SQAT
SOIL QUALITY ANALYSIS TOOL

Deliverable 2.5

Lightweight & heavy-duty sampler device with proximity sensors

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Executive Summary

Farms are at the forefront of the data economy, propelled by digitalisation, robotics, and smart algorithms. However, these advancements exacerbate societal pressures on soil health, demanding cleaner water, healthier soils, increased carbon storage and biodiversity. Current solutions are costly and unsuitable for farmers. With this in mind, the EU-funded SQAT project will develop a smart soil mapping service. Combining multi-level, multi-technology approaches, SQAT offers high-resolution soil property maps and tailored solutions for farmers. Using autonomous robot-mounted sensors and innovative in situ analysis tools, the SQAT system enhances productivity while reducing costs. Co-developing with SMEs, SQAT aims to commercialise its solutions, empowering farmers with variable-rate applications for liming, fertilisation, seeding, tillage, and carbon farming.

To produce high-resolution soil property maps, soil samples must be extracted directly from the field—a process that is typically labor-intensive. The SQAT project addresses this challenge by developing both lightweight and heavy-duty sampler systems, each integrated with a dedicated mobile robotic platform to automate soil sampling. These complementary systems are designed to overcome each other's limitations. The lightweight system offers agility and flexibility, making it suitable for steep or constrained terrain, but it is limited in payload capacity and operational duration. In contrast, the heavy-duty system can extract deeper soil samples and operate for extended periods, though its larger size restricts its use in uneven or confined environments.

The lightweight sampler employs a drill-shaped extractor to minimize weight and is mounted on an existing quadruped robot platform. Meanwhile, the heavy-duty system uses a cylindrical auger for deeper sampling and is based on equipment acquired from Bodenprobentechnik; its robotic transport platform is currently under development. Initial results from both systems demonstrate their ability to fulfill their respective roles effectively. By spring 2026, both platforms are expected to reach Technology Readiness Level (TRL) 7.

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Abbreviations

ABE	Association of Balkan Eco-Innovations
AGRILAB	Agrilab limited liability company
ATB	Leibniz Institute of Agricultural Engineering and Bioeconomy e.V.
EC	European Commission
EV ILVO	Eigen vermogen van het instituut voor landbouw-en visserijonderzoek
HSG-IMIT	Hahn-schickard-gesellschaft fur angewandte forschung ev
ISF-OST	Institute for intelligent systems and smart farming	OST Eastern Switzerland university of applied siences
OFI	Officine innovazione s.r.l.
POI	Point of Interest
RTK	Real time kinematic positioning
TERRATMD	Terra controlling tmd d.o.o
TRL	Technology readiness level
VDBORNE	Van den borne projecten bv
WP	Work Package

1 Introduction

A central objective of the SQAT project is to enhance the efficiency and affordability of generating soil property maps. A critical component of this process involves the collection of soil samples, which provide essential reference data for the prediction algorithms used in sensor mapping. These samples are obtained using autonomous mobile robots equipped with specialized soil sampling devices.

Soil sampling is commonly performed manually by field technicians using hand tools. Three primary techniques are typically employed: soil probes (core sampling), drilling, and spades (removal of a defined soil slice using a shovel). Each method has specific advantages and limitations related to sample composition, accessibility (e.g., stoniness of the soil), cost, and potential for automation. Although some soil sampling devices can be mounted on vehicles, a lot of the process is still often performed manually. Sampling involves traveling to predetermined locations and collecting soil at specified depths, depending on the analysis requirements. Samples are then labelled, stored, and transported to laboratories for physical and chemical analysis. While this approach works, it is labour-intensive, time-consuming, and often inefficient for covering large or remote areas. Moreover, manual sampling introduces variability in depth and consistency, which can reduce the reliability of derived soil property prediction models.

To generate soil property maps, the SQAT project follows a structured approach. Initially, satellite imagery is used to gather preliminary information about the field. This is followed by multispectral scanning of the topsoil, and the extraction and analysis of soil samples. All available data are then combined to produce detailed soil property maps. Since the second step involves scanning the topsoil, the corresponding reference soil samples must be taken from the topsoil layer (0–30 cm). However, deeper sampling—up to 100 cm—can provide additional insights into properties such as nitrogen distribution and soil compaction.

The SQAT project seeks to minimize manual labour and streamline the soil sampling process using automated soil sampler devices. To address the diverse conditions and requirements across different agricultural environments, two specialized sampling devices are being developed. The first is a lightweight sampler designed for operation in constrained or difficult-to-access areas, such as vineyards, where the use of heavier equipment is not feasible. This device will be integrated with a quadruped robot capable of navigating uneven terrain and will focus solely on extracting topsoil samples (0–30 cm) for reference analysis. The second device is a heavy-duty sampler intended for deployment in open fields and other easily accessible locations. It will be mounted on a custom robotic platform designed to accommodate its operational needs and will extract samples from the entire soil profile (0–100 cm).

