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Determination of the position and geometric parameters of agricultural machinery for automated control of the washing process

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ABSTRACT

The article develops and experimentally verifies a method for determining the position and geometric parameters of agricultural machinery for automated washing process control. The method combines photoelectric sensors for verifying the admissible position of the machinery and ultrasonic sensors for determining distances to its upper and side surfaces. Median filtering is used to reduce the influence of anomalous ultrasonic measurements, while the measured distances are converted into geometric parameters using the known dimensions of the experimental installation. The obtained parameters are used by the controller to define the permissible operating area and generate control actions for the washing carriage, pump, and air-blowing system. If the machinery is positioned incorrectly or exceeds the permissible dimensions of the working zone, the technological cycle is blocked. Experimental verification using the developed automated washing installation and a tractor model confirmed correct operation of the positioning subsystem and sufficient accuracy of ultrasonic measurements. The maximum absolute error did not exceed 2 mm. The proposed approach provides direct integration of sensor measurements into the control logic and enables adaptation of the washing cycle to the actual position and dimensions of the machinery. Further research should address the integration of computer vision and adaptive generation of washing-carriage trajectories.

Keywords: Agricultural machinery; automated washing; sensor subsystem; ultrasonic sensing; photoelectric sensing; geometric parameters; positioning; automated control; washing installation

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Introduction. During operation, agricultural machinery comes into contact with soil, plant debris, dust, lubricants, and other contaminants, so cleaning it is an essential part of maintenance. In practice, this process is often performed manually or using systems with preset operating modes [19]. At the same time, tractors, combines, sprayers, trailers, and other machines differ significantly in height, width, and the configuration of their external surfaces, which requires adapting the automated cleaning process to the specific machine. The development of automated and robotic systems in agriculture requires coordinated interaction between sensor, actuator, and control components [3], [18].

For an automated washing system, it is necessary to verify the correct positioning of the equipment and determine its basic geometric parameters before the start of the work cycle. This information can be used to set the permissible limits of the washing carriage's movement, configure the operating modes of the pump and the air-blowing system, and halt the cycle in the event of an incorrect position or exceeding the permissible dimensions.

Modern cyber-physical and computer-integrated systems enable interaction between sensors, controllers, actuators, and data transmission devices [20]. In such systems, information about the state of a physical object is used to generate control actions [11]. A similar principle is implemented in digital twin technologies [14], particularly in smart farming, where the digital representation of an object is updated based on data about its current physical state [22], [17].

In previous studies, the authors developed architecture for a cyber-physical system for washing agricultural machinery that combines the physical, sensor, computational, and interface levels [21], as well as a digital twin of the washing process, in which the geometric parameters of the equipment

are used as input data to determine the system's operating modes [7]. However, the practical implementation of this approach requires accurate determination of the position and dimensions of the real object directly within the installation's working area. Solving this problem is the subject of this study.

Analysis of literary data. Infrared, photoelectric, ultrasonic, magnetic, optical, LiDAR, and radar sensors are used to determine the presence, position, and geometric parameters of vehicles. The choice of a specific sensor depends on the required accuracy, operating distance, and operating conditions. The works by T. Perković et al. [16] and A. Fahim et al. [6] show that ultrasonic and infrared sensors are among the most common methods for contactless vehicle detection.

Photoelectric and infrared sensors are suitable for determining whether a given boundary has been crossed or whether an object is present in a monitored position. Their discrete output signal can be used directly by a controller to enable or disable a process operation. Experimental studies by M. Bachani and co-authors [2] confirm the effectiveness of infrared sensors for detecting the presence of vehicles and the importance of their correct spatial positioning. In an automated car wash, such sensors can be used to verify that a vehicle is in the correct position before measuring its geometric parameters.

Ultrasonic sensors are widely used for noncontact measurement of the distance to an object's surface; their operating principle is based on measuring the time it takes for an ultrasonic pulse to travel to the surface and back. The specifics of such measurements in transportation systems have been studied by A. Carullo and M. Parvis [5]. S. Y. C. Hong and co-authors [9] used ultrasonic sensors in conjunction with the ESP8266 to detect the presence of a vehicle and transmit the obtained data to a server. This approach aligns with the trend of integrating IoT sensors into agricultural information and control systems [1], [10].

The accuracy of ultrasonic measurements depends on the distance to the object, the angle of inclination, and the material of its surface. Experimental studies by A. Haq and co-authors [8] showed that the most stable results are obtained when the surface is nearly perpendicular to the direction of the ultrasonic beam. The need for additional processing and correction of such measurements has also been confirmed by A. Paul and co-authors [15], who proposed a two-stage correction of ultrasonic sensor data for parking systems.

For automated washing, the task is complicated by the irregular geometry of agricultural machinery: the cab, wheels, fenders, mirrors, and attachments form surfaces at varying distances from the sensor. Therefore, a single reading from an ultrasonic sensor cannot directly determine the machine's overall dimensions without taking into account the sensor's mounting location, the geometry of the working area, and the measurement processing algorithm.

