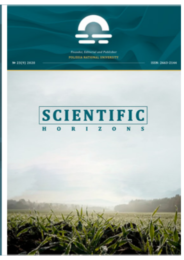
ISSN 2663-2144 e-ISSN 2709-8877

SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua

Scientific Horizons, 29(2), 59-70

UDC 631.3:629.113.004.67 DOI: 10.48077/scihor2.2026.59



Analysis and classification of cleaning systems for visual sensors in agricultural machinery

Ihor Osadchyi*

Graduate Student

National University of Life and Environmental Sciences of Ukraine

03040, 17 Vasylkivska Str., Kyiv, Ukraine

https://orcid.org/0009-0003-7167-589X

***Article's History*:**

Received: 14.01.2026

Revised: 23.04.2026

Accepted: 27.05.2026

Published: 29.05.2026

Abstract. This study aimed to examine and categorise several different cleaning system options for sensor units on agricultural machinery in order to determine how their performance impacts the potential for application in field operations. The research considers the degree of impact of different types of impurities on the efficiency of cleaning system operation (dust, dirt, crop residues and others, associated with the use of machines and equipment). The authors used monographic and abstract logical research methods to consolidate information on scientific publications about the technical solutions that had already been tried out in experimental setups and practice. The classification includes 4 types of the air pattern and has determined the main characteristics of cleaning systems in this mode. Two design configurations were considered in the description of structural implementation: integrated and external systems. The review results demonstrated the advantages of the integrated configuration due to its protection from external influences and maximum compactness. The operation of cleaning systems was divided into modes with constant and variable pulse duration. The efficiency analysis has shown that all types of modes have different performance depending on the type of pollution. In general, pulsed cleaning modes show better results for dry contamination, and cleaning modes with continuous water supply show higher efficiency in the case of wet contamination. The article also considers combined air-liquid cleaning systems, describes their design and the principle of operation. The study showed that air-based cleaning systems are integrated into machinery more effectively and can utilise existing components already incorporated by engineers for other functions, thereby making such solutions more economically efficient. Depending on the type of contamination, the air-blowing system can readily adjust the operating mode of the airflow to ensure maximum cleaning efficiency. The obtained results may be applied in the development and modernisation of sensor cleaning systems for modern agricultural machinery equipped with automatic and autonomous control elements. Based on scientific findings and independent experimental observations, the study examined which types of cleaning systems may be relevant during the operation

***Suggested Citation*:**

Osadchyi, I. (2026). Analysis and classification of cleaning systems for visual sensors in agricultural machinery. *Scientific Horizons*, 29(2), 59-70. doi: 10.48077/scihor2.2026.59.

Corresponding author (igorubee@gmail.com)

of radar sensors in the field and determined the influence of contamination on guidance quality and the overall stability of system performance

Keywords: precision agriculture; radars; contamination; pneumatic system; self-propelled machinery; auto-steering system

INTRODUCTION

Information technology has become an important component of modern agriculture, aimed at meeting the growing food demands of the global population. With such limited possibilities for the expansion of agricultural lands, improving the productivity of their current use has acquired great importance in terms of agricultural development. According to data presented in the study by O. Nikoliuk *et al.* (2024), as of 2024, the total area of agricultural land in Ukraine amounted to 48,109.77 thousand hectares, of which 32,723.51 thousand hectares were arable land, while agricultural land accounted for approximately 79.65% of the total territory of the state. One of the approaches to increasing agricultural production, according to V.V. Adamchuk *et al.* (2026), is the implementation and application of precision agriculture technologies, which have demonstrated their effectiveness over an extended period.

An important component of precision agriculture systems is the automatic guidance of machinery, the purpose of which is to ensure accurate vehicle movement along predetermined trajectories in order to reduce time consumption, fuel and lubricant usage, and material costs. L. Babiy *et al.* (2026) reported a 10-15% increase in the productivity of agricultural machinery when navigation equipment using a Real-Time Kinematic (RTK) correction signal was employed. The study established that the implementation of auto-steering systems with RTK correction signals at large agricultural enterprises demonstrates a high level of efficiency and cost recovery. In particular, the use of such systems allows for an increase in the productivity of the machine by 10-15%, and on average reduces the use of seeds and fertilisers by 10-20%. Due to this, the payback period for the implementation of RTK equipment in machines becomes 2-4 years.

Auto-steering systems use data from various sensors to define the direction and trajectory of the machine. One such source is radar sensors, which monitor the distance between the wheel and the crop row and transmit data to the auto-steering controller for corresponding movement correction. Many manufacturers of self-propelled agricultural machinery create autonomous vehicles that are not operated by humans. Sensors for environmental monitoring in them are based on LiDAR and radar signals. The number of these sensors can reach several dozen, and the stability of their operation is of great importance. Methods of sensor and machine vision systems for guidance of machines along plant rows are widely used in the design of autonomous agricultural machinery and mobile robotic platforms for the purpose of providing the movement of the vehicle with the required precision (under field conditions) (Shi *et al.*, 2023).

As described in the study by S. Debnath *et al.* (2023), light detection and ranging (LiDAR) sensors are considered the most important for the agriculture sector, as they are considered as nondestructive means of remote sensing (not depending on the lighting conditions). Furthermore, the accuracy of the data provided is higher than that of other digital sensing methods. The application of LiDAR in agriculture was also studied by M.R. Karim *et al.* (2024), who emphasised that LiDAR sensors have great potential for use in identifying crops, specifically via the estimation of crop height, the estimation of crop canopies and the spacing between plants and crop rows, and by identifying the agricultural operating environment (field contours, ridges, obstacles faced by agricultural machinery).

At the same time, during operation, sensors are exposed to various forms of contamination, including dust, soil particles, plant residues, and moisture. The study by O. Artyukh *et al.* (2025) described the problem of contamination affecting LiDAR systems, radar sensors, and cameras installed on autonomous vehicles. The authors report that over the period 2020-2025, there was a high level of improvement in the reliability of system perception in challenging conditions, although ensuring flawless work in challenging weather conditions, such as heavy rain, snowfall, fog and poor lighting, is still one of the key challenges. Radar systems can deal with small amounts of contamination using software; however, in challenging conditions, it may be difficult or even impossible to operate machines.

