MASS FLOW DETECTION TECHNOLOGY FOR SEED AND FERTILISER PARTICLES AND ITS APPLICATION IN UAV-BASED SPREADING
/
种肥颗粒质量流量检测技术及其在无人机播撒中的应用建议

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ABSTRACT
The processes of sowing and fertiliser application represent a significant aspect of agricultural production. In order to achieve efficient and precise seeding and fertiliser application, mass flow detection of seed and fertiliser particles can facilitate real-time monitoring and precise decision-making for intelligent seeding and fertiliser application. However, the diversity of seed and fertiliser particle types and particle flow modes presents a challenge for existing detection methods, particularly in meeting the varying operational requirements, especially for particle mass flow detection in low-altitude and high-speed sowing operations of agricultural drones. In such cases, the overlap and flow rate will have a significant impact on the detection results due to the large displacement and the continuous high-throughput dense phase of the particle flow. This paper provides a summary of the existing seed and fertiliser particle mass flow detection techniques and their underlying working principles. It compares the direct detection based on mass with the indirect detection methods based on velocity and concentration, and analyses their respective advantages, disadvantages and applicability. It also explores the possibility of optimising the existing detection methods for the specific needs of agricultural UAVs and considers the potential introduction of cutting-edge science and technology in order to develop an efficient, accurate and convenient detection system to meet the growing market demand.

摘要
播种和施肥是农业生产中的重要环节。在实现高效和精准化播种和施肥作业中，种肥颗粒的质量流量检测能够为智能化播种和施肥提供实时监控和精准决策。然而由于种肥颗粒类型和颗粒流动方式的多样性，现有检测方法较难满足不同的作业需求，尤其是农用无人机低空高速播撒作业中的颗粒质量流量检测，由于排量较大，颗粒流为连续高通量密相，重叠度和流动速度会对检测结果产生较大影响。本文总结了现有的种肥颗粒质量流量检测技术及其工作原理，比较了基于质量的直接检测与基于速度和浓度的间接检测方法，分析了各自的优缺点及适用性。针对农用无人机的特定需求，探讨了优化现有检测方法的可能性，并展望了引入前沿科学技术以研发高效、精准、便捷的检测系统，以满足日益增长的市场需求。

INTRODUCTION

Taking information and knowledge as the core elements, through the cross-border integration of modern information technology and agriculture such as the Internet, Internet of Things, big data, artificial intelligence and intelligent equipment, smart agriculture, which realises information perception, quantitative decision-making, intelligent control, precise inputs, and personalised services in the whole process of agricultural production, has become the development trend of modern agriculture in the world (*Zhao, 2019*). As the premise and foundation of smart agriculture, precision agriculture in the new situation needs to achieve the goals of positioning, timing and quantification, and provide low-input, high-quality and sustainable agricultural production through the monitoring and feedback of each operational link.

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Sowing and fertiliser application are indispensable in agricultural production, and seed and fertiliser particle mass flow detection is an important foundation for precision operations such as precision sowing, precision fertiliser application and yield estimation. The detection of the mass flow rate of seed and fertiliser particles not only helps to know the actual sowing and fertiliser application information in the region and reduce the loss, but also realises the closed-loop control of the discharge rate, which helps to improve the effect of the precision variables of sowing and fertiliser application (*Mahmud et al., 2020*). Therefore, the mass flow detection of seeding and fertiliser particles can provide basic data for realising the whole monitoring and intelligent management of agricultural operations, which can help the precise perception and intelligent decision-making of the agricultural production process (*Lee et al., 2015*).

In recent years, research on seed and fertiliser particle mass flow detection technology has progressed rapidly, resulting in the emergence of numerous types of solid particle mass flow detection technologies and methods. *Ding et al., (2019),* discussed the mechanical electromechanical alarm detection method, machine vision detection method, photoelectric sensing detection method, capacitive sensing detection method, and piezoelectric sensing detection method in their summary of the research progress of small and medium-sized seed sowing detection technology. They also highlighted the advantages and disadvantages of different detection methods and combined these with the requirements of precision agriculture to propose sowing detection indexes for different sowing modes. The existing particle flow detection technology can be classified into two main categories: mass flow detection and volumetric flow detection. The former encompasses techniques such as particle weighing, impact detection, and the measurement of particle volume over a fixed period and fixed volume of particle emission time (*Liu et al., 2018*). In the field of solid particle pneumatic conveying, scholars have investigated a range of detection methods based on mechanical, optical, acoustic, electrical and correlation techniques (*Bergeijk et al., 2001*). A significant proportion of the aforementioned methodologies have been extensively utilized within the domain of agricultural seeding and fertiliser application. However, there is a paucity of research pertaining to the detection of high-throughput dense-phase particle flows exhibiting low void fraction. The mass flow detection of continuous high-throughput dense-phase particle flows is imperative, given that particle motion and deposition are influenced by numerous factors during unmanned aerial dispersal.

The objective of this paper is to provide a comprehensive overview of the existing seed and fertiliser particle mass flow detection techniques, analyse the fundamental principles and limitations of the various detection techniques and their viability in UAV broadcasting applications and suggest potential avenues for further research into particle mass flow detection techniques in agricultural UAV broadcasting.

