ADVANCED PNEUMATIC CONVEYING SYSTEMS FOR GRANULAR AGRIFOOD MATERIALS

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Abstract. Bulk goods, including seeds, powdered materials such as flour and various granular food products, are commonly transported in the agricultural industry by pneumatic conveyors, assuring in this way long-distance coverage, flexible routes, and closed systems for high efficiency. Recent innovations in pneumatic conveying technology are transforming the movement of materials in a multitude of industries, delivering long-term solutions that reduce costs, increase productivity, and minimize environmental impact in different sectors. While using lean-phase, suitable for light and powdered materials, or dense-phase, ideal for fragile or granular materials, it is vital to understand and minimize particle damage and material deterioration. A pneumatic conveyor system consists of several key components such as the air supply system, material pipe feeding device, compressed air or suction source, and a separation device of the material from the air used in conveyance, all components being assembled based on the specific requirements of the conveyed material. Advanced pneumatic conveying systems used in agri-food industry have distinct features, as PLC (Programmable Logic Controller), Human-Machine Interface (HMI) and sensors that improve their performance and suitability. This study will investigate improvements in pneumatic conveying technology, such as material handling efficiency, pressure control and monitoring, integration with Industry 4.0 technologies, environmental sustainability, and safety features. Innovative solutions for material flow control and hygiene standards will be illustrated in this paper, taking into consideration that emphasis on energy conservation and environmental friendliness is increasing, lowering costs and minimizing environmental effects. Additionally, this study highlights the integration of Digital Twins (DT) technology in the design and optimization of conveying lines, enabling predictive maintenance, real-time monitoring, and enhanced decision-making for system efficiency and sustainability.

Keywords: pneumatic conveying systems, granular agrifood materials, Industry 4.0 technologies, agri-food industry.

1. Introduction

Pneumatic conveying systems represent an economical and flexible solution for handling granular agri-food materials, offering a high degree of automation compared to conventional mechanical methods such as screw or belt conveyors. While being one of the most efficient transportation methods, it also presents certain challenges that require attention. The pneumatic systems offer several significant advantages, primarily operating within a closed system that effectively minimizes material losses while simultaneously reducing environmental pollution. Their inherent transport route flexibility allows material movement in virtually any direction, making them highly adaptable to available spatial constraints within industrial settings. Furthermore, these systems integrate seamlessly with essential technological processes including drying, cooling, and particle sorting operations, enhancing overall production efficiency through their versatile functionality and design architecture. However, during transport, the material maintains constant contact with the pipeline walls, and particle-to-particle interaction is significant. The "gentle" character of transportation can only be achieved in low-velocity systems. In dilute phase suspension flows, although contact with pipeline walls is reduced, high-velocity material impact in bend areas can cause considerable damage [1-3].

A specific challenge occurs during the discharge of granular materials into the conveying line. Even if the material enters the pipeline, efficient transport depends on the particle size distribution and permeability. For materials with non-uniform particle distribution, dilute phase transport frequently becomes the only viable option [2].

Automation of pneumatic systems becomes critical for efficiency and safety. Manually operated systems are vulnerable to errors, especially when operators lack a comprehensive understanding of system architecture and operational procedures. To address these challenges, modern industrial control systems such as Programmable Logic Controllers (PLC), Distributed Control Systems (DCS), Process Control Systems, and Safety Instrumented Systems are increasingly integrated into pneumatic conveying setups. These systems collectively contribute to enhanced reliability, fault tolerance, and real-time data processing, essential for optimal exploitation in the agri-food industry [2].

Furthermore, Supervisory Control and Data Acquisition (SCADA) systems play a central role in aggregating and supervising data from various sensors and control units. By providing centralized visualization, control, and analysis tools, SCADA facilitates effective monitoring, anomaly detection, and historical data storage, reinforcing decision-making and enhancing overall system integration within the Industry 4.0 framework.

These advanced systems not only reduce dependence on human factors but also enable real-time monitoring of critical parameters, thus optimizing performance and reducing energy consumption - crucial aspects in the current context of industrial efficiency and sustainability [1,2].

This paper investigates the implementation of advanced computational technologies-Digital Twins, PLC (Programmable Logic Controller), and HMI (Human-Machine Interface) for optimizing pneumatic conveying systems in agri-food applications. The study explores how these digital tools enhance automation, real-time monitoring, and adaptive control, ensuring improved efficiency, reduced material degradation, and greater operational reliability. By integrating sensor data with virtual models, the proposed methodology provides predictive insights that address key challenges in pneumatic transport, contributing to energy efficiency and sustainability.