Computer vision is also used in automatic car wash systems. H. Lim, C. Nam, and S. J. Lee [12] proposed a system for detecting a vehicle's exterior elements before and during washing to prevent the equipment from coming into contact with protruding parts of the vehicle. Computer vision provides more detailed information about an object's shape but requires cameras, additional computing resources, and specialized image processing algorithms.

For the initial determination of the position and basic dimensions of agricultural machinery, a simpler combined sensor system is appropriate, one that combines photoelectric sensors to monitor correct positioning and ultrasonic sensors to determine distances to characteristic surfaces of the machine [4].

The proposed approach is consistent with modern approaches to integrating digital twins with agricultural machinery and robotic systems [13]. In previous works by the authors, the architecture of a cyber-physical system for automated washing [21] and its digital twin [7] were developed; however, the experimental determination of the geometric parameters of a real object directly using a physical setup was not investigated separately.

At the same time, the joint determination of the position and geometric parameters of agricultural machinery directly within the working zone of the washing system, with subsequent use of the obtained data for automated control of the technological process, remains insufficiently studied. A distinctive feature of this task is the direct use of sensor measurement results in the

automated control loop. After confirming the permissible position of the machinery, the determined geometric parameters must be used to set the movement limits of the washing carriage and to generate commands for the actuators.

The purpose and objectives of the research. To adapt the automated washing cycle to a specific object, it is necessary to accurately determine its position and key geometric parameters directly within the system's working area.

The aim of this study is to develop and experimentally validate a method for determining the position and geometric parameters of agricultural machinery in the working area of an automated washing system using photoelectric and ultrasonic sensors, with the resulting data subsequently used for automated control of the washing process.

To achieve this objective, the following **tasks** must be addressed:

- justify the structure of the sensor subsystem and develop a method for determining the position and geometric parameters of agricultural machinery within the system's working area;
- develop an algorithm for using the determined position and geometric parameters of the machinery to generate control parameters for the washing carriage and actuators;
- experimentally evaluate the accuracy of determining the position and geometric parameters of the machinery and verify the use of the obtained data in generating an automated washing cycle.

Research methods. To determine the position and geometric parameters of agricultural machinery, a sensor subsystem has been developed that sequentially verifies the validity of an object's placement and non-contactly determines its geometric parameters. The central controller uses the obtained data to generate operating parameters for the actuators.

The experimental setup includes a movable washing carriage equipped with a NEMA 17 17HS8401 stepper motor and a TB67S109AFTG driver, a diaphragm pump with nozzles, and fans for the air-blowing system. The carriage's end positions are monitored by LJ8A3-2-Z/BX and LJ12A3-4-Z-BX inductive sensors. A FAIH/00-0E–FAID/BP-0E photoelectric sensor pair is used to monitor the object's position, while HC-SR04 ultrasonic sensors are used to determine the distance to its surfaces. Signal processing and control are handled by an ATmega2560-based controller, while the ESP8266 provides the web interface and transmits data to an MQTT server (Fig. 1).

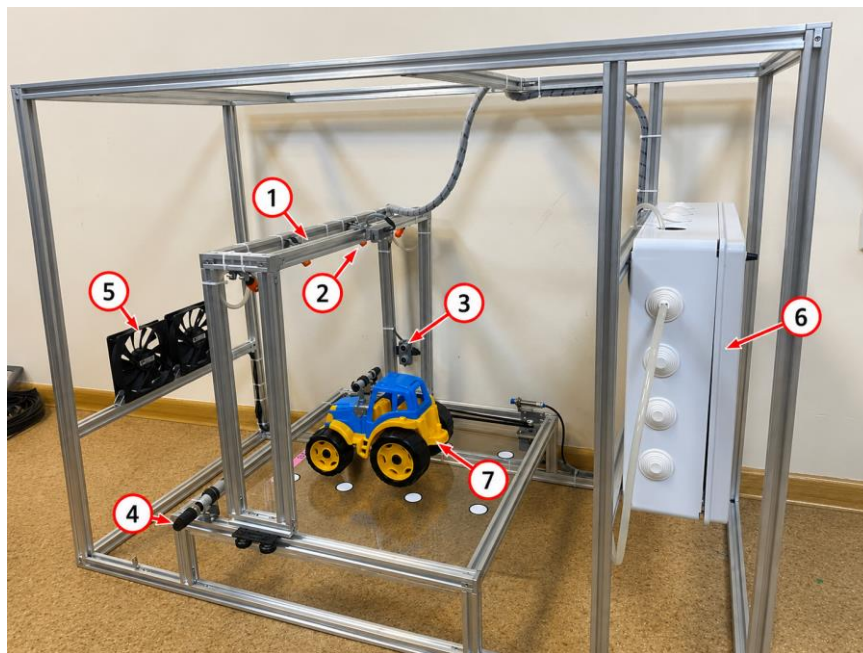


Fig.1. General view of the experimental setup for determining the dimensions and position of agricultural machinery and for automated control of the washing process:
1 – movable washing carriage; 2 – nozzles; 3 – ultrasonic sensor; 4 – photoelectric position sensors; 5 – blow-off system fans; 6 – control unit; 7 – tractor model

Source: compiled by the authors

The sensor circuit combines the PE₁ and PE₂ photoelectric channels to monitor the machine's permissible position and the US₁ and US₂ ultrasonic channels to determine the distances to its top and side surfaces, respectively (Fig. 2).