MATERIALS AND METHODS

Mass flow measurement technology

Direct detection method

In the context of direct measurement, the mass flow rate of a solid particle stream is obtained through the detection of either the instantaneous mass change of the particle stream itself or a sensitive variable that is directly correlated with the aforementioned mass flow rate change. The most commonly employed methods are those based on weighing and Coriolis force.

Weighing method

The majority of weighing methods rely on pressure transducers and their associated accessories to directly obtain particle mass changes. Typically, pressure sensors are employed to directly detect the mass change of the material box, thereby obtaining the real-time mass flow rate of particles (*Wu et al., 2014*). Alternatively, a combination of pressure sensors and springs is utilised (Figure 1) (*Yu et al., 2019*). This detection method has been widely employed in the measurement of grain yield, pneumatic conveying and other mass flow detection of grain flow (*Qu, 2017*). The weighing detection method based on belt scales is, in fact, a calculation of the average value of the mass flow rate of particles passing through each cross-section perpendicular to the direction of belt movement per unit time. The method is straightforward to implement physically, has no specific requirements regarding the physical properties of the particles being measured, and is highly applicable. However, it is susceptible to the influence of the rotational speed of the belt pulley and the distribution of particles above the belt, which can result in cumulative errors (*Zhou and Zhang, 2009*). The deformation and buffering of the spring can serve to counteract the interference of external factors, such as machine vibration. To achieve real-time detection and automatic calibration of fertiliser application, *Li Ang*

(2001), combined a load cell with a strain force transducer to measure the weight and dynamic behaviour of a fertiliser applicator. This combined detection method represents a significant advancement over traditional weighing techniques, offering enhanced precision in measurement. The weighing type is primarily based on the conveyor belt and spring assembly, which is typically employed for quality inspection in indoor seeding quality inspection test beds and roller grain transport lines. However, it is less frequently utilised in actual field operations.

Coriolis method

The Coriolis method is achieved by establishing the relationship between the Coriolis force generated during the vibration or rotation of the component and the mass flow rate of the particles (*Geng et al., 2005*). As shown in Figure 2, the linear relationship between the moment generated by the Coriolis force and the mass flow rate as the particles rotate on the rotating metering disc can be expressed by the equation:

$$M = q_m \omega R^2 \tag{1}$$

where, M is the moment of the Coriolis force relative to the centre of rotation, $\mathrm{N \cdot m}$; q_m is the mass flow rate, $\mathrm{kg/s}$; ω is the measurement of angular velocity, rad/s; R is the measuring wheel outer diameter, m.

Considering the movement of particles on the metering disc and the variation in instantaneous mass distribution, this method yields better detection results under conditions of constant angular velocity and stable instantaneous particle flow. Coriolis-based detection methods convert particle mass and indirectly measure the force and momentum changes generated by particle motion. However, these methods are highly influenced by the flow rate and velocity of grain particles. Accurately capturing these mechanical changes is both the key challenge and the focus for improving detection accuracy.

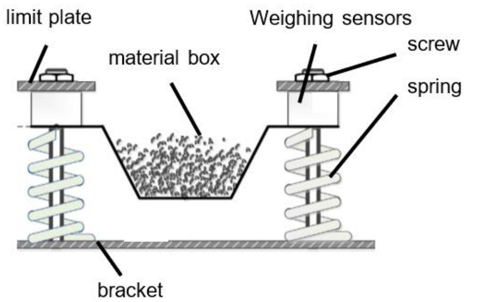


Fig. 1 - Weighing method based on pressure sensor

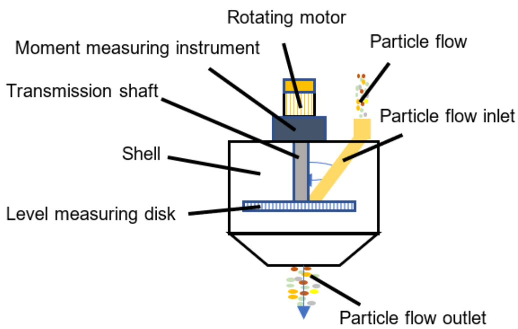


Fig. 2 - Coriolis force method based on rotation mode

Indirect detection method

Indirect measurement refers to determining the mass flow rate of particles by measuring the velocity or concentration of the solid particle stream. For a given particle, if its density and flow velocity are known, there is a correlation between the mass flow rate and the particle stream's concentration and velocity. Thus, the mass flow rate can be indirectly obtained by measuring these two parameters (*Zheng and Liu, 2011; Zou Jing, 2015*). In the following section, the correlation method is introduced taking into account two aspects: particle concentration detection and velocity detection.

Concentration-based detection method

Electrical method

This method mainly uses the charge change generated by the particle flow to obtain the particle concentration, including the capacitance method and the electrostatic method. The capacitance method refers to collecting the amount of output capacitance change generated when the particle flow passes between the poles of the capacitor and establishing the relationship between it and the particle flow rate according to the particle concentration to obtain the flow rate value (*Zhou et al., 2017*).

The capacitance method has the advantages of stable operation, high reliability and strong resistance to dust contamination, but it has low sensitivity to the dense-phase particle flow with small concentration difference. In order to be able to accurately detect the capacitance variable generated by the dense-phase particle flow, the existing technology adopts new methods such as the differential capacitance principle or the construction of spiral capacitance sensors to improve the detection accuracy (*Zhou et al., 2014; Zhou L., 2014*).

