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Speed synchronization of multi-conveyor system using bidirectional interaction topologies

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Abstract

Long production lines composed of multiple stand-alone mode controllers often face challenges when speed synchronization is required, as each setpoint must be manually adjusted one by one. The issue can be addressed by designating one conveyor as the leader, while the others operate as followers that continuously adjust their speeds to match the leader. The main objective of this study is to develop a multi-conveyor leader–follower system based on distributed cooperative control, allowing all follower conveyors to maintain synchronized speeds with the designated leader unit. In this setup, the leader is equipped with the ability to command all followers to align their speeds to its own, which is governed by a fuzzy logic controller (FLC). Each follower operates in one of two modes: a stand-alone FLC mode or a synchronization mode using cooperative control. The cooperative control mechanism relies on speed information shared among neighboring conveyors, as defined by the system topology. Two types of bidirectional interaction topologies are explored in this work: The Bidirectional Coordinated Conveyor Topology (BCCT) and the Bidirectional Leader Coordinated Conveyor Topology (BLCCT). The proposed control strategy was tested on a mini multi-conveyor setup with one leader and four followers. Synchronization tests on two topologies produced RMSE values of 30.88 RPM for BCCT and 43.87 RPM for BLCCT. A brief disturbance was also applied to one follower to assess the controller's resilience and its effect on overall system coordination. The study confirms that combining fuzzy logic with cooperative control enhances synchronization and coordination across conveyors.

1. Introduction

In contemporary manufacturing environments, conveyor systems serve as critical components for ensuring the smooth and continuous movement of materials throughout the production process. They are fundamental to automation, enabling consistent workflow, improved precision, and enhanced productivity across industrial operations. In large-scale or complex production lines, multiple conveyors often operate in sequence or parallel configurations [1], requiring precise coordination to maintain synchronization and product quality. The ongoing transformation toward Industry 4.0 and smart manufacturing has further increased the demand for production systems that are adaptive, interconnected, and capable of real-time coordination [2]. However, traditional conveyor control schemes where each conveyor functions independently or depends on manual speed adjustment struggle to meet these requirements, particularly when dealing with diverse product variations or fluctuating workloads. To overcome these limitations, recent studies have focused on cooperative and distributed control methods that can be applied to multi-conveyor systems, allowing each conveyor to communicate and synchronize their speeds automatically. Developing an effective cooperative control framework for multi-conveyor systems has thus become a key focus in modern industrial automation. Such an approach not only minimizes manual intervention but also enhances flexibility, responsiveness, and overall system intelligence within adaptive manufacturing environments.

The multi-conveyor system referred to here consists of a group of conveyors that are able to coordinate with one another by exchanging shared information. This coordination adopts the concept of a multi-agent system (MAS) [3], where each conveyor is treated as an intelligent agent. Each unit is equipped with the ability to wirelessly send and receive information to and from its connected neighbors, following a predefined communication topology. In this context, the leader-follower MAS model offers a practical solution for coordinating multi-conveyor systems, allowing speed synchronization to be initiated by a single conveyor designated as the leader. Once the synchronization command is issued, all follower conveyors automatically adjust their speeds to match the leader's. This approach makes it easier to set varying speeds across the system as needed. The main advantages of this setup include improved material flow, reduced waiting time, and a boost in overall productivity.

Controlling the speed of a conveyor is closely tied to the motor's performance, whether it uses an AC or DC motor. Most research on motor speed control or conveyor systems has focused on stand-alone setups. Various approaches have been proposed to improve the stability and performance of these independent systems, including the use of conventional PID controllers [4][5][6]; PID combined with genetic algorithms [7][8]; fuzzy logic-based controllers [9][10]; hybrid PID-fuzzy controllers [11][12][13] and predictive control schemes [14][15][16]. However, these methods treat each conveyor as an isolated system, lacking coordination with other units. In real industrial settings, multiple conveyors operate simultaneously, and any mismatch in their speeds can cause material misalignment, product accumulation, or even system downtime. This lack of synchronization represents a key limitation in achieving efficient and reliable production flow.

Recent works have explored coordination between conveyors for various purposes. Erdani et al. [17] developed an IoT-based monitoring system to detect transfer failures in multi-conveyor setups. A hybrid predictive control strategy was proposed by Yaqot et al. [18] to optimize simultaneous material filling and mixing by managing the movement path of a tripper car. Hu et al. [19] introduced an adjacent deviation coupling control strategy, combining fuzzy inference and a speed compensator, to improve accuracy and synchronization in multi-motor control systems. Zhou et al. [20] proposed an energy-efficient control strategy for multi-motor belt conveyors aimed at ensuring stable and coordinated operation. The use of an active speed control algorithm in multi-belt conveyor systems has demonstrated an energy efficiency improvement of up to 16.21%, offering a more sustainable alternative to constant-speed operation [21]. Despite these advances, most studies emphasize monitoring, energy optimization, or motion planning rather than real-time cooperative control for speed synchronization.