2. Advancements in Pneumatic System

2.1. Role of implementing Digital Twins

Digital Twins concept was introduced as an innovative and versatile tool, offering benefits such as real-time monitoring, simulation, optimization, and accurate forecasting, while also improving decision-making and operational efficiency. Digital Twin (DT) is a virtual information framework that fully represents a physical product, either existing or in development, capturing details from the atomic scale to macroscopic geometric characteristics [4]. This technology is redefining efficiency in pneumatic grain transport through the integration of IoT, predictive simulations, and advanced data analytics. These virtual twins optimize system design (e.g. adjusting air velocity for particle integrity), monitor component wear (blowers, pipes) in real time, and anticipate failures through predictive maintenance. Dynamic flow modeling minimizes energy and material losses (e.g. preventing blockages or grain fragmentation), while data-driven after-sales services based on real-time information ensure rapid assistance and adaptive updates. By unifying data across the entire lifecycle (design-operation-maintenance), DT creates a holistic information ecosystem, enabling:

- reduction of operational costs by up to 30% through avoidance of downtime;
- optimization of energy consumption, contributing to CO_2 emissions reduction;
- improvement of sustainability through comprehensive resource utilization.

This convergence between physical and digital facilitates the transition toward autonomous and self-adaptive systems, establishing new standards of intelligibility and efficiency in the grain industry. [5; 6].

2.2. Integrated sensor systems

In a study conducted by T. Suppan et al. [7] a capacitive sensor was developed for measuring the flow in pneumatic conveying systems. The precise regulation of the flow is fundamental to optimizing the pneumatic transport of granular agri-food products. Accurate measurement enhances energy efficiency, maintains a stable material flow, and reduces the risk of losses or product degradation. However, in pneumatic transport, flow measurement remains challenging, especially in horizontal pipelines, due to diverse flow regimes and particle distribution. The sensor developed in this study was based on electrodes mounted circumferentially in a non-conductive pipe section and measured the flow capacitively, being influenced by the dielectric properties of the transported material and the flow regime. Additionally, researchers have studied the influence of the number of electrodes on the performance of the sensor and the potential benefit of the approach based on electrical capacitance tomography (ECT) compared to the calibration-based approach. The analysis of the results from this study highlights the advantage of using ECT with a higher number of electrodes to improve measurement accuracy. However, to develop an optimized sensor, it is important to balance the benefits of this method with the constraints related to instrumentation and hardware specific to the intended application [7].

Numerous studies have explored the acoustic emissions generated by particle-particle and particle-wall interactions during pneumatic transport, highlighting how these signals provide valuable insights into the dynamics of the process [8]. In their research, L. An and colleagues highlighted the effectiveness of the ensemble empirical mode decomposition (EEMD) method in analyzing the acoustic emission signals collected using sensors, enabling the extraction of relevant information to establish relationships between these signals, mass flow, and particle size. With the decomposition of the acoustic emission signal in the time domain, at a particle mass flow rate of 14 $g \cdot s^{-1}$ and a particle size of 150 μm, a progressive reduction in the amplitude of the IMF components (intrinsic mode functions – components derived through the empirical mode decomposition method) was observed, decreasing by several orders of magnitude from the highest value in IMF1 to the lowest in IMF9, along with a corresponding decrease in the instantaneous frequency of each component [8]. J. Zhou et al. [9] demonstrated in their research that the effective acoustic signal of pneumatic conveying is predominantly concentrated in the 0-37.5 Hz region, and the acoustic signal amplitude exhibits a positive correlation with discharge pressure, enabling non-intrusive identification of flow regime transitions.

Y. Ouyang's research [10] investigated the application of dual-electrode electrostatic sensors for velocity measurement of particulate materials in pneumatic conveying systems. Their experimental setup employed wheat seeds as test particles, with airflow velocities ranging from 12 to 30 $m \cdot s^{-1}$ and mass flow rates between 1 and 6 $kg \cdot min^{-1}$. The findings revealed a critical relationship between the transport efficiency and slip ratio, with a maximum slip ratio of approximately 0.65 between the flowing air and wheat seeds. Notably, when this ratio fell below 0.5, Ouyang observed significant particle agglomeration along the pipe bottom, leading to potential system blockages. The data further demonstrated that low air velocities (particularly below 15 $m \cdot s^{-1}$) combined with high mass flow rates (exceeding 5 $kg \cdot min^{-1}$) resulted in inefficient transport and consequently produced significant measurement deviations. The research validated the effectiveness of electrostatic sensing technology for non-intrusive particle velocity monitoring in agricultural pneumatic conveying applications. Following Y. Ouyang's research [10], a novel two-electrode electrostatic sensor, based on seed electrostatic induction, was developed at the University of Saskatchewan, as illustrated in Figure 1 (adapted from the author's thesis).

