Improving the Efficiency of a Conveyor System in an Automated Manufacturing Environment Using a Model-Based Approach

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***Abstract*—Material handling using a conveyor system has numerous advantages, such as proper material handling. It handles loads of varying heights and weights conveniently within a shorter period. Improved efficiency can be achieved during the manufacturing process if the operating parameters of a conveyor system are within the best service range. This paper studied and modeled the design parameters of a belt conveyor system to determine the best design parameters that can yield an efficient manufacturing system. The machine's efficiency was studied, and the operating parameters of the conveyor system that gave an efficient production system were achieved using MATLAB to simulate the parameters. It was observed that when the power rating of the conveyor was set at 8.9x10-4 watts, a higher throughput rate was obtained. Also, the cost of production increases as more power is utilized under varying load conditions.**

***Keywords*—material handling systems, belts, conveyors, simulation**

I. Introduction

A conveyor system is mechanically designed to transport materials from one station to another, and its applications are expected in processing and manufacturing industries such as chemical, mechanical, and automotive. Conveyor systems are effective in material transportation and warehousing; they include gravity, screw belt, vibrating, bucket, hydraulics, chain, grain conveyor systems, spiral, and others [1]. Proper material handling can be achieved using the conveyor system whose operating capacity depends on quantities of materials, nature of work to be done, size and weight of objects, height of objects, speed of handling, etc.[2,3].

The belt conveyor system is widely used among manufacturers due to its high-power conveyance system. It also has higher structural stability and is economically suitable in most environments. A belt conveyor consists of an endless and flexible belt of high strength with two end pulleys (driver and driven) at fixed positions supported by rollers [4]. According to [4], the belt conveyor system is cost-effective when employed in a manufacturing environment. It is widely used in areas of advanced manufacturing, such as in chemical industries, as-coal mining, metallurgy, electrical energy, food industries, etc. [4, 5].

A belt conveyor consists of a flexible and endless belt of high strength with two end pulleys (driver and driven) at fixed positions supported by rollers. The movement of materials and equipment from one station to the other uses conveyor systems that are durable and reliable for proper material transportation and warehousing. Based on different principles of operation, there are different conveyor systems, namely: gravity, belt, screw, bucket, vibrating, pneumatic/hydraulic, chain, spiral, grain conveyor systems, etc. [6, 7].

Effective implementation of decisions has been a difficult task in the olden days of the manufacturing system. Some manufacturers base their decision-making on trial and error, which makes the manufacturing process time-consuming and wastes many resources [8, 9]. Modeling and simulation have been recent approaches for various manufacturing stages [10, 11]. It gives insight into a better understanding of some projected manufacturing plans.

Mathematical modeling and simulation using MATLAB have been valuable tools during the decision-making stage of manufacturing to predict the long-run prospect of a manufacturing process. Mathematical modeling is essential to study the best method and parameters that can be implemented to yield optimal productivity in an advanced manufacturing environment. MATLAB is an iteration tool that can be employed when different classical modeling results are required to be compared against each other. The iteration process provides a more precise outcome which enables the manufacturer to choose the best operating conditions/parameters that can yield higher productivity.

Some past research has been able to develop various approaches to solving manufacturing-related problems. Some of them applied disruptive techniques using different modeling, simulation, and optimization approach to achieve their desired aims. For example, a number of

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researchers have studied and operated the optimization method. Troels used the simulation-based approach during the optimization study of an adaptive robotic manufacturing system that performs a pick and place task on a deformed part [12]. The scanner's effectiveness was improved by integrating a lighting system to a robotic system to perform a pick and place task. This proposed method was able to improve the robotic system performance for higher throughput.

In another research, a numerical optimization approach was developed to study and analyze a suitable process that can facilitate the robotic handling of delicate manufactured parts. An improved technology was devised that can quickly detect various shapes arriving from a conveyor belt in an advanced manufacturing environment [13]. Also, Nikoleta et al., uses the simulation and modeling approach to study the conveyor belt contact forces [14].

The present research studies the design parameters of a belt conveyor system using a model-based approach with simulation. This was achieved using the MATLAB programming tool. MATLAB is a mathematical programming tool that millions of scientists and engineers use to create models, analyze data, and develop algorithms. Fig. 1. Shows the schematic of the conveyor system with all the features during service.