Building on this research gap, this study aims to develop a leader–follower cooperative control framework for multi-conveyor systems to achieve real-time speed synchronization. The proposed approach allows the conveyors to share information dynamically, improving coordination, responsiveness, and overall system performance in adaptive manufacturing environments. To implement this concept, two operating control modes for the conveyor system are developed. The first is a stand-alone mode, where a fuzzy logic controller regulates the motor speed based on its setpoint. The second is a synchronization mode, which employs distributed cooperative control to align the speeds of follower conveyors with that of the leader. In this study, the synchronization concept is realized through two proposed bidirectional interaction topologies inspired by vehicle convoy formations [22][23][24] which are introduced as the Bidirectional Coordinated Conveyor Topology (BCCT) and the Bidirectional Leader Coordinated Conveyor Topology (BLCCT). In the BCCT, the leader shares data only with the first follower, and information then flows back and forth between neighboring followers. Meanwhile, the BLCCT expands this setup by allowing the leader to send its information simultaneously to all followers. Analyzing these two topologies is essential to understand how various ways of exchanging information influence the precision of synchronization, the stability of the system, and the overall performance of control within distributed conveyor environments. The contributions of this work are twofold: (1) the formulation of a leader–follower control approach combining a leader FLC with distributed cooperative control for multi-conveyor speed synchronization, and (2) the introduction of two bidirectional interaction configurations, termed BCCT and BLCCT. This control strategy reflects the core ideas of Industry 4.0 and is well-suited for next-generation manufacturing, packaging, and warehouse automation systems that require flexible, well-coordinated, and synchronized conveyor operations to enable intelligent and efficient production processes.

To facilitate a better understanding of this research, the following sections present the research methodology, which consists of system design, controller design, and experimental procedures. This is followed by the implementation results and their critical analysis.

2. Research Method

2.1 System Design

In this study, five identical conveyors were used to form a multi-conveyor system, with one designated as the leader and the remaining four as followers. The rotational speed of the leader conveyor's motor is controlled using a fuzzy logic controller. The Fuzzy Logic Controller (FLC) was chosen for the leader because it offers adaptive and smooth control without depending on an exact mathematical model. Compared to a conventional PID controller, the FLC manages nonlinear behavior and system uncertainties more effectively, maintaining steady speed and quick response even under changing load conditions. This makes it particularly suitable for leading and synchronizing multiple follower conveyors in a distributed control system. Each follower conveyor is equipped with two control modes: stand-alone mode and synchronization mode. In stand-alone mode, each conveyor independently adjusts its motor speed to match its local setpoint using a fuzzy logic controller. In synchronization mode, however, the followers implement a cooperative control strategy to align their motor speeds with that of the leader. It is important to note that only the leader conveyor has the authority to issue synchronization commands to the system.

Speed synchronization in the multi-conveyor system is achieved using a distributed cooperative control approach. This control algorithm relies on speed information exchanged between neighboring conveyors according to a predefined topology. In this study, two types of bidirectional interaction topologies are used, namely the BCCT, shown in Figure 1(a) and the BLCCT, shown in Figure 1(b). The arrows in the diagrams represent the direction of information flow. In the BCCT configuration, the leader conveyor sends information only to Follower 1, while information exchange between followers occurs bidirectionally based on their sequence. The BLCCT is an extension of BCCT, where the leader broadcasts its information to all followers. Information exchange between followers is represented by an adjacency matrix, $\mathcal{A}$, while the information flow from the leader to each follower is represented by a pinning gain matrix, $\mathcal{G}$ [25]. These matrices are defined in Equations 1 and 2, respectively. In the adjacency matrix, $a_{i,j} = 1$ if conveyor i receives information from conveyor j; otherwise, $a_{i,j} = 0$. The value $g_{1,1} = 1$ if conveyor i receives information directly from the leader; otherwise, $g_{1,1} = 0$.

$$\mathcal{A} = \begin{bmatrix} a_{1,1} & a_{1,2} & a_{1,3} & a_{1,4} \\ a_{2,1} & a_{2,2} & a_{2,3} & a_{2,4} \\ a_{3,1} & a_{3,2} & a_{3,3} & a_{2,4} \\ a_{4,1} & a_{4,2} & a_{4,3} & a_{4,4} \end{bmatrix} \quad (1)$$

$$\mathcal{G} = \begin{bmatrix} g_{1,1} & 0 & 0 & 0 \\ 0 & g_{2,2} & 0 & 0 \\ 0 & 0 & g_{3,3} & 0 \\ 0 & 0 & 0 & g_{4,4} \end{bmatrix} \quad (2)$$

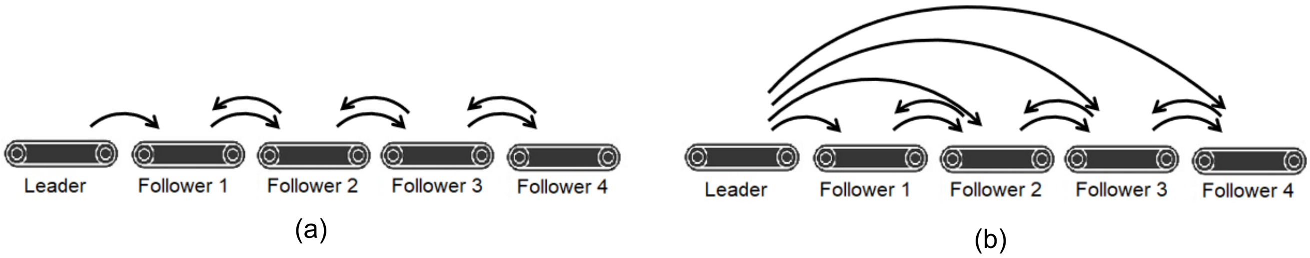

Figure 1. (a) Bidirectional Coordinated Conveyor Topology (BCCT), (b) Bidirectional Leader Coordinated Conveyor Topology (BLCCT)

