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RESEARCH ARTICLE

Robotic Sampling Solutions for Moisture Control in Planetary Mixers of Auger Pressing Briquetting Lines: Requirements and Implementation

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ABSTRACT

Industrial development increasingly relies on automation, reducing human involvement and optimizing operator time. Robotic manipulators are widely used to replace human labor in various production stages, including sampling tasks, where safety and efficiency are crucial. This study focuses on automating the sampling process in a briquetting production line using auger pressing technology. In such processes, moisture control is essential for maintaining quality and stability. The proposed robotic solution enables in-situ sampling from a planetary mixer without modifying its original design. The system includes a six-axis robotic arm, a force/torque sensor, a safety skin, and a 3D vision module. Control is based on an ISA-88 batch framework with real-time coordination for dynamic process optimization. This work outlines a set of requirements and constraints that can be applied to the design of robotic sampling systems in industrial environments, particularly in dusty conditions during the briquetting of fine-grained waste.

Keywords: Auger pressing, briquetting, moisture, robotic arm sampling.

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1. Introduction

The development of modern industry is inextricably linked to automation, reduced human involvement in technological processes and the optimization of operator workload [1], [2]. Robotic actuators or mechanical manipulators that replicate human actions replace humans in production operations at specific sections of industrial production lines [1]–[3]. Extensive studies and comparative analyses have been conducted to evaluate and refine the capabilities of robots to interact with humans or completely replace them. Ensuring the safety and reliability of such interactions is a primary challenge [1], [2]. Robotic manipulators have been successfully implemented in practice as a widespread, cost-effective solution in industries [1]–[5] for a wide range of operations such as sample collection [6].

This article addresses specific aspects of automating critical sections of briquetting lines using auger pressing methods [7], [8]. It focuses on the automation of sample collection from a planetary mixer to determine the moisture content of the mixture. The auger pressing method is used for processing fine-grained by-products of metallurgical production [8]–[10].

Achieving the specified moisture content of the mixture is crucial in briquetting which made from such as dust, gas cleaning residues, sludges, scrap, scale, screening fines, and coal [8]. While using batch-type planetary mixers, the moisture content must be determined not after the discharge but directly inside the mixer so that corrective measures can immediately be in taken in the event of deviation from the required parameters. Moisture content directly affects the stability of the auger pressing process and the quality of briquettes.

Despite the availability of reliable planetary mixer designs in the market [11] (used for various purposes such as cement production for the preparation of moulding compounds and briquetting), effective means for real-time sampling and analysis in the mixing chamber are not available. Moreover, existing industrial ultrasonic or capacitive moisture sensors and samplers are unable to determine the moisture of the materials with an accuracy greater than 1% without calibration—insufficient for stable operation while processing diverse materials.

In the cement industry, the required moisture content is maintained through strict adherence to formulation and precise dosing of components. However, in the context of metallurgical waste processing, the moisture content of the raw materials can vary significantly even within a single shift [8].

The following sections present the core principles and conceptual technical solutions for applying robotic manipulators in the automated sampling process for determining the moisture content of a mixture during metallurgical waste processing. The acquired data can be automatically transmitted to an operator workstation or the production line controller, where it can be used to adjust mixture composition through the dosing of components or the addition of water.

This article aims to define the primary requirements for robotic sampling from planetary mixers for moisture determination, without introducing substantial modifications to the equipment designs available in the market.

2. Materials and Method

2.1. General

The moisture content of the feed mixture before briquetting is a critical factor affecting the stability of the auger pressing process and the mechanical quality of the resulting briquettes. Deviations from optimal moisture levels may disrupt the process and reduce the structural strength of the final product. To ensure precise moisture control under conditions of variable raw material composition, the implementation of a robotic system for automated sampling is proposed. This approach offers advantages such as high repeatability and real-time adaptability.