2 Methods

2.1 Lightweight sampler device

2.1.1 Overview

The objective of this work is to develop a lightweight soil sampling device that a quadruped robot can transport. This approach addresses the limitations of conventional heavy-duty sampling systems, which are often unable to access rough or constrained terrain. A lightweight sampler alone is insufficient unless it is embedded within a broader system that enables both autonomous mobility and the reliable containment of extracted samples. Consequently, the system is divided into four key components: (1) the soil extraction unit, (2) a deployment mechanism for mounting and actuating the extractor on the mobile robot, (3) a sample containment or packaging module, and (4) the quadruped robotic platform itself. Since the robot must carry and operate all subsystems, its design must be carefully adapted to its payload capacity, mechanical constraints, and control capabilities.

2.1.2 Mobile robot platform

The decision to use a quadruped robot in the SQAT project was based on the availability of equipment at ISF-OST. Initially, the project employed the Spot robot from Boston Dynamics, which the institute owned at the time. However, due to internal changes within the university, access to Spot was discontinued. As a result, the ANYmal robot from ANYbotics—already in the acquisition process at ISF-OST—was adopted as a replacement. This transition provided several advantages. Most notably, ANYmal offers significantly greater accessibility for third-party software integration, which had been more restricted with Spot. Additionally, ISF-OST maintains a close collaboration with ANYbotics, enabling faster technical support and the potential to accommodate custom hardware or software requirements.

The ANYmal robot is a state-of-the-art quadruped platform designed for autonomous inspection tasks in industrial environments. It features a rugged, IP67-rated design that can withstand dust, water exposure, and challenging terrain. The platform operates on a swappable battery system, providing up to 120 minutes of runtime, and supports a payload capacity of approximately 15 kg, sufficient for carrying sensor modules and additional hardware. Its onboard sensor suite includes 360° LiDAR, RGB cameras, ultrasonic microphones, and LED spotlights, supporting advanced perception and environment mapping. Obstacle detection and autonomous navigation algorithms further enhance its suitability for field deployment in unstructured environments, making it a viable platform for SQAT's soil sampling application. Although ANYmal was initially developed for industrial inspection and monitoring tasks—such as those performed in oil refineries and power plants—its core navigation functionality is based on local mapping and SLAM (Simultaneous Localisation and Mapping). Unlike outdoor field robots, it is not equipped with a built-in GNSS receiver, as global positioning is typically unnecessary in its intended use cases. However, for the SQAT application, GNSS positioning is essential. This limitation is being addressed by designing a custom mount above the LiDAR unit, which enables the integration of a GNSS antenna with RTK correction capability. Combined with appropriate navigation software, this adaptation enables precise georeferenced positioning suitable for field sampling scenarios.

2.1.3 Extraction unit

Before defining the extraction procedure, it is necessary to establish the desired condition of the soil samples post-extraction. As several components of the SQAT project remain under development at the time of writing, the precise sampling specifications are based on preliminary discussions and are expected to evolve. The current requirements specify that each sample should originate from the topsoil (0-30 cm), weigh between 10–20 grams, and may be a homogenised mixture rather than depth-resolved. If possible, samples should be stored to minimise exposure to atmospheric oxygen and prevent drying out such that the moisture content can be analysed in the lab.

Core sampling is a widely used method in soil analysis. Traditionally, it involves manual operation: an operator travels to predefined coordinates and inserts a cylindrical auger vertically into the ground. Using a cylindrical auger offers a key advantage—minimal disturbance to the internal soil structure, enabling depth-resolved analysis. However, it also requires a substantial insertion force, often necessitating hydraulic mechanisms to reach significant depths when automated. While effective, such systems are too heavy for integration with a lightweight mobile platform, such as the ANYmal robot.

To address mobility constraints, the project employs an alternative approach utilising a drill-shaped auger. Although this method disturbs the sample structure, it requires significantly less insertion force and can penetrate a wide range of soil types when operated with an appropriate combination of rotational speed (RPM) and feed rate.

The extraction system must address two additional challenges: (1) preventing soil from adhering to the auger flutes and (2) collecting dislodged soil efficiently at the surface. The first issue is mitigated using a specially designed component termed the wiper. This element rotates independently around the drill and fits into the flutes, mechanically displacing residual soil as the drill rotates.

To manage the transport of dislodged soil to the surface, the system employs a mechanism comparable to the flutes of a drill bit. In this design, the auger, similar to the spiral flutes of a drill, is encased within a tube that guides the loose soil upward along the drill shaft as it operates. As the soil is dislodged and moves upward, it travels through a dedicated tube, much like shavings being channelled away from a drill bit. The soil then enters an extraction chamber where it is separated from the drill by a wiper mechanism, allowing it to be collected and stored efficiently.