The miniature conveyor used in this study measures 50 cm in length, 10 cm in width, and 8.5 cm in height. It is built from acrylic material, with a belt made of spunbond fabric. The system is powered by a JGA25-370 DC motor, which comes equipped with a hall-effect speed encoder, and is driven using an L298N motor driver. The control unit in this system uses an ESP32 microcontroller, selected for its strong processing performance, built-in Wi-Fi, and support for the ESPNOW protocol. This protocol enables quick and reliable peer-to-peer data exchange without depending on a central router, which is highly beneficial for distributed control systems such as multi-conveyor synchronization. Its low communication delay and stable connection make it effective for real-time coordination between multiple nodes. In addition, the ESP32's processing capability allows it to run fuzzy logic and cooperative control algorithms efficiently, while its small size and energy efficiency make it a practical choice for compact or embedded automation setups. Figure 2 shows the fabricated miniature conveyor, while the electrical hardware design of the conveyor system is illustrated in Figure 3. The list of I/O components along with their pin connections to the ESP32 is provided in Table 1.

Figure 2. Miniature of Multi-conveyor System

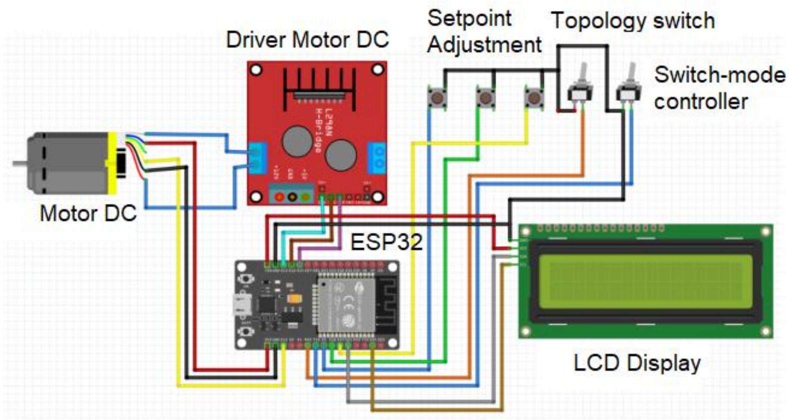

Figure 3. Electrical Hardware Layout for the Conveyor System

Table 1. List of I/O and Their Corresponding Pinout Connections on the ESP32

ESP32 Pinout	I/O Names	Functionalities
GPIO5	Increase Button	To increase the setpoint by 10 RPM per press
GPIO19	Decrease Button	To decrease the setpoint by 10 RPM per press
GPIO18	Enter Button	To set the value as a setpoint
GPIO17	Switch-Mode Controller	To switch from stand-alone mode to synchronization-mode
GPIO16	Switch Topology	To switch the topology from BCCT to BLCCT and vice-versa
GPIO21	SDA I2C	LCD 16X2 for displaying motor conveyor speed
GPIO22	SCL I2C	LCD 16X2 for displaying motor conveyor speed
GPIO15	Hall-effect speed encoder	To measure the motor conveyor speed
GPIO5	Increase Button	To increase the setpoint by 10 RPM per press

2.2 Controller Design

This section explains the controller scheme used in both the stand-alone mode, i.e., the fuzzy logic controller, and the synchronization mode, i.e., the distributed cooperative controller.

2.2.1 Stand-alone Mode: Fuzzy Logic Controller

The stand-alone mode controller uses a fuzzy logic controller (FLC) scheme, which is implemented on all conveyors. The purpose of this FLC is to ensure that the target speed setpoint can be achieved when the system operates in stand-alone mode. The block diagram of the stand-alone mode controller is shown in Figure 4. The control signal generated by the stand-alone mode controller is shown in Equation 3,

$$u_{i,sa} = u_{i,f} + b \tag{3}$$

where $u_{i,sa}$ is the control signal for the stand-alone mode controller, $u_{i,f}$ is the output signal from the FLC, and b represents the bias or control signal when the error $e = 0$.

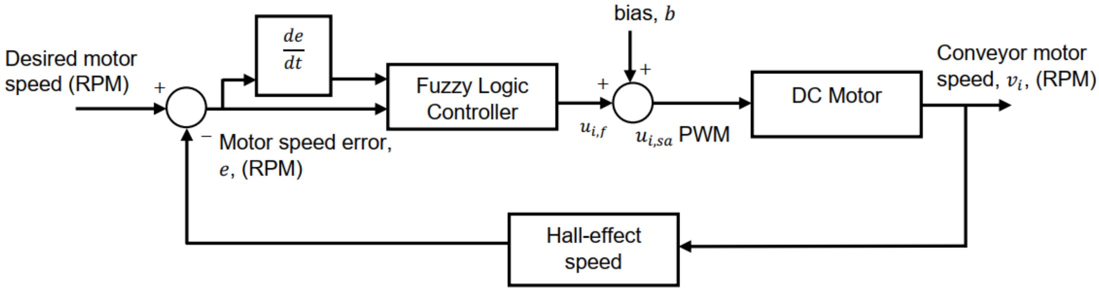

Figure 4. Fuzzy Logic Controller for Conveyor

To produce the control signal $u_{i,f}$, the Fuzzy Logic Controller (FLC) was developed using two input variables: the motor speed error, defined within the range of [−600, 600] RPM, and the rate of change of motor speed error, ranging from [−10, 10] RPM/s. The system has one output variable, the ΔPWM control signal, defined within [−100, 100]. Each fuzzy variable is characterized by linguistic terms: Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS), and Positive Big (PB). These terms are represented by triangular membership functions, while trapezoidal shapes are assigned to the boundary terms to ensure complete coverage of the input and output domains. The detail fuzzification inputs and output is depicted in Figure 5. The fuzzy rule base was formulated based on expert reasoning, such as: IF the error is PS AND the change in error (de/dt) is NS, THEN the output is PS. The complete set of fuzzy rules used in this study is outlined in Table 2. The inference process employs the Mamdani approach, utilizing the min operator for logical AND and the max operator for aggregating all activated rules. The combined fuzzy output is then defuzzified into a crisp control signal through the Center of Gravity (COG) method.