The electrostatic method is used to obtain the particle mass flow rate by detecting the amount of electrostatic charge generated by particle collision and friction and establishing the relationship between particle concentration and charge (*Jia et al., 2019; Wu et al., 2019*). In the actual pipe conveying particle flow, the collision between solid particles, the collision between particles and the pipe wall, and the friction between particles and the air flow generate a large amount of electrostatic charge.

The flow velocity of solid particles can be determined by inter-correlation velocimetry. The mass flow rate of solid particles can be calculated from their velocity and relative concentration (*Qian et al., 2012*).

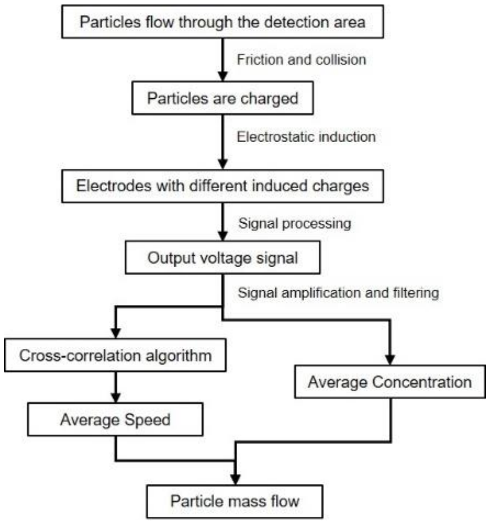


Fig. 3 - Electrostatic method

Research on detection technology based on this method has achieved some results. For example, *Yan and Ma, (2000),* used a pair of axially spaced metal rods mounted on the cross section of the pipe as electrostatic sensing elements and detected the mass flow rate by obtaining the alternating electrostatic signals caused by the particles flowing through the two rods in the pipe and developed a new type of detection instrument called 'StackFlow 2000', which can provide new opportunities for the application of electrostatic sensors. This method offers new possibilities for the development of electrostatic sensors. The distribution of the electrostatic sensing probes and the electrostatic response characteristics are the key factors affecting the detection results when using this method (*Li Guanguan, 2016*). Placement of multiple ring electrodes inside the particle flow tube to obtain the average flow velocity throughout the cross section of the measured tube area can improve the detection accuracy (*Li et al., 2014*).

Volumetric concentration method

This method primarily utilizes the intermittent flow characteristics of particle streams. Changes in particle volume concentration are converted into voltage pulse signals, establishing a relationship between the number of voltage pulses and the number of particles. Based on this relationship, the particle mass flow rate can be calculated from the volume concentration. Common approaches under this method include the photoelectric method, piezoelectric method, and image-based method.

The photoelectric method primarily relies on the blocking effect of the particle flow on light intensity to detect changes in the light signal. A mapping relationship is established between the voltage pulses generated by light intensity fluctuations and the number of particles. Photoelectric sensors typically consist of a transmitter and a receiver, commonly using light-emitting diodes (LEDs) and phototransistors (*Che et al., 2017*). During operation, as the particle stream passes between the transmitter and receiver, it causes variations in the light received, resulting in corresponding changes in the voltage signal. There is a clear correlation between the concentration of the particle stream and the voltage pulse signal. By counting these pulses, the number of particles can be estimated (*Wu et al., 2016; Qiu et al., 2019; Karimi et al, 2017*). For continuous, dense, and high-throughput particle streams, the relationship between the induced voltage and flow rate can be established by constructing a distribution matrix of photoelectric sensors (Fig. 4) or dividing the particle channel into a grid (Fig. 5) to collect changes in multiple continuous voltage signals (*Jiang et al., 2021; Liu et al., 2019*). The relationship between induced voltage and flow rate can also be established by detecting changes in the thickness of the particle pile and using the relationship between the thickness of the particle pile and the mass of the particles (Fig. 6) (*Yin et al., 2021*), or by splitting a dense, high-throughput particle stream into multiple smaller streams using a discrete mechanism and detecting them in parallel with multiple sets of photoelectric sensors (*Nong et al., 2023; Xu et al., 2022; Ding et al., 2020*). *Swisher et al., (2002),* used a trapezoidal optical chamber to transmit laser light to an array detection unit composed of 32 photodiodes, allowing them to determine the instantaneous flow rate of fertiliser from an air-conveyor applicator based on the amount of light blocked by the granules. Regardless of the approach, whether using a photovoltaic line array or segmenting the granular stream, the key to improving this method lies in optimizing the photosensitive components (e.g., by using thin-faced lasers) and enhancing both the signal acquisition accuracy and the range of the photodiode sensors (*Ding et al., 2019; Ding et al., 2021*).

In the piezoelectric method, voltage pulse signals are generated by intermittent collisions between the particle stream and a piezoelectric element. These signals are detected and converted into particle counts. The frequency of collisions, and thus the number of voltage pulses, increases with the concentration of the particle stream. In other words, a higher particle concentration leads to more frequent impacts and a greater number of voltage signals. However, this method is less sensitive to particle streams with only slight changes in concentration. It also requires high-resolution detection capabilities to accurately respond to variations in particle concentration and to generate voltage pulse signals within an appropriate range.

