Technology for accurate positioning of agricultural machinery in precision agriculture based on the GPS satellite signal using the Internet of Things, big data and cloud solutions

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Abstract

The implementation of the project allowed for the development and prototype implementation of the technology of accurate positioning of agricultural machinery in precision agriculture based on the GPS satellite signal using the Internet of Things, big data and cloud solutions. Thanks to the research and development work carried out, algorithmics were developed in such research areas as low quality antenna signal processing in the PPP-RTK CDGNSS approach with minimized TAR, position stabilization by means of expanded space in terms of Kalman's theory, cloud processing of high-volume positional data in the processes of inference and running of agricultural machinery in precision agriculture, data transmission, error reduction procedures, area optimization and inference in precision farming processes. Earlier scientific studies allowed the use of the theory of increasing the accuracy of geostationary measurements with the use of relatively cheap GNSS antennas, where measurement errors can be reduced to several centimeters. Thanks to the use of sensory fusion and Kalmanian approaches, it was possible to construct the foundations of devices for positioning agricultural machines with high accuracy, sufficient for effective precision agriculture. In principle, the device is to be cheap, also available to farmers with small farms and thus not having large funds for investments. This approach will allow to reduce the costs of agricultural production, which, paradoxically, is the most expensive in small farms.

Keywords: *precise agriculture, positioning, GPS, Internet of Things, cloud computing.*

1. Introduction

Precision farming is understood as all manifestations of computer-aided or electronic-aided agricultural activity, which allow for a number of positive effects, such as reducing the amount of fertilizers used or the use of intelligent fertilizers, reducing the emission of biogenic elements to the environment, increasing crops or population, enriching products. agriculture for nutrients or trace elements during growth, immunization of crops or livestock against diseases, etc. To a large extent, precision agriculture uses satellite reference systems to accurately position the agricultural machine relative to the field. Precise positioning allows for more accurate field work and thus provides a number of benefits. For example, sprayers supported by a satellite signal allow for precise spray coverage of crops in a band pattern. The sprayer moves across the field, spraying in a sufficiently wide strip. When turning, the machine stands next to the already sprayed area and moves back. Depending on the precision of the sprayer guidance, two adjacent lanes may overlap or there may be a gap between them. Both phenomena are undesirable. The first can lead to over-fertilization, unnecessary losses in fertilizers and excessive emission of biogenic elements to the soil, as well as overdrying of plants. In the latter case, an area left untreated may be a focus of disease development and spreading to other parts of the field, and causing crop losses. Another example is a device connected with the precision steering system of an agricultural machine, which tests remotely (non-contact) and in real time the level of selected biogenic elements in plants (most often nitrogen). Based on the read results, a precisely guided sprayer doses the amount of fertilizer appropriate to the amount of biogenic elements detected in plants in specific parts of the field. Therefore, the precision of operating and operating agricultural machinery determines the quality and size of the crop, as well as the quality of healthy food (the less and more precisely dosed fertilizers and protective measures, the healthier the food is) and the degree of protection of the natural environment by reducing the unnecessary emission of nutrients to soil and groundwater. (and then - to catchments, rivers, lakes and finally seas and oceans). Hence, the concept of precision farming aims to obtain higher yields of higher quality, lower production costs and reduce environmental contamination.