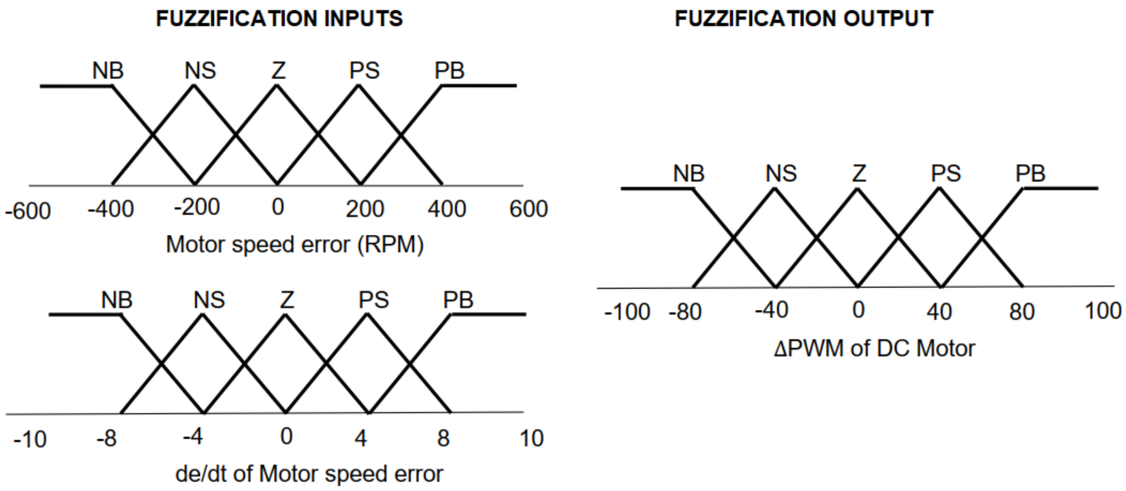

Figure 5. Fuzzification of Inputs and Output

Table 2. Rule-base Evaluation

de/dt \ e	NB	NS	Z	PS	PB
NB	NB	NS	Z	PS	PB
NS	NB	NS	Z	PS	PB
Z	NB	NS	Z	PS	PB
PS	NB	NS	Z	PS	PB
PB	NB	NS	Z	PS	PB

2.2.2 Synchronization Mode: Distributed Cooperative Controller

The synchronization mode uses a distributed cooperative control scheme that leverages both the internal motor speed information and the speed data received from neighboring conveyors. These neighbors can be either other followers or the leader, depending on the conveyor's position and the predefined topology. This controller is embedded in each follower conveyor and its block diagram is shown in Figure 6.

The synchronization signal is designed as in Equation (4),

$$u_{i,sync} = u_{i,c} + b \tag{4}$$

where $u_{i,c}$ is the cooperative control signal, formulated as follows:

$$u_{i,c} = k\left[\sum_{j=0}^{N} a_{i,j}\left(v_j - v_i\right) + g_{i,i}(v_0 - v_i)\right] \tag{5}$$

$k > 0$ is a constant gain, while the bias term b represents the control signal when the cooperative tracking error, $\sum_{j=0}^{N} a_{i,j}\left(v_j - v_i\right) + g_{i,i}(v_0 - v_i) = 0$. Here, v_0 refers to the motor speed of the leader, v_i is the internal motor speed of conveyor i, and v_j is the motor speed of the neighboring conveyors, where $j = 1,..,4$. The terms $a_{i,j}$ and $g_{i,i}$ are elements of the adjacency matrix and pinning gain matrix, respectively.

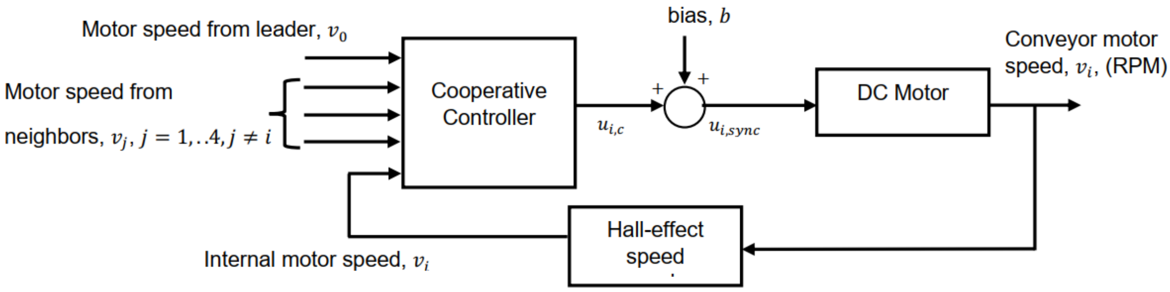

Figure 6. Distributed Control System in Each Follower

2.3 Experimental Procedure

The performance of the two controller designs, i.e. stand-alone mode and synchronization mode, was tested by implementing them on the developed multi-conveyor system. The experiments were conducted using two proposed configurations, namely BCCT and BLCCT. The overall testing procedure is described below and visually summarized in the flowchart presented in Figure 7.

