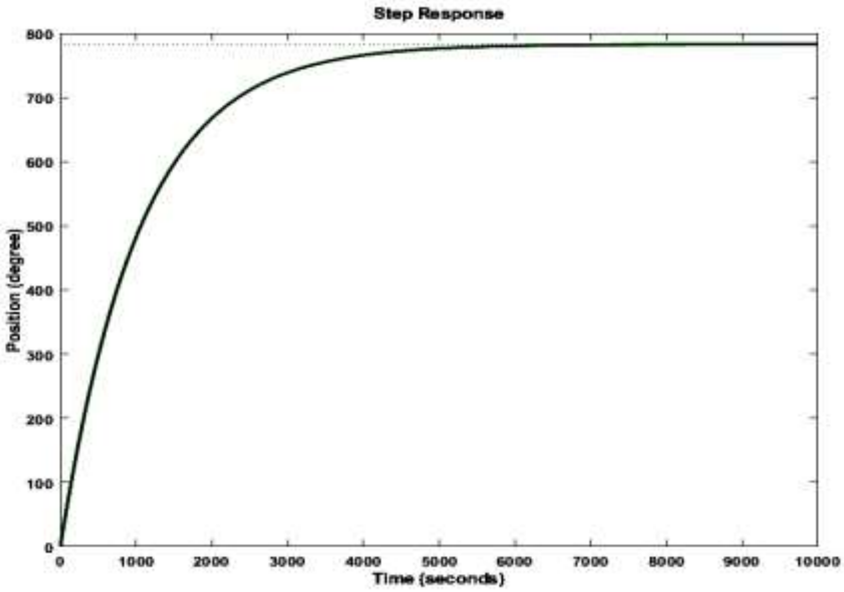

Fig. 3 – Open loop step response of belt conveyor

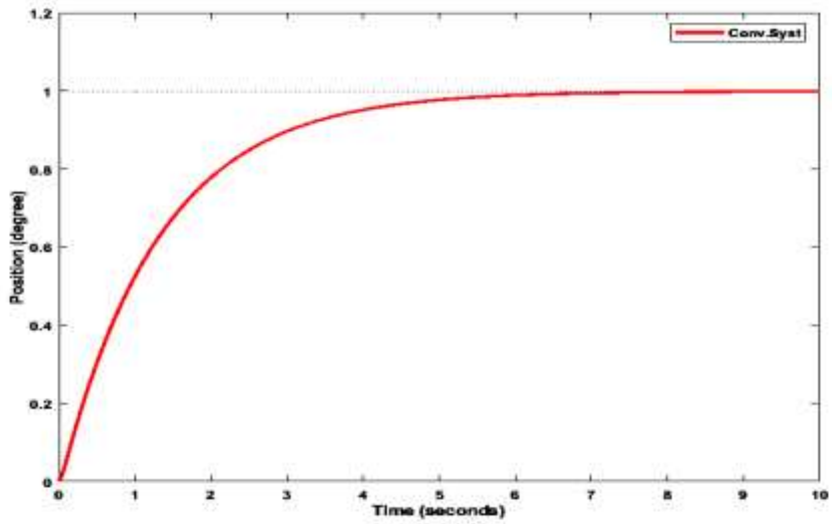

Fig. 4 – Closed-loop step response of belt conveyor without compensator

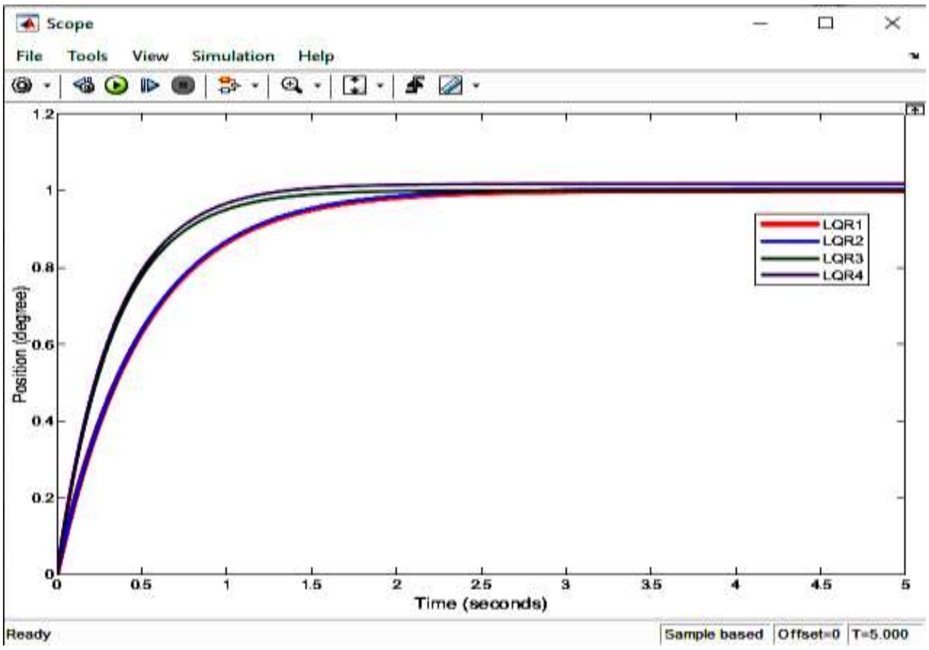

Fig. 5 – Closed-loop step response of belt conveyor with LQR

Table 1 Numerical evaluation of different system state

System	Rise time (s)	Transient time (s)	Settling time (s)	Peak time (s)	Overshoot (%)	Undershoot (%)	Settling min. (degree)	Settling max. (degree)	Peak value (degree)
Open-loop	2.2939e+03	4.0847e+03	4.0847e+03	782.7928	0	0	708.0535	782.7928	1.1011e+04
Closed-loop	2.8700	5.1362	5.1362	9.5641	0	0	0.9014	0.9981	0.9981
LQR1	1.1008	1.9594	1.9594	5	0	0	0.9006	1.0000	1.0000
LQR2	1.1001	1.9586	1.9586	5	0	0	0.9043	1.0046	1.0046
LQR3	0.7347	1.3081	1.3081	5	0	0	0.9012	1.0012	1.0012
LQR4	0.7343	1.3075	1.3075	5	0	0	0.9162	1.0178	1.0178

The step response plots in Fig. 3 to 5 have shown different degree of performance efficiency. In the open loop system (Fig. 3), the dynamic response is outrageously out of proportion for a unit step input. The system parameters are not in any way desirable and as such the system is out rightly not suitable for practical implementation in this state because of the associated very high rise or response time, settling time, and undesirable peak value. The system was then configured in closed-loop form without a compensator and the computer based simulation graph in Fig. 4 indicated that the system exhibited good performance with improved dynamic response as the parameters indicated in Table 1. With LQR compensator added to the belt conveyor operating closed loop and simulated in Simulink with control time bound of 0 to 5 s, the system response was improved as revealed by the parameter listed in Table 1. The variation of the weighting symmetric matrix Q at constant R matrix yielded various optimal K gain matrices. In each tuning of Q diagonal elements of the Q matrix, the system yielded improved performance. This analysis has validated the concept established in the earlier part of this paper that engineering system are usually compensated after their initial design with external elements usually called compensator or controller to enhance their dynamical responses and meet desired performance in industrial application and practical purposes.

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