When similar technologies are used on agricultural machinery, contaminants on sensors can also reduce the accuracy of distance readings to crops or obstacles and eventually cause sensors to fail (Vargas *et al.*, 2021; Matos *et al.*, 2024). This, in turn, results in lower automatic steering system efficiency and in lower economic gains from the modernisation of agricultural machinery. Thus, the analysis of the cleaning systems that could be used to solve this problem is a scientifically important topic that is in need of further development and creation of effective engineering solutions for ensuring stable sensors work in fields (Aarif *et al.*, 2025). Significant attention should be paid to the investigation of various cleaning methods, including pneumatic, hydrodynamic and integrated ones that would ensure the complete removal of dust, dirt and moisture from sensors without disrupting the technological process. Pneumatic systems that use compressed air are the most promising. These systems are simple to operate and can react quickly, and can easily be integrated into the existing machine designs, but the parameters of air supply to the cleaning system and the energy consumption need to be improved.

It is also essential to determine the structural integration of the system itself into sensor or machine units to ensure autonomous operation and eliminate the influence of human factors. In addition, it is advisable to consider the cost-effectiveness of implementing such solutions, as the installation of such systems should not only increase the reliability of the operation of machinery, but also pay off quickly as a result of reducing the frequency of work stoppages and increasing the operational accuracy and reducing maintenance costs. In this regard, the assessment of the existing pneumatic systems for cleaning sensors and the development of a general classification of such systems are important research topics. This approach helps boost the effectiveness of automatic guidance and, thus, promotes overall progress in precision farming. Therefore, this study aimed to analyse and classify sensor cleaning methods used in agricultural machinery, and then to determine their operational effectiveness for potential use during field work.

MATERIALS AND METHODS

The study was based on a review-based and analytical approach with the use of methods for theoretical generalisation and comparative analysis. The basis for the research was the systematisation of scientific and technical literature, the data of experimental studies, published in open access sources and the authors' own observations in the course of agricultural machinery operation. The study procedure includes the following steps.

At the first stage, information sources were selected according to the following criteria: relevance, with emphasis on publications issued mainly within the past five years; scientific or practical significance; the presence of descriptions of sensor cleaning system designs or their individual components; and relevance to the operating conditions of agricultural machinery. Firstly, the following sources were selected: scientific articles, patents, technical reports and materials provided by manufacturers. Secondly, a comparative analysis of selected sources was performed according to the main parameters: design features of cleaning systems, operating principle, type of working medium used (air, liquid and combined), and operating modes. For more objective analysis in all studied sources, a unified set of indicators was selected that determines the effectiveness of cleaning the various types of contamination from sensors, the efficiency of cleaning, energy consumption, design complexity, possibility of introduction and operation reliability. During the third stage, the obtained results were generalised, which made it possible to identify typical technical solutions and develop approaches to the classification of sensor cleaning systems. Abstract-logical methods are used during generalisation of data to systematise heterogeneous content and identify relations between system structural parameters and their operational effectiveness. Then systems were classified according to such criteria as the air flow pattern, the form of construction scheme, operating mode and type of working media. The classification was based on analysis of specific technical solutions, which occur in different sources and are adapted to agricultural machinery operation conditions.

The study also included a comparison of the effectiveness of different cleaning systems using generalised indicators obtained from literature sources. The basic parameters of cleaning system classification were: degree of dry dust removal, plant debris removal, wet and adhesive contaminants removal, energy consumption (compressor power), cleaning cycle time, and adaptability of a system to changing operating conditions. To quantify the efficiency value of sensors' cleaning systems, the data on experimental studies obtained in the analysed scientific literature were used, e.g. 85%-95% of cleaning of the dry dust from a dust air stream; 95%-98% in combined cleaning systems. In addition, it was also used the data of field observations described in the earlier study of I. Osadchyi (2025), which made it possible to consider the practical aspects of applying cleaning systems more carefully, particularly the impact of the operating mode on the efficiency of cleaning different types of contamination and the real feasibility of using pneumatic cleaning systems in operation. To solve the issue of cleaning sensors, cameras, and radar detectors in agricultural machinery, it was investigated how the current structural solutions of the machines can be applied to this task. As part of the study on cleaning sensors, video cameras and radar scanners installed on an agricultural machine, the scientists carried out research on the structural parts of these vehicles, which can be used as elements of a cleaning system. It was established that most self-propelled agricultural machines are equipped with pneumatic systems for suspension, purging the boom, performing maintenance, inflating tyres, and other auxiliary functions. The use of such pneumatic systems makes it possible to use the existing energy source to supply compressed air for sensor cleaning without greatly complicating the structure of the machines.

RESULTS AND DISCUSSION

The first assumption for further consideration of a sensor cleaning system is that most self-propelled agricultural machines are equipped with pneumatic systems for suspension, purging the boom, performing maintenance, inflating tyres, and other auxiliary functions. This creates the possibility of using the existing compressed-air network as a power source for sensor cleaning without complicating the design of the machine. Therefore, it can be concluded that the pneumatic cleaning system is a technically and economically justified solution for its introduction into agricultural machines. Due to the above, in the proposed classification, this type takes precedence. Based on the systematisation and generalisation of the resulting data using an abstract-logical approach, a classification of the main types of cleaning systems of sensors adapted for the purpose of use in agricultural machines has been developed (Fig. 1). In the proposed classification system, information on common technical solutions for cleaning sensors in various sources (scientific articles, patents, technical documentation) was generalised, according to the authors' observations. Classification is implemented according to the spray pattern, configuration, operating modes, and type of the working-medium feed. This approach allows for the systematisation of sensor cleaning systems according to key characteristics of the performance and implementation areas.