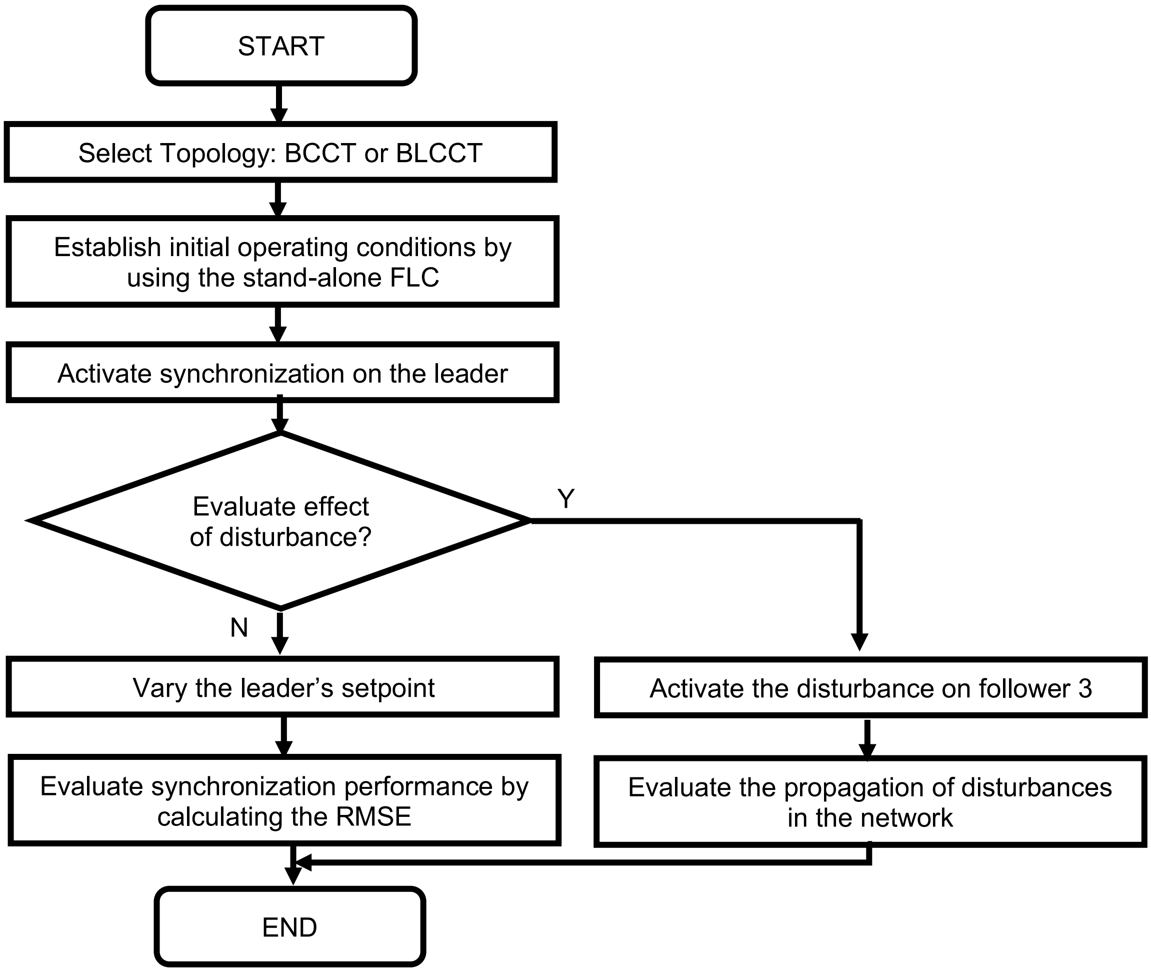

Figure 7. Flowchart of the Testing Procedure

The testing procedure began by selecting the desired system topology through the "Switch Topology" function. Each conveyor was then operated in stand-alone mode using a fuzzy logic controller (FLC), with distinct speed setpoints assigned to each unit to establish initial operating conditions. Once the “Switch Synchronization” command was initiated by the leader, the leader conveyor continued running independently under FLC control, while the follower conveyors transitioned into synchronization mode, adjusting their speeds in real time to match that of the leader. At this stage, two evaluation options are available: testing how accurately the followers can track speed variations by deliberately adjusting the leader’s setpoint or analyzing how a disturbance propagates through the network. After completing the synchronization tests, the Root Mean Square Error (RMSE) for each conveyor was calculated to quantitatively assess the system’s synchronization performance. The RMSE was selected as the main evaluation index since it provides a clear numerical indication of how closely the follower conveyors match the leader’s speed. This metric highlight both the extent and uniformity of speed deviations, giving greater weight to larger errors. These properties make RMSE an appropriate measure for evaluating controller performance, as it captures how effectively the system sustains accuracy in both dynamic and steady-state phases.

