Philipps Universität Marburg

Towards Forest Dynamics' Systematic Knowledge: Concept Study of a Multi-Sensor Visually-Tracked Rover Including a New Insect Radar for High-Accuracy Robotic Monitoring

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ABSTRACT

Forest research is essential for understanding the global carbon cycle and multi-scale forest decision-making, management, and conservation. The need for systematic forest monitoring approaches can be addressed using recent achievements in robotics and computing. Compact sensors and associated data management techniques are revolutionizing this topic. We propose a compact autonomous station hosting a low-range radar for high-detail nocturnal insect (and small species) surveillance with the potential being extended to other niches of stationary data collection aiming mainly at forest animal activity but potentially including vegetation and tree phenology and forest floor conditions. Moreover, we introduce a novel multi-sensor visually-tracked rover concept allowing complex forest phenology monitoring with multiple potential applications. The proposed idea of rover automatic tracking with total station allows for collecting data with centimeter accuracy. A deployed dense control network facilitates it. Furthermore, the network is utilized for accurate tree measurement to interpret the collected sensor data. The demonstrated sample data confirm the effectiveness and high potential of the proposed solutions aiming at systematic forest dynamics monitoring.

Keywords: UGV, SLAM, Forest Floor, Total Station, FMCW Radar, Entomology, Forest Soils, Raspberry Pi

1 INTRODUCTION

Forests play a crucial role in the global carbon cycle and show remarkable uptake potential (Pugh et al., 2019), but a lack of monitoring and model design data makes policy action difficult (Mitchard, 2018). Worldwide deployed forest carbon monitoring systems providing various data and utilizing different methods and assumptions make it difficult to evaluate mitigation performance consistently across scales (Harris et al., 2021). Attempts of the global assessment of the potential of regrowing natural forests for capturing additional carbon indicate problems with the data availability and quality (Cook-Patton et al., 2020). Recently noticed complex forest thermal insulator functions make such measures even more challenging (De Frenne et al., 2019). Forest dynamics, in its extensive sense, is the main focus of the monitoring.

Occurring pervasive shifts in forest dynamics are of vital concern nowadays. At first glance, deforestation is the most distinguishable concern in the forest dynamics scope. While forest cover is increasing in many, mainly developed countries, in tropical and subtropical areas, its degradation continues (Pendrill et al., 2019). Forest transitions, i.e., moving from net loss to net gain of forest area, are expanding. Brazil is a remarkable example of attempting to halt deforestation. Despite their achievements, the problem remains significant. For instance, high-resolution remote sensing data analysis in this region has shown significant degradation of the current vegetation cover and proposed a restoring strategy to increase native vegetation cover by about a third (Rezende et al., 2018). An overview of multiple strategies for timber production in Amazonian forests has shown that "the concession system will not be able to supply the timber demand without substantial reforms in natural forest management practices and in the wood industry sector" and, thus, indicated the necessity in alternative sources of timber (Sist et al., 2021). Regarding forest preservation and restoration strategies, (Arroyo-Rodriguez et al., 2020) have concluded that landscapes should contain at least 40% of forest cover to be optimal for forest-dwelling species.

Forest degradation has been successfully monitored globally using various remote sensing methods (Gao et al., 2020). The verified Global Forest Change dataset (Galiatsatos et al., 2020) suggests that Africa, South Asia, and South America remain hot spots. At the same time, the situation in temperate and boreal forests looks optimistic in view of the deforestation problem. Despite some national and regional achievements (although, sometimes, even well-established remote sensing monitoring in North Europe may lead to confusion (Wernick et al., 2021; Ceccherini et al., 2020)), global deforestation remains challenging. Even in areas with positive dynamics, other, less obvious issues related to forest dynamics should be addressed.

(McDowell et al., 2020) have found an emerging global trend of old-growth forests dwindling in favor of younger stands leading to a reduction in forest canopy cover and biomass. According to them, anthropogenic-driven exacerbation of chronic drivers, such as rising temperature and increasing transient disturbances, including wildfire, drought, windthrow, biotic attack, and land-use change, play a crucial role in this context. These findings have been corroborated by almost thirty years of monitoring Brazil's Atlantic Forest (Rosa et al., 2021), confirming a progressive rejuvenation of the native forest cover.

In addition to complex forest dynamics questions, concrete factors are also under strong consideration. Among them, forest fires are one of the main exceptional factors. For instance, (Boer et al., 2020) reported unprecedented burn areas of Australian mega forest fires. Insect pests are another remarkable concrete factor affecting forest dynamics. (Jactel et al., 2019) expect positive responses of forest insect herbivores to climate change with a shorter generation time, higher fecundity, and survival, leading to increased range expansion and outbreaks. Another aspect of forest insect research is conservation. We have indicated a significant need for more systematic insect monitoring techniques making it hard to respond to the pest challenge effectively (Noskov et al., 2021b).

The mentioned works illustrate the importance of various-scale systematic forest monitoring for forest management and planning, protection, use, policy-making processes responding to natural and anthropogenic disturbances, and conservation. Recent progress in robotics, data processing, and compact sensors allows preparing novel compact devices for forest monitoring. Open-source software and famous electronic circuits guarantee such devices' flexibility, effectiveness, exchangeability, and availability.

The present article proposes a novel approach for systematic forest monitoring using reproducible open-source solutions. Section 2 describes a research area and overall concept of the proposed forest monitoring infrastructure expanded in the following section. First, Subsection 3.1 demonstrates a sensor box for high-detail nocturnal insect monitoring using a radar unit, light trap, camera, and Raspberry Pi;

it can be extended to stationary monitoring of forest floor, vegetation, and phenology. The box functions autonomously using epoch-second timestamps for multi-sensor data merging. Second, Subsection 3.2 introduces a novel multi-sensor visually-tracked rover concept. We adopt the insect radar box's solutions and an idea to use a prism with an unmanned ground vehicle (UGV) (Vaidis et al., 2021). As with the sensor box, all sensors work autonomously using timestamps for data merging. Our innovation is to use a total station (the primary survey instrument measuring angles and distances electronically and calculating the accurate position coordinates) for automatic tracking and rover position continuous recording (using short distance intervals). Third, Subsection 3.3 describes a deployed control network (surveyed reference points) of accurate benchmarks enabling centimeter accuracy sensor positioning. Moreover, we overview the tree-measuring process required for general forest mapping and sensor data interpretation. Finally, we show examples of datasets collected with the rover, including maps depicting georeferenced information.

2 STUDY AREA AND OVERALL CONCEPT

2.1 Study area

A study area resided 7 km North-West of Marburg (Hesse, Germany), near the Caldern distinct. It is mainly covered by a classical German forest consisting of the following tree species: 60% of *Fagus sylvatica*, 30% of *Quercus sp.*, and 10% of *Carpinus betulus* and other species. The area size is ca. 20 ha. This area is covered by RGB point clouds taken by regular unmanned aerial vehicle (UAV) flights. The center of it is under more detailed investigation, where we measured all trees with a total station and collected data with a multi-sensor rover. This is a ca. 5 ha area with height differences from 256 AMSL m to 275 AMSL m. Figure 1 shows a map of the research area.

2.2 Overall concept

Figure 2 illustrates a proposed research schema consisting of three initial tasks, three deployed and verified platforms, and five partially achieved products forming together a research target - forest dynamics' systematic knowledge. Arrows connect the elements of the conducted and planned research. The general idea is that stationary sensor boxes facilitate animal monitoring, while phenology monitoring is carried out with mobile devices like UGV and UAV. Of course, stationary sensor boxes can provide some phenology information, but animals are their primary target. Similarly, a UGV can collect some animal information, while phenology is its main focus. We do not consider UAV within this paper scheduling it for future work. There are the following initial tasks of forest monitoring expanded further:

- Animal surveillance;
- Forest floor, vegetation, and canopy mapping;
- High-accuracy coordinate detection under the canopy.