According to the spray pattern. The first criterion (and one of the main ones) is the shape of the flow from the nozzle, as this affects the efficiency of the process of cleaning the sensors from various contaminants. The nozzles provide direction and characteristics of the flow as it exits the enclosed duct. When passing the medium through the nozzle, the flow velocity at the exit increases and its direction changes into different shapes depending on the shape of the outlet. These shapes are conical spray, flat spray, and circular spray. The types of spray patterns are shown in Figure 2, and the specific applications of each are summarised in Table 1.

According to spray pattern
- Conical spray pattern
- Hollow cone
- Full cone
- Solid jet

According to design type
- Integrated
- Separate

According to operating mode
- Continuous-operation systems
- Variable-frequency operation systems

According to supply type
- Air-based systems
- Combined systems

Figure 1. *Classification of cleaning systems according to different criteria*
Source: *developed by the author*

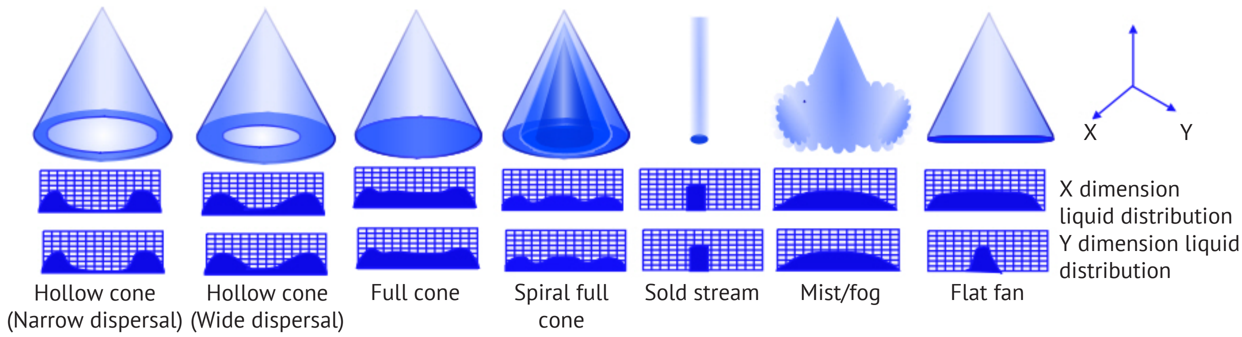


Figure 2. *Spray pattern types of nozzles*
Source: *The Spray Nozzle People (n.d.)*

Table 1. *Application characteristics of different spray patterns*

Type	Characteristics	Field of application
Conical spray pattern	Produces a cone-shaped airflow; provides uniform coverage over a large area with a spray angle of 15°-145°; formed through a simple outlet or deflector surface.	Cleaning of wide optical surfaces, front-facing cameras, and radar antennas with flat geometry.
Hollow cone	Concentrates airflow along the cone perimeter in a fan-shaped pattern; formed by axial, tangential, or spiral nozzles; characterised by high performance but increased air consumption.	Removal of contaminants from the edges of optical elements and wide LiDAR panels.
Full cone	Ensures uniform airflow distribution across the entire cone area; spray angle of 30°-170°; formed by axial, tangential, or spiral nozzles.	Cleaning of flat camera surfaces, wide LiDAR windows, and surfaces with evenly distributed contamination.

Table 1. Continued

Type	Characteristics	Field of application
Solid jet	Narrow, focused airflow; low air consumption; high energy concentration over a small area; effective in pulsed operation mode.	Localised cleaning of small optical elements; used in combination with wide spray patterns or specialised lens surfaces.

Source: *developed by the author*

A conical spray pattern forms a cone-like airflow and has a homogeneous airflow on a large surface area of the detector and a defined opening angle. The spray angles for flat spray patterns can vary from 15° to 145° depending on the nozzle design (Fig. 3). The spray pattern can be obtained by using a simple orifice or a jet deflection on a specially shaped reflective surface.

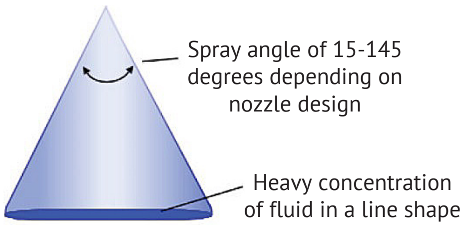


Figure 3*. Conical spray pattern*
Source: *The Spray Nozzle People (n.d.)*

A hollow cone is a fan-like airflow spray pattern (Fig. 4). In the hollow cone, the air flow is concentrated on the contour of the cone, making it ideal for cleaning the edges of optical elements. Similar to other spray patterns, spray angles may vary from 15° to 145° depending on nozzle design. The spray pattern can also be generated by using a simple orifice or a jet deflection on a specially shaped reflective surface (Fig. 4).

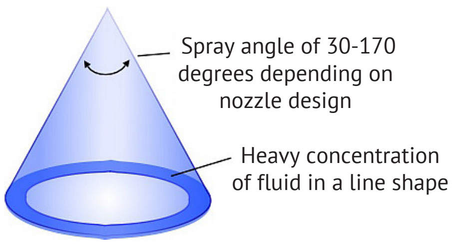


Figure 4*. Hollow cone*
Source: *The Spray Nozzle People (n.d.)*

The hollow cone pattern is produced by three main types of nozzle designs:

- Axial swirl nozzles – internal channels (vanes) impart a swirling motion to the airflow before it exits the orifice.
- Tangential swirl nozzles – airflow is set into rotational (vortical) motion due to an offset outlet positioned perpendicular to the feed channel.
- Spiral nozzles – airflow impacts a protruding spiral surface, which breaks the flow into finer particles.