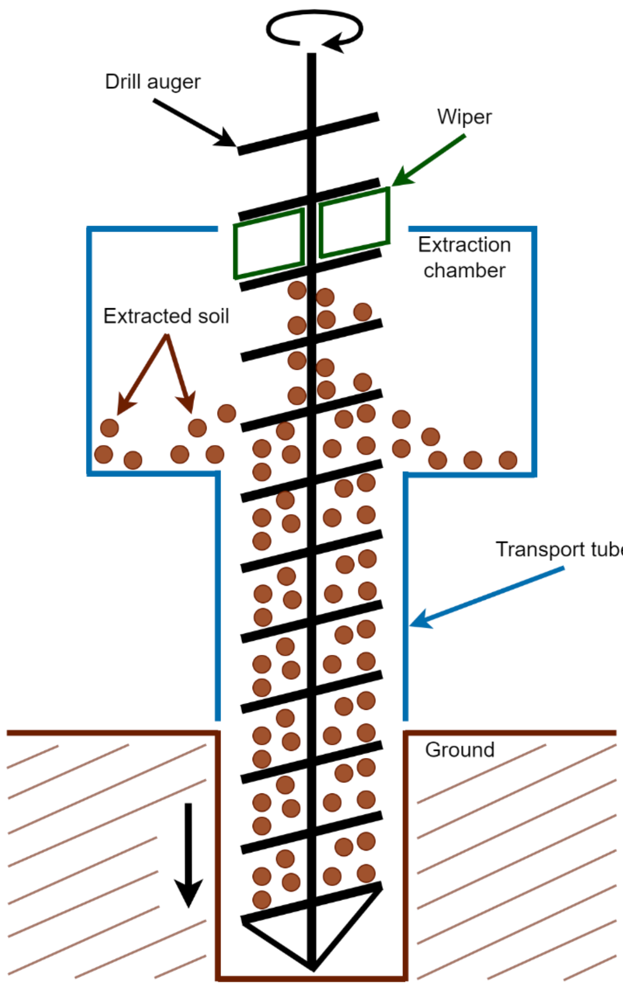

Figure 1: Concept extraction unit

2.1.4 Deployment

For ground-based mobile robots, maintaining a stable centre of gravity (CoG) is crucial for achieving energy efficiency and stable locomotion. Ideally, the CoG should be positioned as low as possible and centred relative to the robot's support polygon—defined by its wheels, legs, or tracks—to minimise instability and prevent unnecessary energy expenditure in balancing asymmetric loads. Based on these considerations, the extraction unit in the SQAT system is not permanently raised; instead, it remains stowed and is deployed only during sampling. This design decision introduces some additional system weight due to the deployment mechanism, but it is expected to be more energy-efficient overall. An asymmetrically positioned payload would require the robot to continuously counteract imbalance, resulting in higher energy consumption than that introduced by the added mass of the deployment mechanism.

Furthermore, the ability to stow the extraction unit enhances mobility and robustness in uneven terrain, which is essential for field applications. Another key design trade-off involves balancing weight and structural stability. Fortunately, the extraction process does not generate significant lateral forces (X or Y directions) under nominal operating conditions. Therefore, only the vertical force (Z direction) applied by the drill during soil penetration and the resulting moment on the mount need to be considered. As discussed in chapter 2.1.3, the use of a drill offers the advantage of reducing vertical loading through its cutting action. A preliminary force analysis estimates that a maximum vertical force of approximately 570 N can be applied before the ANYmal robot risks lifting off the ground. Figure 2 illustrates the deployment concept. The extraction unit is lifted into position using a gas-spring-damper mechanism and retracted via a rope winch. When stowed, the unit is mechanically locked in place, eliminating the need for continuous actuation and ensuring the system remains secure in the event of a power loss. This stowed position is also

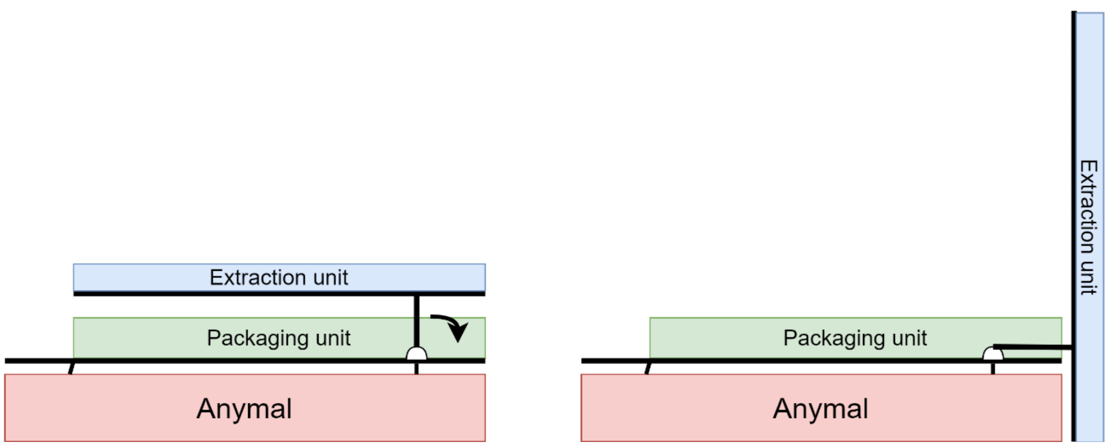

Figure 2: Concept deployment on Anymal left-side folded right-side deployed

used during robot locomotion between sampling sites to maintain balance and mobility.