As mentioned, **animal surveillance** requires stationary sensor boxes. Such boxes can detect various forest animals (including bats, all-size mammals, birds, and invertebrates) using various sensors, like cameras, microphones, and radars. Cameras are mainly configured for motion detection and often require to attract animals; microphones can reflect soundscape, making them especially effective for ornithology. Wide-spread compact and energy-efficient cameras and microphones are often used in compact sensor boxes. Despite this, cameras and microphones have limited usage and are required to be enriched by other sensors. Recently-available radar units have great potential for animal surveillance in autonomous sensor boxes, especially in the forest. In contrast to cameras, radar does not require visuals with the target making

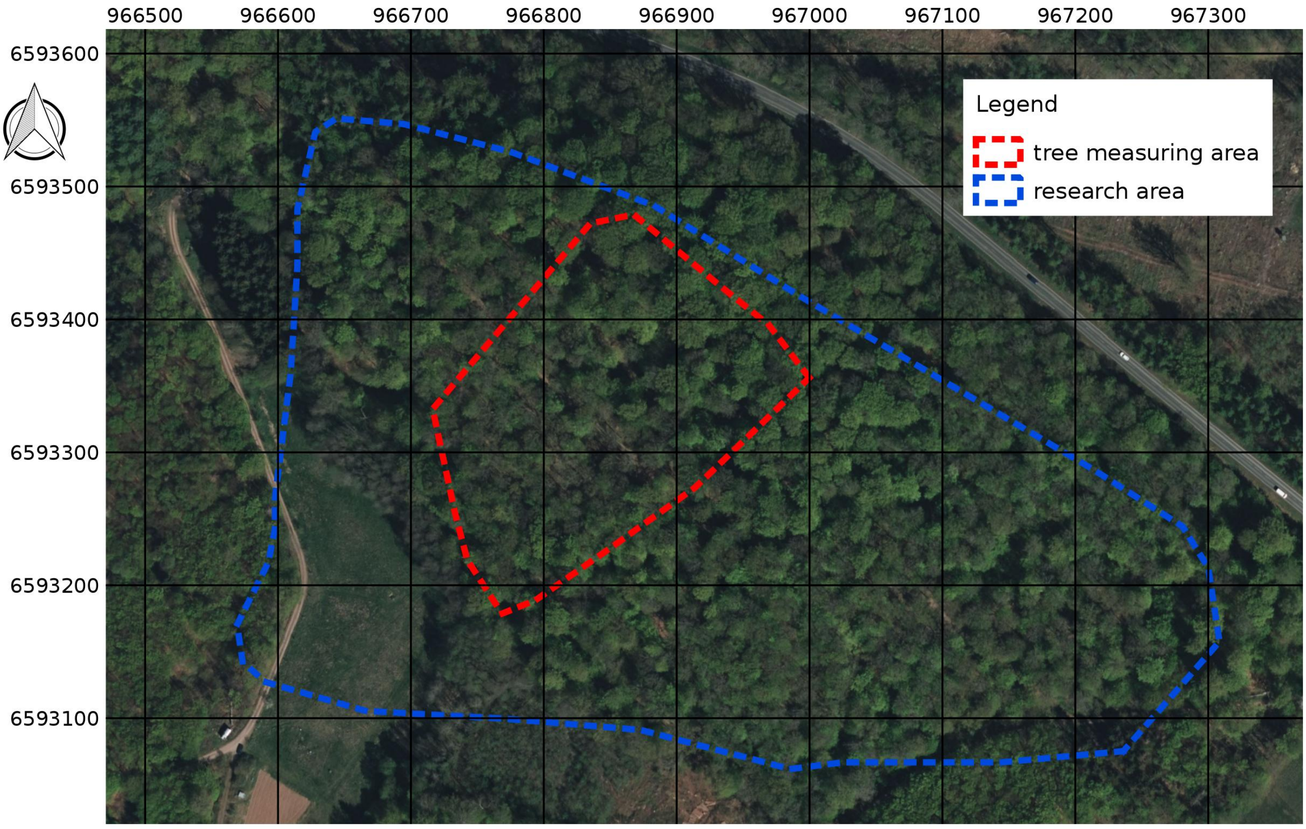

Figure 1. Research area map. Coordinate system: EPSG 32632 (WGS 84 / UTM Zone 32N). Satellite imagery of Bing maps.

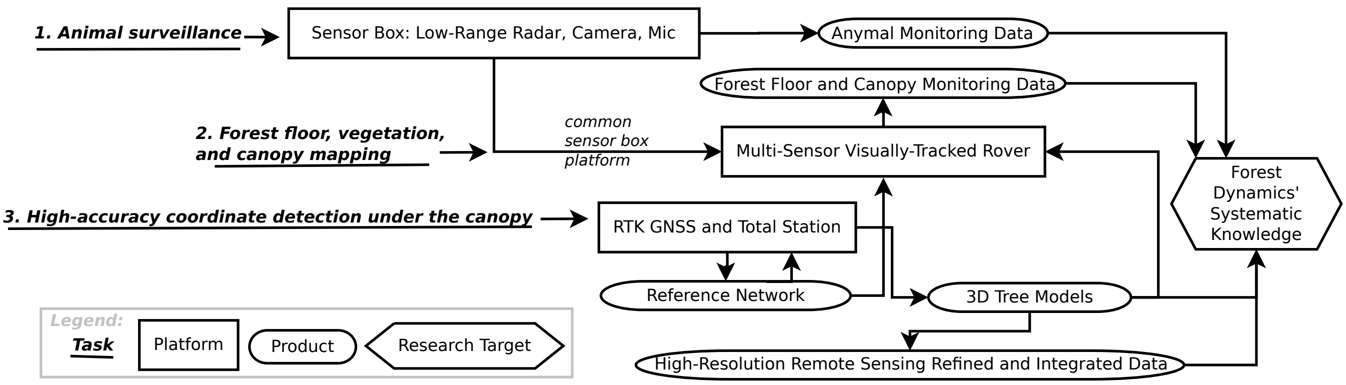

Figure 2. Research infrastructure. Connections of tasks, products, and the research target.

it a good candidate for nocturnal observations or when the targets are hidden by obstacles like fog or even solid material (see (Taravati, 2018)). Compact radar units are just starting their way in this niche.

This article presents an autonomous sensor box where radar is a key component. Here, we continue the work started in (Noskov et al., 2021b) and especially (Noskov, 2021). Currently, the radar box aims mainly at nocturnal insects. We also use a camera and microphone, extending the use cases of the sensor box. Prospectively, it can cover a broader range of forest animal behavior topics.

A core part of this work dedicates to **forest floor, vegetation, and canopy mapping**. We propose a novel solution for conducting systematic research under the forest canopy aiming the centimeter accuracy. For this, we have developed a multi-sensor rover. Since accurate coordinate detection is impossible with RTK GNSS in the forest environment, we propose using an attached prism followed by a total station recording coordinates of the prism with a short interval. It is important to mention that currently high-accuracy monitoring behind crowns in the forest is hardly possible. The proposed approach with a visually-tracked rover resolves this.

High-accuracy coordinate detection under the canopy requires a network of surveyed (usually with a total station and/or GNSS system) reference points (reference network) to orient the total station. We have transferred the total station coordinates from the closest meadows, where several benchmarks have been measured with sub-centimeter accuracy using RTK GNSS. The oriented total station allows tracking the moving rover and recording its coordinates with about centimeter accuracy. Every piece of recorded information (photos, point cloud sets, audio, temperature measurements, and collecting radar frequencies) is currently geotagged. That means that each photo, for example, is attributed with coordinates (XYZ) of the closest (by time) point recorded by the total station.

All elements of the proposed forest monitoring infrastructure, shown in Figure 2, are connected and converged, pursuing an ambition to increase the forest dynamics' systematic knowledge. The sensor box contributes to the knowledge with the animal monitoring data. Moreover, it also delivers a common sensor platform utilized by the rover. The RTK GNSS and Total Station element is used for establishing a reference network, which is utilized for measuring trees and orienting the total station for tracking the rover. The rover collects heterogeneous data relating to vegetation phenology and forest floor, contributing to the forest dynamics knowledge. 3D accurate tree models with semantic information are valuable by themselves. However, we also use them for the rover data interpretation and plan to use them for UAV point cloud data adjustment in the following work. In the next section, we expand on details of the elements and design of the developing forest monitoring infrastructure.