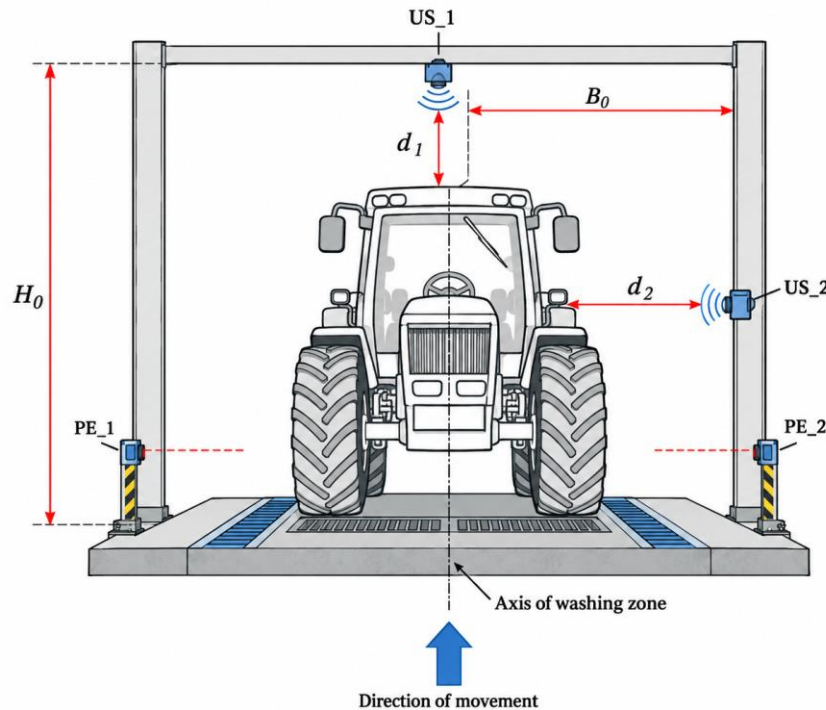


Fig.2. Scheme for determining the position and geometric parameters of agricultural machinery in the working area of an automated system

Source: compiled by the authors

The upper channel, US₁, measures the distance d_1 to the top surface of the equipment, while the side channel, US₂, measures the distance d_2 to its right surface. Based on the known design dimensions of the system, these measurements are used to determine the object's height and the coordinates of its side contour. The photoelectric channels PE₁ and PE₂ generate discrete signals indicating the object's position and are used to enable or block progression to subsequent stages of the automated cycle.

For the experimental setup, the design parameters were $H_0 = 390$ mm and $B_0 = 235$ mm and remained constant throughout the experiments.

The state of each photoelectric channel, PE₁ and PE₂, is represented by a binary variable. The indicator of a valid machine position is determined by comparing the current combination of signals with a specified valid configuration:

$$K_p = \begin{cases} 1, & P = P^*, \\ 0, & P \neq P^*. \end{cases} \quad (1)$$

Upon $K_p = 0$ initiation, the ultrasonic measurements and actuators are enabled. Once the condition is met, $K_p = 1$ the geometric parameters are determined. For this purpose, an ultrasonic distance measurement method is used, based on measuring the time it takes for a sound pulse to travel from the transducer to the object's surface and back.

The distance from the i -th ultrasonic sensor to the surface is defined as:

$$d_i = \frac{c \cdot t_i}{2}, \quad (2)$$

where d_i is measured distance, m; c is speed of sound in air, m/s; t_i is time between the generation of the ultrasonic pulse and the detection of the reflected signal, s.

At an air temperature of approximately 20°C , $c \approx 343\text{ m/s}$ is used in the calculations. For each position of the object, a series of n -th repeated measurements was performed. To reduce the influence of isolated outliers, the resulting distance was determined as the median of the series of measurements:

$$\tilde{d}_i = \text{median}(d_{i1}, d_{i2}, \dots, d_{in}). \quad (3)$$

Median filtering improves the stability of the estimate against unstable reflections from complex-shaped surfaces. The height of the structure is determined based on the upper measurement channel:

$$H = H_0 - \tilde{d}_1. \quad (4)$$

The coordinate of the right contour relative to the chosen reference plane is determined using the lateral channel:

$$y_R = B_0 - \tilde{d}_2, \quad (5)$$

where $\tilde{d}_2$ is the median distance from the right ultrasonic sensor to the surface of the equipment.