2.1.5 Packaging unit

To prevent post-extraction interaction between the soil samples and the environment—particularly oxidation and drying—airtight sealing is essential. Simultaneously, the packaging solution must be as lightweight as possible and capable of storing associated metadata. The adopted approach draws inspiration from the food packaging industry. Soil samples are enclosed in weldable plastic bags that carry either a QR code or an NFC chip containing relevant metadata such as GNSS coordinates, sample ID, and client information. The sealing process is performed directly on the robot using a simple mechanism that involves two heated wires, which weld the plastic shut to ensure an airtight seal with minimal mechanical complexity. Packaging material is supplied from a roll of weldable plastic film stored onboard the robot. Once a sample is collected, a transport trolley delivers it to the sealing unit, where the film is cut and sealed around the sample. This method minimises packaging weight while maintaining a robust and scalable sealing process suitable for autonomous field operation.

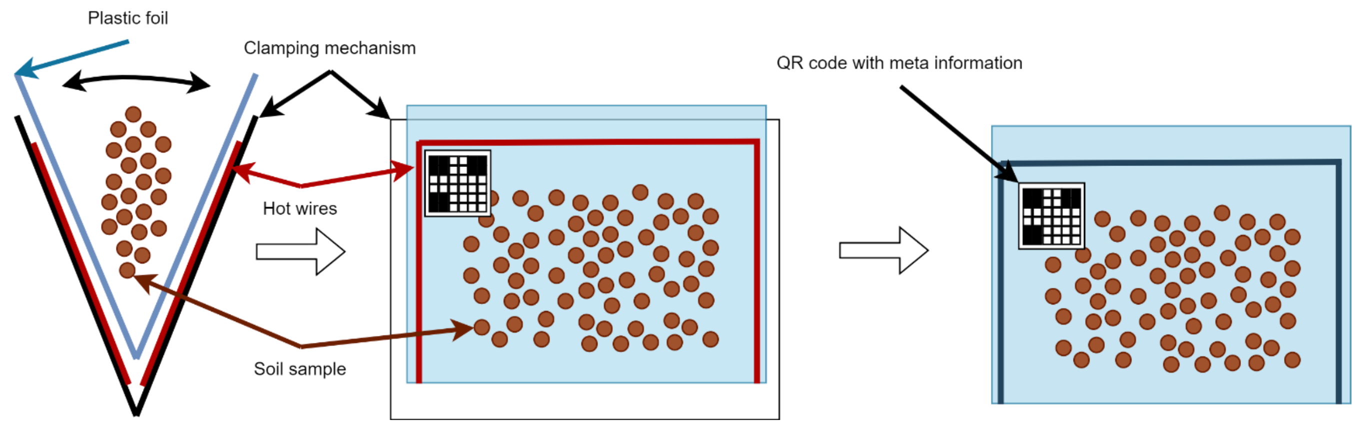

Figure 3: left to right 1. soil sample gets deposited in clamping mechanism within plastic foil, 2. clamping mechanism closes, and foil gets welded by hot wires, 3. finished packed sample with QR code for meta data

2.2 Heavy-duty sampler device

2.2.1 Overview

Since soil sampling for agricultural purposes is time-consuming and labour-intensive, the development and validation of a heavy-duty sampling device are key objectives within the SQAT project. The goal of this heavy-duty sampler is to be versatile and to improve both time and labour efficiency, while maintaining comparability with traditional manual soil sampling methods. The sampling device used is the MP-4.100 soil sampler, manufactured by the German company Bodenprobentechnik Peters GmbH, which has been integrated onto an in-house developed autonomous robot. By introducing autonomy, the system enables the collection of a higher number of soil samples, allowing for high-resolution mapping of soil properties. The main system components remain the same as previously described: the autonomous robot, the extraction unit, the mounting and deployment mechanism, and the sample containment unit.

2.2.2 Mobile robot platform

The autonomous carrier for the sampling probe is specifically designed as a proximal soil sensor carrier platform. The robot is essentially built using two front axles from a Segway ATV. It has a four-wheel steer, four-wheel drive configuration, allowing for flexible manoeuvring. The robot features excellent suspension, enabling it to drive quickly across fields. Additionally, the large tyres, with a diameter of 0.76 m, ensure a smooth driving experience. The total weight of the robot (excluding the soil probe) is around 1200 kg, with a battery capacity of 45 kWh. The platform can reach a top speed up to 20 km/h and has a nominal and peak traction output torque of 2400 Nm and 5700 Nm, respectively The robot will also be well-balanced: the battery pack is mounted on the left side, while the soil sampler and a penetrometer for measuring soil resistance are mounted on the right side. When using the soil probe, the robot will be supported by hydraulic stabiliser legs, ensuring a level platform and a stable soil sampling process.