Currently, there are many devices on the market for precise guidance of agricultural machinery. Nevertheless, practically all of them offering satisfactory positioning precision, functionality and durability are associated with expenses of over 5,000 PLN. The Trimble CFX750 system with an accuracy of approx. 30 cm costs approx. 16,000 PLN gross, while increasing the accuracy to 15-20cm requires the use of an additional expensive antenna (cost about PLN 4,000 gross) and the requirement to pay an additional subscription (cost about PLN 1600 gross per year). Other devices for precision farming, but not offering accuracy below several dozen cm or 1m, are: Nomad 900L (approx. PLN 7,000 gross), Juno T41C (approx. PLN 6,000 gross), Juno 3B (approx. PLN 3,500 gross), Teejet CL 230 (approx. PLN 7,000 gross), Muller Track Guide (approx. PLN 8,000 gross), Topcon system 110 (approx. PLN 11,000 gross). Most of them (the cheaper ones, e.g. EZ-Guide 250, Juno T41C, Nomad 900L) are closed systems and do not allow for expansion with more precise antennas or other devices or communication with them (e.g. with cameras, on-board computer, automatic control systems). The high prices of devices, especially without appropriate software and the ability to communicate with other computerized agricultural equipment, mean that many farmers with smaller farms are not interested in making investments (farms with a sown area of up to 50 ha occupy a total of over 80% of the agricultural area, i.e. approx. 13 million ha. and there are nearly 1,200,000 of them [1]). The average income per 1 conversion ha is PLN 1975 (according to the Announcement of the President of the Central Statistical Office of 23 September 2016 on the average income from work in individual farms per 1 conversion ha in 2015), and the profit after deducting hired labor, depreciation of machinery, fertilizers, pesticides, fuel, storage, harvest and sale costs, it constitutes a small, often several percent share, hence a small farmer (up to 50 ha) simply cannot afford a set of equipment for nearly PLN 10,000. The results of the implemented project meet these needs by providing processor devices that do not require expensive GPS receivers, but ensure the accuracy of positioning of agricultural machinery with an error margin of less than 30cm. The cost of the device was estimated at 2,000. PLN net. In addition, there is a possibility of subscription sale, which will further facilitate access to this type of equipment for farmers with small farms.

Moreover, as shown by scientific studies, there is a great demand on the market for low-cost GPS positioning technologies [2]. The problem is usually not the computing power of mobile processors, but significant interference in the path of the radio signal reaching the receiver from the satellite. These interferences are generic and cannot be prevented. Expensive solutions use significantly better radio systems, including antennas. In order to ensure the affordability of the technology, the applicant intends to apply an innovative GPS signal recording system with correction systems based on inertial, magnetic field strength, directional and optical sensors. The application of an approach using methodologies such as Kalman's theory will allow to introduce further corrections to the disturbed signal and thus achieve precise point positioning (PPP).

2. Theory

2.1. Determining the state

In determining the filter state, we take into account a component with real values. It models the relative position of the antenna and its velocity. We also take into account a component with integer values. This component models the phase ambiguities that are inherent in carrier phase differential positioning techniques. Earlier studies [3] [4] have investigated this resolution. It is therefore required to correctly define the solution for the CDGNSS positioning processes.

The real-valued filter state has a component defined for the moment t_k and it is denoted by the symbol $\boldsymbol{x}_k$, where $t_k = kT$. T is the time interval between successive updates of the filter state. This component takes the form:

$$\boldsymbol{x}_k = [\boldsymbol{r_o}, \boldsymbol{r}_k, \dot{\boldsymbol{r}}_k]^T \tag{1}$$

where we used the following markings:

$\mathbf{r}_o$ is a 3×1 size vector taken as a constant vector; it describes the relative position between the reference antenna and the center point of the movement of the moving antenna.

$\mathbf{r}_k$ is a 3×1 size vector that describes the relative position of the antenna moving relative to the center point of its movement, at time t_k .

$\dot{\mathbf{r}}_k$ is the size of the hand change at the time t_k .

The filter component that takes integer values $\boldsymbol{n}_k$ at time t_k can be written as follows:

$$\boldsymbol{n}_k = [N_1, N_2, ..., N_{\mathrm{SV}-1}]^T \tag{2}$$

where

$\mathbf{n}_k$ is a vector of size $(N_{SV - 1})$×1 describing phase ambiguities with integer values, one for each pair of satellites.

N_{SV} is the number of all satellites observed.

We assume one reference satellite for all pairs of satellites.

2.2. Modeling dynamics

In the model, we assume that the real-valued $\boldsymbol{x}_k$ component of the filter evolves in accordance with the second-order Gauss-Markov process with mean-reverting. This process reflects movement that is correlated with time and inverts the value of the mean. This movement is experienced by the sensor when it moves together with the deployed mounting arm of the locating device. The integer-valued $\boldsymbol{n}_k$ state component is mapped by a constant. This is because the phase ambiguities remain constant as long as the sensor keeps the phase synchronized for each received signal.