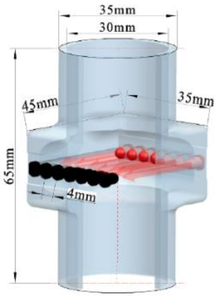


Fig. 4 - Mass flow detection method of continuous dense particle flow based on infrared sensor *(Jiang et al., 2021)*

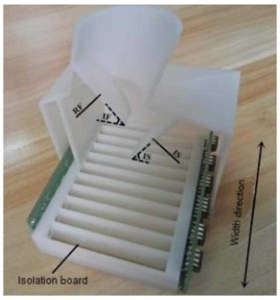


Fig. 5 - The dense particle flow is divided into a single row of small particle flow *(Liu et al., 2019)*

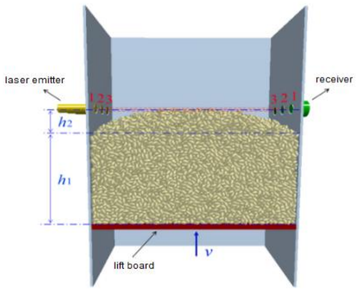


Fig. 6 - Photoelectric sensor array *(Yin et al., 2021)*

The photoelectric and piezoelectric methods are relatively simple in principle and construction and have been widely used in fertiliser application and seeding (*Jia et al., 2018*). Both methods essentially detect voltage pulse signals generated by the inductive element of the sensor and should be used in such a way as to ensure that a clear and stable signal is obtained as far as possible. For example, the detection accuracy of photoelectric sensors is susceptible to dust and other contaminants, and measures such as the installation of protective covers can be taken to ensure a clean detection environment (*Ji et al., 2016*). Piezoelectric sensors are more sensitive to intermittent particle flow, and when detecting continuous particle flow, detection accuracy can be improved by using easily deformable materials (e.g. piezoelectric films), signal conversion and adaptive noise cancellation algorithms (*Wang et al., 2019; Xiong et al., 2018*).

The imaging method mainly uses high-speed camera technology to obtain images of the falling particle flow and counts the number of particles in unit space through image processing, which is also a volume concentration-based detection method (*Back et al., 2014*). This method can obtain not only the particle flow information, but also the spatial motion trajectory of the falling particles (*Yazgi and Degimencioglu, 2007*). However, due to the high environmental requirements of this method, which requires a complex test bench to place the camera, light source, computer, etc., it is generally only used for laboratory testing (Lu et al., 2019). In order to widen the scope of application, researchers have used a digital camera (Nikon, D70) and a charge-coupled device digital colour camera to capture images of seed and fertiliser particles, determine the number and size of particles, and experimentally verify the feasibility of these methods (*Navid et al., 2011; Back et al., 2014*).

The accuracy of image recognition is the basis of the image method. Since the image is mainly derived from the dynamic flow and static distribution of particles, and the number of particles is mostly used as the detection target, it will be affected by various factors such as light, vibration of the detection device, and overlapping of particle materials, and the detection error is relatively large. To improve the detection performance, neural networks and other image segmentation and feature extraction methods are also combined with image processing (*Tan et al., 2014; Zhao et al., 2022*).

In addition, to improve the detection accuracy of the existing detection system under the noise interference of field operations, the point cloud data collected by LiDAR has been used to characterise the geometric feature changes of particles as volume changes, and a related algorithm for calculating fertiliser emissions has been developed *(Zhao et al., 2021*). This method requires processing and analysis of the point cloud data and is currently mostly used for indoor static particle flux detection platforms.

Attenuation method

This method mainly uses the principle that electromagnetic waves, sound waves, etc. are attenuated by the medium and the particle concentration is obtained by detecting the wave intensity before and after the emitted wave passes through the particle flow tube. Visible light, laser, microwave, X-ray, γ-ray and ultrasonic waves can be used as wave sources for the attenuation method. Using microwave as an example, the change in wave intensity through the particle flow can be characterised by the energy of the echo signal. By detecting the energy of the Doppler echo signal in the pipe, the density of the particle flow can be obtained, and then using the flow rate, the particle mass flow rate can be obtained (*Isa and Wu, 2006*). The traditional method of calculating the particle density is to use the power spectrum calculation to obtain the energy information of the signal. In the process of random signal acquisition, the power spectral density is commonly used to represent the distribution of the average power in the frequency domain, which can be used to obtain the total power P by integrating the operation over the entire frequency range, with the following equation:

$$P = \int_{f_{min}}^{f_{max}} s(f) d_f \tag{2}$$

where, P is the echo signal power; $s(f)$ is the power spectral density of the signal; f_{min} is the lower limit of the Doppler bandwidth; f_{max} is the upper limit of the Doppler bandwidth.

Power spectrum estimation methods include classical power spectrum estimation and modern spectrum estimation. Classical spectral estimation methods include the correlation function method (BT method) and the periodogram method, which is based on the FFT (Fast Fourier Transform) to estimate the power spectral density function, which is greatly affected by the transfer function and needs to be selected according to the actual situation (*Deng et al., 2014*). Modern spectral estimation methods include AR model spectral estimation, MA model spectral estimation and ARMA model spectral estimation methods (*Li Ying, 2015*). When using this method, if the order of the parametric model is too low, it is difficult to accurately distinguish the frequency components, and if the order of the parametric model is too high, there is a possibility of distortion in the display of the true amplitude ratio, which affects the estimation of the true spectral peaks.