2.2. Technical Justification

The moisture content of the charge before briquetting critically impacts both the stability of the auger extrusion process and the quality of the resulting briquettes. Deviations from optimal moisture parameters can lead to process instability, poor moulding, and reduced mechanical strength of the products [7], [8]. Some types of charge, such as coke fines, are particularly sensitive to moisture levels, with an acceptable range of only 0.5%. This requires highly accurate measurements and control at the preparation stage.

In addition, ensuring the minimum allowable moisture content significantly reduces subsequent energy costs for drying the briquettes or decreases the time required for natural drying, directly affecting the economic efficiency of the entire production process. In scenarios involving variable raw material composition and unstable environmental parameters, traditional methods of sample collection and moisture control are not sufficiently flexible and responsive.

The primary risk factors for humans during manual sampling include dustiness, noise, and vibration. Furthermore, the monotony of the work can lead to a decrease in concentration.

Therefore, using a robotic arm for automated sample collection and transfer to a moisture analyser is a reasonable solution. This approach facilitates high accuracy, repeatability, and adaptability, permitting real-time decisions on adjusting the charge composition before briquetting.

2.3. General Description of the Moisture Measurement Technology and Process Features

Automated sample collection includes several sequential stages as shown in Fig. 1. At the first stage, the charge, binding components, and water are fed into the planetary mixer through weight-based dosing devices. After the components are added, the material is mixed until a homogeneous mass is achieved. After the completion of the mixing cycle and the stoppage of the mixer paddles, a sample collection hatch is automatically opened. At this instant, the robotic manipulator collects the sample from the mixing chamber. The collected sample is then directed by the manipulator to the moisture analyser (analytical scales) installed directly at the production site. This allows for the prompt moisture measurement and, if necessary, the adjustment of the charge composition. In addition, the manipulator can perform auxiliary operations, such as cleaning the work area, removing the measured sample and discarding it into a designated container. After all operations are completed, the robotic manipulator returns to its initial position, awaiting the next sampling cycle.

2.4. Requirements for the Technological Process

The duration of one complete technological cycle of automated sample collection and analysis varies depending on conditions and the need for adjustments. The main cycle includes four key stages: dosing the charge, binders, and water, mixing the materials in the planetary mixer, sampling with the robotic manipulator, and performing moisture analysis using an integrated weighing moisture meter.

If the measured moisture parameters deviate from the specified values, the system allows for automatic adjustment of the composition. This includes additional dosing of components, re-sampling, and subsequent analysis. The different stages and time required for one cycle are summarised in Table I.

Such a flexible process organization permits a prompt response to fluctuations in the properties of the raw material and helps maintain stable charge parameters—crucial for the quality of the product during the briquetting stage.

2.5. Equipment

The sampling station is shown in Fig. 2. The design is flexible to accommodate the manual moisture analysis (if necessary), which enables the production process to continue uninterrupted during manipulator maintenance.

For automated moisture analysis of the mixture, a gravimetric moisture analyser (precision-balance type) is used, permitting sample loads up to 10 g through the intake port. A primary requirement for the measurement accuracy is maintaining the maximum absolute error within 0.05%—essential for briquetting—as discussed in Section II.B.

The sampling actuator is implemented using a six-axis industrial robotic manipulator (arm). The arm should offer high positional accuracy, with a repeatability of at least ±0.03 mm (as is customary in industry). To operate safely and reliably near a planetary mixer, the manipulator must conform to ISO 10218-1 safety requirements, including suitable stopping distances and response times. Its maximum payload must not be less than 10 kg, enabling

