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DATA COLLECTION METHOD FOR CREATING DIGITAL TWIN OF PLANTED FORESTS

Abstract: The complete enumeration of trees employed in forestry typically pertains solely to ripening and maturity stands and does not incorporate the utilization of digital stocking models, which could potentially simplify this task in small wood cutting areas, as well as when addressing research or environmental concerns. The existing digital models of forest stands provide data on the size, species, and categories of technical feasibility of forest plants. However, they lack the capability to store information on the spatial structure of the stand and the actual location of the woody plants that comprise it. The objective of this project is to devise a methodology for acquiring data on forest stand accounting, thereby enabling the creation of digital twins of forest stands and their subsequent updating. In order to attain this objective, the methodologies of analyzing scientific and technical literature, functional and technological analysis, and the brainstorming method were used. As a result of the research, a methodology was proposed for gathering data to generate digital twins of the forest. This methodology is intended to be implemented during the stage of establishment forest crops and facilitates the determination of spatial coordinates for each plant subject to accounting. Knowledge of these coordinates will further facilitate the creation of flight assignments for unmanned aerial vehicles (UAVs) during remote survey of the territory. In addition, it will help to rationally plan the location of utility corridors for the movement of forest machines, taking into account the minimization of damage to the remaining trees and the negative impact on the soil. It will also help to assign forestry measures using automated and robotic systems. A digital twin of the forest obtained using the proposed method will allow for a highly accurate implementation of a comprehensive accounting of woody plants, assessing the processes and indicators of the development of forest and green spaces, assigning agrotechnical and forestry measures, and more rationally planning logging.

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Introduction

Despite mechanization, there is still a high proportion of hand-work in forestry, and automation and robotization of forestry activities are constrained by the insufficient development of digital technologies and the specific natural production conditions in the industry. This circumstance has several objective reasons, among which it is necessary to emphasize the need to consider a large number of changing factors, including uncontrollable and difficult to predict natural factors.

Presently, computer modeling and forecasting techniques are extensively employed in the development of forestry measures (Türkay & Aydın, 2023; Díaz-Yáñez et al., 2019; Rukomojnikov & Sergeeva, 2024). Nonetheless, they fail to furnish an objective development of the forest stands over time, as the majority of existing solutions fail to adequately consider the spatial distribution of trees within the stand and complete enumeration.

The rapid development of digital technologies makes it possible to collect, store and process large volumes of technological and technical data. This makes it possible to use the concept of “digital twins” when solving production problems within the framework of the approach of the fourth industrial revolution (Industry 4.0). In industry, a “digital twin” is a complex digital representation of an industrial object that characterizes the state and behavior of a physical object in a real environment through models and data (Haag & Anderl, 2018). A distinctive feature of digital twins is that they are created together with the physical object and they are virtual analogues of the object throughout its entire life cycle, while data on the state of the physical object is actively updated in real time and accumulated during its use, including through the use of sensors installed on the real object (Anderl, Haag, Schützer & Zancul, 2018). The concept of “digital twins” is now not only applied to industrial facilities, for example, it is considered an integral part of the digital ecosystem of a smart city (Cureton & Dunn, 2020).

In forestry, the concept of “digital twins” can also be used when establishing forest crops in exploitable forests, taking into account the specifics of the industry. Digital twin data can be used to implement “precision forest recreation” technologies in forest management (Castro et al, 2021), similar to “precision farming” technologies in agriculture. The data gathered and updated during forestry activities will be utilized for future measures, and the usage of modeling on the digital twin will enable a more rational choice of the timing of measures and the appropriate technologies and machines. The advancement of digital technologies and automation in forestry necessitates the creation of digital twins of tree stands, based on complete enumeration data encompassing the spatial location of each tree in the stand. These twins will be continuously updated during objective monitoring of tree growth, during forestry measures from planting tree seedlings to technical maturity and clear-cutting in the stand. Additionally, sensors installed for a long time in the stand can be used to collect data, reading data on microclimate parameters and the growth of individual trees.

A digital twin is a virtual representation of a real physical object that encompasses all details about the real object. The virtual model and the real object are interconnected through a bilateral data flow, thereby uniting the model and the object into a system that

passes through all phases of the life cycle: design, production, operation, and disposal (Grieves & Vickers, 2017). A distinctive feature of a digital twin from a traditional computer model is a much larger coverage of the parameters and processes of a real object, a bilateral data flow and support for the entire life cycle. Theoretically, studying a virtual model is equivalent to studying the corresponding real object. The development of computer technologies allows an increasing number of objects to create digital twins. Currently, the concept of a digital twin is used not only to solve technical problems, but also to predict the development of various objects and events in the real world.