Assuming the machine is centered relative to the axis of the work area, its transverse dimension is determined by the formula

$$B = 2|y_R - y_C|, \quad (6)$$

where y_C is the coordinate of the machine's longitudinal axis, the position of which is specified by the positioning system.

Given the known position of the longitudinal axis and the symmetrical placement of the machine, its transverse dimensions can be determined using equation (6). If the positioning subsystem only confirms a valid position without precise centering, the determined coordinate of the right contour is used directly as the boundary of the working area. The main signals and parameters used in the proposed method are given in Table 1.

Table 1. Parameters of the sensor-based subsystem for determining the position and dimensions of equipment

Designation	Parameter	Data Source	Usage
$p_1, p_2, \dots, p_m$	States of the photoelectric sensors	FAIH/00-0E–FAID/BP-0E photoelectric channel	Verification of the admissible vehicle position
K_p	Admissible-position indicator	Result of logical analysis	Permission/blocking of the washing cycle
t_1	Signal travel time of the upper channel	HC-SR04 ultrasonic sensor	Determination of d_1
t_2	Signal travel time of the side channel	HC-SR04 ultrasonic sensor	Determination of d_2
$\tilde{d}_1$	Distance to the upper surface	Calculated value	Determination of vehicle height
$\tilde{d}_2$	Distance to the right-side surface	Calculated value	Determination of lateral position
H	Vehicle height	Calculated according to Eq. (4)	Formation of the working area
y_R	Coordinate of the right-side contour	Calculated according to Eq. (5)	Limitation of the working area
B	Vehicle width	Calculated according to Eq. (6)	Adaptation of the washing-cycle parameters

Source: compiled by the authors

To account for measurement errors, contour irregularities, and safety clearances, the specified geometric parameters are supplemented with manufacturing allowances:

$$H_s = H + \Delta H, \quad (7)$$

$$B_s = B + \Delta B, \quad (8)$$

where ΔH and ΔB are specified process margins that account for sensor measurement errors, irregularities in the equipment's outer contour, and the required safety distance between its surface and the installation components

The resulting set of parameters can be represented as the object's state vector:

$$X = [K_p, H, y_R, B]. \quad (9)$$

Based on what does the central controller generate the control parameter vector:

$$U = f(X) = [L_c, v_c, T_p, T_f, \dots], \quad (10)$$

where L_c is permissible carriage travel length; v_c is carriage travel speed; T_p is pump operating time; T_f is air-blowing system operating time.

The sequence of operations for the proposed method is shown in Fig. 3.

The accuracy of the sensor-based determination of geometric parameters was evaluated by comparison with reference values obtained from direct measurement. For the k -th experiment, the absolute and relative errors were determined:

$$\Delta_k = |x_k - x_k^{ref}|, \quad (11)$$

where x_k is the value obtained by the sensor system; x_k^{ref} is the reference value.

$$\delta_k = \frac{|x_k - x_k^{ref}|}{x_k^{ref}} \cdot 100\%. \quad (12)$$

For a series of N experiments, the mean absolute error MAE , the root mean square error $RMSE$, and the standard deviation were calculated as follows σ :

$$MAE = \frac{1}{N} \sum_{k=1}^N |x_k - x_k^{ref}|, \quad (13)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{k=1}^N (x_k - x_k^{ref})^2}. \quad (14)$$

$$\sigma = \sqrt{\frac{1}{N-1} \sum_{k=1}^N (x_k - \bar{x})^2}, \quad (15)$$

where $\bar{x}$ is the average value of the repeated measurements.

The accuracy of the photoelectric subsystem was evaluated as the proportion of correctly classified positions:

$$A_p = \frac{N_{correct}}{N_{all}} \cdot 100\%, \quad (16)$$

where $N_{correct}$ is the number of correctly identified states; N_{all} is the total number of checks.

Methodology and Conduct of Experimental Studies of the Automated System.

Experimental studies were conducted on the developed automated washing system (Fig. 1) to verify the proposed method, evaluate the accuracy of sensor measurements, and assess the correctness of control actions.