The real-valued filter state component evolves over time as follows:

$$\boldsymbol{x}_{k+1} = \boldsymbol{\Phi}\boldsymbol{x}_k + \boldsymbol{\Gamma}\boldsymbol{w}_k \tag{3}$$

where:

$\mathbf{\Phi}$ is a transition matrix for individual states,

$\mathbf{\Gamma}$ is the process noise effect matrix,

$\mathbf{w}_k$ is the process noise at time t_k, represented by a random Gaussian sequence with a discrete time mean of zero and a covariance matrix $\boldsymbol{Q}$, which takes the form:

$$\boldsymbol{w}_k \sim N(\mathbf{0}, \boldsymbol{Q}), E\left[\boldsymbol{w}_k \boldsymbol{w}_j^T\right] = \boldsymbol{Q}\delta_{kj} \tag{4}$$

The state transition matrix for real-valued states is the moment transition matrix from t_k to t_{k+1} for a second-order Gauss-Markov process of discrete-time and mean-reverting.

$$\boldsymbol{\Phi} = \begin{bmatrix} \boldsymbol{I}_{3x3} & \mathbf{0}_{3x3} & \mathbf{0}_{3x3} \\ \mathbf{0}_{3x3} & f \cdot \boldsymbol{I}_{3x3} & \frac{1-f^2}{\sqrt{1+f^2}} \cdot \boldsymbol{I}_{3x3} \\ \mathbf{0}_{3x3} & \mathbf{0}_{3x3} & f \cdot \boldsymbol{I}_{3x3} \end{bmatrix} \tag{5}$$

where

$$f = e^{-T/\tau_0} \quad (6)$$

is the correlation coefficient between the state components $\boldsymbol{r}_k$ and $\dot{\boldsymbol{r}}_k$, where τ_0 is the average time of decorrelation during antenna movement.

The noise effect matrix can be defined as:

$$\boldsymbol{\Gamma} = \begin{bmatrix} \boldsymbol{0}_{3x3} & \boldsymbol{0}_{3x3} & \sqrt{1-f^2} \cdot \boldsymbol{I}_{3x3} \end{bmatrix} \quad (7)$$

And the noise covariance matrix in the process can be written as:

$\boldsymbol{Q} = \sigma^2[\boldsymbol{I}_{3x3}]$ (8)

where σ is the calculated standard deviation of the time-dependent antenna variation mapped by the state components with real values $\boldsymbol{r}_k$ introduced in formula (1), calculated for each of the dimensions.

In order to apply the dynamic model in the case of a stationary antenna, the antenna motion decorrelation time should be assumed to be equal to infinity, i.e. $\tau_0=\infty$, and the process noise should be set to zero, i.e. $\boldsymbol{Q}=\boldsymbol{0}_{3x3}$.

2.3. Measurement model

The filter takes the measurement vectors $\boldsymbol{y}_k$ for $k = 1,\dots,K$, each of which is populated according to a single time epoch of the doubly differenced carrier phase measurements. The measurement model links $\boldsymbol{y}_k$ with the components of the filter state with real and total values, i.e. $\boldsymbol{x}_k$ and $\boldsymbol{n}_k$, thanks to the following adaptation of the linearized GNSS carrier phase measurement model, in accordance with [5]:

$$\boldsymbol{y}_k \triangleq \begin{bmatrix} \phi_{AB,k}^{21} \\ \phi_{AB,k}^{31} \\ \vdots \\ \phi_{AB,k}^{N_{SV}1} \end{bmatrix} = \boldsymbol{r}_{xk} + \boldsymbol{H}_{xk}(\boldsymbol{x}_k - \overline{\boldsymbol{x}}_k) + \boldsymbol{H}_{nk}\boldsymbol{n}_k + \boldsymbol{v}_k \quad (9)$$

where:

$\varphi^{i1}_{AB,k}$ is a double differential phase measurement between reference receiver *A* and mobile receiver *B*, satellite indexed *i*, satellite indexed *1*, and reference satellite at time t_k.