There exist numerous fields of application for digital forest twins, such as the rehabilitation of patients, as a means of psychological and physiological recovery for individuals who are unable to independently visit a genuine forest (Hejtmánek, Hůla, Herrová & Surový, 2022). In this instance, a comprehensive examination of the actual parameters of the forest stand is not necessary, but rather a compositional representation of the forest in virtual space. Given the current level of development of graphic systems and their visualization, there are no problems with creating forest stands in digital space for this purpose (Hanqing et al., 2023).

If we consider digital forest twins from the perspective of assistants in the appointment and implementation of forestry activities, then completely different requirements are imposed on them. In this case, it is necessary to obtain the spatial coordinates of each tree, as well as knowledge of the changes in the forest stand during tree growth. For example, the European Union plans to use digital forest twins to predict and visualize the state of our planet, including in relation to the carbon footprint, modeling and forecasting of timber reserves (The project website for Forest Digital Twin Earth Precursor (DTEP), 2021). A digital forest twin, as a virtual representation of a real system, should reflect all the essential characteristics, properties, processes and operations inherent in a real forest.

The capability to consider the coordinates of each tree in a forest stand enables not only a more efficient allocation and design of forestry activities, but also the usage of this information to automate various forestry operations.

Currently, the following traditional methods are used to determine the position of each tree plant in a stand during compartment description: the quadrature method, the ordinate method, triangulation, building the transit traverse, and a number of other methods. These methods are most widely used today in gardening and park management (Leafy Learning, 2020). All known methods are very labor-intensive, require the use of expensive equipment and large manual labor costs (Sevko & Kotsan, 2020; Sirozhenko, 2017; Arbuzov, 2013). In addition, as practice shows, such methods are not applicable to young crops.

With the advancement of aerospace technology, novel techniques have emerged. The most advanced method is the use of satellite images. This method is used to predict forest disturbances (Buma & Livneh, 2017), and analyze forest cover (Joshi et al., 2006). As noted by the authors of the study (Jiang et al, 2022), when constructing a digital twin of a forest using remote sensing images and machine learning, a variety of challenges arise, including a lack of data, low accuracy, the necessity to segment a large image into smaller ones, necessitating substantial computing resources and lots of storage space. This method enables to obtain only the coordinates of the crowns of overstory in ripening and maturity stands (Method for updating forest taxation data based on machine learning, 2020; Method of grading complex, mixed, uneven-aged plantings, 2013). Simultaneously, the precision in

determining the coordinates of individual trees using space images is inadequate to address the forestry tasks. Furthermore, this approach necessitates significant financial expenditures for conducting space photography and decoding the resulting images.

Aerial photography using aircraft, including unmanned aerial vehicles, can be used to solve forestry problems (Säynäjoki, Maltamo & Korhonen, 2008). The usage of manned aircraft presents the same challenges as the usage of satellite data, as these aircraft, for flight safety reasons, operate at considerable heights and are also associated with significant financial expenses. A cheaper method is to use unmanned aerial vehicles (UAVs), but their use in forestry for forest stand taxation is also limited. When unmanned aerial vehicles (UAVs) operate under the forest canopy, in dense stands, and at low levels, the probability of their collision with thin branches significantly increases, resulting in an accident and equipment damage. Modern computer vision systems installed on UAVs are not yet capable of operating independently, without operator intervention, in such conditions. Operating a UAV from a great height does not allow one to notice the target young growth of coniferous crops among deciduous plants, nor to assess the condition of seedlings in the grass in summer (Vogel' & Yuferev, 2018; Lopatin, 2020).

The technology of surface and airborne laser scanning is widely acknowledged (Chen, Haodong, Duanchu, & Di, 2024). This technology is used to obtain taxation characteristics during inventory and study of ripening and maturity forest stands. While airborne laser scanning technology has long been used industrially in a number of countries (Kauranne et al, 2017), surface laser scanning technology is currently quite expensive and very labor-intensive, which allows it to be used only for certain scientific tasks when the speed and cost of work are not of key importance (Ghimire, Xystrakis & Koutsias, 2017; Starikov & Baturin, 2015). In addition, surface and airborne laser scanning, as well as aerospace images, are well suited for ripening and maturity stands of trees, and therefore do not allow the full implementation of the “digital twin” concept.