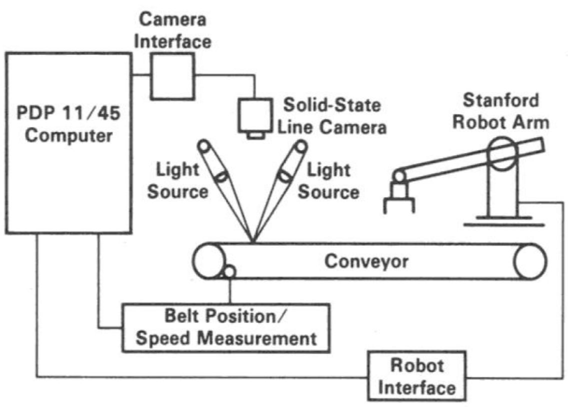

Figure 1. Schematic of the Conveyor System during Service.

II. Design Model for the Conveyor System

The research was carried out to study how the efficiency of a conveyor belt system could be improved in an automated manufacturing environment. Classical models were developed to describe the various parameters that make up the belt conveyor system. The parameters were modeled at different stages, and multiple equations were developed. Considering parts arrive from the workstation via the conveyor system, the parts are scanned by the vision camera, which promptly sends a signal to the robot, which tracks and picks up the parts and places them in the predetermined location. The arrival and pickup cycle operate continuously, whereby unpicked parts will return and arrive with the following process. The working parameters were studied, modeled, analyzed, and simulated using MATLAB to determine the best design parameters that gave optimal throughput during service.

Notation/parameters

N_f=Number of visible parts fed through the conveyor system
c = Centre of work envelope
d = Diameter of fed part
α = Minimum clearance required = d/2
w = Height and width of the workpiece
P_b= probability that work has been fully cleared
v= Velocity of the belt
T_r= The robot throughput rate
R_b=The arrival rate of parts from the conveyor (parts/mm^2).
B_T = Belt Tension
L_b = Load belt
L_i = Idler load
L_c = The load due to the conveyed material
l = Length of the conveyor system
H = Height of the conveyor system
f = The coefficient of friction
g = Acceleration due to gravity
w= Width of the work envelope
p_b = Probability that work has been cleared work from the work envelope
r_b = Arrival rate of part
C_c = Conveyor capacity
P_p = Power required to drive the pulley system.
P_m = Power required to drive the motor
L_s= Average waiting time of products in a queue
ρ_n = Productivity rate of each robot
C_p = Server production cost per hour
t_p = Time taken by the robot to feed and pick a part
t_c = time taken by a camera to visualize part and send a signal to the robot.

The conveyor system considered in this research is a conveyor system that uses a belt mechanism that can operate at a reduced operating time and under varying load conditions. The study assessed the operation of a conveyor system that conveys parts from one workstation to another. This model described a manufacturing process whereby a robot was implemented to pick up arriving parts for the belt conveyor system. During service, the conveyor belt experiences various tensile stresses due to the weight of loads that pass through it.

The conveyor load can be in the form of conveyed materials (L_c), loads as a result of the idler guiding the movement of the rolling belts (L_i), and loads arising from the rotational effects of the belt drives (L_b). Properly selecting the idler load is an essential parameter of the conveyor system. This can determine the maximum load capacity required of the conveyor system that cannot cause failure during service. Eq. (1) can be implemented when considering the idler load.

$$L_i = \frac{Idler\ mass\ (m_i)}{spacing\ between\ idlers\ (i)}. \quad (1)$$

During operation, the conveyor belt can be affected by stress due to the load that passes through. These stresses can cause damage and wear if they are not adequately managed. The weight of the load conveyed is required to achieve the tensile effect of the conveyor belt. The load from the conveyed material can be achieved using Eq. (2), expressed as the conveyor capacity ratio to the rotating belt speed.

$$L_c = \frac{C_c}{v} \quad (2)$$

The coefficient of friction must be considered when studying the tensions of the conveyor belt system. This can be evaluated by considering the length and height of the conveyor system, acceleration due to gravity, angle of inclination angle, and the conveyor belt's loading effect tension can be obtained using Eq. (3).

$$B_T = 1.37 \times f \times l \times g \times (2 \times L_i + 2 \times L_b + L_c \times cos\partial + (H \times g \times L_c) \quad (3)$$

The robot picked and placed down parts arriving from the manufacturing plant via the conveyor system using the first-in, first-out approach. During this process, the parts come in a Poisson manner with varying mean arrival rates λ and in the form of a negative exponential distribution that follows the impatient behavior of customers in the M/G/I queuing system.