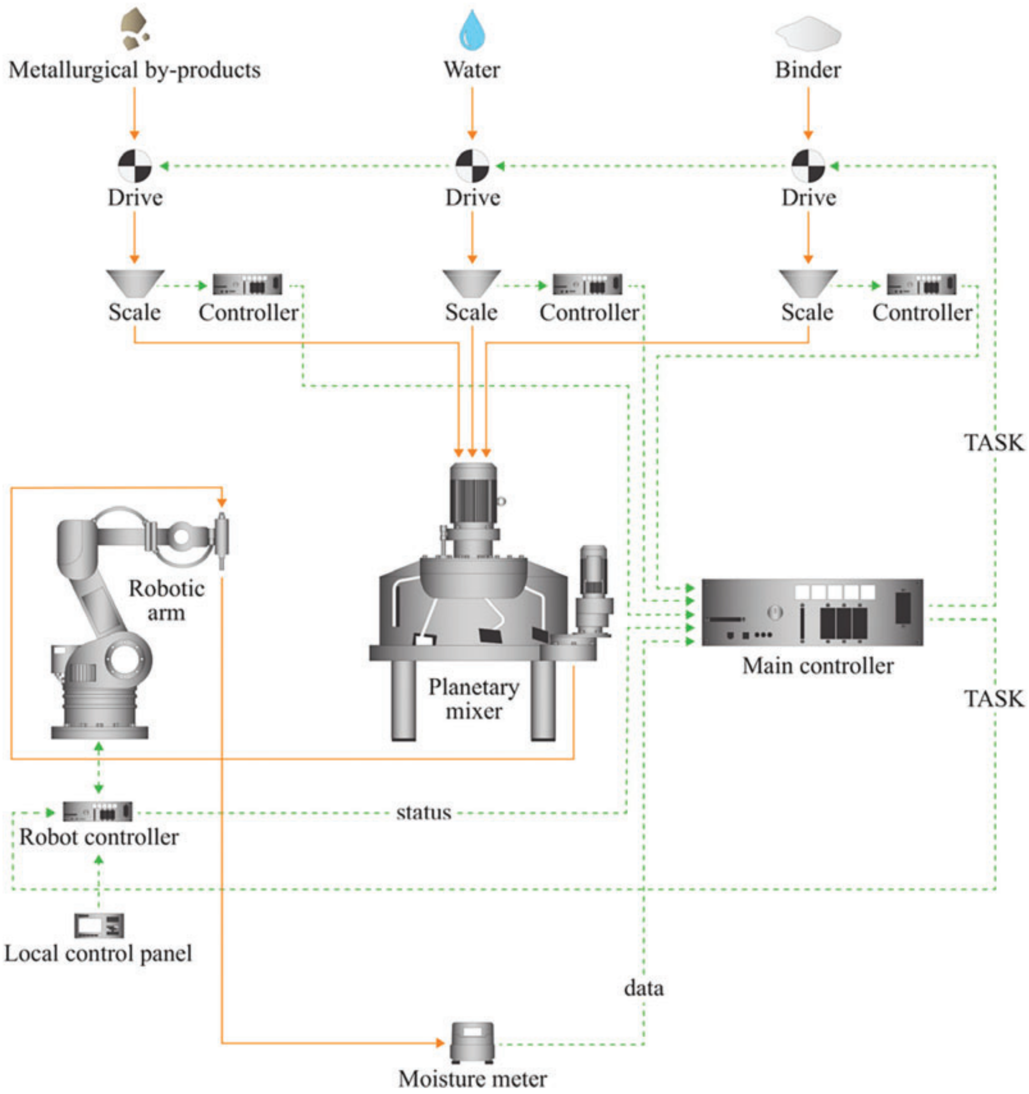

Fig. 1. Scheme of technological process.

TABLE I: Duration of the Technological Cycle for Automated Sampling and Moisture Analysis

Process stage	Time (min)	Comments
Dosing of components	5–6	Feeding of the mixture, binders, and water via scales
Mixing	2–4	Performed in a planetary mixer
Sample collection	1	Executed after the mixer blades stop
Moisture analysis	6	Using on-site gravimetric moisture analyser
Total (basic cycle)	14–17	Without correction procedures
Optional stages:		
Additional dosing	2	If moisture is outside acceptable range
Second sample collection	1	After correction of the mixture
Second moisture analysis	6	Re-analysis of corrected sample
Total (extended cycle)	23–26	Includes correction and repeated measurement

it to handle the sampling end effector, force/torque sensor, and auxiliary attachments without loss of performance [12], [13].