As evidenced by the literature review, a multitude of technologies exist at present to gather data on the state of the forest stand, however, none of them are capable of fully meeting the requirements of forest management. Thus, the topic of the article, devoted to the development of a methodology for collecting, storing and updating objective control data on the growth of forest stands, in a form convenient for their use in a digital format and processing using electronic computing systems to improve the automation of processes in forestry, seems to be an urgent task.

Materials and Methods

The objective of the work is to devise a methodology for acquiring data on forest stand accounting, thereby enabling the creation of digital twins of forest stands and their subsequent updating.

In order to attain the established objective, it was imperative to accomplish the subsequent tasks:

- study the characteristics of digital twins of forest stands and their areas of application;
- study known methods for collecting data on the state of forest stands used to create their digital twins;

- study the requirements for the input data for building digital twins of the forest, intended for the purpose of assigning forestry measures and modeling the growth of forest stands;
- developing a method for collecting data during the life cycle of a forest stand, necessary for building its digital twin.

The following methods were used in order to achieve the set goals and objectives:

- patent information retrieval and analysis of scientific and technical literature. The usage of these techniques enabled us to examine a diverse range of scientific and technical literature, conference materials, materials presented at exhibitions and forums, as well as examine patent documents. Based on the results of the literature analysis, the most valuable and informative sources were selected, all collected information was systematized, and a detailed analysis was carried out. This allowed us to establish not only the entire range of applications of digital twins for forestry purposes, but also identify problems due to which the use of digital twins in forestry is limited and also the reasons for these restrictions.

- system and functional-technological analysis. The use of these methods allowed us to systematize the data obtained during the analysis of scientific and technical literature and present them in the form of a complex system consisting of a number of simpler subsystems, identify similar subsystems among various devices and combine devices with similar subsystems. These methods allowed us to examine the problem being solved thoroughly and identify the strengths and weaknesses of digital forest twins. We also studied the technical and technological features of their creation.

- brainstorming method. This approach enabled us to identify solutions to address the issues identified during the initial stages of research that hinder the application of digital forest twins for forestry purposes. Specifically, we proposed a novel approach for gathering and aggregating data that guarantees enhanced functionality of digital forest twins, as well as the technical devices to ensure the feasibility of implementing the proposed approach.

Results

During the analysis of literature in the first part of this article it was discovered that all known technologies for gathering information for constructing digital twins of forest stands utilized for forestry work are designed to determine the coordinates and obtain taxation characteristics in existing, primarily ripening and maturity forest stands. These technologies are associated with serious problems due to the crowdedness of tree crowns and the small trunk diameters. When using the "Digital Twin" concept for forest crops, it is necessary to create a virtual model at the stage of designing the forest stand and its establishment. This requires an understanding of the characteristics of the reforestation resources area, the outcomes of a field survey, the characteristics of the forest restoration method employed, the characteristics of the planting material used, and the coordinates of every individual plant subject to accounting. Moreover, while most of the information about the forest crop project can be entered later, information about the coordinates of the location of the planting material (undergrowth) can only be obtained directly during planting or sowing.

During the research work, it was determined that in order to construct digital twins of a forest, it is necessary to possess the following data:

- coordinates of each tree, characterizing its spatial position;

- characteristics of the planting material and the forest planting process;
- changes in the taxation characteristics of each tree over time;
- conditions accompanying the development of the forest stand and the growth of each tree.

During the analysis of the existing methods of gathering data, the known level of technological advancements, including computer vision capabilities for UAVs, robotic and automated systems, and programs for modeling the growth of tree stands, we proposed the following method for constructing digital twins of tree stands comprises several stages.

The first stage is carried out at the design stage of forest restoration work, for example, after harvest cutting or in areas damaged by forest fires. It begins with a survey of the reforestation resources area. For each territory to be recorded, its descriptive characteristics are compiled: area, soil composition, climate zone, landscape of the area, state of the existing young growth. For each vigorous tree from the existing young growth, a taxation characteristic is compiled and its spatial coordinates are recorded, which are plotted on an area map. If artificial reforestation is necessary, a planting plan is drawn up. Then, during the process, the actual data of the work are recorded. Namely, for each seedling the characteristics of the planter (surname or identification number, length of work, educational background, age, etc.), type of planting material (species, bare root tree system or root-balled tree system, height of the stem, etc.), source of its receipt, planting method (Kolesov's planting iron, planting tube, etc.), actual spatial coordinates of placement, planting date, soil conditions, method of preliminary preparation of the planting area (tillage, fertilization, etc.) are indicated. These data will be useful in the future for collecting statistics on planting conditions and establishing the reasons for good or unsatisfactory survival ability of plants. The responsible person forms descriptive characteristics in advance and enters them into the database as a characteristic of a specific plant along with the actual coordinates of the planting place, which are automatically recorded during the relevant work. It is important to note that planting work can be carried out both manually and with forest planting machines. The information gathered during this stage of the work will not only enable us to construct a database that serves as the foundation for constructing a digital model of the forest stand, but also to control the completeness of the work carried out, including soil cultivation and planting, and to identify potential deviations, incomplete works, and errors.