Velocity-based detection methods

Impulse momentum method

This method primarily utilizes the impact force generated by granule flow striking the force-measuring plate and force sensors, combined with the functional relationship between the impact force and the mass flow rate of granules, to determine the mass flow rate. The key to ensuring the detection accuracy of this approach lies in effectively extracting the valid deformation caused by the granule flow impact (*Chen et al., 2005; Zhou et al., 2006*). When the continuous particle flow passes through a fixed cross-section, the relationship between the cumulative particle mass *W*, the instantaneous mass flow rate m_i, the flow velocity v_i and the instantaneous flow rate Q_i is expressed as follows:

$$W = \sum_{i=1}^{n} Q_i(t)\Delta t = \sum_{i=1}^{n} m_i(t)v_i(t)\Delta t \tag{3}$$

If the continuous flow of particles hits the force plate continuously, the momentum of the moving particles will change after the collision with the force plate. Assuming that the velocity of the particles after the collision is zero, then the following formula is established:

$$I_i(t) = m_i(t)v_i(t) \tag{4}$$

From equation (4) it can be seen that if the particle collision momentum as well as the flow rate can be obtained, then the particle mass flow rate can also be obtained. The force plate deforms under the impact of the particle flow, the stress generated by the deformation is detected by strain sensors, and the relationship between the stress and the momentum can be determined by test calibration (equation 5).

$$I_i(t) = kU_i(t) \tag{5}$$

where, Δt is the timed sampling interval; $I_i(t)$ is the impulse of the particle flow, N·s; $m_i(t)$ is the mass of grain per unit length at any position on the conveyor belt at time t, kg; $v_i(t)$ is the instantaneous velocity of the grain at time t, m/s.

In order to resolve the issue of the test plate being vulnerable to a variety of factors, *Ding Yongqian (2009)*, investigated a pulse method based on velocity detection, which allows particles to flow through the test device by their own gravity and initial velocity without the need to maintain a constant velocity of motion. The method can calculate the particle flow rate based on the weight difference between two load cells and known structural parameters to determine the instantaneous mass flow rate and the total mass of particles to be detected. To improve the detection accuracy of the pulse method, *Fulton et al., (2009),* simulated different field slopes experienced during field operations, investigated the effect of harvester traverse roll and pitch on the detection accuracy of existing mass flow sensors, and provided suggestions for optimising the detection method for different slopes. *Schrock et al., (1999),* developed a new diaphragm grain mass flow sensor to isolate the grain from the load cell by using a flexible fabric-reinforced rubber diaphragm to reduce the possibility of cracking and entrapment of other contaminants behind the sensing element.

Pressure method

When faced with a continuous dense grain flow, the flow rate value can be obtained by collecting the continuously changing pressure generated by the grain flow acting on the pressure sensors and establishing the relationship between pressure and grain flow rate. As shown in Fig.7, multiple pressure sensors are arranged along the cross section of the particle flow between the two side walls of the deflector plate to establish the relationship between the instantaneous thickness of the particle flow and the pressure. Mathematical modelling methods are used to fit the thickness distribution equation of the cross section of the particle flow, and then the equation is integrated to obtain the instantaneous cross sectional area of the particle flow. The particle flow rate is used to establish the relationship between instantaneous mass and cross-sectional area, which in turn allows for the relationship between pressure and particle mass flow rate to be determined (*Geng et al., 2021*).

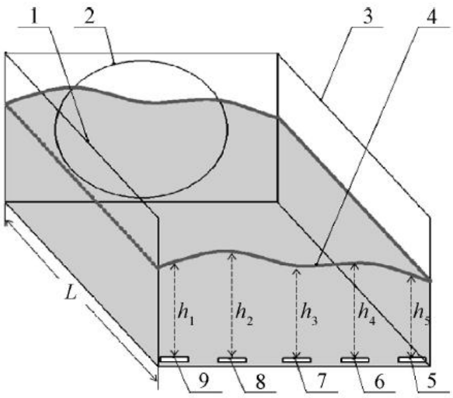


Fig. 7 - Schematic diagram of particle flow mass flow detected by piezoelectric sensor *(Xiong et al., 2018***)**

1 - Right wall of the concave deflector plate; 2 - Tail of the grain collection elevator; 3 - Left wall of the concave deflector plate; 4 - Cross-section of grain flow; 5 - First reference position; 6 - Second reference position; 7 - Third reference position; 8 - Fourth reference position; 9 - Fifth reference position.

The method treats the flowing particle cluster as a solid mass of uniform density and establishes the relationship between particle flow pressure and flow velocity by detecting the force of the solid mass on the pressure sensor in real time, making it relatively friendly to dense phase particle flows and capable of obtaining large pressure signals. In addition to production measurement, the method can also be used in pneumatic conveying with a venturi to establish a relationship between the mass flow rate of solid particles by testing the difference in air flow pressure before and after gas-solid two-phase flow through the venturi (*Mailander and Moriasi, 2011*).

Doppler method

This method is a new non-destructive testing technique in which the measured element does not need to be in direct contact with the grain flow and there is no problem of corrosion and wear.

Moreover, in addition to microwaves, electromagnetic waves such as millimetre waves and lasers, as well as ultrasonic waves, can be used as the emitted wave source of this detection method (*Yin Guang, 2012; Rafael et al., 2023*). It has been widely used in grain particle flow detection (*Penirschke et al., 2008*). However, wave propagation is not only affected by the differential reflection caused by varying grain flow characteristics, but also by other factors that influence the reflected wave, which can interfere with the frequency shift (*Pang et al., 2008*). Developing appropriate detection structures and signal processing methods tailored to different grain characteristics is essential for ensuring the accuracy of this detection method.

