Improved Robotic Platform to perform Maintenance and Upgrading Roadworks: The HERON Approach

Grant Agreement Number: 955356

D3.4: Point of interest georeferencing and precise localisation software

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Legal Disclaimer

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Abbreviation Lists

Table 1: Abbreviations

Abbreviation	Definition
CORS	Continuously Operating Reference Station
DGPS	Differential Global Positioning System
EPN	EUREF Permanent Network
EUREF	Regional Reference Frame Sub-Commission for Europe
GIS	Geographic Information System
GLONASS	Global Navigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HD	High Definition
HEPOS	Hellenic Positioning System
IAG	International Association of Geodesy
KPI	Key Performance Indicator
NTRIP	Networked Transport of RTCM via Internet Protocol

Abbreviation	Definition
PPK	Post-Processing Kinematics
RI	Road Infrastructure
RTCM	Networked Transport of RTCM via Internet Protoco
RTK	Real Time Kinematics
SSD	Single Shot Detector
VRS	Virtual Reference Station
WP	Work Package
YOLO	You Only Look Once

Table 2: Abbreviations of the Partners' names

Short name	Participant organization name
ICCS	Institute of Communications and Computer Systems
ACCI	Acciona Construcción S.A.
OLO	Olympia Odos Operation S.A.
UGE	Université Gustave Eiffel
ETHZ	Eidgenössische Technische Hochschule Zürich
ROB	Robotnik Automation
CORTE	Confederation of Organisations in Road Transport Enforcement
STWS	SATWAYS - Proionta Kai Ypiresies Tilematikis Diktyakon Kai Tilepikinoniakon Efarmogon Etairia Periorismenis Efthinis EPE
RISA	RisaSicherheitsanalysen Gmbh
INAC	InnovActs
IKH	Ainoouchaou Pliroforiki SA -IKnowHow-
RG	Resilience Guard Gmbh

Glossary of Terms

Table 3: Glossary of terms

Term	Explanation
Visual servoing	Visual servoing, also known as vision-based robot control and abbreviated VS, is a technique which uses feedback information extracted from a vision sensor (visual feedback) to control the motion of a robot.

Executive Summary

This deliverable is written in the framework of WP3 – AI-based algorithms and tools Recognition, Classification and Localisation of the Points of Interest of the HERON project under Grant Agreement No. 955356. Deliverable 3.4, namely “Point of interest georeferencing and precise localisation software”, includes the software methods for precise 3D geo-referencing of the classified points of interest. This report illustrates the outcomes of Task 3.4, titled: “Georeferencing and Precise 3D Localization of Points of Interest” corresponding to M17-M26 of the HERON project.

D3.4 details the work done in the HERON project to create efficient infrastructure maintenance solutions. The report begins by outlining our approach to georeferencing points of interest, explaining the proposed functionalities and their adaptability to changing project needs. The report then dives into localisation strategies from both ground and aerial sources, showing how our system can handle diverse data types while maintaining precision. The use of various positioning systems, particularly Real-Time Kinematic (RTK-GPS), is thoroughly explored. This highlights the importance of these advanced techniques in achieving the goals of the HERON project.

In summary, this report presents the advanced georeferencing and localisation software developed as part of the HERON project, demonstrating its potential to transform infrastructure maintenance.

1 Introduction

1.1 Purpose of the Document

This deliverable report, titled D3.4 "Point of Interest Georeferencing and Precise Localisation Software", forms a vital part of the HERON project's endeavors to develop a comprehensive solution for effective infrastructure maintenance. The central objective of this report is to elucidate our software's functionalities in precisely georeferencing and localizing points of interest, both from ground and aerial sources, utilizing state-of-the-art positioning systems, particularly real-time kinematic positioning (RTK-GPS).

This report is structured to offer a detailed walkthrough of our georeferencing and localization approaches and their criticality in the project. Beginning with an overview of our overall approach to georeferencing, we explore the proposed functionalities and their priorities. The following sections provide a deep dive into the distinctive localization strategies for ground and aerial sources. Subsequently, we delve into a comprehensive discussion on the various positioning systems in use, with a specific focus on RTK-GPS. We conclude the report with a synthesis of our findings, insights, and implications in the context of the HERON project.

The remainder of this document is organized as follows. Chapter 2 of the report provides a detailed exposition of the HERON project's overall approach to georeferencing points of interest. It elaborates on the proposed functionalities of our software and ranks their priority in accordance with the project's demands. Chapter 3 focuses on the localization of points of interest derived from ground sources, elaborating on the methodologies and techniques applied. Chapter 4 extends this discussion to localization from aerial sources, shedding light on the unique challenges and solutions thereof. Chapter 5 delves into an exploration of the available positioning systems, placing a particular emphasis on the application of RTK-GPS for precise localization. Finally, Chapter 6 encapsulates the report's conclusions, offering insights drawn from the report and their implications on the broader objectives of the HERON project.