The M/G/I queuing system uses only the server and operates in a first-in, first-serve manner. The repeatability of the manipulator motion correlates with the deterministic feeding time μ (mean service time). The remaining parts not picked up were redirected for pickup in the next cycle.

The power required to convey materials on a conveyor belt is of two types. The power needed to drive the pulley (Pp) and the power necessary to drive the electric motor (Pm). Eqs. (4) and (5) were developed to determine the suitable power required when considering both powers for the design of the conveyor belt mechanism. The belt tension and the velocity are required and considered when considering the power required to drive the pulley system [6].

$$P_p = \frac{T_b \times V}{1000} \text{(Kw)} \quad (4)$$

The equation presented in Eq. (5) relates the relationship between the power required to drive the pulley, the power needed to drive the electric motor, and the frictional drive.

$$P_m = \frac{P_p}{D_f} \quad (5)$$

The acceleration of the conveyor belt can be determined using Eq. (6)

$$A = \frac{(B_{ts} - T_b)}{L \times (2 \times L_i + 2 \times L_b + L_c)} \quad (6)$$

During service, the conveyor system was operating continuously and was not over-saturated or starved. The area within the work envelope was assumed to have the same height and width, and all arriving parts were well guided to prevent falling off of parts. The diameter of the part fed was assumed to be less than 20 mm, with a constant velocity throughout the operation.

As the conveyor moves past the vision camera, the manipulator senses the arriving parts and quickly picks up the parts. During this process, the conveyor moves continuously with a minimum distance α between the work envelope and the boundaries within the parts arriving from the work station. Not all parts that come through the conveyor system during service can be picked up.

Therefore, the probability of work being cleared from a workstation must be considered. To determine the numbers picked up by the manipulator, it is required to calculate the likelihood that arriving parts have been cleared from the work envelope. Eq. (7) was developed to calculate the probability function developed in [15].

$$p_b = \frac{(w-d-2\alpha)^2}{(w-d)^2} \quad (7)$$

The velocity equation is given in (8).

$$V = \frac{\pi D n}{60} \quad (8)$$

The center of the work envelope c was considered when developing the expression that relates the height, width of the work envelope, speed driving the belt, and the diameter of the conveyor belt. Eq. (9) was modeled to be implemented when determining the center of the work envelope.

$$c = \frac{w\pi(\alpha+d)^2}{(w-d)^2 v} \quad (9)$$

Similarly, the arrival rate of parts from the workstation via the conveyor system was modeled and presented in Eq. (10).

$$r_b = \frac{1}{c}\frac{(w-d)^2 v}{w\pi(\alpha+d)^2} \quad (10)$$

The number of parts that are fed through the work envelope (11) was obtained by relating the width and height of the work envelope, the velocity of the conveyor system, the probability that work has been cleared from the work envelope, the center of the work envelope, and the arrival rate of parts from the work station to the pickup point.

$$[N_f] = \left(\frac{w}{v}\right) r_b p_b e^{-rbc} \quad (11)$$

Bringing together the expressions above, an equation was developed to be used when the throughput rate must be determined before embarking on a manufacturing process. This was achieved and presented as Eq. (12)

$$T_r = \frac{N_f}{[\left(\frac{w}{v}\right) + t_p + [N_f] t_c]} \quad (12)$$

From queuing mathematical theory, the total cost of production was determined given that the time spent by the robot during the manufacturing process was represented as C_p and the cost of waiting for each product to be packaged = (t). The average waiting time of products in a queue was modeled as:

$$L_s = \frac{1}{\mathrm{m}_{\mu_j} - \mathrm{n}_{\lambda i}} \times \mathrm{t} \quad . (13)$$

Waiting time per unit hour was expressed as:

$$L_s = \frac{\mathrm{n}_{\lambda i}}{\mathrm{n}_{\lambda t} - \mathrm{m}_{\mu_j}} \quad (14)$$

The cost of production T was expressed in terms of waiting time and modeled as:

$$T = mcp\mu_j + c_w \rho_n w L_s \qquad (15)$$

After substituting the parameters into (15), the production cost was expressed as:

$$T = mC_p\mu_j + C_w\left(\frac{{\lambda_i}^2}{(\mu_j(\mathrm{m}_{\mu_j} - \mathrm{n}_{\lambda i})^2}\right) \qquad (16)$$

The modeled equations were simulated against each other using MATLAB, and the outcomes were presented graphically.