$\mathbf{r}_{xk}$ is a vector of doubly differenced model ranges based on the filter state real values defined before $\bar{\boldsymbol{x}}_k$.

$\mathbf{H}_x$ is the measurement sensitivity matrix for the real-valued filter state components.

$\mathbf{H}_n$ is the sensitivity matrix of the measurement of the filter state components with integer values at time t_k.

$\mathbf{v}_k$ is a vector of doubly differenced noise measurements with discrete time.

Each of the components $\boldsymbol{v}_k$ is modeled as Gaussian white noise with a zero mean discrete time. From here we can write down:

$$\boldsymbol{v}_k \sim N(\boldsymbol{0}, \boldsymbol{R}), E\left[\boldsymbol{v}_k \boldsymbol{v}_j^T\right] = \boldsymbol{R}\delta_{kj} \quad (10)$$

where $\boldsymbol{R}$ is the covariance matrix for a noise measurement with dimensions $N_{SV-1} \times N_{SV-1}$.

Hence, we can write the noise measurement covariance matrix as:

$$\boldsymbol{R} = \sigma_{\phi}^{2}\begin{bmatrix} 4 & 2 & \dots & 2 \\ 2 & 4 & & \vdots \\ \vdots & & \ddots & \\ 2 & \dots & & 4 \end{bmatrix} \tag{11}$$

where σ^2_φ is the standard deviation for the undifferenced measurement of the noise phase. To simplify the model, it is adopted for all antenna-satellite pairs. The measurement sensitivity matrices can be written as:

$$\boldsymbol{H}_{xk} = \begin{bmatrix} \rho_{B,k}^{21} & \rho_{B,k}^{21} & \boldsymbol{0}_{1x3} \\ \rho_{B,k}^{31} & \rho_{B,k}^{31} & \boldsymbol{0}_{1x3} \\ \vdots & \vdots & \vdots \\ \rho_{B,k}^{N_{SV}1} & \rho_{B,k}^{N_{SV}1} & \boldsymbol{0}_{1x3} \end{bmatrix} \tag{12}$$

$$\boldsymbol{H}_{n} = \begin{bmatrix} \lambda & 0 & \dots & 0 \\ 0 & \lambda & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \lambda \end{bmatrix} \tag{13}$$

where $\rho^{i1}_{B,k}$ is the 1×3 single positioning vector difference between the estimated position of the moving antenna of the receiver, satellite indexed i, satellite indexed 1, and the reference satellite at time t_k, and λ is the wavelength for the GNSS signal.

2.4. Residuals of phase

After processing the data by the CDGNSS filter, its output, apart from the history of position estimates with the accuracy of the order of a centimeter, also shows the history of phase residuals $\tilde{\boldsymbol{y}}_k$. They can be viewed as deviations from any double differential phase measurement from its alignment at the antenna phase center point. The rest can be written as:

$$\widetilde{\boldsymbol{y}}_k = \boldsymbol{y}_k - \boldsymbol{r}_{xk} - \boldsymbol{H}_n \widehat{\boldsymbol{n}}_K \tag{14}$$

where $\boldsymbol{r}_{xk}$ is now determined from the state of the true-valued filter at time t_k and represents an estimate of the ambiguity of the integer-valued filter from all measurements taken up to time t_K.

3. Research domain

The following areas of new knowledge were investigated during the project implementation:

- Low quality antenna signal processing in the PPP-RTK CDGNSS approach with minimized TAR.
- Position stabilization by means of expanded space in terms of Kalman's theory.
- Cloud processing of high-volume positional data in the processes of inference and running of agricultural machinery in precision agriculture.
- Data transmission, error reduction procedures, area optimization and inference in precision farming processes.

