2023 The 23rd International Conference on Control, Automation and Systems (ICCAS 2023)
Yeosu Venezia Hotel & Utop Marina Hotel, Yeosu, Korea, Oct. 17∼20, 2023

Transfer Speed Optimization of Advanced Automated Material Handling Systems in Serial Production Lines

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Abstract: An automated material handling system (AMHS) is part of a production system that transports products from one machine to another for manufacturing processes. While conveyor belts have been commonly employed as AMHS, the increasing demand for enhanced performance has led to the emergence of advanced AMHS based on linear motors. A feature in these advanced AMHS is that they often allow non-uniform transfer speed setup, i.e., transfer speeds are allowed to be different by individual sections within the production system. This characteristic introduces an opportunity in determining the optimal transfer speed vector for the maximum productivity. In this paper, we propose an algorithm for optimizing the transfer speed vector using an analytical throughput evaluation method. The effectiveness of the algorithm is demonstrated through an example involving five machines.

Keywords: Smart Factory, Industry 4.0, Production system, AMHS

1. INTRODUCTION

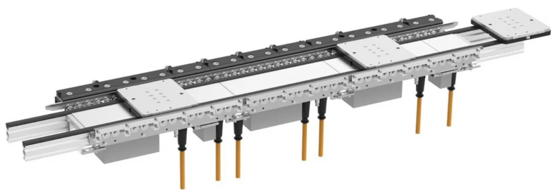
An automated material handling system (AMHS) is part of a production system that transports products from one machine to another for further manufacturing processes. Traditionally, Conveyor belts have been utilized as the primary AMHS in various production systems. However, the growing demand for improved capabilities, such as precise control of position and safe transport of sensitive or fragile products, has prompted the exploration of new solutions[1]. In response to these demands, advanced AMHSs have emerged, as depicted in Figure 1. These systems utilize linear motors for product transportation, effectively overcoming the limitations associated with traditional conveyor belts.

One notable feature of advanced AMHS is that they often allow non-uniform transfer speed setup, i.e., transfer speeds are allowed to be different by individual sections within the production system. This characteristic introduces an opportunity in determining the optimal transfer speed vector for the maximum productivity. While achieving the highest possible speed would be ideal, the limited resources available for controlling each linear motor prevent all products from simultaneously attaining maximum speed. As a result, there is a need for a method to allocate these limited resources and determine the transfer speed vector to ensure the optimal operation of the AMHS.

This paper introduces an optimization method for determining the transfer speed of an AMHS within a production system. Our focus is specifically on a synchronous exponential serial line characterized by machines with identical cycle times and uptime and downtime following an exponential distribution for each machine. The transfer speed of the AMHS is influenced by the location of the product within the system. Presented algorithm is validated with an example involving five machines.

The structure of this paper is as follows: Section 2 provides an overview of the considered serial production line and presents the formulation of the optimization problem. Section 3 presents the proposed optimization algorithm. To illustrate its effectiveness, an example is presented in section 4. Section 5 provides the conclusion.

(a) Justek, Loop-type Conveyor System[2]



(b) Festo, Multi-Carrier-System (MCS)[3]

Fig. 1.: Examples of AMHS based on linear motor

2. PROBLEM FORMULATION

This paper considers a serial production line with an unideal machine and buffer. A machine suffers random failure and repair, and a buffer may take time to transport a product even if it is not empty. This is because the product should move internally in the buffer from the entrance to the exit facing the downstream machine. An AMHS is employed in this production line for product conveying.

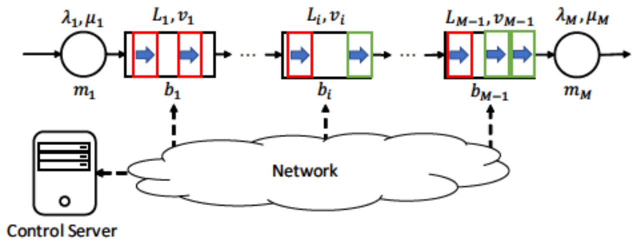


Fig. 2.: Illustration of serial production line with server-controlled AMHS

A product is placed on a pallet and transported through a buffer. The position and speed of pallets are centrally controlled by a server through a network.

Fig. 2 illustrates the considered serial production line with M machines and $M-1$ buffers. In Fig. 2, circles represent machines. The production line is synchronous, i.e., all machine in the production line has identical cycle time. The uptime and downtime of each machine are assumed to follow an exponential distribution, characterized by parameters λ_i and μ_i, respectively. For more details on the exponential machine behavior, refer to [4].