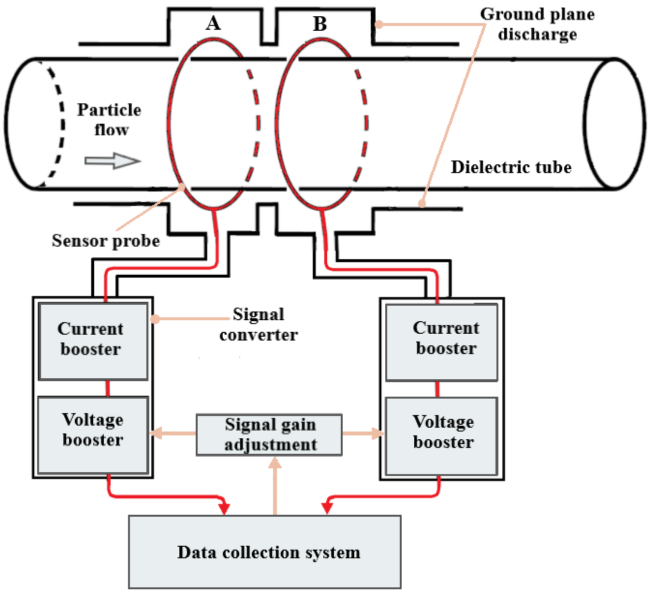

Fig. 1. **Schematic representation of a two-electrode electrostatic sensor [10]**

W. Guo and X. Qian demonstrated in their research [11] that the integration of electrostatic and acoustic emission (AE) sensors enables efficient measurement of multiple particle parameters, including velocity, mass flow rate, and concentration. A significant finding of their study reveals that measurements conducted in the central region of the pipeline provide the highest accuracy, thus establishing an important reference value for future full-section particle parameter measurements.

The complex flow dynamics of pneumatically conveyed particles, along with the impact of various conveying conditions, present challenges for existing measurement techniques in detecting the dynamic parameters of full-section particles in large-scale pipelines. To enhance the study and measurement of local particle parameters within pneumatic conveying systems-while also providing essential data for full-section measurements, optimizing material distribution, and reducing energy consumption-a novel approach was developed. By integrating electrostatic induction and the piezoelectric effect, an invasive multi-sensor fusion measurement device was designed. This device enables the measurement of key local parameters, such as particle velocity and mass flow rate, across different sections of circular pipelines [11].

The acoustic emission (AE) sensor is positioned in the AE sensor unit bracket, securely fastened with the surrounding silicone, and the wave-guide element and the AE sensor are positioned vertically in Figure 2 in order to enable sensor fusion and fully detect the flow of particles in the pipeline area [11].

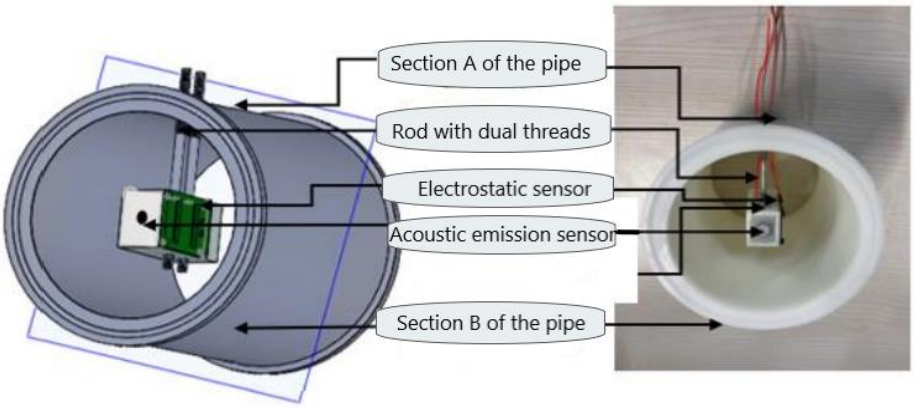

Fig. 2. **Three-dimensional representation and physical prototype of embedded multi-sensor array for pneumatic conveying systems [11]**

Numerous practical issues, including external site noise and state changes of running particles, make it difficult to monitor local characteristics of particles in pneumatic conveying pipes [8]. The measurement positions were placed at the quarters, two-quarters, and three-quarters of the circular pipe, designated region, region II, and region III, respectively, as shown in Figure 3 to prevent the turbulence caused by the size and shape of the electrostatic sensor design and to obtain detailed parameter information for each area of the pipe [11].