The above activities concerned the following research issues, on the basis of which new knowledge in the form of a new technology was created:

- Methodology of minimizing multipath suppression in obtaining high resolutions.
- A methodology for reducing errors by analyzing data from a moving antenna or antenna array.
- Methodology for the implementation of artificial aperture processes in the DD GNSS approach.
- The methodology of supporting the positioning in the PPP approach using inertial sensors.
- Positioning support methodology in the PPP approach using directional sensors.
- Methodology for determining the superposition of radio and non-radio measurements in precise and fast positioning based on the Kalman theory.
- The methodology for collecting positioning data with a hierarchical and contextual structure.
- A methodology for processing high-volume positioning data using distributed cloud mechanisms.
- Methodology for the implementation of spatial inference processes and running agricultural machines on the basis of processed positioning data of a large volume.
- Functional and computational design methodology for IoT devices for positioning agricultural machinery.
- A methodology for secure data exchange and reduction of errors during data processing in the cloud from devices.
- Methodology of area optimization and inference in precision farming processes on the basis of data from devices.
- Creation of a new technology and its verification in real conditions and obtaining readiness for its implementation in the target system.

4. Results

The implementation of the above-mentioned research issues and the implementation of development works in the above-mentioned areas of new knowledge allowed for the creation of a new technology for accurate positioning of agricultural machines in precision agriculture based on the GPS satellite signal using the Internet of Things, big data and cloud solutions. As part of the implementation tests, a device for precise positioning of agricultural machines was designed, mounted e.g. on the roof of a farm tractor.

One of the major problems in precision farming is the precise reading of the agricultural machine's position in two aspects. The first one covers the geoposition's position without taking into account the arrangement of the machine in space as a solid. This position is read by means of GPS sensors (GPS wave receivers). The use of five independent receivers located at a known mutual distance, called the artificial aperture approach, allows the results to be averaged and thus correct the correct geoposition reading. Hence, in the first aspect of positioning, the machine is treated as a geometric point. The second aspect involves the position of the agricultural machine in three-dimensional space (tilts are detected by accelerometers, alignment with the Earth's magnetic field by magnetometers) relative to the center of the geometric rotation. Measurements are then taken with MEMS sensors and averaged using Kalman approaches. Thanks to the use of MEMS sensors on unfolded arms, their linear displacement increases (compared to the situation with folded arms) for the same angular displacement. In addition, in the case of the movement of the agricultural machine during operation, dynamic overload readings are made by means of MEMS sensors on unfolded arms, which also in the Kalman approach are used to improve GPS positioning (interpolation with the use of sensors of different physical nature). To sum up, the unfolding of the arms increases the displacement of the sensors for the same rotation of the agricultural machine body, which in turn results in a more accurate determination of its position in three-dimensional space, and additionally enables better correction of GPS reading errors. At the same time, when the agricultural machine ceases to be positioned, e.g. it leaves the field, drives into the garage, the arms are retracted and thus their damage is avoided (the machine outline is reduced).

The device in question allows to increase the accuracy of geo-positional measurements as well as in the three-dimensional space of the agricultural machine by the simultaneous use of GPS sensors that are distant from each other and the distance of MEMS sensors from the geometric center of rotation of the machine as a solid. In the case of precision farming, it is not enough to know the exact position of the agricultural machine as a geometric point. It is also necessary to know about its inclination to the ground and its orientation in relation to the directions of the world. Failure to take into account the inclinations leads to incorrect readings of the machine's position in relation to the plowing, which in turn may lead to missed spraying or sowing. Incorrect orientation, in turn, leads to a loss of accuracy in the machine's movement along a predetermined trajectory. The use of multiple sensors, both GPS and MEMS, at a distance from each other and from the center of the geometric rotation of the machine body results in their greater relative sensitivity and allows for more precise corrections than in the case of one sensor located close to the center of rotation. On the other hand, the function of folding and unfolding the arms allows the use of remote sensors during machine operation and folding them while driving or parking the machine, which reduces the risk of their damage.