The construction of the manipulator must have a minimum protection rating of IP67, ensuring reliable operation in environments with high levels of abrasive dust and moisture. It must be capable of performing supporting continuous operation within a 60-s sampling time window. Integration with industrial communication protocols, such as PROFINET, is required to enable seamless connectivity with Siemens WinCC-based control systems.

Since the robot is not equipped with an integrated collision detection system, an external six-axis force/-torque sensor must be installed at the flange to monitor contact forces and detect irregularities in the material behaviour. This allows the implementation of adaptive control strategies and predictive maintenance routines. To protect human workers near the robot, a tactile safety system AIRSKIN® is added [14]. This system can detect

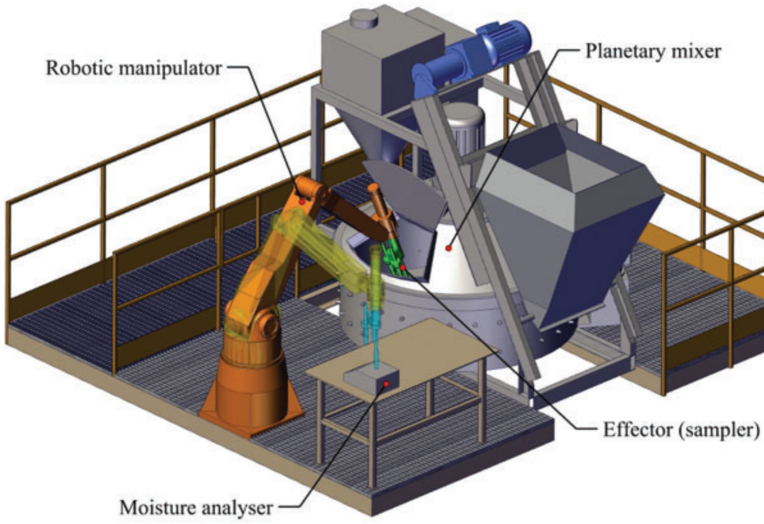

Fig. 2. Layout diagram of the equipment.

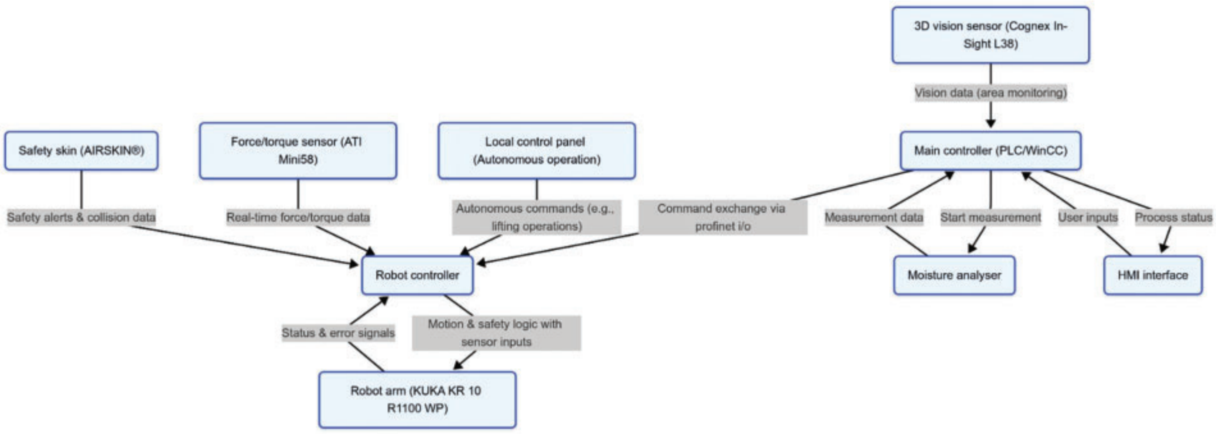

Fig. 3. Three-tier software architecture for automated robotic sampling control.

contact forces as low as 5 N, allowing for rapid intervention to prevent impacts, and is compliant with EN ISO 13849-1 (PL e/Cat. 3), EN/IEC 62061 (SIL 3), and ISO/TS 15066 collaborative robot standards.