3 ELEMENTS AND DESIGN

3.1 Compact Insect Radar Box

Our extensive review of insect monitoring approaches with special reference to radar techniques has shown a high potential for novel radar solutions for entomology Noskov et al. (2021b). The review has confirmed the need for more compact short-range radar applications in insect research. We showed that while many camera-based solutions are available, very little attention is denoted to compact radar sets. We have proposed to use a frequency-modulated continuous-wave (FMCW) compact radar. The review indicates the demand for novel compact radar data processing and interpretation solutions. Moreover, the first mockup setup of the radar on a rover basis has been shown. Since the radar unit was designed for much larger targets, the FMCW signal from the insect target seems weak and unstable. We have proposed and demonstrated a radar setup assembled with a light trap. It allows for collecting ground truth information to better interpret highly uncertain FMCW radar data.

With the utilized radar unit, seeing the clear insect signals was impossible. In Noskov et al. (2021a), we have conducted a series of lab experiments to find out how to extract the insect signal from very noisy data. A novel metric (Sum of Sequential Absolute Magnitude Differences(SSAMD)) has been proposed as a solution. SSAMD allows extracting insect presence and biomass information from very uncertain radar data. Multiple lab experiments confirmed it. Moreover, several experiments have been conducted with a light diffuser to prove the ability to use the radar set with a light trap.

We have built an autonomous compact energy-effective device comprising a radar unit, light trap, and several other sensors for fieldwork. Figure 3 shows the prepared compact sensor box; Figure 3a is its photo taken in the forest. Its size is 40x30x25 cm; the camera holder's length is 108 cm. The main enclosure is a regular domestic plastic box with a lid with a hole we made for our radar unit. As in the previous work, we use the 60 GHz radar; comprehensive technical details are provided here Noskov et al. (2021a).

Figure 3b shows the components of the designed compact insect radar box. The 12V car battery is the only heavy component. Most energy is required for an ultraviolet (UV) light-emitting diode (LED). The aluminum sheet reflects the light returning from the bottom of the light diffuser. This improves the performance of the light trap equipped with only one LED.

The managing block comprises Raspberry Pi, radar data cables, power, battery connection, and other miscellaneous wires – standard car battery connection black and red wires with regular clamps power the device. Radar data cables consist of a standard Ethernet cable connected to a radar data cable going to the radar unit attached to the lid. The miscellaneous cables consist of LED management wires, a polarity protection circuit, an LED driver, and some other wires. The polarity protection circuit prevents the radar unit from damaging by the wrong polarity (misconnected battery). We use the Mean Well ldb-350l DC-DC Constant Current Buck-Boost LED driver. It manages UV LED, providing sufficient power and allowing turning it on and off via a Raspberry Pi interface.

We use the Microsoft LifeCam HD-3000 web camera with a usage indicator (blue light) and an internal microphone. Real-Time Clock (RTC) circuit facilitates accurate time. Two wires connected to pins let Raspberry Pi turn on/off LED via the DC-DC Constant Current Buck-Boost LED driver. The computer is powered by a USB-C cable connected to a USB 12V-to-5V converter in the power wire bunch.

The device's energy consumption requires a full battery for about 12 hours with the turned-on radar, camera, Raspberry Pi, and UV LED. Since UV LED requires the most energy, we use the ldb-350l LED driver to manage the LED working hours. Because of changing night-time, we set up working hours twice a month to optimize the LED usage; of course, it can be easily automatized in future work. Moreover, Raspberry Pi turns off the device at a specific time in the morning (usually 9 a.m.) to prevent unnecessary battery discharging. Therefore, we need to charge/replace the battery nearly every day. Currently, it can be done only manually. A person needs to come to pick up the device in the morning, set it to charge during the day, upload the collected data, free the disk space for new data if required, bring it back to the forest in the evening, and start the radar box. This workflow requires at least one hour a day (about half an hour in the morning and half an hour in the evening). Thus, all personal issues have interrupted the process. The workflow can be significantly simplified by using solar panels in the future.

The designed sensor box has worked within two warm seasons of 2021 and 2022 during no-rain nights (usually from 8:00 p.m. till 09:00 a.m.) in the forest automatic weather station's area. This allows for comparing insect radar with the full range of meteorological data collected by the station. It is important because the weather is one of the main factors defining low insect flight. Long time series of data have been collected. The data comprise light trap photos taken with the 5 s time interval and radar frequency data with the 0.02 s time interval used for SSAMD calculations. SSAMD values are calculated for a 1 s time interval. These time series enable us to calculate the presence and biomass information supported by ground truth light trap photos.

Figure 3a. Insect Radar's Photo.

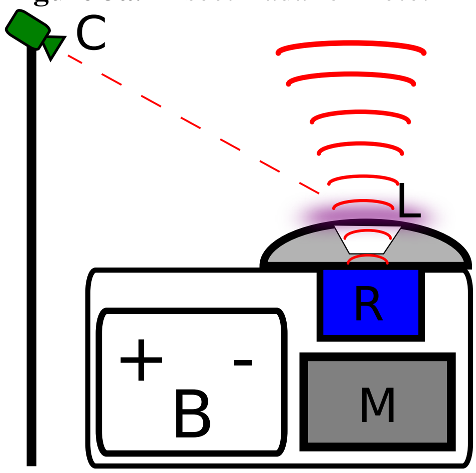

Figure 3b. Insect Radar's Schema.

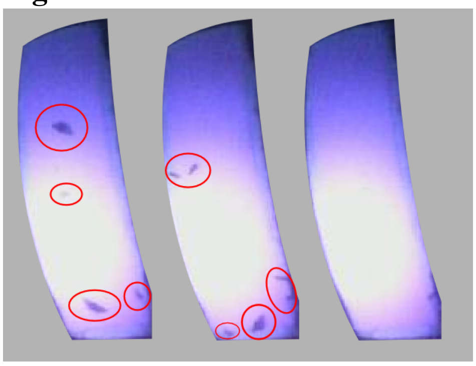

Figure 3c. Light Trap's Photos.

Figure 3. Insect Radar and a Light Trap: **(A)** Operating the insect radar box in the forest; the camera is pointed at the light trap, **(B)** Insect Radar Box's Schema: R - radar, M - managing block (consisting of RaspberryPi, cables, and other components), C - camera with an internal microphone, and L - light trap (ultraviolet LED, reflecting aluminum sheet and a plastic light diffuser), and **(C)** Examples of light trap's photos taken on 22.08.2022 (from 23:00 to 23:20).

Table 1 summarizes the data collected in 2021 and 2022. It informs that we have observed 66 nights (35 in 2021 and 31 in 2022) by today. Every night datasets contain the radar's frequency and light trap's photo data. From August 2022, the device also records audio from the camera's internal microphone. It mainly aims to filter out the signal from larger animals (e.g., badgers) approaching the radar.

Figure 4 shows an example of the measured SSAMD values for 20 minutes. In Noskov et al. (2021a), we have concluded that insect targets correspond to the SSAMD interval from 500 to 3000 ("the threshold of 500 for insect detection" and "all peaks larger than 3000 should be considered suspicious and likely caused by larger (than insects) targets"). In this example, one can see that the most of the time SSAMD indicates the insect presence. Three times SSAMD is higher than 3000 indicating potentially large targets (like a bat). Since the light trap attracts multiple insects, it attracts bats as well. At least once camera made a photo of hardly visible bat, thus, peaks larger than 3000 should be carefully checked for the bat presence or other larger targets. Dew, fog, and rain are another major interrupting source, which has to be investigated in future work (the weather station's data enables us to filter out interrupted data easily).