2.2.3 Extraction unit

The extraction unit MP-4.100 from Bodenprobentechnik Peters is an automatic, heavy-duty soil sampling device equipped with a high-frequency hammer that features adjustable sensitivity. The probe can sample soil up to a depth of 100 cm and automatically separates the sample into four distinct depth layers. The sampling depth of these four layers can be freely selected in centimetre resolution. When performing single-layer sampling, four mixed samples can be stored in separate containers, or two depth layers with two mixed samples are also possible. If the probe does not penetrate sufficiently within a given number of hammer blows, due to an obstacle in the soil, the sampling process is aborted to prevent damage to the device. In such cases, the operator can choose to discard or retain the sample. The soil probe can easily sample up to 100 cm in hard and dry soils.

2.2.4 Deployment

The complete soil sampling process runs fully automatically once the robot has received the sampling locations. During autonomous operation, the robot follows a predefined trajectory with assigned sampling points. When approaching a sampling point, the robot slows down until it reaches the exact location. At the sampling point, the robot stops and automatically lowers its stabilising legs. The robot's programmable logic controller (PLC) then communicates with the soil probe's PLC to initiate the measurement. The extraction unit automatically lowers and begins hammering the probe into the soil to the selected depth. After sampling, the probe is retracted and automatically emptied into the storage containers according to the preset layer separation settings. Finally, the extraction unit is raised again, and the soil probe PLC signals the robot's PLC that the measurement is complete. The robot then raises its stabilising legs and moves to the next sampling point. Once the robot has collected either one four-layer separated mixed soil sample or four single-layer mixed soil samples, it moves to the edge of the field where the storage containers are manually emptied (which can be automated later on).

2.2.5 Packaging unit

The only storage facility currently available consists of four storage containers integrated into the soil sampling probe. This allows for the storage of either four mixed soil samples or one mixed soil sample separated into four depth layers. Although this is a limitation, the next phase of the project aims to incorporate a carousel-like sample storage mechanism on the robot, enabling the storage of as many samples as can be processed by the lab-on-the-field system, which is currently capable of processing 16 mixed samples. A similar packaging identification approach will be adopted, as described in Section 2.1.5, to establish a uniform package identification approach.