To detect the open or closed state of the mixer and monitor the workspace in real time, a 3D vision system (e.g., Cognex In-Sight L38) is employed. With a scan range up to 1100 mm, a scan rate of 7 kHz and IP65 protection, it supports robust environmental operation and straightforward integration into the control system via PROFINET.

The custom-designed main actuator (effector, sampler) is tailored for aggressive process conditions. It is constructed from stainless steel and resistant to abrasion. A three-point sampling mechanism enables material collection from different areas within the mixer, resulting in a combined sample of 50 g–60 g. A built-in miniature sample divider reduces this to a target mass of 8 g–10 g and returns the excess material into the mixer. The end effector features a quick-release interface (such as the ATI Mini58 force/-torque sensor), providing real-time feedback on contact forces to support precision handling and adaptive motion. Samplers must not exceed a total mass of 6 kg (including its housing and integrated mechanics) so as to remain within the dynamic load range of the robot and maintain motion precision [5].

In addition to the primary actuator for sampling, the system must include a secondary service actuator (equipped with a mechanical hook or similar device), which is intended for auxiliary operations.

To integrate the robotic system with the production line equipment, the mixer must be additionally equipped with an automated sampling hatch. The size of the access opening should be at least 400 mm × 400 mm to ensure unobstructed access for the manipulator and to eliminate potential kinematic constraints during its operation.

3. Algorithm and Description of Software Solution

3.1. *General*

The automation of sampling in our planetary mixer system is guided by a control algorithm designed to coordinate the actions of the mixer, the robotic manipulator and the moisture analyser within an ISA-88-based batch process framework. The goal is to ensure that each sampling cycle is executed reliably and safely, with precise timing and synchronised operations. The algorithm is structured to support a closed-loop system: The mixer signals the "batch completion", the robot collects a representative sample, and the moisture analyser immediately assesses the humidity. The output data is then transmitted back to the main