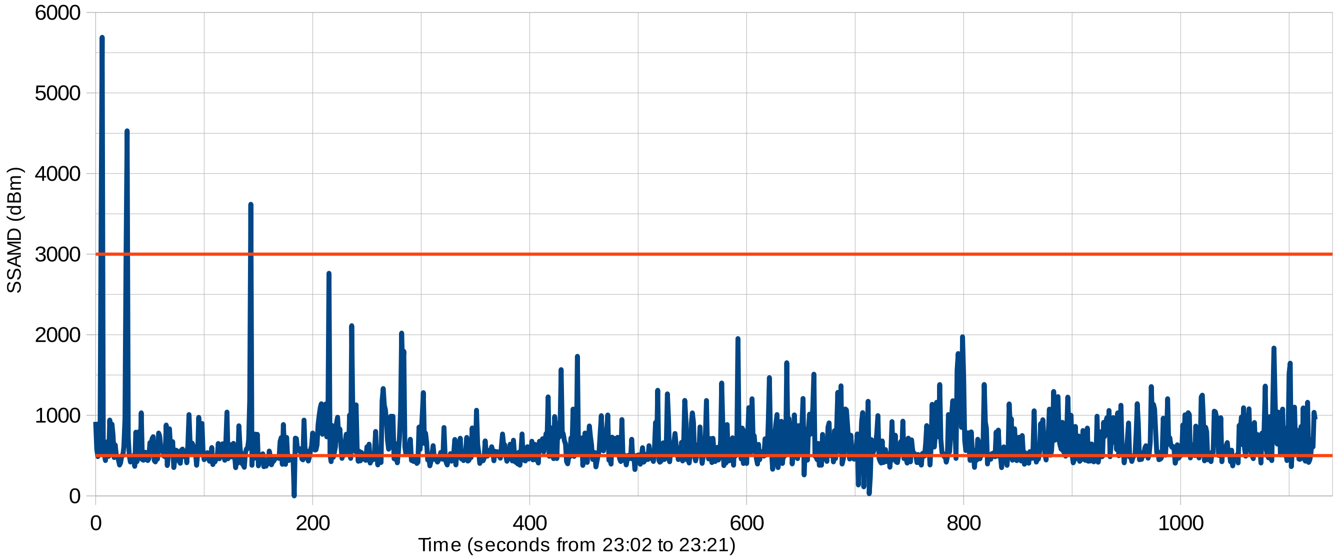

Figure 4. Example of SSAMD measurements on 22.08.2022. The SSAMD insect detection interval is depicted by red lines (500 and 3000).

Figure 3c shows three light trap photos. The two first subfigures (left to right) with several insects are for SSAMD about 1000. The last (right) subfigure is for SSAMD slightly lower 500 (i.e., no insects). Our original idea was to calculate (automatically) the number of insects in the radar radiation zone (around the light traps' symmetry axis). However, multiple observations during the fieldwork have confirmed that this approach might need rethinking. Insects' behavior around the light trap is quite complicated. Most of the time, they are not calm, flying and crawling around. Furthermore, many insects are not visible by the camera but are observed by the radar. For instance, we often saw a dynamic night behavior of several hornets flying around the light trap but not caught by the camera. Bats were also quite active and likely responsible for a typical situation when multiple insects attracted by the light trap disappeared almost instantly. Thus, instead of analyzing the immediate situation (a light trap photo and the corresponding SSAMD value), we will try to work with aggregated values of the number of insects on photos and SSAMD values for a time interval (e.g., one hour). It can let us filter out unnecessary events and see the correspondence of aggregated (average or median) measures for a larger time interval.

Table 1. Overview of insect radar data collected in 2021 and 2022.

Year	Month	Number of Observed Nights
2021	June	9
	July	9
	August	2
	September	11
	October	2
	November	2
Yearly: 35		
2022	August	14
	September	13
	October	4
Yearly: 31		
Overall: 66		

Table 2. Rover's sensors

ID	Name	Specification	Aim
Navigational (SLAM)			
L	RpLidar	360°, 2D	Localization, general mapping
F	RGB Global Shutter Camera	70°, 1920x1080 pixels	Navigation, forest floor and understory
Thematic			
S	RGB Camera	60°,5 MP	Tree crown phenology
R	Radar	60 GHz, see Noskov et al. (2021a) for details.	Insects, small flying animals, and tree crowns
G1	NoIR Camera	60°, UV-1000 nm 8 MP	Forest floor
G2	Thermal Camera	110°, 32x24 pixels	Forest floor temperature
G3	IR Thermometer	8-14 µm	Forest floor temperature

In Noskov et al. (2021b), we have proposed the idea of a mobile radar based on a rover. We have even prepared a mockup setup. The prepared radar box has confirmed that it is possible to use such a radar unit installed on a rover. In the next subsection, we discuss the UGV usage with radar and multiple other sensors allowing us to collect high-granularity spatial forest data.

3.2 Multi-Sensor Visually-Tracked Rover

While drones remain very popular in forest monitoring, rovers show high prospects due to several advantages. In our case, using rovers is beneficial since it enables us to apply multiple sensors and conduct accurate low-viewpoint large-scale forest mapping. In addition, an acquired rover can carry relatively heavy sensors (as the discussed insect radar box) and has good maneuverability in the forest.

We use a Jackal UGV produced by Clearpath Robotics jac (2023). Figure 5 introduces the proposed rover design. Notice that the rover's top black lid size in the view from above is 48x32 cm. Table 2 provides a list of the installed sensors. Our rover setup conceptually consists of two main blocks: navigational and thematic. Both have separate computers with connected sensors. All sensors are attached to the top lid of the rover.

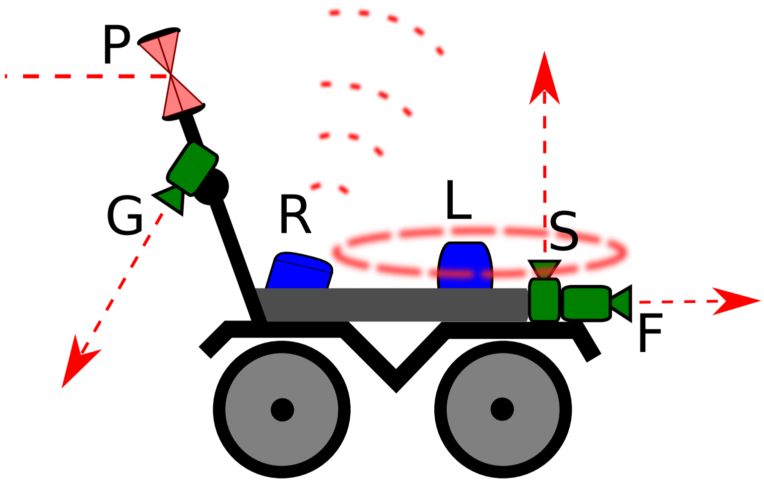

Figure 5. Rover's schema. Navigational block: P - 360°prism, L - RpLidar, F - front camera (RGB global shutter cameras); thematic block: S - sky-oriented camera with a flash light and an attached microphone, R - low-range radar, and G - ground-oriented sensors (NoIR camera, infrared thermometer, and thermal camera).

3.2.1 Navigational Sensors

The navigational block facilitates simultaneous localization and mapping (SLAM) tasks. Its main aim is to keep track of the rovers' location and map the environment. The navigational block comprises the rover's internal computer and two connected sensors: RpLidar (for navigation, vegetation, trees position, and other obstacles general mapping), infrared and RGB global shutter cameras (for navigation and low vegetation and forest floor information acquisition).

RpLidar S1 rpl (2023) is a portable Time-of-Flight laser range scanner. The Time-of-Flight ranging technology guarantees that the ranging resolution does not change with distance. The device has a range radius of 40 m. It is designed to avoid strong daylight interference. RpLidar S1 has a stable ranging and high-resolution mapping performance in an outdoor environment. The front camera is the Intel RealSense Depth Camera D435 rea (2023). The manufacturer claims it offers the widest field of view of all their cameras and a global shutter on the depth sensor that is ideal for fast-moving applications. It is a stereo solution, offering quality depth for various applications. The wide field of view fits applications such as robotics or augmented and virtual reality, where seeing as much of the scene as possible is vital. It offers a range of up to 10 m, making it a good candidate for forest monitoring applications.

As mentioned earlier, RpLidar and the front camera are connected to the rover's internal computer carrying out SLAM tasks. They form the navigational block of the introducing rover concept. These sensors are crucial for prospective autonomous navigation in the forest. However, since we currently drive the rover manually using a wireless controller, it is mainly used for general mapping purposes (i.e., trees, obstacles, vegetation, understory, and forest floor positioning and mapping).

3.2.2 Thematic Mapping Sensors

Both navigation sensors are far-side horizontally aiming. By contrast, thematic mapping sensors aim at the sky or the ground. The radar unit and sky-oriented camera (both sky-oriented) are mixed up with the navigational sensors). As mentioned earlier, all thematic sensors are connected to Raspberry Pi.