According to the forest assessment schedule, the next stage of work will be carried out after some time, for example, after two or three years. At this stage of work, the territory is surveyed remotely using a UAV. Since the spatial coordinates of the plants are already known, they are used in the flight mission. As a result of the survey, the history of each tree growing on it is supplemented with new characteristics. By employing this approach, it is possible to assess the growth of each tree with greater precision and ease by knowing the precise location of each seedling. This is especially important for identifying the percentage of dead undergrowth. Also, based on the coordinates of the plants and their characteristics (species, assumed trunk height according to modeling, crown closure, etc.), it is possible to establish the necessary volumes of reinforcement planting or assign weeding. It is also possible to assess the effectiveness of certain measures to promote forest restoration, for example, after fertilization, or carrying out forest amelioration work, etc.

These surveys are conducted at certain intervals. The result is a digital twin that fully corresponds to the real forest stand and changes with it. The digital twin of the forest stand obtained by this method allows predicting the growth of trees in a particular area. A dis-

tinctive feature of this method is that it allows creating a digital twin together with the establishment of forest crops, and also provides for taking into account the actual spatial coordinates of each individual tree in the forest stand, recorded when planting plants and verified during the on-site primary investigation of the digitalized territory. Knowing the exact spatial coordinates and main characteristics of the tree, mainly its species, significantly facilitates and increases the accuracy of subsequent surveys of this territory using UAVs, decoding images, and forming flight tasks.

The outcomes of the forest inventory obtained through periodic inspection of territories permit determining the survival rate, updating data on the quality of work performed by specific workers, and drawing conclusions regarding the planting material. The results are entered into the database to update the digital twin. If necessary, reinforcement plantings are assigned based on the forest inventory results, but in this case, with uneven loss of growing forest, information on the coordinates of the dead plants will allow the interplanting to be assigned pointwise only in the necessary areas.

Knowledge of the descriptive characteristics of the forest stand as recorded during the initial area survey and their changes over time enables to accurately predict the implementation of forestry measures, such as the duration of selective cutting. The proposed method provides data that will allow us to create automated systems for selecting trees to be cut.

Discussion

Availability of data on the location of seedlings, their state, as well as data on unwanted herbaceous and tree and shrubbery vegetation, which can be obtained during a survey with a UAV, will allow for more effective assignment of agrotechnical and silvicultural tending. Due to the lack of personnel in the forestry industry, tending a plantation is carried out in smaller volumes than necessary, which often leads to the suppression of valuable forest crops. In addition, low-skilled workers are often involved in agrotechnical and silvicultural tending, which can lead to massive damage to crops. In the case of machine tending, the presence of a database with the exact coordinates of the plants to be recorded will reduce the likelihood of a machine-tractor aggregate collision into plants due to the ability to signal the tractor driver about a deviation from the direction of work. Furthermore, with the development of robotic solutions in the forestry industry, the availability of coordinates for the location of individual seedlings can be used to operate compact autonomous machines, since today computer vision technologies do not yet allow for the effective separation of seedlings of target species from unwanted vegetation. The availability of coordinates will allow for the effective prevention of damage to seedlings by autonomous decisions when combating unwanted vegetation in inter-row spacing and row of trees.