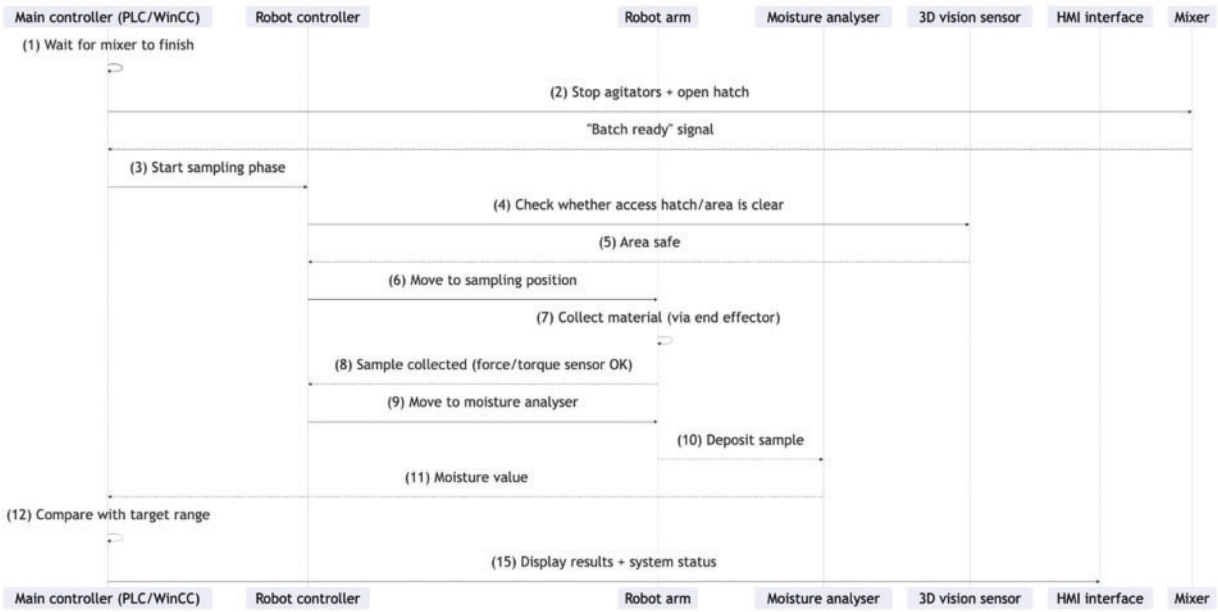

Fig. 4. UML sequence diagram depicting the high-level software workflow. This diagram depicts the interactions among the main controller (PLC/WinCC), robot controller, robot arm, moisture analyser, and 3D vision sensor for one full sampling cycle.

controller, which determines whether corrective measures (such as additional dosing or re-mixing) are required.

3.2. *Description with the Function of the Functions*

The software architecture comprises three layers to isolate and manage control functions, (Fig. 3). At the top level, the Siemens WinCC-based main controller (running on a high-performance PLC) implements the general batch logic, defining the recipe and orchestrating transitions between process phases. This layer uses ISA-88 batch control principles to separate the process into clearly defined phases, such as mixing, sampling, analysis, and correction. The middle layer is dedicated to the real-time motion management of the robot controller, where pre-programmed trajectories are executed.

The robot controller equipped with PROFINET connectivity handles the low-level details of path planning, collision prevention, and cycle movements. At the lowest level, integrated safety routines and diagnostic protocols monitor the mechanical subsystems and sensor feedback to ensure that environmental and safety thresholds are not exceeded. In addition to the data from the internal sensors of the robot, data from the ATI Mini58 force/-torque sensor, the AIRSKIN® safety skin and the Cognex In-Sight.

3.3. *Control Logic and Sequence of Operations*

The core of the process is encapsulated in a state-machine algorithm that implements the sampling phase according to the ISA-88 framework. The sequence begins when the mixer completes its blending cycle, and its internal sensors confirm that the agitators are halted and the access hatch is open. Next, the mixer sends a “batch complete” signal to the PLC, which in turn initiates the sampling phase by dispatching a “start sampling” command to the robot controller over PROFINET. After receiving this command, the robot first uses the Cognex In-Sight L38 3D vision system to verify that the sampling area is clear and that the hatch of the mixer is safely open. Meanwhile, the sensor feedback from ATI Mini58 allows the robot to detect any abnormal forces and make real-time trajectory adjustments. During its approach, the AIRSKIN® safety system monitors the surface of the robot: If any unintended human contact is detected, the system triggers an immediate stop to ensure safety [15] [1]–[3]. After the robot reaches the designated sampling zone, its routine is designed to capture a composite sample. First, the robot collects material from three distinct points within the mixer, resulting in an aggregate sample of approximately 50–60 g. Next, an integrated sample divider reduces the overall sample size to a target mass of 8–10 g suitable for moisture analysis. The remaining material is then automatically returned back into the mixer. After confirming sample acquisition via the force sensor, the robot retracts and moves to the moisture analyser, where it deposits the sample for measurement. The analyser then transmits the moisture data to the PLC. Depending on whether the measured value falls within the tolerance limit, the PLC either authorises the discharge of the briquette batch or initiates a corrective cycle. At every stage, the combined sensor inputs are used to monitor whether the system maintains accurate, safe, and repeatable operations within the defined 60-s cycle time. A high-level software workflow diagram, illustrating the sequence of interactions between the main controller, robot controller, sensors, and the moisture analyser, is presented in Fig. 4.