III. Discussion of Results

Innovation introduces the implementation of various measures and theories in the manufacturing industries. This has resulted into increase in economic productivity.

Queuing theory is one of the most efficient and widely used mathematical techniques to perform research on waiting lines and queues in commercial manufacturing applications.

The implementation of the queuing mathematical theory was suitable in this research in analyzing the parts that randomly arrived from a conveyor system. Robot picked and placed down parts arriving from the manufacturing plant via the conveyor system using the first-in, first-out approach.

During this process, the parts come in a Poisson manner with varying mean arrival rates λ and in the form of a negative exponential distribution that follows the impatient behavior of customers in the M/G/I queuing system.

The research was carried out to study how the efficiency of a conveyor belt system could be improved in an automated manufacturing environment. Classical models were developed to describe the various parameters that make up the belt conveyor system. During service, the conveyor system was operating continuously and was not over-saturated or starved. The area within the work envelope was assumed to have the same height and width, and all arriving parts were well guided to prevent falling off of parts.

Modelling and simulation as an efficient decision-making tool was employed to study and analyze the service of the conveyor system. MATLAB was employed to analyze and simulate the various classical models presented to describe the conveyor system in this present study. The simulation outcome provided the best operating conditions/parameters that gave optimal productivity.

The throughput rate, power required to drive the pulley, belt tension, and cost of production were studied and presented in graphical manner. The graph of throughput against the power required to drive the pulley was presented in Fig. 2. The result indicates that below the maximum power rating of a given pulley system, throughput increases as the power rate also increases. This shows that the highest throughput rate was obtained when the power rating was set at 8.9×10-4 watts. If the power driving the pulley is increased beyond the selected range, there will be a decrease in the throughput rate.

Also, the relationship between the belt tension and the throughput rate was studied and presented in Fig. 3. If the belt tension is not well set, or too loose, it either causes slipping away of the belt thereby causing idle time or, if the belt is too tight, it can build up friction and lead to excessive stress on the belt. This might cause slippage and damage to the belt, which can slow down the production process and reduce the throughput rate. The graph of belt tension against throughput shows a critical point beyond which any increase in tension results in a significant increase in throughput. This indicates that the minimum belt tension I required above maximizes the system's production. This

In Fig. 4, the relationship between the **cost** of production and the power needed to drive the electric motor of the conveyor system was studied and presented. It was observed from the graph that the two variables have a linear relationship. The power rating must be maintained within the selected power range that gave a reduced cost of production.

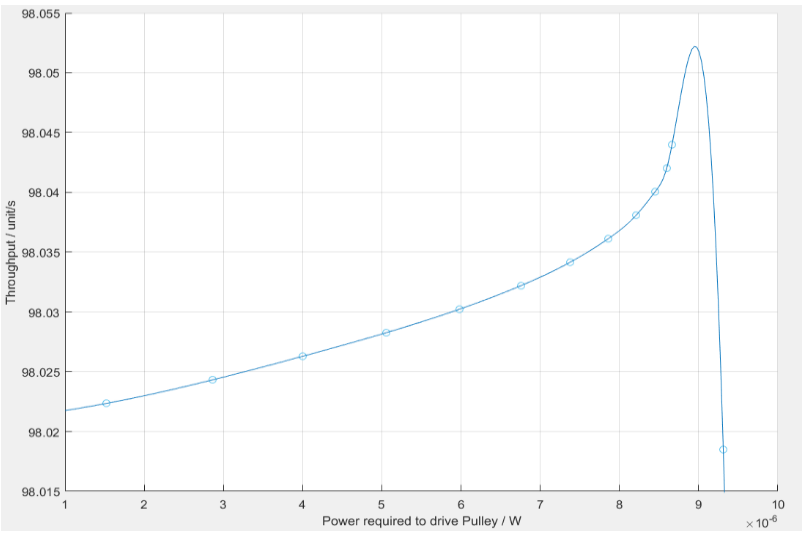

Figure 2. Graph of throughput against power required to drive the pulley.