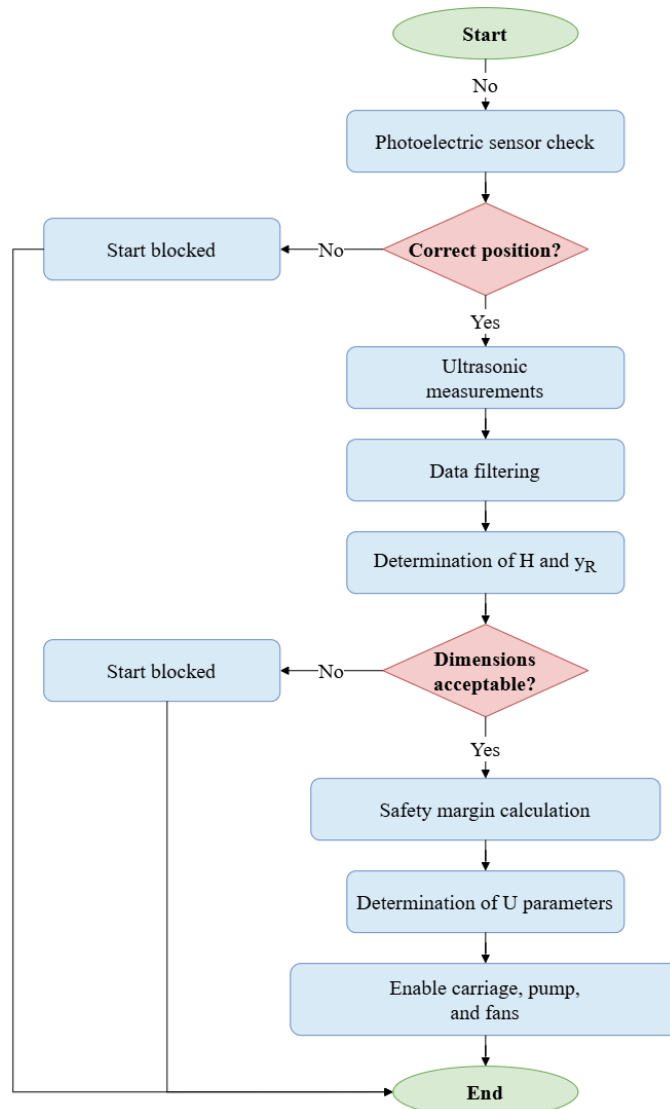


Fig.3. Block diagram of the algorithm for determining the position and geometric parameters of agricultural machinery and for generating automated control parameters
 Source: compiled by the authors

A tractor model was placed in the system's working area, and its position was varied relative to the longitudinal axis. Reference values for position and geometric parameters were obtained through direct measurements and compared with the results from the sensor subsystem.

The experimental studies were conducted in three stages:

- 1) verification of the positioning subsystem;
- 2) evaluation of the accuracy of determining geometric parameters;
- 3) comprehensive verification of the use of the obtained data for automated control.

In the first stage, the PE₁–PE₂ positioning subsystem was tested. The tractor model was placed in the permissible position and in configurations with an offset relative to the working area. For each position, the signals from the photoelectric channels and the Kp signal generated by the controller were recorded, after which the system's output was compared with the actual state of the object. The experimental configurations of the object's position are shown in Fig. 4.

For each configuration, the sensor subsystem's solution was compared with the actual state of the object. Overall positioning accuracy was defined as the proportion of correctly classified positions; false blocking of a valid position and false authorization of a start for an invalid position were monitored separately. In the second stage, the accuracy of determining geometric parameters using the top US₁ and side US₂ ultrasonic channels was evaluated. The design parameters H₀ and B₀ were set according to the values established for the experimental setup.

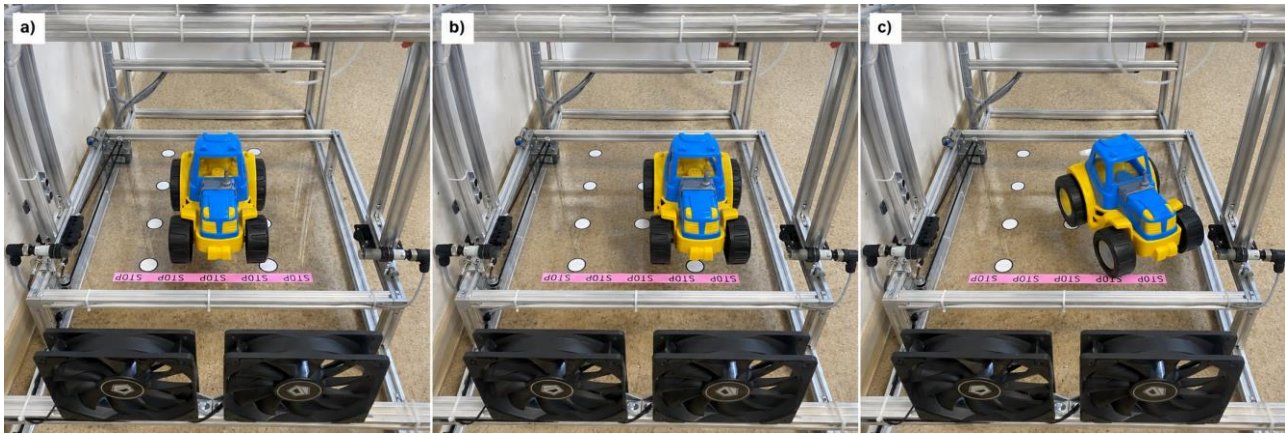


Fig.4. Experimental configurations of the vehicle model in the washing zone:
a – correct position; b – lateral displacement; c – position corresponding to washing cycle blocking

Source: compiled by the authors

For each configuration, the reference values for height and the position of the right contour were determined by direct measurement, and the corresponding sensor readings were calculated from the US_1 and US_2 data according to the relationships given above. For each configuration, a series of repeated measurements was performed, which made it possible to evaluate both the accuracy and repeatability of the sensor readings. To reduce the influence of isolated outliers, the median of the series of repeated measurements was used as the final value. This approach is particularly important for surfaces with complex geometries that produce unstable ultrasonic reflections.