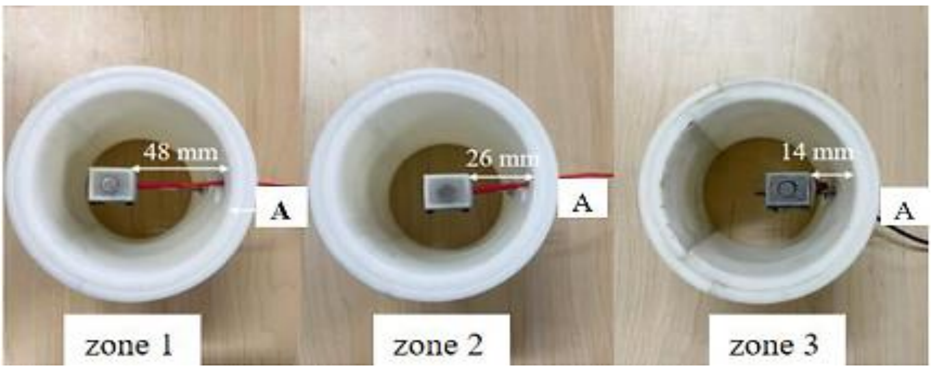

Fig. 3. **Physical representation of the measurement device at various positions along the central pipe [11]**

2.3. Development of learning media for pneumatic control systems for separation and transportation of goods based on Programmable Logic Controller (PLC)

Aldi et.al. described in their research the design and development process of a pneumatic system, which began with the integration of colour sensors and HMI. They then created a model using the Festo

FluidSim application. Following this, the hardware assembly was divided into two categories: main and supporting hardware. The main hardware included a metal separator system, a colour separator, and a robotic arm, while the supporting hardware consisted of tables, conveyors, and control panels. Once the hardware was assembled, the authors developed PLC and HMI programs using MELSOFT Series GX Works2 and Live Studio software, respectively. After completing both hardware and software components, they conducted testing and data collection to evaluate the tool's performance. The tool testing aimed to determine the required bar pressure, achieving a 100% success rate [12].

Specific details on the PLC configuration utilized are contained in PLC FX3U 48MR presented in Figure 4a. Specifically, '48' denotes the total number of I/Os on the PLC unit, 'M' typically indicates that PLC utilizes AC power, which is typically between 220-240 VAC, and 'R' denotes that the output type is relay. Figure 4b provides a schematic representation of the functional architecture of a programmable logic controller (PLC) [12].

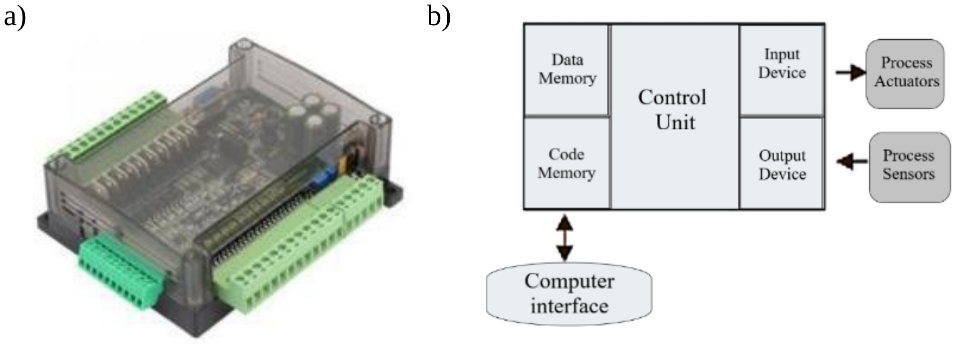

Fig. 4. **PLC FX3U 48MR (a); Functional diagram of a programmable logic controller (PLC) architecture (b) [12]**

2.4. Human Machine Interface WECON

The Human-Machine Interface (HMI) serves as a data display interface for operators, allowing users to input controls through various formats such as schematics, menus, and graphics. Its primary function is to facilitate monitoring, control, and data acquisition within a system. Typically, an automated control system comprises key components like plants, sensors, and controllers. HMI plays a crucial role in automation by enabling users to easily access and manage the system efficiently. Additionally, it provides continuous system monitoring, helping operators make informed decisions based on real-time conditions [12]. In PLC programming, two methods are made as common in the industrial world, namely automatic and manual methods. Figure 5 presents a flow diagram of PLC program planning [12].