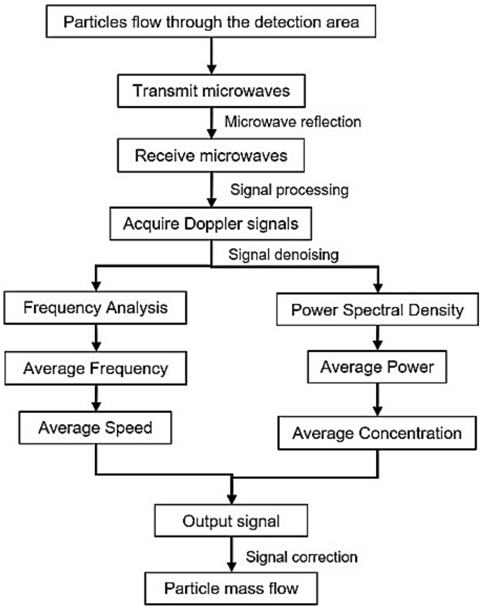


Fig. 8 - Microwave detection method based on doppler effect

Acoustic method

This method primarily involves acquiring acoustic signals generated by particle collisions and establishing their relationship with particle flow velocity, which is then used to calculate the mass flow rate (*Wang et al., 2017*). When the particle flow hits the steel plate during the free fall under gravity, the particle-particle collision and particle-steel plate collision can excite strong elastic waves, and the particle flow hitting the steel plate at different velocities will produce large differences in acoustic signals. Due to the damping effect of air and the relatively weak collisions between particles compared to collisions with a steel plate, acoustic signals are difficult to capture. However, an acoustic emission sensor can be used to detect the signals generated by the collision and friction of solid-phase particles with a steel plate (*Wei et al., 2011*). This method relies on acoustic signals produced during particle flow interactions, but when the particles are small or the collisions and friction are light, the resulting signals are weak and difficult to detect. Additionally, noise in the surrounding environment can further increase measurement errors. Therefore, accurately capturing and processing the effective acoustic signals generated by the particle flow is key to improving detection accuracy.

Summary of existing detection methods

The above detection methods obtain particle flow information from different angles, which can basically realise the detection needs in different scenarios, but they all have certain limitations (Figure 9). In the direct detection method, the detection element is in direct contact with the particles, which will definitely cause wear, corrosion and relaxation deformation of the sensor in the long run, and if it is in the pneumatic pipeline, it will also have a certain effect on the normal pressure drop in the pipeline, which will affect the efficiency of particle transport. In the indirect detection method, the concentration-based detection method is more sensitive to the particle concentration, and the light wave and acoustic wave are not only more demanding on the environment, which is affected by dust, impurities, temperature and humidity, but also the signal processing and analysis are relatively complicated. In particular, the detection of high-throughput dense-phase particle flow requires higher resolution and sensitivity of sensors, and the spatial distribution of sensors in the detection area as well as the post-signal processing techniques are more difficult than those of dilute-phase particle flow detection and require complex information conversion. The velocity detected by the velocity-based detection method is basically the average velocity of the particle flow, and the flow state and spatial distribution of the particles will directly affect the detection results, which can easily cause detection errors.

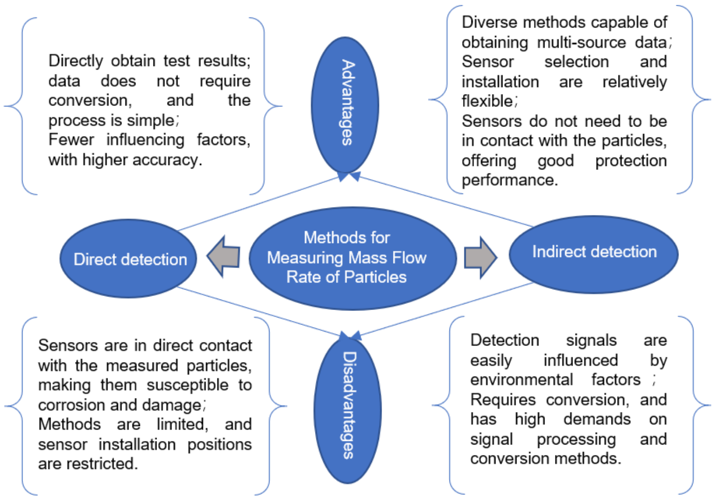
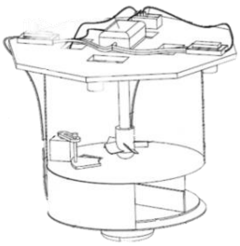


Fig. 9 - Comparison of different detection methods

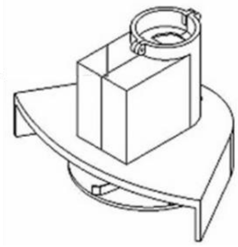
In practice, the flow state and emission environment of seed and fertiliser particles are diverse, and there is still much room for improvement in the existing technology, and it is difficult to achieve good detection results using only the single method mentioned above. In order to improve the detection effect, researchers have attempted to fuse electrostatic sensors, differential pressure sensors and accelerometers, and constructed a data-driven model based on support vector machines to estimate the mass flow rate of a solid particle stream (*Faisal et al., 2022*). The machine vision system is characterised by its high precision, real-time capabilities, automation and intelligence. The image-based mass flow detection method of dense-phase particle flow is expected to yield significant achievements in the future (*Liang Yongan, 2022; Wang Dingkang, 2022*). The use of neural networks to model the relationship between the mass flow rate of solid particles and a variety of sensitive variables can also improve the detection effect (*Ding Mingwei, 2022; Zhu Siqi, 2020*).