The accuracy of geometric parameter determination was evaluated using absolute and relative errors, MAE, and RMSE, while repeatability was assessed using standard deviation.

To assess possible systematic bias in the sensor measurements, the mean sign error was additionally determined:

$$ME = \frac{1}{N} \sum_{k=1}^N (x_k - x_k^{ref}), \quad (17)$$

where N is the number of experimental observations.

A positive value of ME indicates that the sensory subsystem systematically overestimates the result, while a negative value indicates that it underestimates it.

In the third stage, the interaction between the sensory and executive subsystems was tested. When the object was in a permissible position, the controller performed ultrasonic measurements, determined the geometric parameters, and generated control commands. If the object was in an impermissible position or exceeded the permissible dimensions, the activation of the carriage, pump, and blowing system was blocked.

The functionality of the automated control system was verified by checking whether the unit's response conformed to the specified logic. If the object's position did not fall within the permissible range, the carriage movement and pump activation were blocked. If the position was correct, the system proceeded to determine the geometric parameters and generate the operating cycle. The operation of the inductive limit switches, which limit the carriage's movement at its end positions, was monitored separately. Additionally, the operation of the inductive limit switches at the carriage's end positions was monitored.

Furthermore, the response time was determined t_r – the interval from confirmation of the object's valid position to the controller's generation of a complete set of control parameters. This metric t_r characterizes the time required for the system to transition from confirming the object's position to generating the parameters for the automated cycle.

Results of Experimental Studies and Their Analysis. The results of the experimental studies were analyzed sequentially for the positioning subsystem, the ultrasonic channels for determining

geometric parameters, and the integrated automated cycle. In the first stage, the accuracy of determining the permissible position of the tractor model based on signals from the PE1 and PE2 photoelectric channels was evaluated. The results are presented in Table 2.

Table 2. Results of experimental verification of the vehicle positioning subsystem

No.	Object Position	Actual State	PE_1	PE_2	K_p	System Decision	Correctness
1	Valid position	1	1	1	1	Authorization	Correct
2	Shifted to the left	1	0	0	0	Blocking	Correct
3	Shifted to the right	0	1	0	0	Blocking	Correct
4	Incomplete entry	0	0	0	0	Blocking	Correct
5	Valid position	1	1	1	1	Authorization	Correct

Source: compiled by the authors

For all five reference positions, the system's decision corresponded to the actual state of the object. If the position was valid, the controller allowed progression to the next stage of the cycle; however, in the event of lateral displacement or incomplete positioning, the activation of the actuators was blocked. The position classification accuracy was 100%.

The accuracy of the upper ultrasonic channel US₁ was evaluated for five reference heights in the range of 120-175 mm. The reference values were determined by direct measurement, and the calculated height was determined by the median value of a series of ultrasonic measurements. The results are presented in Table 3.

Table 3. Experimental results of vehicle height determination

No.	H^{ref} , mm	$\tilde{d}_1$, mm	H , mm	Δ_H , mm	δ_H , %
1	120	269	121	1	0.83
2	130	261	129	1	0.77
3	145	245	145	0	0.00
4	160	229	161	1	0.63
5	175	217	173	2	1.14

Source: compiled by the authors

For the upper channel US₁, the absolute error in the studied range did not exceed 2 mm; the maximum relative error was 1.14 %, the MAE was 1.00 mm, the RMSE was 1.18 mm, and the mean absolute error was approximately –0.20 mm. For the reference height of 145 mm, the sensor reading and the reference value coincided exactly. This indicates the absence of any significant systematic overestimation or underestimation of the measured height (Fig. 5).

As can be seen in Fig. 5, the US₁ results are located near the line of perfect agreement. Within the studied range, no monotonic dependence of the error on the object's height was observed, which, together with the small ME value, indicates the absence of a pronounced systematic bias.

The accuracy of the lateral ultrasonic channel US₂ for determining the position of the object's right contour was evaluated in a similar manner. The reference coordinates were determined by direct measurement, while the sensor coordinates were determined using the median values of the US₂ distance. The results are presented in Table 4.

For the US₂ side channel, the absolute error was 0-2 mm, the maximum relative error was 1.90%, the MAE was 1.00 mm, and the RMSE was 1.18 mm. For the base configuration, the calculated position of the right contour matched the reference value. The achieved accuracy is sufficient for defining the boundaries of the system's operating range.