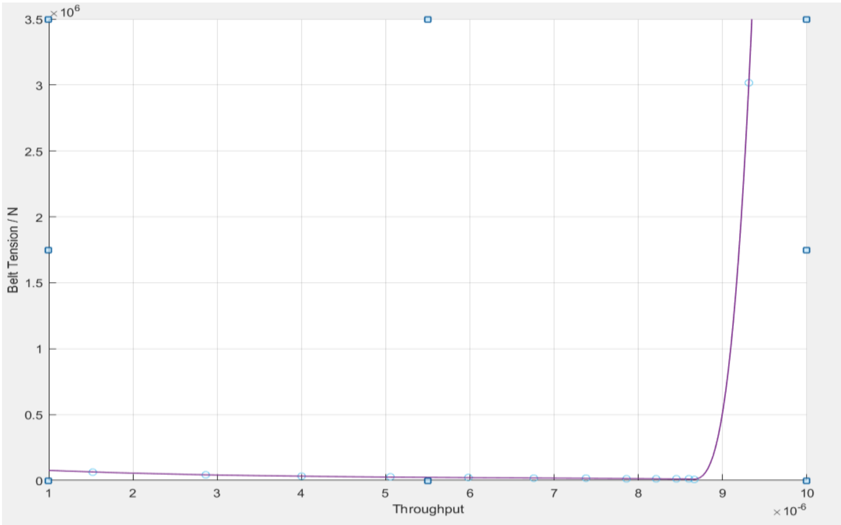

Figure 3. Graph of belt tension and throughput

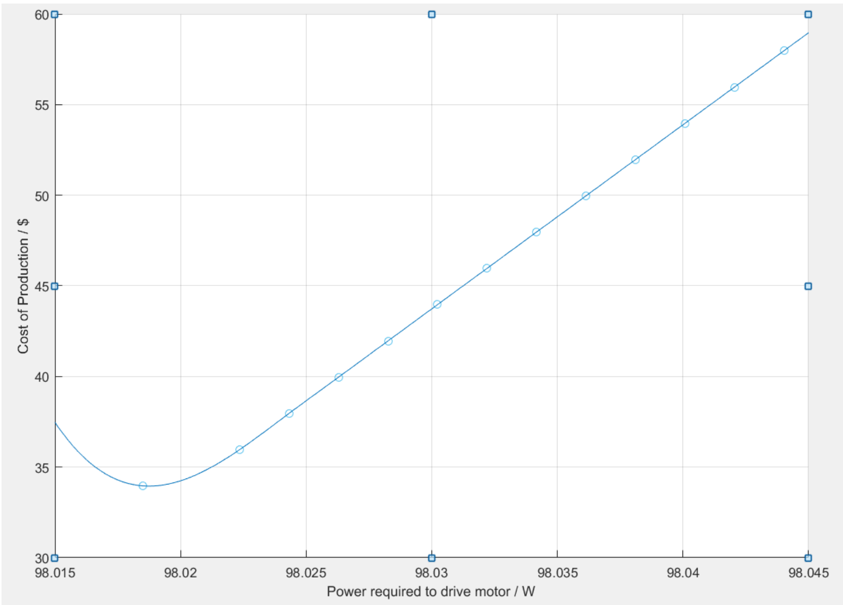

Figure 4. Graph of cost of production against the power required to drive the motor.

IV. Conclusion

In previous studies, focus is mainly on how to regulate the conveyor belt with the loads designed for its operation.

In this present research, the model-based approach using MATLAB to study the belt conveyor system during a pick-up task was studied. Classical models were developed to describe the various parameters that make up a functional belt conveyor system. Each parameter was represented with different notations to derive equations that suit the conveyor system. The belt tension was studied and varied to determine its optimal throughput settings. Subsequently, the power required to drive the pulley was also studied, and the highest throughput rate was obtained when the power rating was set at 8.9×10^{-4} watts. Also, the cost of production increases as more power is utilized under varying load conditions. The results obtained show that the research outcome can be efficiently used when an improved manufacturing process.

The research also arrived at a suitable expression that can be introduced in a manufacturing environment where optimal throughput is required (Eq. (12)). The outcome of the research provided manufacturers with the best-operating conditions that can yield efficient throughputs when implemented in a real-life manufacturing environment. The research can transform life, business, and the global economy in a great manner which can promote competitiveness and enhance productivity in an advanced-manufacturing environment

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Salawu Ganiyat performed the research with supervision by Glen Bright. Glen Bright contributed to the conceptualization of the content; both authors approved the final submission.

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