3 Results

3.1 Lightweight sampler device

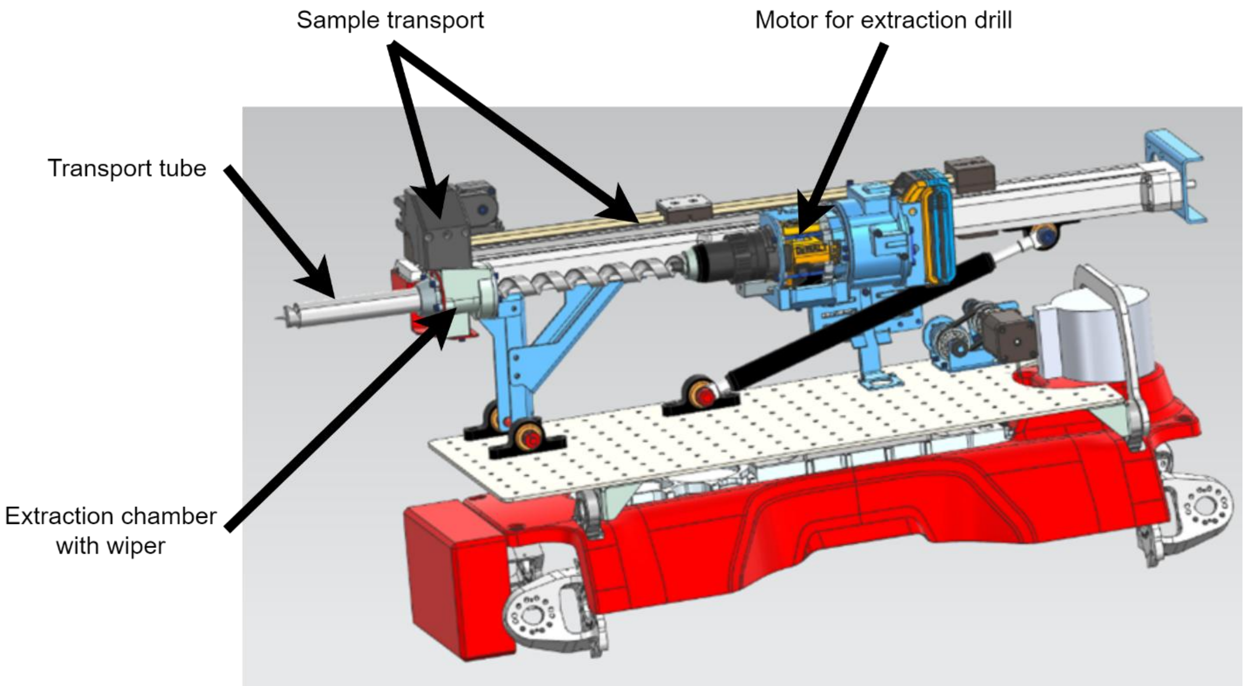

Figure 4: CAD prototype lightweight sampler device left-side

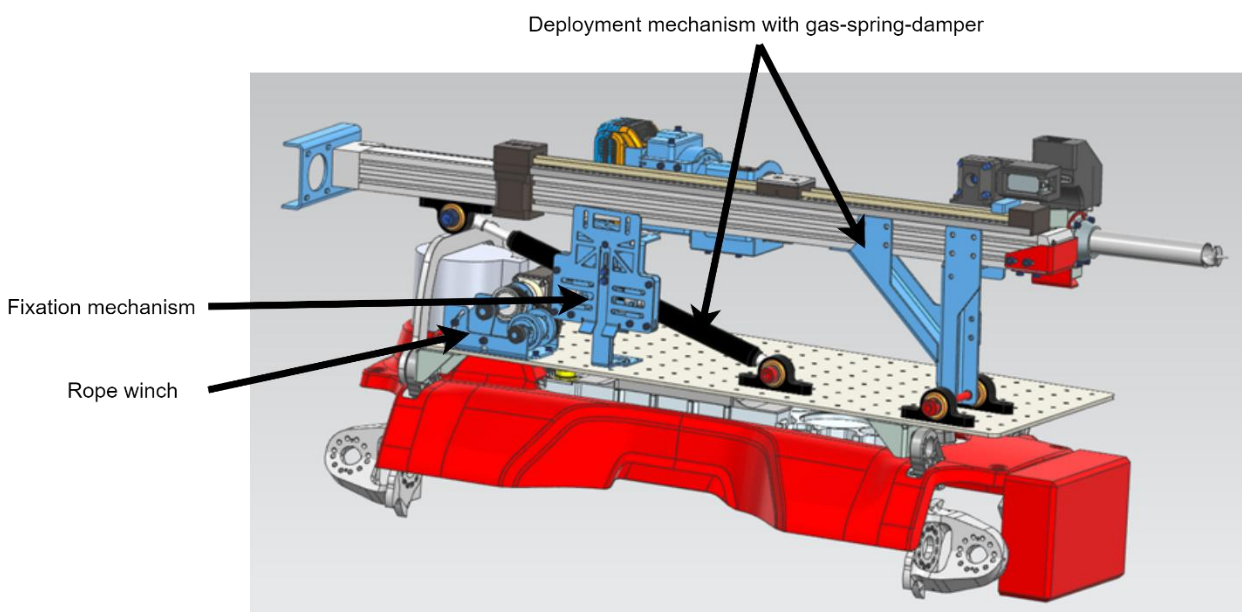

Figure 5: CAD prototype lightweight sampler device right-side

Figure 6: mounted prototype on Anymal left-side folded state, right-side deployed state