These spray patterns are used to clean the front-view camera, wide LiDAR panel, and radar antenna of flat geometry. A spray pattern has the advantages of high cleaning performance and uniformity for cleaning on a large surface area of the target object, but it also has disadvantages such as increased air flow and possible dispersion of contaminants to the neighbouring surface area. A full cone spray pattern is a spray pattern that gives a uniform airflow over the entire area of the cone. The pattern is well-suited for cleaning the flat camera surfaces and wide windows of LiDARs. In the study by S. Son *et al.* (2024) on the optimisation of the spray cleaning performance for LiDAR sensors, the full cone spray pattern was used. The cone angle usually varies between 30° and 170° depending on nozzle design (Fig. 5). The full cone can be formed using the axial and tangential swirl nozzle and spiral nozzle.

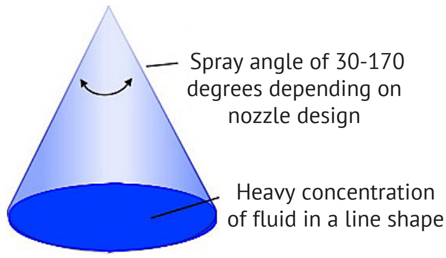


Figure 5*. Full cone*
Source: *The Spray Nozzle People (n.d.)*

A solid jet is a spray pattern that has a concentrated airflow in a narrow stream. A solid stream is a concentrated stream of air with simple geometry. This is produced by directing the air into an orifice of special shape, which forms the solid stream as a narrow jet. The main advantage of such a spray pattern is its high impact intensity in a small area, as well as its low air consumption. In the pulsed mode, it has a pronounced mechanical cleaning effect. Its main limitation is the very small working area, which requires its use in combination with specialised lens-based surfaces or together with wider spray patterns (Fig. 6).

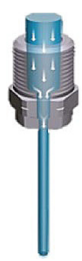


Figure 6*. Solid jet*
Source: *Lechler (n.d.)*

According to the design type. According to the structural layout, pneumatic cleaning systems can be classified into two main types: the integrated and the separate. In an integrated design, the lens (an optical element in the sensor) and cleaning unit are located in the same enclosure. It is possible in two variants: (1) in the form of a monolithic single unit located inside the machine structure; (2) in the form of a separate unit located outside the structure. The first type describes a single monolithic part that is included in the machine body, where the cleaning nozzles and the sensor lens are part of the same unit, which is integrated into the casing or chassis of the vehicle. The air channels are also included in the body of the vehicle. An example of this kind of solution is presented in the patent WO2016045828, showing a device in the form of a compact module with an integrated air cleaning mechanism (Fig. 7).

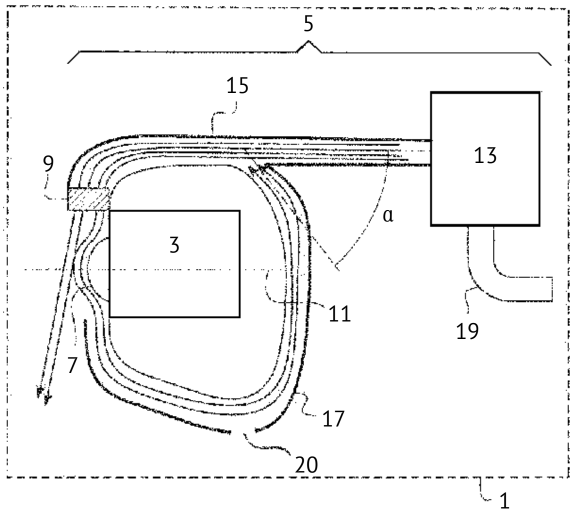


Figure 7. *Design of an integrated cleaning system*
Note: *3 – optical sensor; 5 – protective housing for the optical sensor; 7 – convex optics; 9 – nozzle; 11 – optical axis; 13 – air pump; 15 – outlet channel; 17 – suction channel; 19 – air inlet; 20 – condensate drainage opening*
Source: *PatentScope (n.d.a)*

Invention relates to a device for protecting an optical sensor including at least one nozzle (9) for jetting air in front of the optical sensor (3), wherein said jet nozzle is arranged at one side of the optical sensor and fluid connected to an air pump (13) via an exhaust duct (15) such that an air jet emitted by said jet nozzle is parallel to the optical sensor surface, and at least one suction duct (17) is arranged at a side of the optical sensor opposite to said jet nozzle. The suction duct is fluid-connected to the pump exhaust duct downstream of the pump, such that suction in the suction duct is produced by the Venturi effect. The main advantages of this solution are maximum compactness and protection against external influences.

The second type is an externally located additional separate unit, where the sensor and cleaning device make up a separate unit, which is mounted on the outside of the machine, the nozzles being mounted around or above the lens. Patent WO2018130610 (PatentScope, n.d.b) served as a sample to create a separate unit design with telescopic nozzles (Fig. 8).

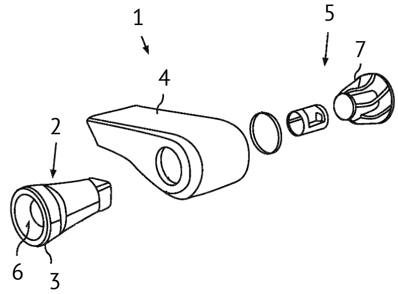


Figure 8. *Design of a separate cleaning system*
Note: *1 – camera for a motor vehicle; 2 – camera for detecting the surrounding environment; 3 – lens unit; 4 – camera holder; 5 – cleaning device; 6 – external surface of the lens unit; 7 – fan element*
Source: *PatentScope (n.d.b)*

The invention relates to a camera (1) for a motor vehicle, comprising a camera (2) for detecting the surrounding environment of the vehicle, where the camera (2) includes a lens unit (3) with at least one lens, a holder (4) for securing the camera (2) to the vehicle, and a cleaning device (5) for cleaning the external surface (6) of the lens unit (3). The cleaning device (5) comprises a fan element (7) mounted on the holder (4) and designed to generate an airflow for cleaning the external surface (6) of the lens unit (3). Among the main advantages of this solution are simplicity of installation and dismantling, the ability to quickly change in case of failure, and versatility in choosing the location on the machine.