1.2 Intended Audience

This specific deliverable report is public and therefore can be accessed by any interested stakeholder. Envisioned stakeholders involve, amongst others, the HERON end users. In particular, these are road operators, who are agents in the monitoring procedure as well as monitoring information consumers. Other envisioned stakeholders could be those interested in consuming tracking information to develop information products. These may incorporate risk and health assessment modules that need monitoring feedback and information in order to provide up-to-date hazard, risk, and vulnerability assessments.

1.3 Interrelations

The findings of the HERON project's D2.1 and D2.2 deliverables, titled "End-user needs and KPIs report" and "Architecture specification" respectively, act as cornerstones for this particular document. D2.1, which focuses on user needs, encompasses an analysis of current methods, desires, and anticipations of infrastructure stakeholders. Meanwhile, D2.2, centered on the system's architecture and design, provides the specifics of the HERON platform structure, guidelines, and toolkit for developmental tasks. Consequently, these two key deliverables directly address the issues and constraints related to georeferencing information entering the HERON system, with the goal of streamlining the RI maintenance processes effectively. Lastly, this report highlights the necessary components that are essential in order to geo-refer and map the detected and classified defected POIs as defined from the previous tasks of WP3 (i.e., Tasks 3.1-3.3) and described in D3.1-D3.3.

2 Georeferencing of the HERON points of interest

The accurate georeferencing and localization of points of interest on the road surface, including the various HERON PoIs, such as potholes, cracks, faded markings, traffic cones, and road signs, plays a crucial role in the effective management of road maintenance and repairs. This process ensures that road defects are precisely identified, enabling efficient planning and timely intervention. The utilization of GPS coordinates is a key component in achieving this goal, as it allows for precise determination of the location of these points of interest.

By leveraging GPS coordinates the HERON UGV as well as road maintenance teams, engineers, and authorities can pinpoint the exact geographic location of the various road defects and areas of interest. This information is invaluable for planning maintenance activities, allocating resources effectively, and prioritizing repairs based on the severity and location of the identified issues. Thereby, such data can directly benefit traffic flow and safety, resulting in decreased CO_2 emissions, fuel costs, and time delays [1]. In parallel, the utilization of GPS data brings a standardized and accurate method of referencing and documenting road defects, ensuring consistency and reliability in the management of road infrastructure.

Furthermore, the advancements in modern technology have introduced new possibilities for road defect detection through the integration of drone functionality (see Section 4.6 of D3.1). An inspection aerial drone equipped with high-resolution RGB cameras and GPS capabilities can capture detailed imagery of the road surface, allowing for enhanced localization and identification of road defects. Thus, the specific integration of drone technology, combined with GPS coordinates, enables a comprehensive approach to road defect detection and management, which will be exploited by the HERON UGV for the effective georeferencing and precise localization of the PoIs, as these were identified in D2.1.

It is also underlined that the combination of GPS coordinates and drone imagery offers several advantages in the realm of automated road maintenance, and, therefore, to the HERON system. On the one hand, as already mentioned, the utilization of GPS coordinates ensures precise georeferencing of the identified road defects and PoIs. Thereby, this spatial reference allows for accurate mapping and documentation of the defects, facilitating effective communication between maintenance teams, authorities, and other stakeholders. The standardized coordinates enable easy integration of the data into a Geographic Information System (GIS) software, providing a visual representation of the road defects and supporting data-driven decision-making processes.

On the other hand, the integration of UAVs allows for efficient data collection and analysis. More specifically, drones can capture detailed imagery of the road surface from various angles and perspectives, providing a comprehensive view of the defects. The high-resolution images obtained through drone technology can be analyzed using various state-of-the-art computer vision techniques, like the deep machine learning frameworks that were analyzed in D3.1-D3.3, enabling automated recognition, detection, and classification of various road defects and PoIs. This approach significantly contributes to the goals and objectives of the HERON system and improves the efficiency of defect localization compared to manual inspections, saving time and resources in road maintenance operations. It is noted that the expected reduction of resources due to the usage of the HERON system is summarized in Table 4 of D3.1.

It is also emphasized that the combination of GPS coordinates and drone functionality offers a proactive approach to road maintenance. Regular drone inspections can be scheduled to monitor road conditions, identify potential defects, and prevent further deterioration. By detecting and addressing road defects at an early stage, it is possible to minimize the risk of accidents, extend the lifespan of the road infrastructure, and reduce overall maintenance costs.

However, it is important to acknowledge the challenges and considerations associated with the integration of drone technology for road defect detection. Factors such as weather conditions, airspace regulations, and the need for trained personnel to operate drones and analyze the collected imagery must be taken into account. Adhering to safety protocols and ensuring compliance with regulations is essential to mitigate risks and ensure the effective implementation of drone-based defect detection methods.