3. Results and Discussion

3.1 Test Results and Performance Analysis of the Stand-alone FLC Controller

Since the leader operates only in stand-alone mode using the FLC controller, the testing results and analysis for this control mode can be observed from the leader conveyor, as shown in Figure 8. The experimental outcomes of the stand-alone FLC controller show that the leader conveyor is capable of following the target speed, though the response still fluctuates noticeably near the setpoint. The speed fluctuations indicate that although the fuzzy rules and membership functions guide the system effectively toward the target speed, they are not fully tuned for precise steady-state control. The RMSE value of 48.23 RPM reflects these variations, showing that the controller achieves good stability but still allows small speed deviations. This means the FLC responds quickly and remains robust against short disturbances, but with slightly lower steady-state accuracy. In practice, the controller focuses on smooth and adaptive performance rather than strict precision, which aligns with the typical behavior of fuzzy control systems.

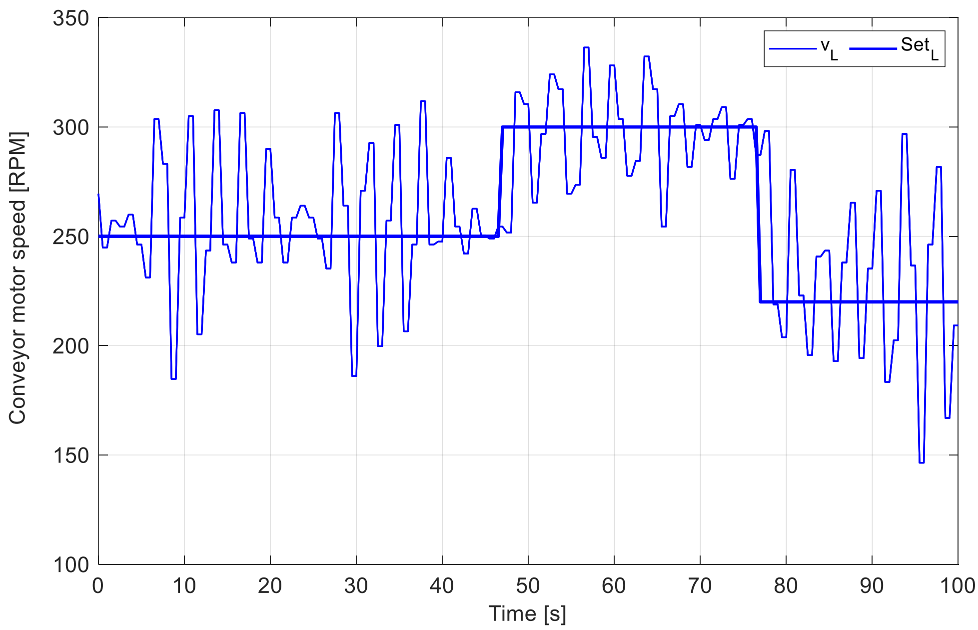

Figure 8. Conveyor Leader Motor Speed Using FLC

3.2 Synchronization Test Results and System Performance Analysis on BCCT Topology

To demonstrate the followers’ ability to synchronize with the leader, each conveyor is initially set to a different speed by running them in stand-alone mode using the FLC controller. When the synchronization mode is initiated, each follower conveyor shifts its operation to the cooperative control scheme, dynamically tuning its speed to follow the leader, which remains governed by the FLC. The setpoints used during both stand-alone and synchronization modes are provided in Table 3.

Table 3. List of All Conveyor Used as Setpoints for BCCT Topology Evaluation

Time	Setpoint [RPM]				
t [s]	Leader	F1	F2	F3	F4
$0 < t \leq 25$	250	270	290	220	200

$25 < t \leq 55$	250	Synchronization mode
$55 < t \leq 85$	300	
$85 < t \leq 100$	220	

The experimental results demonstrate that the cooperative control strategy successfully synchronizes the follower conveyors with the leader once the coordination phase begins. During the initial phase, each conveyor operates independently, producing distinct speed responses typical of stand-alone operation. When synchronization mode is activated, the followers quickly adjust their speeds to match the leader, even though their initial setpoints differ. The smooth convergence of the speed trajectories shown in Figure 9 confirms the effectiveness of the distributed coordination method in maintaining uniform motion across all conveyors. However, as summarized in Table 4, the average RMSE increased from 25.13 to 30.88 RPM, indicating that while synchronization improves collective alignment, it slightly reduces individual tracking accuracy. This outcome highlights a common trade-off in distributed control systems: improving global coordination can sometimes limit the precision of individual nodes. Despite this, the slight increase in RMSE remains within an acceptable range, suggesting that the cooperative mechanism prioritizes system-wide harmony over strict local accuracy. Overall, this behavior reflects a well-balanced design, favoring coordinated performance and robustness, which are essential in practical multi-conveyor automation scenarios.