3.4. *Implementation and Optimization*

Before commissioning on the production floor, the complete sampling algorithm and motion routines should be validated using offline simulation tools integrated into a digital twin framework. This approach creates a virtual replica of the entire production cell [including the planetary mixer, robotic manipulator, and all sensor systems (force/torque, AIRSKIN® and 3D vision)], which facilitates the simulation of realistic process conditions.

TABLE II: Key Equipment Requirements for Sample Collection from Planetary Mixer in Auger Pressing Briquetting Line

Category	Requirements
General design of the area	Manual sampling must be possible during maintenance of the manipulator without affecting the technological process
Moisture analyzer	Type: Analytical balance with intake opening Sample mass: ~10 g Absolute error: $\leq$ 0.05 % Automatic emptying of the analyser after measurement must be provided
Robot manipulator	Axes: 6 Payload: 10 kg Reach: up to 1100 mm Repeatability: ±0.03 mm Speed: up to 140 cycles/min Protection rating: IP67 (dust- and moisture-resistant) Interface: PROFINET
Force/torque sensor	Model: ATI Mini58 Integrated with ForceTorqueControl software Responds to changes in material consistency and collisions
Safety system	AIRSKIN® (tactile system) Sensitivity: from 5 N Compliance: EN/ISO 13849-1 (PL e/Cat. 3), EN/IEC 62061 (SIL 3), ISO/TS 15066
3D vision system	Model: Cognex In-Sight L38 3D Range: up to 1100 mm Scan rate: 7 kHz Protection: IP65 Interface: PROFINET
Effector (sampler)	Material: Stainless steel with food-grade coating Allows sample collection from three different points inside the mixer Total collected sample mass: 50–60 g Built-in sample divider reduces mass to 8–10 g Excess material is returned to the mixer Quick-release interface with ATI Mini58 for force feedback
Mixer design	Automated sampling hatch required Minimum hatch opening size: 400 × 400 mm
Software and algorithms	Three-layer architecture (WinCC/PLC, robot controller, and sensor systems) Control based on ISA-88, Integrated digital twin for optimisation and validation
Control and safety sequence	Sequence: Mixing completed → hatch opens → 3D vision check → robot samples from three points in the mixer Feedback from: Force sensor, AIRSKIN®, and Cognex vision system

The digital twin helps optimise robot trajectories, test cycle times, and identify potential conflict areas, such as those involving the internal blades of the mixer or adjacent equipment. The presence of the digital twin allows continuous predictive maintenance by logging diagnostic data (e.g., joint torque, cycle frequency, and environmental sensor readings) and compares them against model predictions, enabling early detection of wear or performance deviations. This integration not only streamlines the commissioning process but also supports ongoing reliability and safety improvements in the production environment. Limitations are the potential degradation of the sensor performance due to dust accumulation, especially on the 3D vision system, force sensors, safety skin and sensor drift. To address this, it is recommended to use protective enclosures, air purging, and predictive maintenance.

4. Conclusion

In this study, an automated sampling and moisture analysis system using robotic manipulators has been proposed for the charge material used in briquetting. The developed system significantly improves the accuracy and repeatability of moisture control, which is critical for ensuring the stability of the auger pressing process and the quality of the produced briquettes. The introduction of robotics into this process helps minimise the influence of the human factor, enhances safety and reduces the time required for preparing and adjusting the charge composition. The system also provides flexibility and adaptability, facilitating rapid response to changes in raw material properties and environmental parameters. Such robotics-based solutions contribute to improved production performance and economic efficiency, making it suitable for use in modern industrial conditions, especially in environments with fluctuating raw material composition and unstable environmental factors. The technical parameters for the system design are outlined in Table II.

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Conflict of Interest

The authors declare that they do not have any conflict of interest.

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