Flow regulation and detection methods in drone seeding

The two main parts of the UAV spreading device are particle discharge and particle spreading, where the particle discharge method is related to the adjustable range of discharge and particle displacement adjustment, which mainly affects the particle discharge accuracy, and the particle spreading method is related to the particle diffusion trajectory and deposition range, which mainly affects the deposition width and uniformity (*Song et al., 2020*). Figure 10 shows the discharge mechanism in the existing UAV spreading device, which is mainly based on grooved wheels, horizontal baffles and centrifugal discs. It is typically installed at the bottom of the material box, having a simple structure and being easy to manipulate.



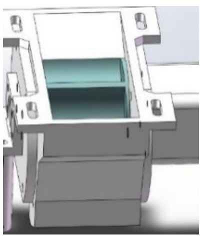
Horizontal baffle
(Li et al., 2016)



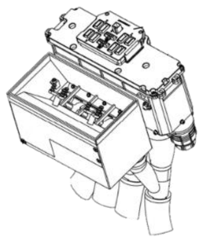
Horizontal baffle
(Su et al., 2022)

Horizontal baffle
(Song et al., 2020)

Gear disk
(Huang et al., 2020; Huang et al., 2022)

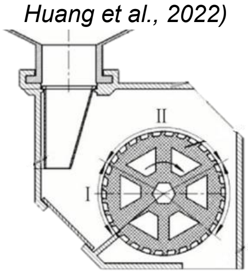


Groove wheel
(Song et al., 2018; Song et al., 2018)

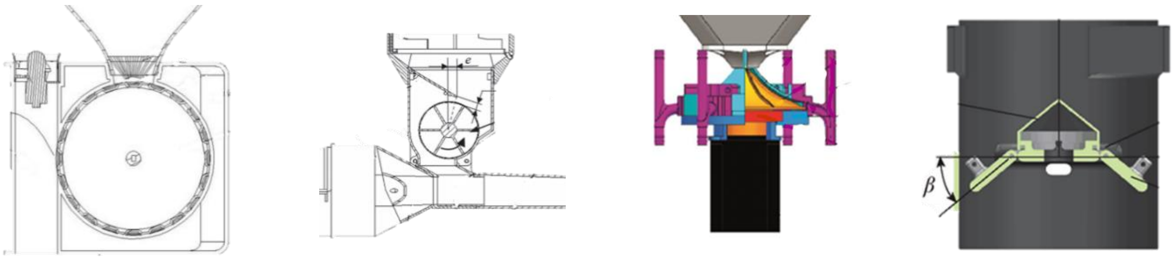


Groove wheel
(Li and Su, 2018)

Groove wheel
(Liu et al., 2022)



Groove wheel
(Zhang et al., 2020)



Groove wheel *(Chen Bo, 2019)* | Groove wheel *(Wang et al., 2023)* | Centrifugal disc *(Huang et al., 2020)* | Centrifugal fan blade *(Ren et al., 2021)*

Fig. 10 - Method of displacement regulation and detection for UAV seeding

Song et al., (2021), designed a UAV variable fertiliser application system using an opposite laser sensor. The transmitting and receiving ends were fixed around the connecting pipe between the material box and the fertiliser discharger. Real-time detection of particle flow was achieved using the photoelectric principle, enabling mass flow detection of fertiliser particles. DJI Innovation employed a Hall sensor mounted on the agitator of the spreader. As the agitator rotates, the magnet on the Hall sensor interacts intermittently with magnetic strips on the side wall of the spreader. Variations in particle flow rate cause different levels of resistance as particles pass through the agitator, altering its rotation speed. These changes result in varying Hall sensor signals, which reflect the state of the particle flow (*Huang and Zhang, 2020*). To obtain more accurate detection results, Huang Junhao et al. developed a detection device based on differential weighing. The system uses multiple sensors to detect vibration noise and applies filtering techniques to improve detection accuracy (*Huang et al., 2024*).

RESULTS

Adaptation of different detection methods

The configuration of sensors, characteristics of detection components, and information processing techniques vary widely across different detection methods. Selecting an appropriate particle mass flow detection method tailored to specific discharge mechanisms is essential for accurately acquiring detection data and improving overall measurement precision. During UAV spreading operations, particle flow is highly susceptible to noise and vibration caused by the high-speed rotation of the rotors, which poses challenges to accurate mass flow detection. Additionally, conventional detection methods often fall short in terms of accuracy and resolution. Therefore, there is a pressing need to develop innovative detection technologies that offer strong anti-interference capability, high resolution, and rapid response time.