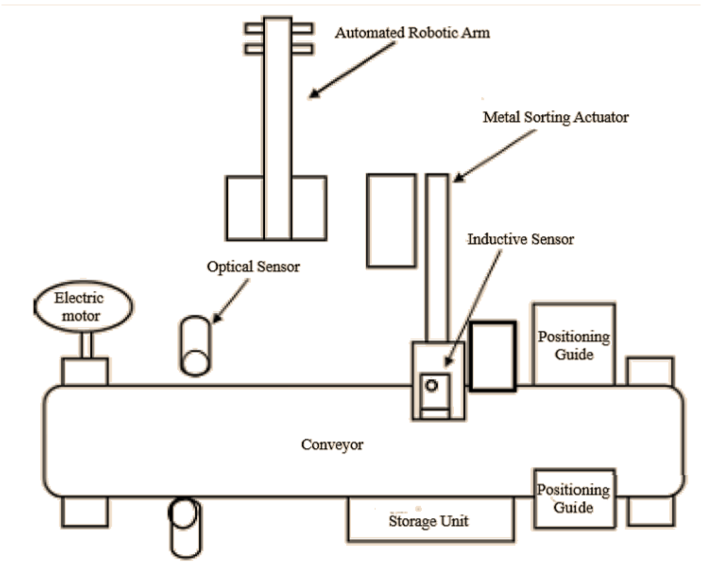

Fig. 5. **Diagram of the conveyor belt and sensor placement [12]**

This learning media operates in two modes: automatic and manual. In automatic mode, the conveyor belt moves the material, which then passes through a color sensor and an inductive sensor. If the material is white and contains metal, the inductive sensor signals PLC to activate the solenoid valve, directing air into the cylinder to push the material off the conveyor. If the material lacks these properties, it continues to the end of the belt, where the robotic arm lifts it. In manual mode, the actuator can be controlled individually and operated via HMI [12].

Conclusions

The advancements in pneumatic conveying systems have demonstrated quantifiable improvements in the transport of granular agri-food materials. The integration of Digital Twin (DT) technology has enabled real-time system monitoring, predictive maintenance, and design optimization, leading to a reduction of operational costs by up to 30% and enhanced energy efficiency through optimized airflow control and reduced CO_2 emissions.Electrostatic and acoustic emission sensors have significantly improved the precision of flow measurement and particle velocity monitoring. For example, in the experiments by Y. Ouyang, wheat seeds were tested under airflow velocities of 12-30 $m \cdot s^{-1}$ and mass flow rates between 1 and 6 $kg \cdot min^{-1}$, revealing a critical slip ratio threshold of 0.5, below which agglomeration and blockages increased. Additionally, the acoustic emission analysis conducted by L. An et al. confirmed that signal amplitudes within the 0-37.5 Hz range correlate with flow regime transitions and material characteristics, offering a non-intrusive method for regime detection. The combination of electrostatic and AE sensors in multi-sensor fusion devices improved the accuracy of central pipeline measurements, a key finding in Guo and Qian’s study, which also led to more effective system diagnostics and particle parameter analysis. Moreover, the development of automated control systems using PLCs and HMI interfaces, as demonstrated by Aldi et al., achieved 100% sorting accuracy during operational testing. These systems also provided flexibility through dual-mode (automatic/manual) operation, enhancing user control and system responsiveness. These findings emphasize the critical role of modern sensor integration, automation, and digital modeling in increasing the efficiency, reliability, and sustainability of pneumatic conveying systems. Continued advancements, including AI-driven diagnostics and smart material pipelines, are expected to further enhance performance, reduce maintenance needs, and support the evolution of smart agri-food infrastructure aligned with Industry 4.0 principles.

Author contributions

All authors have contributed equally to the study and preparation of this publication. Authors have read and agreed to the published version of the manuscript.

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