Rectangles in Figure 2 denote the buffers, with each buffer b_i having a length of L_i. The pallets within a buffer are conveyed at a speed of v_i. Red rectangles within a buffer signify that the pallets are currently being conveyed and are not yet available for the next machine. On the other hand, green rectangles indicate that the pallets have reached the end of the buffer and can be taken by the next machine for further processing, one by one.

To formulate the optimization problem, we consider the resource limitation based on the following conventions.

- The speed of pallets on the AMHS is determined solely by the buffer they are in.
- Within each buffer, there operates enough number of pallets so that transportation within the buffer is never hindered due to the lack of pallets.
- The control server groups pallets within the same buffer and controls them simultaneously with one control message.

Accurate position control requires an inverse relationship between the control period and speed. To maintain a position error below a specified threshold ϵ_{max}, the speed and control period can be related as follows:

$$v_i T_i < \epsilon_{max}, \qquad (1)$$

where T_i represents the control period of the pallet group in buffer b_i. The above condition means that the movement in a control period cannot exceed the allowed error ϵ_{max}. Since the control of pallets involves network communication, each buffer needs to send its state and receive control messages every T_i seconds. In other words, a buffer in the production line generates $2/T_i$ messages per second. Thus, considering the capacity of the router c_{max}, the following inequality should be satisfied:

$$\sum_{i=1}^{M-1} \frac{2}{T_i} \le c_{max} \qquad (2)$$

Based on the aforementioned resource limitations and equation (1), we can formulate the design problem as maximizing the throughput (TP) of the production system as follows:

$$\begin{aligned} \max_{v_1, v_2, \ldots, v_{M-1}} \quad & TP(v_1, v_2, \ldots, v_{M-1}) \\ \text{subject to} \quad & \frac{2}{\epsilon_{max}} \sum_{i=1}^{M-1} v_i < c_{max}, \\ & v_i < v_{max} \end{aligned} \qquad (3)$$

In this optimization problem, the objective is to maximize the throughput of the production system by determining the speed set $[v_1, v_2, \ldots, v_{M-1}]$. The first constraint ensures that the sum of speeds for each buffer is limited by a certain value. The second constraint is from the physical limitation of AMHS. Even if the network resource is unlimited, the transfer speed is constrained by the hardware performance of AMHS.

3. TRANSFER SPEED SET OPTIMIZATION

Due to the nonlinear and stochastic nature of the production system, solving the optimization problem directly becomes challenging. Therefore, this paper proposes an algorithm based on an aggregation method to address this issue. The aggregation method provides an analytical approximation for evaluating the throughput [5]. The aggregation method calculates the throughput of the production system from the reliability parameter of machines and buffer capacity. The reliability parameter of machines is given as λ_i and μ_i. The buffer capacity N_i can be calculated from L_i and v_i as follows[6]:

$$N_i = \left\lfloor \frac{L_i}{l_p} \right\rfloor - \left\lceil \frac{L - l_p}{v_i} \right\rceil + 1, \qquad (4)$$

where N_i is capacity of buffer b_i, and l_p is length of pallet.

The variation of TP when the transfer speed of a buffer decreases can be evaluated using the aggregation method:

$$TP_i^- = TP(v_1, \ldots v_{M-1}) - TP(v_1, \ldots, v_i - v_u, \ldots, v_{M-1}), \qquad (5)$$

where v_u is unit speed. Similarly, the variation of TP when the transfer speed of a buffer increases can be evaluated as:

$$TP_i^+ = TP(v_1, \ldots v_{M-1}) - TP(v_1, \ldots, v_i + v_u, \ldots, v_{M-1}), \qquad (6)$$

The transfer speed optimization utilized (5) and (6) to reallocate the transfer speeds of the buffers. Detailed algorithm is as follows:

(1) Calculate TP_i^- using (5) for $i = 1, ..., M-1$.
(2) Determine buffer index k_{min} for which TP_i^- is the smallest.
(3) Calculate TP_i^+ using (6) for $i = 1, ..., M-1$.
(4) Determine buffer index k_{max} for which TP_i^+ is the largest.
(5) Decrease $v_{k_{min}}$ by v_u (unit speed) and increase $v_{k_{max}}$ by v_u.
(6) Repeat step (1)-(5) until arriving at a limit cycle.
(7) Choose the set of transfer speeds on the limit cycle that maximizes the throughput TP.

The algorithm aims to optimize the transfer speeds by focusing on buffers that are least sensitive to velocity decrease (k_{min}) and most sensitive to velocity increase (k_{max}). This approach aligns with the concept of bottleneck, as the algorithm reallocates speeds to maximize the throughput of the bottleneck buffer.