The radar unit has been described in detail in the previous section and Noskov et al. (2021a). Although initially the radar unit was aimed mainly at insects, with the rover, we are trying to extend its applications. Since the first rover trial started at the end of October 2022, it was too late to use it for insect targets (it should be done in the next warm seasons). Therefore, we have decided to use radar for phenology monitoring (observing tree crowns with radar). October-November is a leaf-off time. Variable conditions of crowned should produce the variable reflecting radar signal. Therefore, we expect a stronger reflection in the earlier measurements (at the end of October) and a weaker signal in the later measurements (in December). In this field, campaign we have focused on the various aspects of the leaf-off phenology event. The detailed results will be reflected in future publications.

The second sky-oriented sensor is the HBV-1825 FF Camera Module 5MP HD Lens 60°Field of View USB Camera Module with Flash and Microphone. As discussed earlier, this fieldwork aims to tree crowns. The sky-oriented camera lets us see detailed changes in tree crowns along the leaf-off time. Prospectively, we can also use this sensor for insects. For instance, in Noskov et al. (2021b), we discussed examples of successful solutions, even for nocturnal species (e.g., Ruczynski et al. (2019)). We also use an internal microphone during the rover's measurements. It is needed only for registering the measurement conditions (e.g., the rover's fall). Prospectively, it can reconstruct an avian soundscape or estimate the human impact (e.g., road noise).

Further, we describe ground-oriented sensors: Raspberry Pi NoIR Infrared Camera Module 8MP v2.1 noi (2022) (NoIR stands for "no infrared filter"), Optris CT Infrared-Thermometer ith (2021), and MLX90640 IR Array Thermal Imaging Camera (32x24 Pixels, 110°Field of View, I2C Interface) Shaffner (2021). The infrared camera and infrared thermometer aim at nearly the same point on the ground, resided at 45 cm backward from the rover. While the thermal camera aims at a point on the ground resided at 1 m backward from the rover.

So far, we have used the infrared camera for registering the forest floor visible patterns compound mainly from fallen leaves, grass, moss, rotting wood, etc. Accurate centimeter positioning data will be an excellent source for advanced research on forest soils, microhabitats, and forest floor microbiomes. Moreover, the infrared thermometer aimed at the same area provides us with the temperature of an observed ground patch. Prospectively, we can use the NoIR infrared camera to observe the forest ground nocturnal processes.

Finally, the mentioned thermal camera makes 32x24 pixel thermal maps of a larger ground patch. It aims at a ground point resided at 1 m backward from the rover. This allows preparing accurate thermal forest timeseries maps. Moreover, calculating the average temperature facilitates collecting temperature point data, where the point represents a wide area behind the rover.

All thematic sensors are resided along the symmetry axis of the rover in the following length and height (from the ground) correspondingly starting from the very front point of the rover towards the very back point in a view from above: RealSense Depth (front) Camera - 6 cm, HBV-1825 FF Camera (sky-oriented) - 11 cm, RpLidar - 19 cm, Radar - 31 cm, and ground-oriented sensors -46 cm. All these sensors record valuable multi-source data, which require a novel merging and positioning approach we propose in the rest of this section.

The forest environment is a complicated environment causing specific problems for systematic monitoring: lack of the GNSS signal making it impossible to obtain RTK-corrected measurements, poor GSM coverage, cross-country situation, multiple obstacles (trees, fallen trees, and branches, understory, slopes, etc.), low accessibility, etc. Therefore, to address these challenges, in the present article, we propose three main principles for UGV high-detail multi-sensor monitoring introduced in this section: autonomy, timestamp synchronization, and visual tracking.

3.2.3 Autonomy and Timestamp Synchronization

We also adopt the design solutions introduced for the insect radar box for the UGV. Moreover, we have designed the rover using discussed autonomous monitoring approach. The rover drives manually with a wireless controller. However, all sensors are preconfigured in lab conditions and are not intended (although it is possible if needed) to be manipulated in the field. They all start recording data automatically with the start of the rover and shut down when it is powered off.

We use three unconnected computers (Raspberry Pi, the rover's internal computer, and the total station's tablet) to collect various data sourced from multiple sensors; these data are merged using exact time stamps (epoch seconds). Before starting field measurements, we ensure that the clocks of all computers are synchronized perfectly. In our case, we accept when the clock deviation does not exceed one second. All data slices collected by sensors are addressed with an epoch-seconds timestamp. This makes it possible to merge data residing in the different computers correctly afterward.

3.2.4 Prism for Visual Tracking

It is well known that RTK-corrected accurate GNSS measurements are often impossible in the forest (even in the no-leaf winter). In our forest, a satisfactory (fixed) signal is possible only in meadows and some specific rare segments of roads crossing the forest. A reachable signal accuracy of meters or even tens of meters makes our data useless for collecting high-detail timeseries. Thus, the only reasonable way is visual tracking by the total station. This allows reaching a centimeter spatial accuracy of collecting data.

Visual tracking requires an oriented robotic total station and a prism installed on a rover. Robotic total stations allow automatic prism tracking and automatic coordinate recording with a specified time or distance interval.

We have equipped the rover with a 360°prism allowing (automatic) tracking of the coordinates with very short intervals and an accuracy of about 2 cm using the robotic total station. The prism can be fixed on a prepared prism holder residing on the same pole of the thematic mapping sensors. Figure 9 depicts the fully equipped rover with the prism ready for measurements.

The total station is oriented using the deployed dense reference network in the key area. Correct orientation is a critical point in the fieldwork with the multi-sensor rover. Only correctly oriented total station allows accurate data positioning. In the next section, we expand on this topic.

3.3 Forest Reference Network for High-Accuracy Sensor Positioning and Tree Measurements

As discussed, using the rover requires exact positioning in the forest. While GNSS cannot provide satisfactory accuracy of coordinates in the forest due to signal interactions by tree crowns, a dense control forest is very actual for such research. Thus, we have decided to deploy a dense reference network in the forest key area (about 5 ha). This area is covered by regular UAV RGB point data timeseries obtained by our colleagues in recent years. Therefore, we intended to deploy a dense reference network to cover this area. We consider at least three applications of this control network: UAV timeseries adjustment, tree monitoring, and sensor positioning (including UGV).

Initially, we thought about the adjustment of the mentioned UAV timeseries. UAV data have been georeferenced with a regular GPS system, usually giving the device position not higher than 5 m accuracy. Additional factors make the accuracy of the registered points even worse. This causes the indication of the same tree in timeseries often challenging. Rectifying point cloud timeseries requires a dense set of equably distributed 3D landmarks. Trees are the only objects widely distributed in this area. Thus, we can use them to increase the absolute accuracy by approaching tens of centimeters of point coordinates. So, we have decided to measure trees using the total stations' reflectorless mode. Measuring trees requires a dense benchmark network.

Leaves and vegetation in the forest make the survey challenging; therefore, it was conducted in winter. First, we measure several times basis benchmarks in meadows where the GNSS signal is excellent. There were two meadows with three basis benchmarks each (overall, six basis benchmarks with a sub-centimeter absolute accuracy of the XYZ coordinates). All other forest benchmarks are resided in between two meadows. The benefits of the winter survey are as follows: the prism remains visible even through dense branches of low trees. Forest benchmarks defined with basis (meadow) benchmarks have an accuracy of up to 2 cm. While forest benchmarks defined with other forest benchmarks can have a lower accuracy of about 20 cm. 20 cm accuracy is satisfactory for the UAV data refinement and tree monitoring, but we aim for the centimeter accuracy for sensor (rover) positioning. Thus, the rover measurements have been conducted with only 2 cm accuracy benchmarks.

We have measured all trees in the center of the key area (504 trees). For tree measuring, we install the total station in any position with a good target object visibility and accessibility of at least three benchmarks. Then, we orient it with accessible benchmarks and measure target objects in the reflectorless mode. We have applied two approaches for measuring trees: brief and detail. In brief mode, we measure a few points along a tree stem. The highest point usually resided about the beginning of crowns because crowns make a specific tree hardly reachable (a random intermediate branch can be measured instead of the target tree). We have measured a few trees in the detailed mode. In this mode, we measure many points along the stem.

What is more, we measure all major branches. In many cases, the laser reaches the very tip of branches. This allows the construction of accurate and detailed 3D tree models; Figure 6 portrays a tree 3D model consisting of the measured points.

These accurate data are valuable for UAV and multi-sensor rover data refinement. The rover data interpretation also requires this tree information because trees are the main objects in the research area. Figure 7 overviews the results of the conducted survey. As discussed, there are six original basis benchmarks resided in two meadows. Furthermore, 28 forest benchmarks resided in the forest between two meadows. Five hundred-four measured trees are also depicted on the map.