Separate design type. The modular type is a set of independent parts, including a lens exposed to the environment and a nozzle system mounted separately. In particular, this principle is used in the cleaning system of a radar camera for the sprayer AGCO/Fendt RoGator 900. The distinctive feature of this configuration is that the sensor is installed at one point, while the nozzles are at a distance and are connected by air lines to the compressor. The separate configuration allows maximum freedom of sensor and equipment placement, adjustment of the angle of incidence of the airflow on the sensor, upgrade of existing sensor systems, independent maintenance and repair of sensors and the cleaning system itself, and the implementation of centralised systems with a distribution system to service several sensors. In agricultural machinery, this type of configuration is common due to the need to protect expensive sensors from mechanical damage, as well as the ability to position the sensor in an optimal position with respect to the working space (Fig. 9). The example in the Raven Industries Manual (n.d.) shows how nozzles were placed taking into account the direction of movement of contamination and the optimal position of sensors relative to the object being scanned during operational tasks. The advantage of this solution is that field maintenance can be carried out without the use of special equipment, as can be seen in the patent WO2016045828, WO2018130610 (PatentScope, n.d.a.; n.d.b).

Figure 9*. Sensor with a separate cleaning configuration*
Source: *Raven Industries Manual (n.d.)*

According to the operating mode variability. By the type of variability of the operating mode, these systems can be divided into systems operating in a constant mode and variable-frequency operation systems. According to G. Sanders & A.V. Keeping (2024), constant-operation systems are characterised by continuous air supply during machine operation, constant pressure and flow velocity, and the formation of an air curtain in front of the sensors, providing uninterrupted protection against contamination. These systems are used in conditions of heavy contamination of working surfaces of the sensors (grain harvesting, processing of straw), in conditions of high speed of movement of agricultural machines as well as critical sensors where loss of visibility even for a short time is unacceptable, for example, sensors of fully and partially autonomous machines of the 4-5th SAE level of automation (Komesker *et al.*, 2024; Liu *et al.*, 2025). The advantages of systems operating in a constant mode are complete protection of sensors of all types of contamination, the lack of switching cycles "on/off", increasing the reliability of operation, simplifying the system, not requiring a complex algorithm for turning on the sensors, as well as the possibility of creating a prevention barrier, preventing contamination deposition on optical surfaces of the sensors. The main drawback of the system is high energy consumption of the compressor (it can reach 3-5 kW in continuous power), and high wear of the machine. In order to reduce the energy consumption of constant operation systems, new technical solutions are used, in particular aerodynamic air knives, instead of traditional nozzles that increase the effectiveness of using compressed air.

The main feature of systems operating in variable frequency mode is that the cleaning operation is periodically carried out, with the possibility of setting the frequency, changing the intensity of the cleaning process depending on the degree of contamination, and setting a certain mode of operation of the sensor depending on the conditions in which the system operates. Its main advantage is energy savings up to 60% compared with systems operating in a constant mode. On the other hand, variablefrequency systems have disadvantages: a relatively complex control system that requires the creation of programmes and parameter configuration (Market Research Future, 2024). The variablefrequency system operates on the principle of pulse modulation, as illustrated in Figure 10.

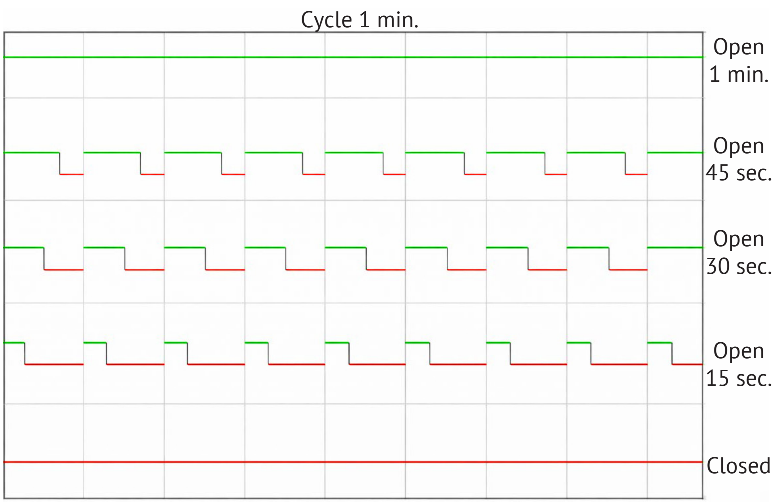


Figure 10*. Operating cycles of the air valve*

Source: *X. Fan (2020)*

According to the type of medium supply. The air-based systems use only clean air to clean sensors. The degree of efficiency in cleaning different types of contamination is largely dependent on their nature. It was determined that it is possible to clean 85-95% of dry dust and 70-80% of plant debris in a single cleaning cycle, while wet contamination in the form of small quantities of mud can be cleaned to only 30-70%; in the case of wet contamination in the form of organic matter (which is very adhesive), this can range from 20% to 60% (Son *et al.*, 2023). However, the main benefits of the air-based systems can be described as the lack of consumables, i.e. liquids, easy maintenance of the system and its operation at sub-zero temperatures, environmental friendliness, high-frequency operation capability, and absence of traces or blurring on the sensor. (Acuity Laser, 2025). At the same time, the system also has significant limitations, in particular, low effectiveness against sticky and wet contamination, high energy consumption, and the requirement for a powerful compressor. The air-based systems are more suitable in dry seasons and regions with little humidity in the air, dry regions or areas with a high amount of sandy soil, during operations in high dustiness (e.g. ploughing, land cultivation or tilling), before cleaning sensors using liquid-based sensor cleaning systems on autonomous machines.