For example, in Finland, the UAVs are already used in works to identify coniferous seedlings in grassy vegetation using in order to survey forest crops (Lopatin & Poikonen, 2023). During this work, specialists encountered the problem of poor visibility of coniferous crops in the grass. In the fall, when the grass becomes withered, coniferous trees become at least somehow visible, in the summer, when the grass is green, coniferous seedlings are practically indistinguishable in it. The proposed method provides for knowledge of the exact spatial coordinates and individual characteristics (primarily the tree species) of each individual plant to be counted, which makes it possible to significantly simplify the search for seedlings using UAVs and multispectral cameras by reducing the search area (Figure

1a). During cleaning cutting in young stands, it is often difficult for the operator of a forest machine to visually track all the trees of the target species, especially if the rows are uneven. This can lead to damage to the target trees by the working tools of the machines or the forest machine running over them. Knowledge of the exact spatial coordinates will allow the creation of assistance systems for forest machine operators and reduce the damage probability to the forest stand (Figure 1b).

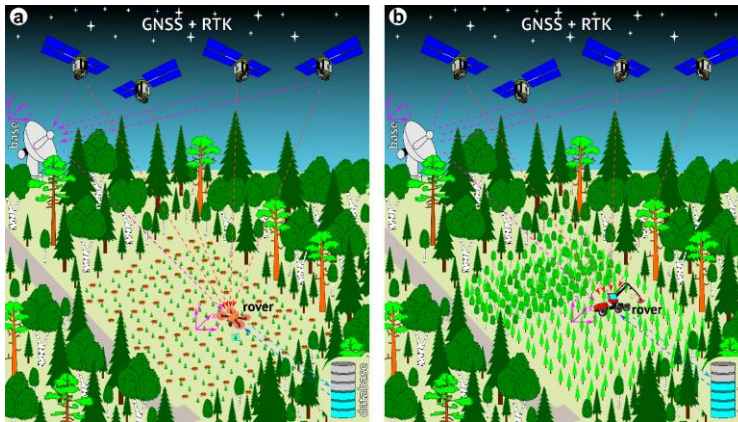


Fig. 1. Usage of data in seedling survey using UAVs (a) and mechanized tending in young stands (b) (drawn by authors)

In order to determine the coordinates of the tree's location in space in the global coordinate system, a satellite navigation system can be used to measure distances, time, and location of objects. However, the accuracy of GNSS receivers in household appliances is completely insufficient for inventory tasks. One solution to the issue of attaining coordinates with sufficient precision is the utilization of global positioning systems that employ the RTK mode ("Real Time Kinematic"), which enables the acquisition of an object's position in global coordinates with a standard error of no more than 20 mm (Elagin, et al.,2020).

The coordinates of the tree's location in space on the plot can be determined by using a local coordinate system. The coordinate system is connected to a compartment grid (poles) and, during forestry work, anchor sensors are installed at consistent positioning points each time, relative to which the coordinates of the beacon sensors are established using trigonometrical method. The usage of Ultra-Wideband technology for identical purposes enables the obtaining of an absolute error in determining the distance between the anchor sensor and the beacon sensor that does not exceed 200 mm (Novichkov et al, 2021). The advantages of these solutions are the ability to abandon satellite navigation, which may be problematic under a complete forest canopy.

The currently existing designs of such devices are quite compact, have autonomous power supply and can be easily installed on planting equipment. For instance, in order to implement the collection of information regarding soil cultivation, a track recording device (Figure 2) may be installed on the base machine, and the planting tubes of workers employed for planting seedlings with a root-balled tree system may be outfitted with devices that record the planting point and store the coordinates of the seedling (Figure 3) in a specialized database.

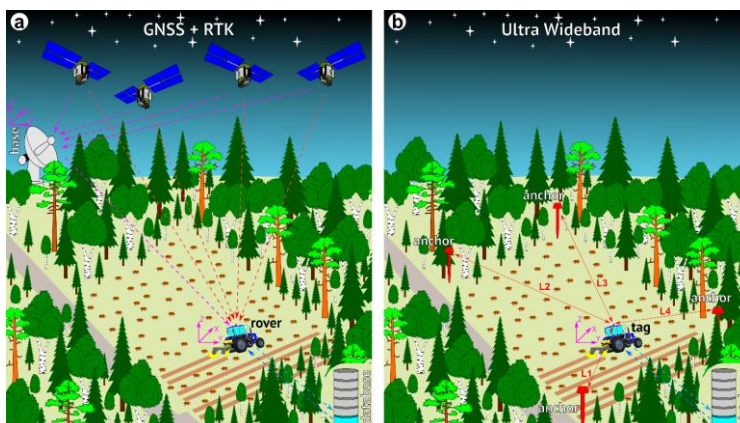


Fig. 2. Collection of information during soil preparation: a – using global satellite navigation; b – using local navigation (drawn by authors)