3.4 Visually Tracked Rover Workflow and Results

The deployed reference network allows fieldwork with the rover. We have limited the measurement area to the area of the measured trees. We have used only forest benchmarks defined with the basis (meadow) benchmarks to orient the total station. We need it to reach the maximum possible accuracy of collected rover data.

A single person can conduct the rover fieldwork thanks to the robotic total station and selected equipment. First, we need to bring the equipment as close as possible to the measurement area. A single person can borrow the equipment to a station position. A station position is a point where one sets up and orients a total station.

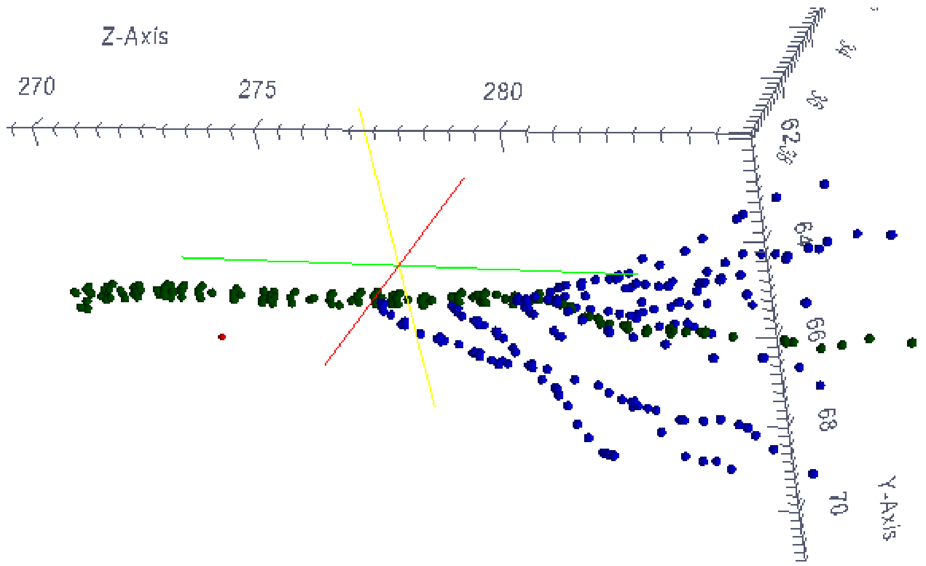

Figure 6. 3D model of a tree measured in the detailed mode. Green points - the stem, blue points - the main branches.

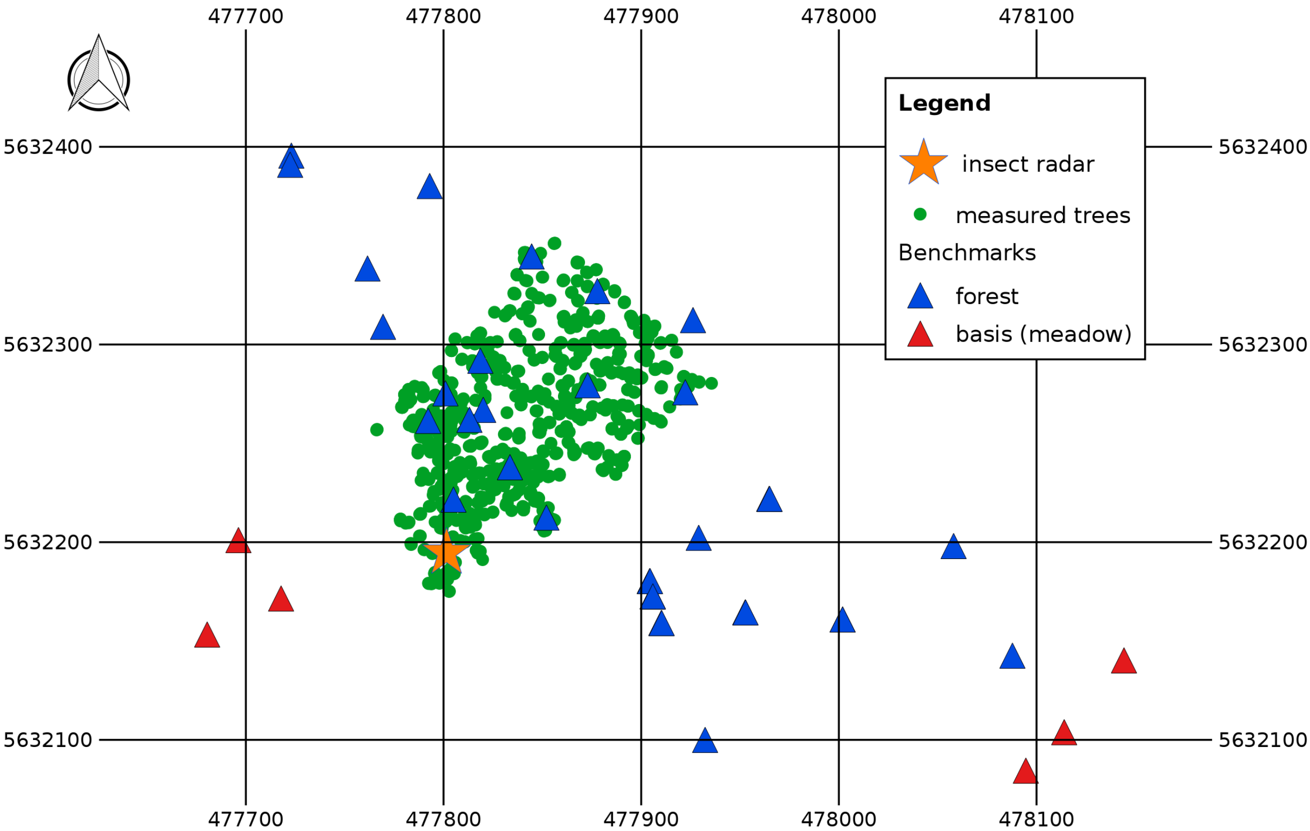

Figure 7. Map of the installed benchmarks and measured trees. Coordinate system: EPSG 32632 (WGS 84 / UTM Zone 32N).

After this, we need to install a pole with a prism on a benchmark and hold it with a pole tripod. Then, we set up the total station and measured the first benchmark. Furthermore, we measure other accessible benchmarks. We have used from three to six benchmarks to orient the total station. We estimate the accuracy of the measured rover position coordinates to be about two centimeters for every coordinate. We have used four stations for every round.

To start measurements with the rover, we attach the prism, turn it on, check the time synchronization, and point the total station to the attached prism. Figure 8 demonstrates pointing the rover's prism from the total station. Then, we lock the prism and start a tracking mode of the total station using a 3D distance interval of 20 cm (i.e., the total station records a point in every 20 cm of the moved prism). Finally, using the Sony PS4 Bluetooth controller, we drove the rover around the station (the maximal range was about 50 m from the rover to the total station).

Figure 8. Setting-up for automatic measurements: Aiming the oriented robotic total station at the rover's prism.

Figure 9 shows the rover ready for measurements: it is equipped with the prism, turned on, and connected to the wireless controller (the permanent blue light of the controller placed on the top of the rover in the photo is signaling it is connected and ready to operate). As discussed, the rover records all data automatically after turning it on.

Regarding data collection, the navigation and thematic mapping sensors follow different approaches to data collection. The former uses The Robot Operating System (ROS) services to save data in the bag format. Every six seconds, the rover computer starts writing a new bag file for two seconds; it saves several frames of RpLidar and the front camera. Moreover, all data from rovers' available internal sensors are

Figure 9. Operating the rover.

recorded. The latter uses similar solutions to those we have utilized for the insect radar box. In particular, the radar and temperature sensors record sensor data continuously, making the 0.02 seconds pause between the recorded data slices.

Furthermore, cameras save a photo, firstly, from the sky-oriented USB camera, secondly, from the ground-oriented NoIR camera, and then make a break of two seconds. Finally, the microphone records the audio continuously. Currently, we use the microphone to have more information regarding the workflow. For instance, if the rover is overturned (which happened several times), the audio clearly reflects this. In the future, a microphone can be used for recording birds' songs (for the forest soundscape reconstruction).