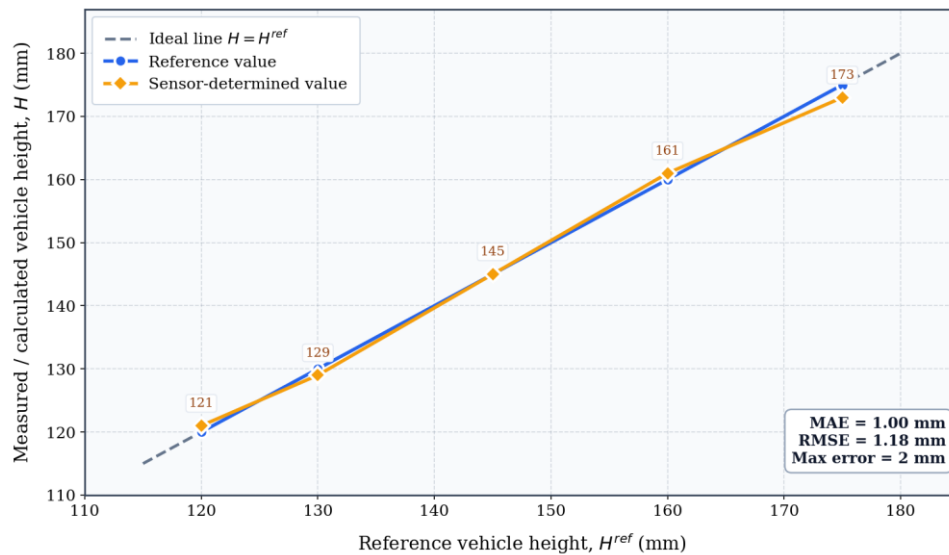


Fig.5. Comparison of reference and sensor-determined vehicle height

Source: compiled by the authors

Table 4. Experimental results of determining the lateral position of the vehicle

No.	y_R^{ref} , mm	$\tilde{d}_2$, mm	y_R , mm	Δ_y , mm	δ_y , %
1	55	179	56	1	1.82
2	65	171	64	1	1.54
3	77	158	77	0	0.00
4	90	144	91	1	1.11
5	105	132	103	2	1.90

Source: compiled by the authors

For both ultrasonic channels, the maximum absolute error did not exceed 2 mm, indicating comparable accuracy in determining vertical and lateral geometric parameters. The repeatability of ultrasonic measurements was assessed based on the deviations of individual readings from the median of the corresponding series. Potential emissions were determined using the interquartile range criterion. The results are shown in Fig. 6.

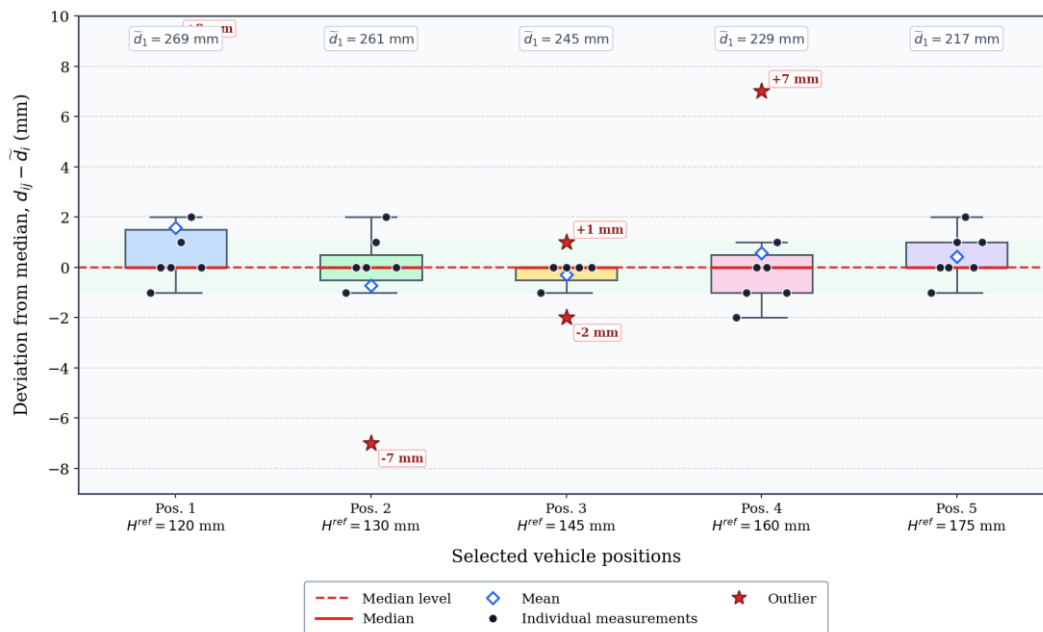


Fig.6. Distribution of deviations of repeated ultrasonic measurements from the median for selected vehicle positions

Source: compiled by the authors

The majority of the repeat measurements were concentrated within approximately ± 2 mm of the median. In some series, isolated deviations of up to +9 and –7 mm were observed, associated with unstable reflection of the ultrasonic signal from surfaces with complex geometries. At the same time, these values had virtually no effect on the median of the series, confirming the appropriateness of using median filtering.