Combined air–liquid systems integrate the positive features of both air and liquid-based systems to achieve maximum performance (XenomatiX, 2022). Such systems can be built based on different sequential principles. Air pre-blowing can be applied for 0.5-1 seconds for cleaning large and dry contaminants, followed by liquid spraying for 1-2 seconds for removing sticky contaminants, finishing with air blowing for 1-2 seconds to remove liquids. The second configuration is based on simultaneous operation, where the liquid is delivered as a fine aerosol, and the airflow simultaneously disperses the liquid and removes contaminants using specialised dual-component nozzles. The third one is adaptive, which means the system will automatically choose the appropriate mode depending on the type of contaminants: dry dust – air mode, sticky contaminants – air–liquid combined mode, and critical contamination – liquid cleaning (Solero Technologies, n.d.). The component base of the combined systems includes the components of the air-based system and adds a liquid tank, liquid pump, heating system (optional), dual nozzles (separate), nozzle for air and liquid, liquid sensors, and a controller of operating modes.

The working fluid can be used for different purposes: distilled water, water solutions with added detergents or surfactants, water solutions with surfactants that reduce the temperature needed for water freezing, or alcohol-based water solutions for low-temperature operation. In the research by S. Son *et al.* (2024), the performance of the liquid cleaning system is investigated by examining various influencing factors such as washer pressure, spray time, spray angle, and spray distance. In this regard, it was shown that the degree of cleaning increased with the increase in pressure and spray time. The highest percentage of cleanability was achieved when the point of impact was located at a distance of 10 mm, and the angle of spraying in the range from 20° to 30° (Fig. 11). A fan-type washer nozzle with a spraying angle of 60° was applied in the experiment, which is typical of most washer nozzles.

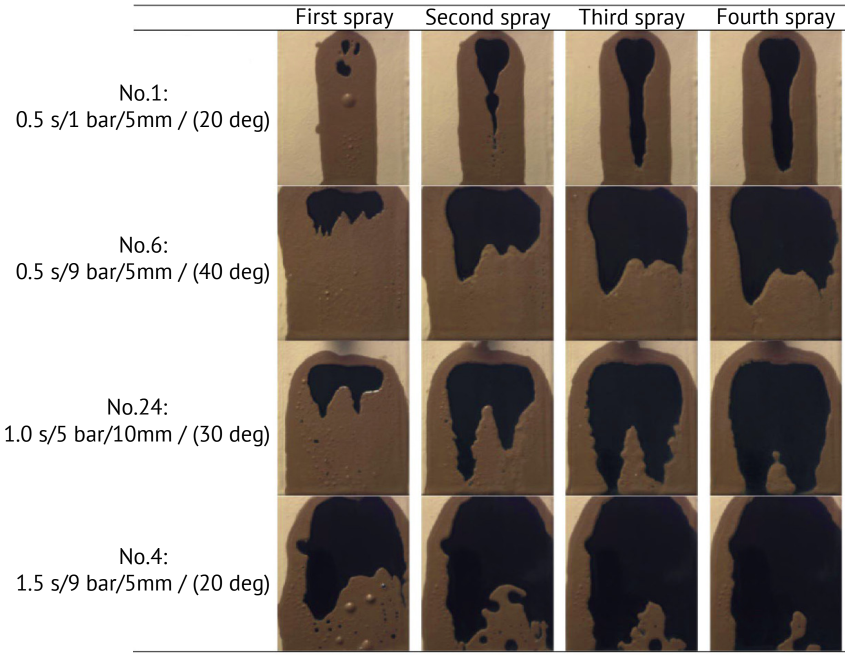


Figure 11. *Sample photographs of experimental results under four standard conditions*
Source: *S. Son et al. (2024)*

The main advantages of these systems are their universality, high efficiency of cleaning different types of contaminants, the possibility of operation in a wide temperature range, and economic consumption of liquid during final blowout with air. However, the disadvantages of these systems are a more complex design and cost, the need to maintain two subsystems, and greater mass and dimensional characteristics compared with simple systems using only air for cleaning (Valeo, 2024). A drawback of combined systems is a temporary deterioration of the sensor performance due to the presence of water droplets on it, which substantially reduces the visibility of the background and causes blurred image artefacts. Such problems were discussed in the study of R. Qian *et al.* (2018), where the authors noted that areas occluded by droplets cannot be detected by cameras, and information about the background is mostly lost. To solve this problem, generative neural networks based on machine learning methods are used.

Examples of practical implementation of combined systems of sensor cleaning are numerous technical solutions developed by leading manufacturers for the automotive industry. Some of them use separate nozzles with a liquid spray element and an additional air channel for drying off the remaining liquid. This type of system provides effective cleaning and drying of the sensor surface. Such cleaning systems are designed for cleaning the window of LiDAR under various weather conditions using a combination of water and air. In this case, the system cleans rainwater, dust, and other contaminants. It may also have a defrosting function, allowing it to operate in cold weather. Some other systems are equipped with nozzles with adjustable pressure and variable flow intensity to ensure the economic consumption of liquid and the stable operation of the sensor at high vehicle speeds. In modern industrial designs, an adaptive system of sensor cleaning is used in which the pressure of spraying and the flow rate are automatically adjusted depending on the degree of the sensor surface contamination, as well as the operating mode of the system (Vitesco Technologies, 2024).

Combined systems are most appropriately applied under conditions of variable weather factors and high levels of contamination. Such systems are especially relevant for autonomous machines of classes 3-5, for which it is important to maintain continuous, reliable operation of sensors and for systems that have long-term operation cycles, which exclude the possibility of manual cleaning of equipment. Similar operating conditions apply to military machines that have been retrofitted to operate autonomously. Solutions for this type of equipment are described in an article by a manufacturer of electronic surveillance and control systems (Ascencione, 2024).