Since each photo has a timestamp, they can be georeferenced using the accurate coordinates of points recorded with a short distance interval from the total station. Prospectively, we can classify the taken photos using machine learning algorithms and prepare high-detail maps representing tree crowns and the forest floor.

Figure 10 shows an example of a photo taken from the ground-oriented NoIR camera. One can notice that it is highly contaminated by infrared radiation. However, as shown in the figure, such photos can be refined to make them look natural. The benefits of using a NoIR camera are possible nocturnal observations with infrared lighting and the feasibility of using it as a multispectral imaging system (as proposed in Lopez-Ruiz et al. (2017)), allowing us to calculate, for example, vegetation indices. In addition, a removable infrared filter can equip the camera. However, we do not consider it because the global shutter front camera covers the ground surface providing good-quality high-resolution RGB photos.

Figure 10. Ground-oriented NoIR camera photo example. Left - original image, right - processed image with the reduced impact of the infrared radiation (as recommended in Thomas (2021)).

Figure 11 shows an example of a photo taken with the sky-oriented camera. One can notice that such data reflect the crown conditions. The left subfigure is an original photo; the right subfigure results from classification. The original photo was classified using an unsupervised classification algorithm providing three groups of pixels: leaves, tree stems and branches, and sky. It allows for calculating statistics required for ecological modeling.

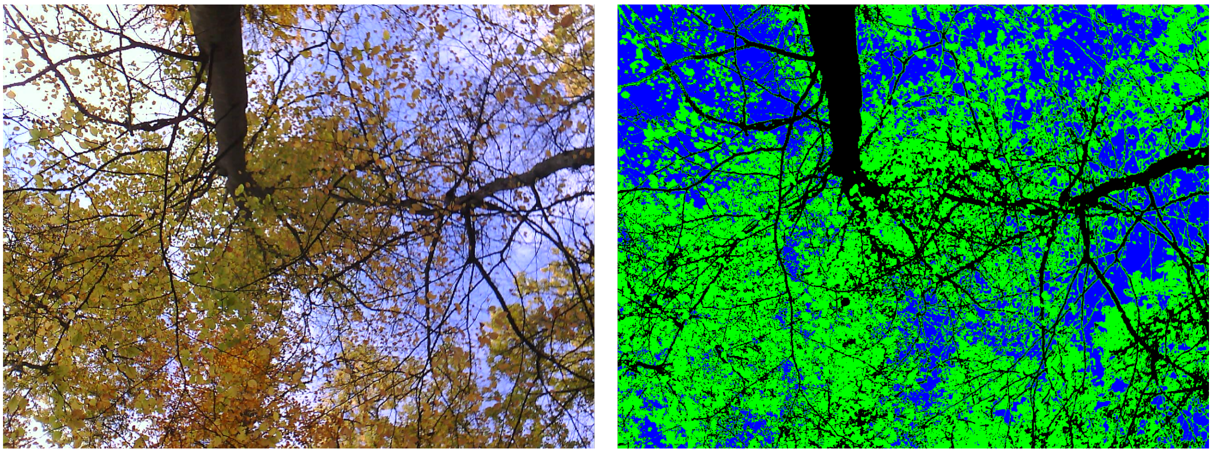

Figure 11. Example of a photo taken by the sky-oriented camera: Left - original image; right - classification results: blue pixels - the sky (ca. 25%), black - tree stems and branches (ca. 25%), and green - leaves (ca. 50%).

Now, we demonstrate examples of maps summarizing the work conducted with the rover so far and the temperature information collected. Since radar/lidar data and photos require intensive data processing, we have focused on surface temperature data. It is a straightforward data source that only requires a short workflow description and simple interpretation.

Figure 12 overviews the routes made by the rover. There were four rounds. One round means that we collect data from all planned stations. In the next round, we repeat the procedure. The figure shows the time when the points were measured. For one round, we need two working days. Thus, we outline the points taken on the second day of the round. The time is portrayed by coloring a time interval denoted by hours-minuter (HH:MM format). The presented maps show routes taken in four rounds: the first round - the 28th and 29th of October 2022, the second - 2nd and 3rd of November 2022; the third - 10s and 12s of November 2022, and the fourth - 29s and 30th of December 2022. The maps show the area covered by the rover routes and when the measurements were taken.

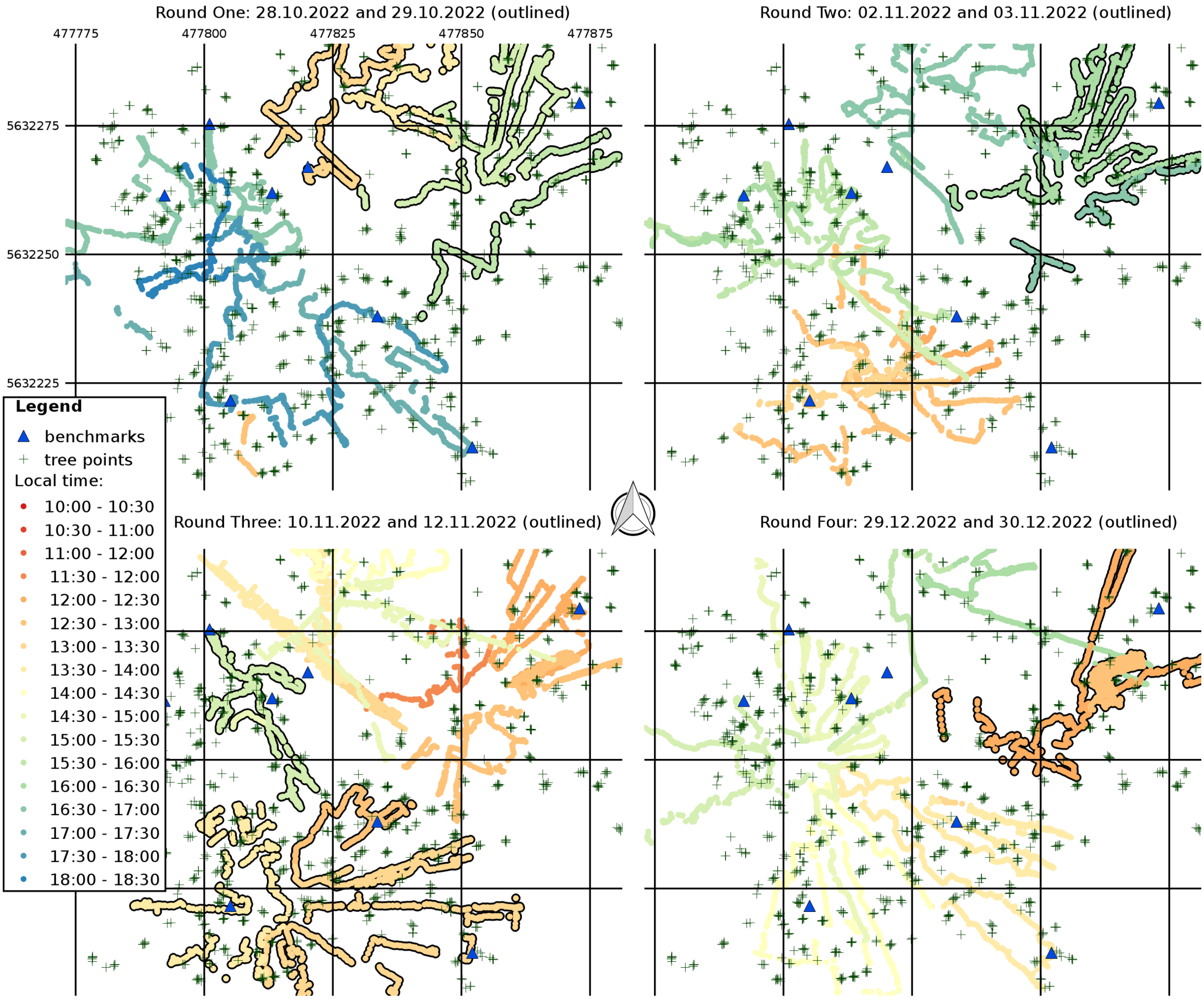

Figure 12. Rover field work routes: Time maps (epoch seconds) of measurements. Coordinate system: EPSG 32632 (WGS 84 / UTM Zone 32N).