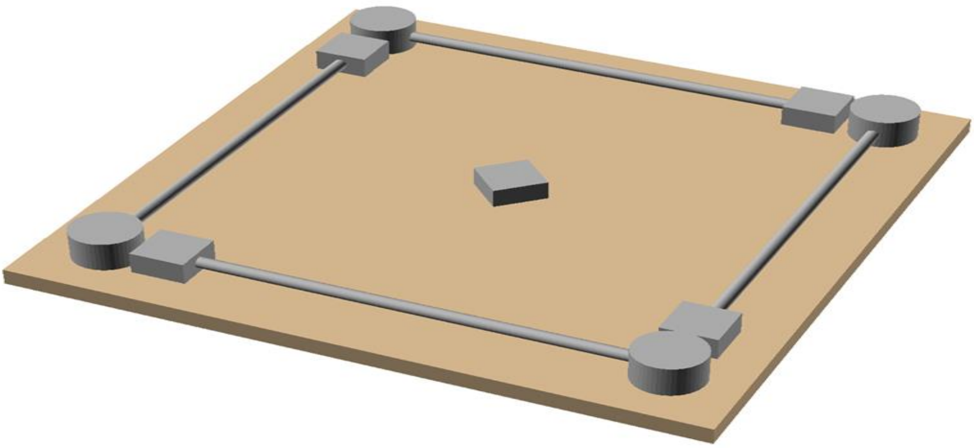

Figure 1. Functional outline of a device for precise positioning of agricultural machines with folded arms for mounting MEMS and GPS sensors. In the center of the device there is a central sensor that allows to increase the precision of the measurements.
Source: *own materials.*

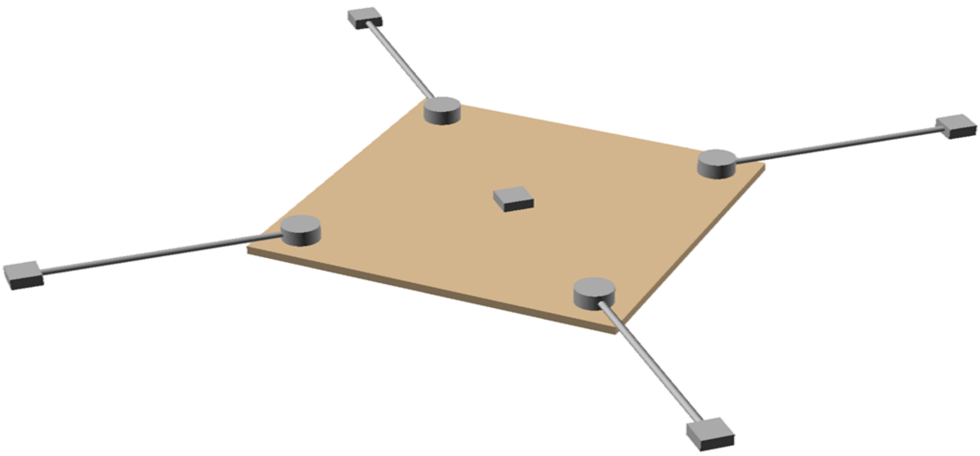

Figure 2. *The unfolded mounting arms allow for a significant increase in the precision of measuring the position of the agricultural machine in three-dimensional space using MEMS and GPS sensors.*
Source: own materials.

5. Summary

The aim of the project was to generate new knowledge through the implementation of research and development tasks, in the form of technology for accurate positioning of agricultural machinery in precise agriculture based on the GPS satellite signal using the Internet of Things, big data and cloud solutions. This technology will allow the introduction of new products and services related to precision farming and information processing to the market, supporting the optimal use of resources such as fertilizers, pesticides, water, fuel, working hours, and at the same time will significantly contribute to the protection of the natural environment through reduced nutrient deposition. from farmland to groundwater. Paradoxically, smaller farms that cannot afford expensive precision farming solutions are more expensive because they incur higher costs related to the sub-optimal use of production resources. In addition, they also record greater losses in yields caused by imprecise dosing of the agents. Hence, they need to use inexpensive technologies and devices that improve the quality of agricultural activity. The results of the implemented project meet these needs. However, the results obtained in the project should not be treated as final. The constantly increasing power of computing clouds and cheap electronic sensors will allow for another significant reduction in agricultural production costs in the future.

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