In terms of recommendations for the usage of different types of systems, air systems are the best choice for dry conditions; dry mineral dust; where water is unavailable; where weight constraints exist; where air temperature is below zero, and if no heating system is installed for the sensor. In contrast, combined systems are appropriate for varying operating conditions, when there are adhesive organic contaminants on the sensors; when a high degree of reliability is required for the sensor operation; during long operating cycles; and when machines operate autonomously without operator intervention. Washing system companies are developing more advanced and "smart" sensor cleaning systems that can keep more than 10 objects clean using a water pressure of up to 7 bar and are built around a single integrated infrastructure (Valeo, n.d.; Solero Technologies, n.d.; Schafer Technologies, n.d.). Thus, the current state of development of sensor cleaning systems is typical of agricultural machinery development: from simple devices such as air nozzles to multifunctional combined solutions with centralised washing and cleaning systems with separate infrastructure. Further development of such systems towards higher levels of automation and reduced energy consumption is a necessary condition for the reliable operation of autonomous agricultural machinery at SAE levels 3-5.

CONCLUSIONS

In conclusion, based on the results of the analytical review and comparative analysis of the reviewed scientific and technical literature, it was found that pneumatic systems for cleaning sensors are classified by the following key parameters: design, air flow pattern, modes of operation, and type of working substance. At the same time, these parameters play a significant role in the effectiveness of pneumatic cleaning systems under different operating conditions. The review results show that the stability and efficiency of visual, radar, and LiDAR sensors for agricultural machinery directly depend on the cleanliness of cleaning systems. Contamination of the sensor in the form of dust, mud, plant residues, moisture and others has a negative impact on sensor operation, reducing the quality of transmitted signals and accuracy of measurements. This, in turn, reduces the efficiency of automatic steering systems for agricultural machines. During the study, existing technical solutions were analysed and generalised, and classified based on the most relevant criteria: airflow pattern, structural configuration, operating modes, and type of working medium. It has been established that pneumatic systems are structurally simple, do not rely on consumables and are effective at removing dry contaminants; however, their effectiveness is significantly reduced in the presence of moisture or sticky substances. Conversely, the most versatile and efficient are the combined air-liquid systems that can effectively clean sensors from various types of contamination due to the complex mechanical effect of the airflow and the physicochemical effect of the liquid.

The study results showed that the appropriateness of a particular type of system for cleaning depends on the machine's operating conditions, the nature of contamination, continuity of sensor operation, and the constraints of machine operation. Using existing systems based on a pneumatic drive for cleaning sensors in agricultural machinery does not significantly change the machine's design, which is a positive factor for implementation. Future studies should focus on the development of adaptive intelligent systems for sensor cleaning, which automatically determine the type of contamination and degree of contamination and select optimal operating modes for cleaning systems. Additional experimental research under field conditions will be necessary to adjust energy parameters, optimise the design of the nozzles and air and liquid supply modes. Attention should also be focused on the integration of the cleaning system with the data processing algorithms of the sensors, which should provide more reliable operation of automatic steering systems, increasing the efficiency of agricultural machinery.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

REFERENCES

[1] Aarif, M.K.O., Alam, A., & Hotak, Y. (2025). Smart sensor technologies shaping the future of precision agriculture: Recent advances and future outlooks. *Journal of Sensors*, 1, article number 2460098. doi: 10.1155/js/2460098.
[2] Acuity Laser. (2025). *Cleaning and maintaining laser sensors in dusty environments*. Retrieved from https://www.acuitylaser.com.
[3] Adamchuk, V.V., Perepelytsia, N.M., & Hrytsyshyn, M.I. (2026). Intellectual agriculture – a determinant of innovative development of technical support of agricultural production. *Bulletin of Agricultural Science*, 2(875), 42-51. doi: 10.31073/agrovisnyk202602-05.
[4] Artyukh, O., Ruban, D., Tarasenko, O., Petriuk, Yu., & Ruban, H. (2025). Unmanned transport. Modern technologies, challenges, and prospects. *Science and Technology Today*, 5(46), 1159-1198. doi: 10.52058/2786-6025-2025-5(46)-1159-1198.
[5] Ascencione. (2024). *2025 vision sensor lens cleaning: Enabling undefeatable autonomous vehicles with essential lens maintenance*. Retrieved from https://ascencione.com.
[6] Babiy, L., Yurkiv, M., Chetverikov, B., & Burshtynska, H. (2026). Accuracy of GPS and RTK navigation and their impact on reducing overlaps and losses during field work. *Precision Farming*, 1(2), 25-34. doi: 10.23939/pa2025.02.025.
[7] Debnath, S., Paul, M., & Debnath, T. (2023). Applications of LiDAR in agriculture and future research directions. *Journal of Imaging*, 9(3), article number 57. doi: 10.3390/jimaging9030057.
[8] Fan, X. (2020). Discuss and provide examples for the PWM Process. In *Proceedings of the 5th international workshop on materials engineering and computer sciences (IWMECS)*. doi: 10.25236/iwmecs.2020.011. London: Francis Academic Press.
[9] Karim, R., Reza, N., Jin, H., Haque, A., Lee, K.-H., Sung, J., & Chung, S.-O. (2024). Application of LiDAR Sensors for crop and working environment recognition in agriculture: A review. *Remote Sensing*, 16(24), article number 4623. doi: 10.3390/rs16244623.
[10] Komesker, M., Meltebrink, C., Ebenhöch, S., Zahner, Y., Vlasic, M., & Stiene, S. (2024). Validation scores to evaluate the detection capability of sensor systems used for autonomous machines in outdoor environments. *Electronics*, 13(12), article number 2396. doi: 10.3390/electronics13122396.
[11] Lechler. (n.d.). *Nozzle spray patterns and classification*. Retrieved from https://www.lechlerusa.com.
[12] Liu, Q., Yu, R., Suo, H., Cai, Y., Chen, L., & Jiang, H. (2025). Autonomous driving in agricultural machinery: Advancing the frontier of precision agriculture. *Actuators*, 14(9), article number 464. doi: 10.3390/act14090464.
[13] Market Research Future. (2024). *Automotive sensor cleaning system market*. Retrieved from https://www.marketresearchfuture.com.
[14] Matos, F., Bernardino, J., Durães, J., & Cunha, J. (2024). A survey on sensor failures in autonomous vehicles: Challenges and solutions. *Sensors*, 24(16), article number 5108. doi: 10.3390/s24165108.
[15] Nikoliuk, O., Pyvovar, P., Nazarkina, R., Stolnikovych, G., & Bohonos, M. (2024). *Dynamics of the land fund: How land resources of Ukraine have changed after February 24, 2022*. Retrieved from https://kse.ua.
[16] Osadchyi, I. (2025). Investigation of pneumatic cleaning system effectiveness for radar navigation sensors on self-propelled sprayers in field conditions. *Technology, Energy, Agriculture Transport AIC*, 3(130), 89-98. doi: 10.37128/2520-6168-2025-3.
[17] PatentScope. (n.d.a). *WO2016045828 – device for protection of an optical sensor*. Retrieved from https://patentscope.wipo.int.