Figure 13 demonstrates the surface temperature recorded along the rover routes. It is the average of the thermal camera's pixel values (°C) covering the area of the camera's field of view, with the center residing about one meter behind the rover. While the infrared thermometer represents a relatively small spot at the ground behind the rover (in the middle of the NoIR ground-oriented camera's field of view), the thermal camera shows a relatively large area behind the rover, providing more relevant forest floor temperature information. The maps clearly show the forest's autumn cooling process. Since one-round measurements take two working days, intraday temperature fluctuations strongly impact the recording data. This should be carefully addressed for detailed surface temperature modeling in future work.

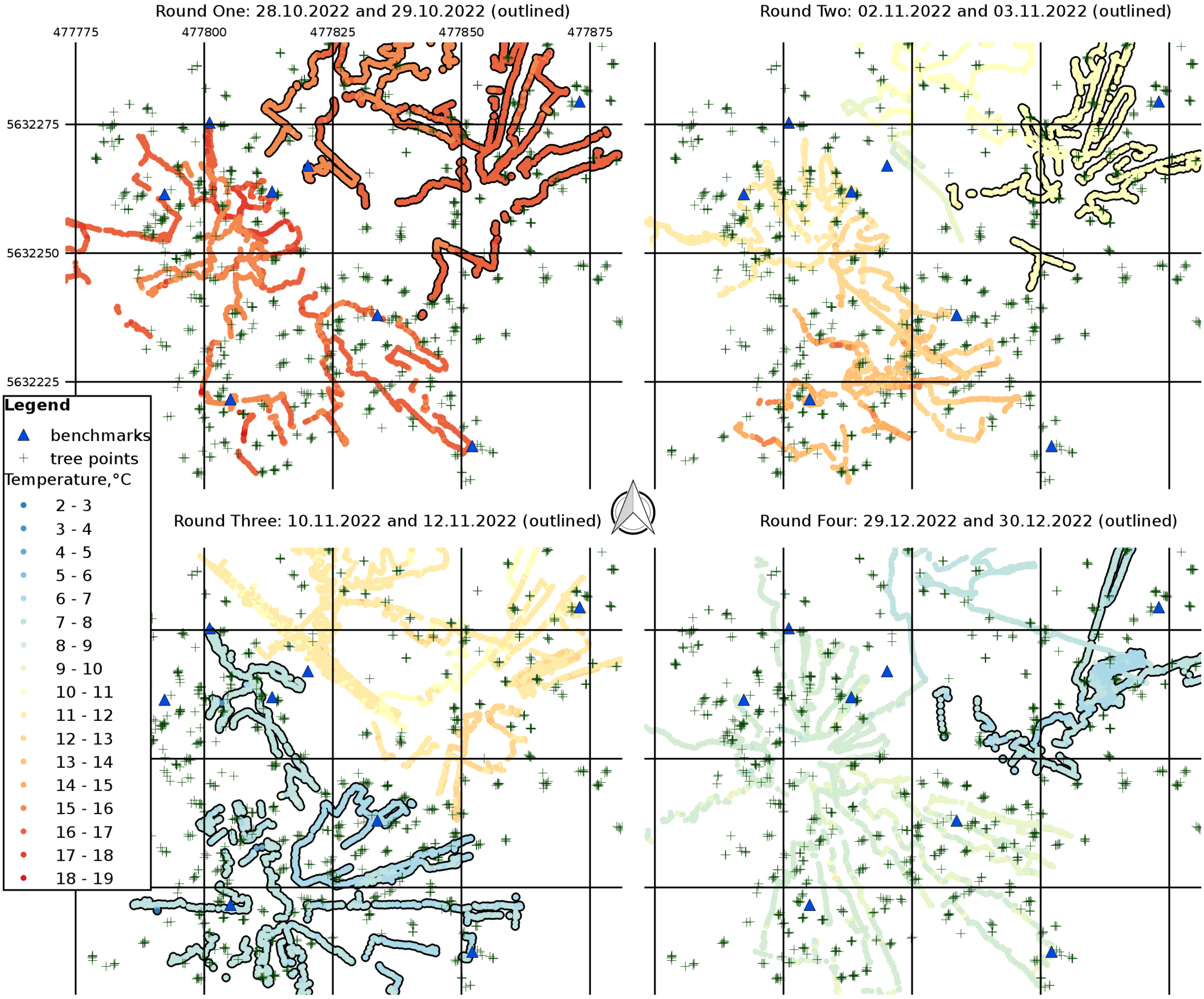

Figure 13. Temperature maps. Coordinate system: EPSG 32632 (WGS 84 / UTM Zone 32N).

The demonstrated time and temperature maps confirm the possibility of collecting high-detail forest data with the possible centimeter accuracy. Using timestamps, we have already geotagged all taken photos from the sky- and ground-oriented cameras. Most of the points presented in the time maps have relevant photos. We can easily add geotags to the ROS *.bag files' data slices, but they require more advanced processing since both sensors provide point data. Point data are susceptible to the rover's orientation. We can address it by calculating the rover's movement vectors using consecutive position coordinates. Point coordinates can be easily calculated by knowing the coordinates and orientation of the rover; different control experiments are required to estimate the accuracy of RpLidar and front camera RGB point coordinates. Moreover, knowing the orientation, we can convert photos taken from the sky- and ground-oriented camera into georeferenced imagery with the potential to prepare centimeter accuracy timeseries.

4 CONCLUSIONS AND FUTURE WORK

Recent progress in computers, robotics, and equipment allowed us to prepare the devices and solutions for high-detail automatic forest monitoring. The introduced devices share common principles:

- They are based on popular open-source compact solutions that enable connecting multiple easily replaceable sensors.
- We propose the autonomous timestamp-based concept for data collecting. It allows the merging of data from various sources.
- Extending the autonomous approach, the presented devices do not require manipulations and configurations for data collecting.

They start gathering data shortly after powering on the devices. It facilitates fieldwork; irrelevant data are filtered out afterward.

We have introduced these principles with the proposed compact insect radar box. The conducted fieldwork has shown its effectiveness. Despite the challenging field conditions, we have brought the earlier lab achievements into the forest and collected relatively long and meaningful timeseries using the radar, camera, and light trap. A preliminary evaluation of these data confirms the effectiveness of the proposed approach. In the next step, we will conduct a detailed analysis of the collected data to research the low nocturnal insect flight. After filtering out the raw data and extracting the insect information, we will use the detailed weather station data to investigate the meteorological factors of the low nocturnal insect flight.

Good progress with the insect radar box has inspired us to more complex solutions. The prepared rover setup has inherited the achievements of the insect radar box. The navigation and multiple thematic sensors work autonomously and separately using timestamps for data merging. The proof-of-concept fieldwork confirmed that our UGV could conduct real measurements in real forest conditions. Several rounds of measurements in the forest have allowed us to collect a large dataset concerning the forest phenology, trees, understory, and forest floor. Several camera sensors, a lidar, a radar, and two thermal sensors facilitate it. The collected data are immediately geotagged using a timestamp. In addition, we have demonstrated the ability to prepare accurate timeseries maps. Prospectively, we want to calculate the rover's orientation for assigning accurate coordinates of the point datasets. Furthermore, it will be likely possible to prepare imagery using sky-, ground-, and front-oriented cameras.

The rover follows a novel principle of visual tracking. It means that the rover is equipped with a prism, and an oriented robotic total station follows this prism automatically and writes position coordinates using a short distance interval. To our knowledge, this is one of the earliest attempts to apply a visual tracking rover for monitoring purposes. In future work, we will present the results of the rover data processing and discuss measured forest processes.

We ensure centimeter positioning in the forest with the dense reference network in the forest. Several applications require this control network. We have used the network for tree measuring and sensor positioning. Further, we need to increase the accuracy of the distant benchmarks. Moreover, more trees should be measured in the detailed mode.

CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

Conceptualization, A.N. and J.B.; methodology, A.N. and S.A.; software, A.N.; validation, A.N., S.A. and J.B.; formal analysis, A.N. and J.B.; investigation, A.N., S.A. and J.B.; resources, A.N., S.A. and J.B.; data curation, A.N.; writing—original draft preparation, A.N.; writing—review and editing, A.N. and J.B.; visualization, A.N.; supervision, J.B.; project administration, A.N. and J.B.; funding acquisition, J.B. All authors have read and agreed to the published version of the manuscript.

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