Table 4. RMSE of all Conveyors in BCCT Topology Evaluation

Conveyor	RMSE (RPM)	
	Stand-alone Mode	Synchronization Mode
Leader	36.69	31.46
Folower 1	21.96	35.49
Follower 2	16.69	17.88
Follower 3	18.37	43.01
Follower 3	31.96	26.56
Average RMSE	25.13	30.88

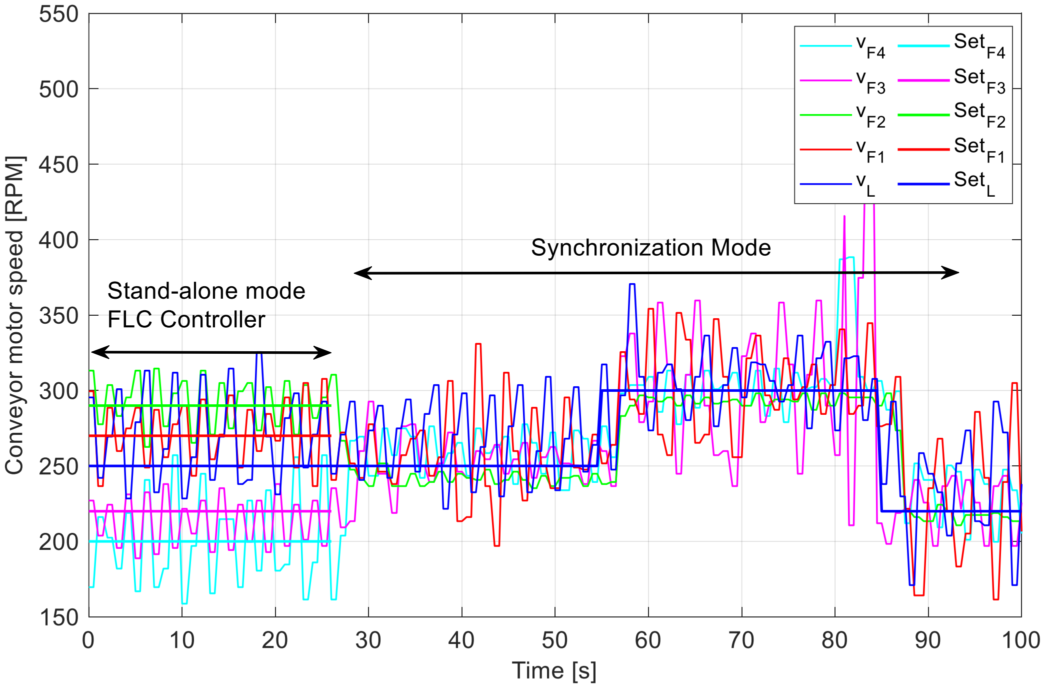

Figure 9. Synchronization Multi-conveyor System in BCCT Topology

3.3 Synchronization Testing and System Performance Analysis on BLCCT Topology

The testing for the BLCCT topology followed the same procedure and used the same setpoints as in the BCCT topology, as shown in Table 3. Figure 10 presents the test results for the system under the BLCCT configuration. In the initial phase, all conveyors operate in stand-alone mode, each with its own speed setpoint. When the synchronization command is issued by the leader, all follower conveyors begin synchronizing with the leader conveyor. The experimental findings under the BLCCT configuration indicate that broadcasting information directly from the leader does not necessarily lead to better synchronization accuracy. As summarized in Table 5, the average RMSE rose from 23.28 RPM in stand-alone mode to 43.87 RPM after synchronization, showing a noticeable drop in coordination efficiency. This increase implies that variations in the leader's speed create instability within the network, which spreads to the follower conveyors through their cooperative links.

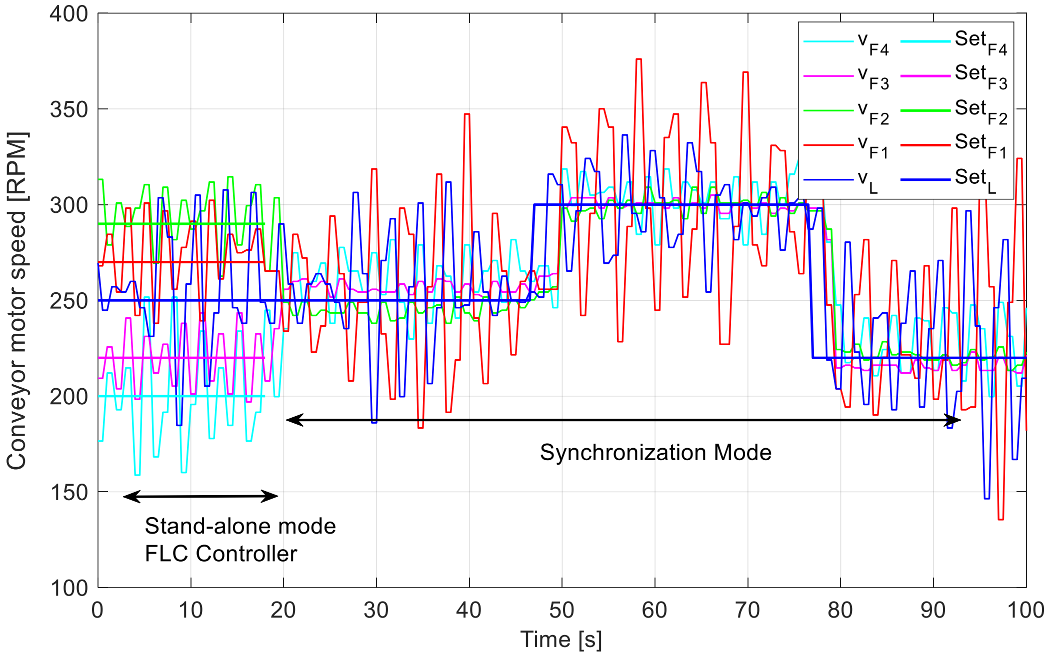

Figure 10. Synchronization Multi-conveyor System in BLCCT Topology

Table 5. RMSE of all Conveyors in BLCCT Topology Evaluation

Conveyor	RMSE (RPM)	
	Stand-alone Mode	Synchronization Mode
Leader	33.53	46.06
Folower 1	20.89	57.66
Follower 2	16.58	37.34
Follower 3	16.38	36.03
Follower 4	29.01	42.24
Average RMSE	23.28	43.87