[18] PatentScope. (n.d.b). *WO2018130610 – camera device for a motor vehicle with a cleaning device for providing the air stream, camera system as well as motor vehicle*. Retrieved from https://patentscope.wipo.int.
[19] Qian, R., Tan, R.T., Yang, W., Su, J., & Liu, J. (2018). Attentive generative adversarial network for raindrop removal from a single image. *arXiv*. doi: 10.48550/arXiv.1711.10098.
[20] Raven Industries Manual. (n.d.). *Radar row guidance and air knife kit for AGCO/ Fendt RoGator 900 with Factory VSN* .Retrieved from https://files.coakleytech.com.
[21] Sanders, G., & Keeping, A.V. (2024). *I can see clearly now: Keeping AV sensors clean in inclement conditions*. Retrieved from https://www.wardsauto.com.
[22] Schafer Technologies. (n.d.). Retrieved from https://www.schaeffler.com.
[23] Shi, J., Bai, Y., Diao, Z., Zhou, J., Yao, X., & Zhang, B. (2023). Row detection-based navigation and guidance for agricultural robots and autonomous vehicles in row-crop fields: Methods and applications. *Agronomy*, 13(7), article number 1780. doi: 10.3390/agronomy13071780.
[24] Solero Technologies. (n.d.). *Electromagnetic 3/2-way valve for ADAS sensor cleaning systems*. Retrieved from https://solerotechnologies.com.
[25] Son, S., Lee, W., Jung, H., Lee, J., Kim, C., Lee, H., Cho, S., Jang, J., Lee, M., & Ryu, H.-C. (2023). Experimental analysis of various blockage performance for LiDAR sensor cleaning evaluation. *Sensors*, 23(5), article number 2752. doi: 10.3390/s23052752.
[26] Son, S., Lee, W., Lee, J., Lee, J., Lee, H., Jang, J., Cha, H., Bae, S., & Ryu, H.-C. (2024). Examining the optimization of spray cleaning performance for LiDAR sensor. *Applied Sciences*, 14(18), article number 8340. doi: 10.3390/app14188340.
[27] The Spray Nozzle People. (n.d.). *Guide to spray properties: Fluid distribution*. Retrieved from https://www.spray-nozzle.co.uk.
[28] Valeo. (2024). *LiDAR cleaning: Sensor cleaning system*. Retrieved from https://www.valeo.com.
[29] Vargas, J., Alsweiss, S., Toker, O., Razdan, R., & Santos, J. (2021). An overview of autonomous vehicles sensors and their vulnerability to weather conditions. *Sensors*, 21(16), article number 5397. doi: 10.3390/s21165397.
[30] Vitesco Technologies. (2024). *Advanced sensor cleaning system*. Retrieved from https://www.vitesco-technologies.com.
[31] XenomatiX. (2022). *Sensor cleaning*. Retrieved from https://xenomatix.com.

Аналіз та класифікація систем очистки візуальних датчиків сільськогосподарських машин

Ігор Осадчий
Аспірант
Національний університет біоресурсів та природокористування України
03040, вул. Васильківська, 17, м. Київ, Україна
https://orcid.org/0009-0003-7167-589X

Анотація. Метою дослідження було проаналізувати та класифікувати варіанти систем очистки датчиків, які встановлюються на сільськогосподарських машинах, якість роботи яких напряму впливає на можливість використання техніки в польових роботах. Проаналізовано вплив різних типів забруднень на ефективність систем очищення датчиків пилом, брудом, пожнивними рештками та іншими матеріалами, які супроводжуються експлуатацією машин та обладнання. Під час дослідження застосовувалися монографічний та абстрактно-логічний методи, що дозволили скомпонувати наукові джерела, в яких описувалися технічні рішення, випробувані в лабораторних та практичних середовищах. Проведено класифікацію систем очищення за формою факела, де описано 4 типів з основними характеристиками. В описі конструктивного виконання було розглянуто два варіанти – інтегрований та зовнішній. Результати огляду показали перевагу інтегрованої конструкції через свою захищеність від зовнішніх впливів та максимальну компактність. Роботу систем очистки було поділено на режими з постійним та змінним часом пульсації. Кожен з режимів має свою ефективність в залежності від типу забруднення. Встановлено, що з сухим забрудненням ефективніше працювати пульсуючим режимом, тоді як з вологим забрудненням – режимом постійної роботи. Також розглядалися комбіновані повітряно-рідинні системи, їх конструктивні особливості з описом принципів роботи. Дослідження показало, що повітряні системи очищення найкраще інтегруються на техніку та можуть використовувати наявні компоненти, які передбачені інженерами для виконання інших задач, що, в свою чергу, робить таке рішення економічно ефективнішим. В залежності від типів забруднень, система обдуву може легко змінювати режим роботи повітряного обдуву та забезпечити максимальну ефективність очистки. Отримані результати можуть бути використані при розробці та модернізації систем очищення датчиків у сучасній сільськогосподарській техніці з елементами автоматичного та автономного керування. Базуючись на наукових та власних дослідах, вивчити які типи систем очистки можуть бути актуальними під час роботи радарних датчиків на полі та визначити вплив забруднень на якість ведення та стабільність роботи системи в цілому

Ключові слова: точне землеробство; радари; забруднення; пневматична система; самохідна техніка; система автоводіння