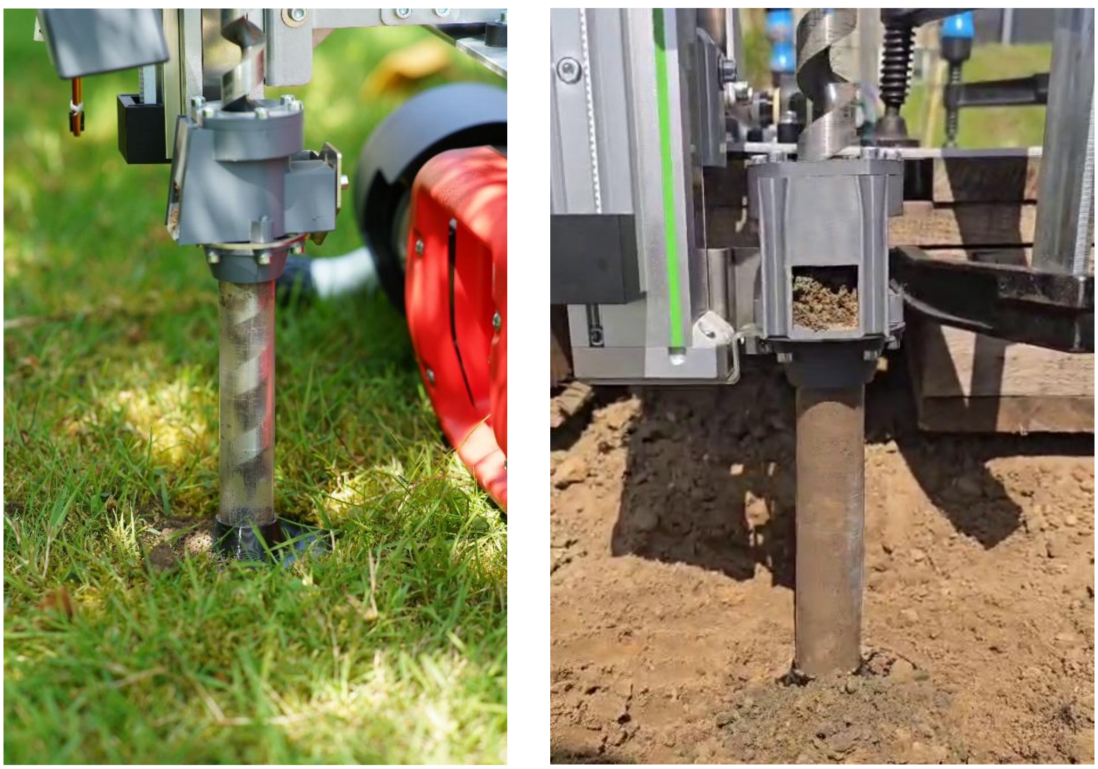

Figure 7: Extraction unit left-side pre-sample extraction right-side, during sample extraction

3.2 Heavy-duty sampler device

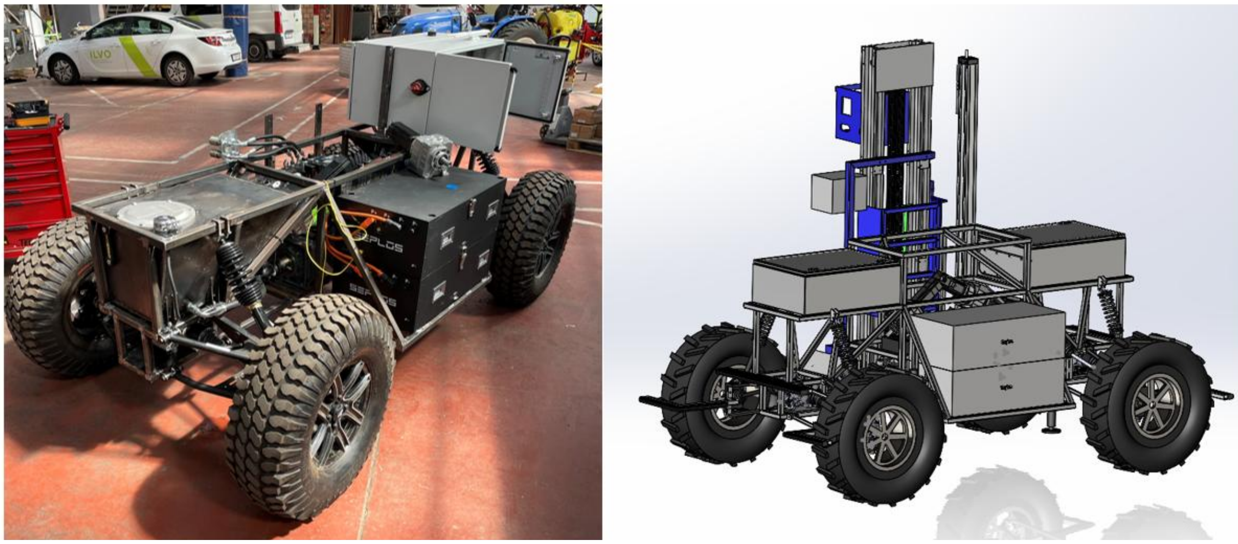

Figure 8: The in-house developed autonomous robot alongside its 3D CAD model.

Figure 9: The soil probe MP-4.100 by Bodenprobetechnik Peters.

4 Discussion

4.1 Lightweight sampler device

Initial tests with the ANYmal robot indicate that battery capacity will be a critical factor in the usability of the lightweight sampler. In a preliminary trial, the prototype was mounted on the robot without modifying the control software to account for the additional payload. As a result, the battery drained significantly faster than it did during operation without a payload. While no precise measurements were taken during this test, the impact was evident. This limitation is expected to improve as the prototype matures and the robot is adapted to recognise and optimise for the payload. Nonetheless, battery capacity remains a key constraint for the practical deployment of the SQAT system when using the lightweight sampler.

The images in Figure 7 show that the extraction unit functions as intended. Early tests revealed that the quantity of extracted soil depends on the drill's rotational speed (RPM) and drive speed. Due to the presence of a wiper, these two variables are interdependent, linked by the pitch of the drill flutes. Since both parameters were manually controlled during testing, no quantitative data was collected, and an exact trade-off between RPM and drive speed cannot be reported at this stage. However, a theoretical lower bound for RPM exists at the product of drive speed and flute pitch. Operating below this threshold results in improper wiper movement, which can potentially cause the drill to seize or the extraction chamber mount to experience excessive stress. This relationship requires calibration in future development stages.