In the final stage, the generation of control actions based on the results of positioning and the determination of geometric parameters was verified. The results of the comprehensive verification are presented in Table 5.

Table 5. Results of integrated experimental verification of the automated installation

Mode	K_p	Dimensions admissible	Carriage	Pump	Fans	Result
Correct position	1	Yes	Enabled	Enabled	Enabled	Cycle started correctly
Incorrect position	0	–	Blocked	Blocked	Blocked	Start blocked
Exceeding the permissible dimensions	1	No	Blocked	Blocked	Blocked	Start blocked
Admissible dimensions	1	Yes	Enabled	Enabled	Enabled	Cycle started correctly

Source: compiled by the authors

The operating cycle was initiated only when two conditions were met simultaneously: the object was in a valid position, and its geometric parameters fell within the boundaries of the working zone. A violation of even one of these conditions resulted in the carriage, pump, and blowing system being locked.

The average time from confirmation of the permissible position to the generation of control parameters in ten repeated tests was 438 ms, with a range of 421–459 ms and a standard deviation of approximately 12 ms. This variation indicates the stable repeatability of the algorithm for generating control commands. Further research should focus on integrating computer vision with an ultrasonic sensor subsystem to more accurately determine the external contour of the vehicle.

Conclusions. This article justifies the structure of the sensor subsystem and develops a method for determining the position and geometric parameters of agricultural machinery within the working area of an automated washing system. The proposed approach combines position control based on signals from photoelectric sensors with the determination of height and lateral coordinates based on data from ultrasonic channels. A distinctive feature of the method is the sequential generation of a reliable description of the object's state using median filtering of measurement results, which reduces the impact of isolated anomalous readings.

An algorithm has been developed to use the determined positions and dimensions of the equipment for automated control of the washing system. The algorithm ensures the sequential conversion of sensor data into control parameters for the carriage, pump, and fans. Logical conditions for enabling and disabling the operating cycle have been established: if the equipment is in an incorrect position or exceeds the permissible dimensions, the activation of the actuators is blocked; if the specified conditions are met, permission is granted to execute the process cycle.

The effectiveness of the proposed method has been experimentally confirmed. The accuracy of determining the reference positions was 100 %. For the upper and lateral ultrasonic channels, the average absolute error was 1.00 mm, RMSE = 1.18 mm, and the maximum absolute error did not exceed 2 mm. The maximum relative error was 1.14 % and 1.90 %, respectively, confirming the feasibility of using the obtained data to create an automated washing cycle.

Further research should focus on integrating computer vision tools and a Raspberry Pi to more precisely determine the outer contour of the equipment, combine visual and ultrasonic data, adaptively generate the washing carriage's trajectory, and test the developed approach on actual agricultural machines of various sizes and under different contamination conditions.

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Визначення положення та геометричних параметрів сільськогосподарської техніки для автоматизованого керування процесом миття

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АНОТАЦІЯ

У статті розроблено та експериментально перевірено метод визначення положення та геометричних параметрів сільськогосподарської техніки для автоматизованого керування процесом миття. Метод поєднує використання фотоелектричних датчиків для перевірки допустимого положення техніки та ультразвукових датчиків для визначення відстаней до її верхньої та бічних поверхонь. Для зменшення впливу аномальних ультразвукових вимірювань застосовується медіанне фільтрування, а виміряні відстані перетворюються на геометричні параметри з використанням відомих розмірів експериментальної установки. Отримані параметри використовуються контролером для визначення допустимої робочої зони та формування керуючих сигналів для мийної каретки, насоса та системи обдуву. У разі неправильного розташування техніки або перевищення нею допустимих розмірів робочої зони технологічний цикл

блокується. Експериментальна перевірка з використанням розробленої автоматизованої мийної установки та моделі трактора підтвердила правильну роботу підсистеми позиціонування та достатню точність ультразвукових вимірювань. Максимальна абсолютна похибка не перевищувала 2 мм. Запропонований підхід забезпечує пряму інтеграцію даних датчиків у логіку керування та дозволяє адаптувати цикл миття до фактичного положення та розмірів техніки. Подальші дослідження повинні бути спрямовані на інтеграцію систем комп'ютерного зору та адаптивне формування траєкторій руху мийної каретки.

Ключові слова: сільськогосподарська техніка; автоматизоване миття; сенсорна підсистема; ультразвукові давачі; фотоелектричні давачі; геометричні параметри; позиціонування; автоматизоване керування; мийна установка

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