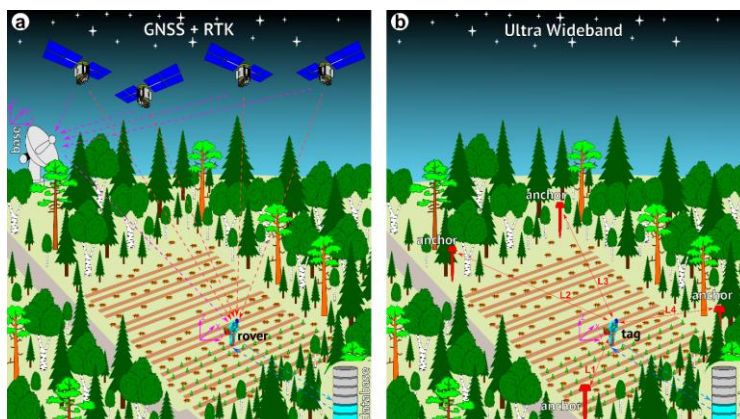


Fig. 3. Collecting information about the coordinates of each seedling during planting: a – using global satellite navigation; b – using local navigation (drawn by authors)

In order to implement the proposed methodology, various devices have been developed at Petrozavodsk State University, including:

- the design of a self-mobile unmanned wheeled platform (patent on a design RU 134396). This platform can be used for inventorying territories, carrying out planting work. A device for recording spatial coordinates of woody plants subject to accounting can be installed on this platform;
- several designs of devices for remote monitoring of the increase in the diameter of a tree trunk, during long-term observation and transmitting the measured data to an electronic computer: patent RU 213059 "Device for tracking the growth of the diameter of a tree strum", patent RU "Method for tracking the growth of the diameter of a tree body", patent RU 213060 "Device for measuring the diameter of a tree strum", patent RU 2776691 "Method for measuring the diameter of a tree body".
- to ensure aerial photography, a design was developed for the suspension of a multi-spectral camera on a drone, and a prototype was manufactured. These technical solutions are also patented: RU 2780022, RU 2783091 "Suspension of the multispectral

camera to the drone", RU 133987 "A set of devices for a multispectral camera of an unmanned aerial vehicle".

During each tending and inspection, it is possible to specify the forest cultivation area, which will allow for more efficient assignment of dates and machines for cleaning cutting in young stands. During mechanized tending, it is also possible to use data on the location of target trees to assist forest machine operators in their work. With the availability of tree coordinates, it is feasible to strategically plan the location of utility corridors in advance, using computer simulation, when employing mid-range forest machines, in order to minimize the risk of damage to the best remaining trees and minimize the negative impact on the soil. Additionally, it is possible to more effectively select trees of the target species that require removal during thinning.

Conclusion

During the course of the research, an examination was conducted on the characteristics of digital twins of forest stands and their potential applications. It was discovered that existing digital twins of forests do not accurately reflect the actual state of the forest stand and cannot be used effectively for the purpose of assigning forestry measures. This is due to the fact that known methods do not assume knowledge of the spatial coordinates of individual trees that comprise the forest stand.

As a result of the research conducted, an innovative approach to gathering data on the state of forest stands was suggested. This approach is based on the usage of spatial coordinates of all trees in the forest stand and the tracking of their growth from the moment of planting as a descriptive characteristic of the forest stand. In order to facilitate the collection of such information, specialized equipment was developed that has successfully passed the test and demonstrated its operational capability.

A digital forest twin, obtained using the proposed method and based on knowledge of the spatial coordinates of each individual plant in a forest stand, will allow for a highly accurate implementation of a comprehensive accounting of woody plants, assessment of processes and indicators of forest and green space development, assignment of agrotechnical and forestry measures, and more rational planning of logging.

The implementation of computer vision, which is currently extensively used in numerous industries, in forests presents numerous challenges due to various objective factors, including objects of shaped forms, a significant number of moving obstacles, such as the movement of small branches during wind gusts, etc. The proposed method, which takes into account the spatial coordinates of individual plants, will automate a significant share of manual labor by simplifying the use of UAVs for remote inspection of forest crops.

Currently, work is underway to develop an experimental device for capturing the coordinates of planted seedlings and to develop a test database that incorporates the proposed methodology, in a manner that is convenient for its maintenance and utilization for its intended purpose. Information is being accumulated on the selected experimental sites in order to enter primary information into the test database. This must be filled in before the stage of planting woody plants.

Conflicts of Interest: The authors declare no conflict of interest.

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