Another influencing factor is the diameter of the transport tube. Initial tests using a PTFE tube with a 3 mm tolerance around the drill allowed operation, but left a gap where soil accumulated, posing a risk of cross-contamination. Subsequent tests with an aluminium tube and a 0.1 mm tolerance resolved this issue, but they led to drill blockage due to dense soil compaction. Residual soil remained on the tube walls in both cases. These results indicate that the current transport tube configuration is suboptimal and requires redesign. Additionally, depending on the soil texture and moisture content, the soil may compact within the extraction chamber, potentially clogging the entire system. This issue can be addressed by increasing the chamber's internal volume to accommodate more material and reduce pressure buildup.

The images in Figure 6 show that the deployment mechanism works as intended. The current design likely represents one of the lightest mechanical solutions possible for this function, offering a minimal-weight approach that does not compromise functionality. However, side-to-side stability issues were observed during deployment. The side stability issue is expected to be resolved by replacing the single gas-spring-damper with a symmetrical arrangement using two units. Additionally, the locking mechanism exhibited a design flaw: it was initially intended for linear motion, while the deployment occurs radially. Despite this, the mechanism remained stable due to the knee-lever effect, which unintentionally locked it in place. For future iterations, a high gear ratio will be implemented in the actuator, allowing the mechanism to self-lock without continuous motor power, thus eliminating the need for a separate locking device.

The prototype currently lacks a packaging unit. This omission was a deliberate decision, as the overall system will undergo significant design changes that would substantially impact the design of the packaging module. Furthermore, during the development process, certain disadvantages of the prototype inc. the first draft of the packaging unit—such as the risk of cross-contamination between samples—have not yet been resolved.

Despite the current limitations, the prototype demonstrates the strong potential of this approach. Valuable insights were gained during the testing and integration week at ILVO (Summer 2025, Ghent, Belgium), where collaboration with technical partners contributed significantly to the system's improvement. The feedback and experience gathered during this phase are now being integrated into the next development cycle, guiding the refinement of the overall system.

4.2 Heavy duty sampler device

Since the robot is still under development, the testing phase has not yet started. A prototype will be completed soon. At present, the robot can only be operated manually via a remote controller. Several issues in the robot’s PLC still need to be resolved, the software framework must be integrated to enable autonomous navigation, and minor mechanical modifications may be necessary to further optimise the design.

The mechanical design must meet several critical requirements. The battery pack and soil sampler must be properly balanced, so stability tests will be essential. Additionally, the sampling protocol requires the deployment of stabilising legs, which still need to be securely mounted. A potential risk is that the deployment of these legs takes too much time, negatively affecting the sampling efficiency. In that case, alternative solutions will be investigated (e.g., blocking the suspension during sampling).

Several questions remain unanswered, such as how long the robot can operate autonomously, what the energy consumption will be, how it handles bumpy fields, and how many samples can be collected per hour. These aspects will be evaluated during field trials. The battery is modular and can be upgraded if battery life proves insufficient.

Initial tests of the soil sampler, when mounted on a compact tractor, showed excellent performance with rapid sampling. Since the sampler was developed by a specialised company, no major issues are expected regarding the sampling mechanism itself. However, integration with the robot and communication between the robot’s PLC and the sampler’s PLC may pose challenges. Therefore, thorough interface testing will be crucial before field testing.

It should be noted that the robot currently has limited onboard storage capacity. Only the four sample containers provided with the sampler are available, which is considered insufficient. To address this, a student will work on developing an expanded storage mechanism during the next academic year, enabling the robot to store a larger number of samples, in line with the processing capacity of the lab-on-the-field system.

5 Conclusion

The objective of this deliverable was to develop two distinct soil sampling systems: a lightweight sampler for deployment on a quadruped robot and a heavy-duty version. Both systems are still under development, primarily due to their integration with their respective robotic platforms. The lightweight system has demonstrated promising results in initial tests; however, significant modifications are planned to advance it to the next Technology Readiness Level (TRL). The upcoming development phase will further explore the feasibility of using quadruped robots in agricultural applications.

For the heavy-duty sampler, the core sampling mechanism—based on the Bodenprobentechnik system—has been successfully tested. However, the carrier vehicle remains in the early stages of development. Although neither system is fully integrated at this point, both meet the performance requirements of their respective use cases and show strong potential to fulfil the objectives of the SQAT project.

To quantify the state of both systems in TRLs they are both still in a development stage where the lightweight system is between 4 and 5 and the heavy duty between 5 and 6. Both systems are expected to reach full operational capability (at least 6-7 TRL) by Winter 2025 and be fully functional by March 2026 (7-8 TRL). These planned milestones align with the timeline for the SQAT use-case evaluations and task T2.4, which is scheduled for completion by October 2026.

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