4. NUMERICAL ILLUSTRATION

To validate the proposed algorithm, we provide an example of a 5-machine production line. The parameters for this example line are as follows:

$$\begin{aligned} \lambda_i &= [0.0111, 0.0333, 0.0667, 0.0333, 0.0111], \\ \mu_i &= [0.1, 0.1, 0.1, 0.1, 0.1], \\ L_i &= [1, 5, 5, 1], \\ l_p &= 0.2. \end{aligned} \quad (7)$$

In this system, we set the constraint for the optimization problem (3) as follows:

$$\sum_{i=1}^{M-1} v_i \leq 1.2, \quad v_i < 1. \quad (8)$$

The investigation is conducted by the following procedure.

1. Evaluate the throughput of the production line when the transfer speed is infinite. This represents the case of an ideal buffer. The throughput of this case is denoted as TP^*.
2. Evaluate the throughput of the production line when the transfer speed is uniformly distributed among the buffers. Specifically, we set $v_1 = v_2 = v_3 = v_4 = 0.3$. The throughput of this case is denoted as TP_u.
3. Evaluate the throughput of the line when the proposed optimization algorithm is applied. The initial speed is set to $v_1 = v_2 = v_3 = v_4 = 0.3$. The throughput of this case is denoted as $TP_o(n)$, where n is the number of iterations.
4. Compare TP_u and TP_o with TP^*.

The evaluation of throughput uses discrete-event simulation. Because of the stochastic characteristic of a production system, the simulation is repeated 20 times. The average of the outcomes obtained from each simulation is considered as the final result. In each simulation, the data from the initial period until all machines experience 500 failures is discarded to avoid the transient effects. This period is the warm-up phase of the simulation. The subsequent period, during which all machines encounter 5,000 failures, is used to evaluate the throughput TP of the production system.

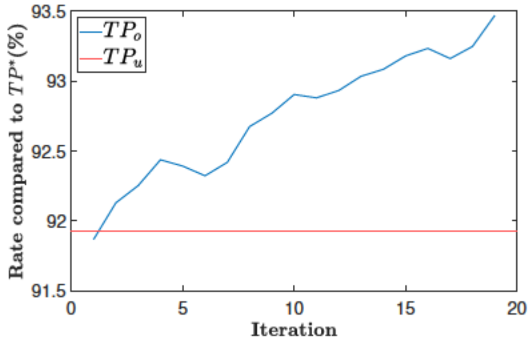


Fig. 3.: Rate compared to TP^* of TP_o (blue line) and TP_u (red line)

The results of the investigation are presented in Figure 3. When the buffers in the production line are assumed to be ideal, the throughput of the system is calculated to be 32.3039 parts per hour. This serves as the reference throughput. In the case where the transfer speeds are uniformly distributed among the buffers, denoted as TP_u, the throughput is measured to be 29.6962 parts per hour. This represents 91.9275% of the ideal throughput TP^*.

The optimization process begins with the initial transfer speeds set uniformly. As the iterations progress, the optimized transfer speeds lead to an increase in throughput. As shown in Figure 3, the optimized throughput TP_o tends to rise over the course of the iterations. At the end of the optimization process, TP_o reaches a value of 30.1942 parts per hour, which corresponds to 93.4694% of the ideal throughput TP^*. The optimal transfer speed set corresponding to this result is as follows:

$$v_1 = 0.21, \; v_2 = 0.39, \; v_3 = 0.39, \; v_4 = 0.21. \quad (9)$$

Note that the symmetry of the line parameters induces symmetry in v_i, $v_1 = v_4$ and $v_2 = v_3$. Comparing the throughput results between TP_u and TP_o, it can be observed that the proposed optimization algorithm achieves a 1.6772% improvement in throughput through the optimization of transfer speeds. This demonstrates the effectiveness of the algorithm in enhancing the overall performance of the production system.

5. CONCLUSION

This paper presents a transfer speed optimization algorithm for advanced AMHS that has the capability to control the speed of individual products. The optimization problem is formulated based on the constraint of network resource limitations. The proposed algorithm utilizes an aggregation method to evaluate the throughput analytically. The key idea of the algorithm is to allocate resources to the bottleneck buffer in order to maximize the system's performance.

The effectiveness of the algorithm has been demonstrated through a practical example of a 5-machine production line. The results show that the proposed algorithm achieves a 1.6772% improvement in throughput compared to the case of uniformly distributed transfer speeds.

Future work of this paper includes extending the problem to optimize both the length and speed of the buffers simultaneously. By addressing these aspects, further improvements can be made in optimizing the efficiency and effectiveness of AMHS.

ACKNOWLEDGEMENT

This work was supported by the DGIST R&D program of the Ministry of Science and ICT of KOREA (23-DPIC-16).

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