Table 1

Adaptation analysis of different detection methods applied to unmanned aerial dispersal

Detection Method	Feasibility	Limitations	Improvement Suggestions
Weighing Method	The feasibility is relatively strong. The load of the material box on the drone is limited and easy to plug and unplug. Pressure sensors can meet the requirements, allowing for real-time measurement.	This method mainly focuses on detecting changes in the weight of the material box, and the stress conditions of the material box have a significant impact on the detection results.	Multiple pressure sensors can be set up, using the differential principle to obtain the actual net load changes of the material box.
Coriolis Force Method	The feasibility is relatively poor. The size of the drone is limited, and most existing discharge mechanisms have compact structures, resulting in limited space for particle descent, making it difficult to generate Coriolis force.	The detection device is somewhat complex and has high installation requirements; it needs particle flow to generate Coriolis force for accurate detection.	/
Concentration-Based Method	The feasibility is relatively strong. During the drone's dispersal, the particle flow is substantial, and the signal changes based on particle volume concentration are significant and easy to obtain.	To acquire complete and accurate detection information when the particle flow is large, some methods require complex sensor arrangements, which can lead to signal redundancy and make signal processing difficult.	Improve signal processing methods and consider introducing deep learning algorithms to optimize the information processing process for faster and more accurate detection information.

Detection Method	Feasibility	Limitations	Improvement Suggestions
Velocity-Based Method	The feasibility is average. During the drone's dispersal, the distance from the material box to the dispensing mechanism is short, and the flow space for particles is limited, resulting in low speeds and making it difficult to generate noticeable signal changes.	Due to size constraints, the drone's discharge mechanism is small, and the range of particle speed variation is limited, making detection more challenging.	Optimize the signal detection circuit to amplify or convert the measured velocity-based signals to achieve significant signal changes.

Despite the existence of numerous existing seed and fertiliser particle flow quality flow detection methods, these are predominantly utilised in ground machinery with relatively slow operating speeds and small displacements. The response time and detection accuracy of these methods are generally adequate to meet requirements. However, when considering the implementation of these methods in the context of UAV seeding, it is evident that the response speed is inadequate. Furthermore, timely signal processing becomes challenging due to particle overlap and the rapid flow rate, which can result in incomplete information and increased error in the final calculated particle mass flow rate. In light of these challenges, this paper puts forward the following perspective:

1) In order to accelerate the realisation of unmanned precision operations, high-throughput dense-phase particle mass flow detection techniques applicable to agricultural UAV seeding need to be further optimised. For example, the existing unmanned aerial dispersal is divided into unconstrained diffuse dispersal and strip/shot dispersal with some constraints, and the corresponding discharge devices are mostly centralised and monolithic, which produce particle streams with different void ratios, and the installation location, mode, volume and weight of the sensors should be considered when performing the optimisation.

2) Existing sensors are typically designed for specific operating scenarios or particular types of particles, resulting in limited applicability. To address the diverse requirements of seed and fertiliser particle detection, it is necessary to explore innovative detection methods by integrating advanced technologies from various fields. For instance, flow tomography, such as X-ray imaging, can be used to obtain high-resolution, three-dimensional structural images by penetrating the material.

3) Current research has shifted from the development and performance optimisation of sensors to the integration of detection systems. How to use the existing detection information to develop an intelligent seed and fertiliser detection system and connect it to the management of smart agriculture to achieve a benign closed-loop operation system will be an important research topic in the field of smart agriculture in the future.

CONCLUSIONS

The application of unmanned aerial vehicle (UAV) spreading technology in seeding and fertiliser distribution plays a vital role in advancing agricultural precision. In precision operations, real-time information on particle mass flow is a fundamental prerequisite for effective particle displacement control and overall operation planning. Therefore, the study of high-throughput, dense-phase particle mass flow detection is crucial for achieving UAV-based precision seeding. This paper presents a comprehensive review of the principles, usage conditions, and adaptability of current mass flow detection methods for seed and fertiliser particle streams in UAV applications. The main conclusions are as follows:

Whilst the weighing and correlation methods are relatively simple to implement and have been used in UAV dispersal, the adaptability of other methods in this field remains to be investigated. For example, among the concentration-based detection methods, the electrical method is more sensitive to obvious signals. The short flow time and low velocity of particles in UAV dispersal produces relatively weak capacitance changes or electrostatic signals, which are not easily captured accurately and require signal amplification.

The application of volume concentration methods necessitates the consideration of detecting overlapping particles in high-throughput dense-phase particle flows, a consideration that extends to the expansion of the detection area of the sensor and the optimisation of the detection device. The employment of the image method requires the consideration of the accuracy of particle identification, whilst real-time image processing algorithms must be developed to meet the requirements of high-speed seeding by UAVs. The acoustic method utilised in the speed-based method primarily relies on the detection of particles impacting the detection plate sounding. However, in the context of UAV sowing operations, the high-speed rotation of the rotor wing generates significant vibrations, which can confound the distinction between particle impacts and sound from the detection plate, thereby compromising the detection of the target signal. Consequently, the method is not particularly well-suited for utilisation in UAV sowing.

In the context of direct or indirect detection, any scenario that necessitates direct contact between the particle flow and the detection element is susceptible to damage to the detection element. Consequently, non-contact detection methods should be prioritised wherever feasible. The future of agriculture is unmanned, with intelligent seeding and fertiliser operations being a key development trend. In order to achieve this, existing mass flow detection technology needs to evolve beyond basic detection to include the ability to access data on the intelligent management platform. This will allow it to be integrated into a large database, facilitating accurate decision-making and providing data support.

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