3.4 Synchronization Testing and System Performance Analysis Under Disturbance on a Follower

The impact of disturbances on the synchronization of the multi-conveyor system was evaluated by introducing a disturbance to Follower 3. This scenario was tested under both BCCT and BLCCT topologies. The synchronization results for both configurations are shown in Figure 11(a) and Figure 11(b). It can be observed that disturbances affecting Follower 3 directly influence Conveyors 2 and 4, as indicated by the degraded synchronization in those conveyors. The disturbance experiment on Follower 3 offers meaningful insight into how resilient and responsive the BCCT and BLCCT tseopologies are when facing unexpected disruptions. The findings indicate that a disturbance introduced at one follower does not stay confined but instead propagates through the system, notably influencing its neighboring conveyors (Followers 2 and 4). This behavior reveals the critical role of cooperative communication links in sustaining synchronized motion across the network. The noticeable drop in synchronization among conveyors directly linked to Follower 3 suggests that the overall system stability relies strongly on the consistency and reliability of these intermediate nodes.

Remarks: The observed performance gap between the BCCT and BLCCT configurations is largely attributed to differences in how control signals and information circulate through the system. In the BCCT setup, the presence of two-way communication links among neighboring conveyors enables localized feedback and mutual adjustment, effectively smoothing oscillations and supporting consistent synchronization. Meanwhile, the BLCCT topology, despite maintaining bidirectional communication, relies more heavily on leader-driven coordination, which tends to amplify the propagation of speed variations from the leader to its followers, leading to higher RMSE values. In summary, while the

BLCCT offers simpler coordination through a leader-focused structure, the BCCT provides improved synchronization consistency compared to BLCCT. The primary drawback of the proposed control scheme in both topologies is its vulnerability to factors such as disturbances and variations in the leader's speed, all of which can degrade synchronization accuracy and weaken the system's overall stability.

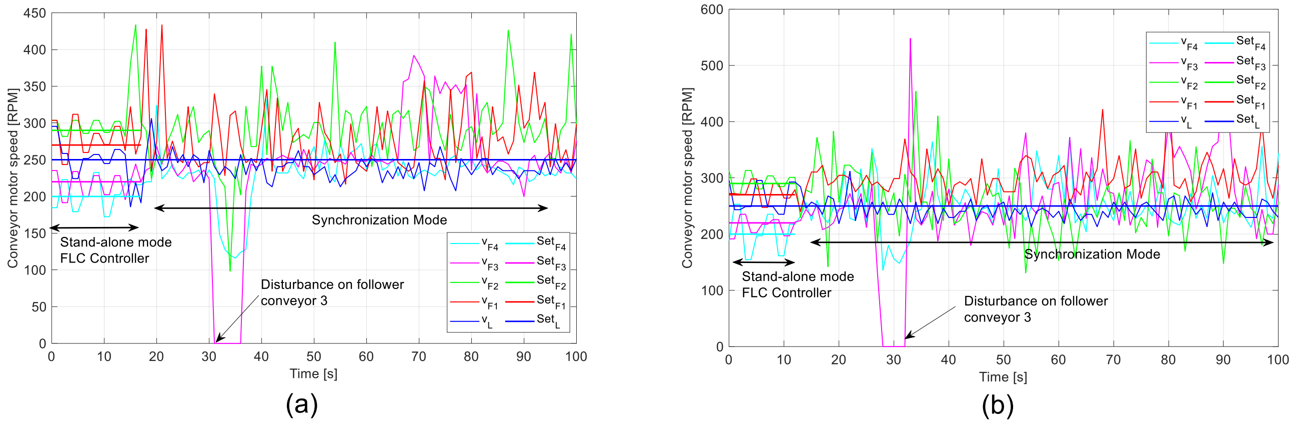

Figure 11. Synchronization of Multi-conveyor System when Disturbance Occured in Follower 3, (a) BCCT, (b) BLCCT

4. Conclusion

This study proposed a dual-mode control strategy to synchronize motor speeds across a multi-conveyor setup, combining a standalone fuzzy logic controller (FLC) with a cooperative synchronization mechanism. Experimental evaluations confirmed that the cooperative approach effectively maintained speed alignment in both BCCT and BLCCT configurations, allowing follower conveyors to closely track the leader conveyor governed by the FLC. The FLC achieved an RMSE of 48.23 RPM in regulating the leader's speed. During the synchronization experiments, the BCCT configuration showed an increase in average RMSE from 25.13 RPM in stand-alone operation to 30.88 RPM when synchronization was enabled. Meanwhile, in the BLCCT arrangement, the average RMSE rose from 23.28 RPM to 43.87 RPM. These findings suggest that although synchronization in the BCCT topology enhanced coordination among conveyors, it slightly compromised individual tracking precision, revealing a balance between collective stability and local accuracy. In contrast, the BLCCT setup exhibited greater sensitivity, where fluctuations in the leader's speed caused instability to spread through the system. Disturbance evaluations also confirmed that any disruption in one follower tended to affect nearby conveyors, underscoring the network's vulnerability to interconnection dynamics. Future investigations could explore adaptive and refine communication architectures to enhance robustness and ensure consistent synchronization in more complex industrial environments.

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