Thus, the precise georeferencing and localization of road defects using GPS coordinates are essential for effective road maintenance and repair management. The integration of drone technology further enhances defect detection capabilities by providing detailed imagery and facilitating efficient data collection. The combination of GPS coordinates and drone functionality offers opportunities for improved road maintenance practices, supporting timely interventions, data-driven decision-making, and proactive infrastructure management. By harnessing these technologies, road authorities and maintenance teams can optimize resources, enhance road safety, and ensure the longevity of road infrastructure.

2.1 GPS coordinates for precise localization of the HERON PoIs

GPS-based localization of the various areas of interest will provide the HERON platform with precise and standardized georeferencing capabilities, thus aiding in efficient planning during the intervention phase. In this section, the various functionalities that are related to the precise localization of the HERON PoIs by utilizing GPS coordinates are described. In particular, these are summarized below:

Table 4: Functionalities and priorities for localization of HERON PoIs

Functionality	**Priority**
Accurate coordinates of the PoIs through GPS-enabled devices	***Mandatory***
Accurate localization of the PoIs through digital mapping tools and GIS software	***Optional***
Precise localization of the PoIs through distinctive landmarks and reference points	***Optional***
Enhanced localization through validating and refining georeferenced PoIs	***Mandatory***
Efficient road maintenance through utilizing a database with GPS coordinates	***Optional***

2.2 UAVs for precise localization of the HERON PoIs

UAVs can provide an aerial perspective of the area under maintenance, capturing road defects from angles not easily accessible from the ground and therefore from the sensors mounted on the robotic platform. Moreover, rapid data collection and analysis through drones can improve efficiency as well as save time and costs in road maintenance operations. In this section, the various functionalities that are related to the precise localization of the HERON PoIs by utilizing drone technology are described. In particular, these are summarized below:

Table 5: Functionalities and priorities of localization of HERON POIs from UAV sources

Functionality	**Priority**
Accurate coordinates of the PoIs through GPS-enabled devices	***Mandatory***
Automated detection of PoIs through drone-captured images and CV techniques	***Mandatory***
Georeferencing through the integration of drone GPS data and captured images	***Mandatory***
Enhanced visualization through integrating drone imagery into GIS software	***Optional***
Comprehensive aerial views through satellite imagery	***Optional***

3 Localization of HERON PoIs from the ground sources

This chapter delves into the pertinent functionalities for georeferencing data derived from HERON's ground sources. It's important to note that these services are accessible via the software developed within the HERON framework and the accompanying infrastructure set to be deployed. However, functionalities requiring particular landmarks as reference points would necessitate preliminary surveying work prior to system implementation at the pilot sites. In this context, HERON will primarily rely on the precision of GPS devices and will resort to supplementary georeferencing sources for enhancing positioning accuracy as required.

Accurate coordinates of the PoIs through GPS-enabled devices (*Mandatory)*

GPS-enabled devices, such as smartphones or dedicated GPS receivers, are valuable tools for obtaining accurate latitude and longitude coordinates. These devices utilize advanced positioning technology to determine precise geographic coordinates of a given location. By leveraging high-precision modes and ensuring a strong GPS signal, the accuracy of acquired coordinates is significantly enhanced. Thereby, this combination of GPS-enabled devices, high-precision modes, and strong GPS signals enables reliable and accurate geolocation, providing a solid foundation for georeferencing and localizing various points of interest on the road surface.

Accurate localization of the PoIs through digital mapping tools and GIS software (*Optional)*

Digital mapping tools and GIS software can play a pivotal role in the precise localization of the various HERON PoIs. By utilizing such tools, road maintenance engineers and professionals can mark the exact locations of various road defects, so that the HERON system knows in advance the exact location of the PoI. This process involves placing markers or pins at specific coordinates and establishing a digital representation of the localized points. Through the integration of digital mapping tools and GIS software, road authorities gain the ability to visualize and manage the identified points of interest with accuracy and efficiency. The combination of these technologies enables effective planning, resource allocation, and decision-making for road maintenance and repair operations.

Precise localization of the PoIs through distinctive landmarks and reference points (*Optional)*

As already mentioned in the previous sections, accurately localizing points of interest on the road surface, is essential for effective automated road maintenance and repair management. Aiding in this process are distinctive landmarks and recognizable features that serve as reference points, facilitating precise localization. More specifically, intersections, buildings, road signs, and various other objects can play a crucial role in pinpointing the desired points on the road surface. By leveraging these distinctive landmarks and reference points, the HERON UGV could enhance the accuracy and efficiency of georeferencing the identified road defects. These recognizable features provide valuable context and help establish a reliable spatial reference for the identified points of interest, streamlining maintenance planning, resource allocation, and repair prioritization.

Enhanced localization through validating and refining georeferenced PoIs (*Mandatory)*

In the process of georeferencing and localizing PoIs on the road surface, it is imperative to ensure the accuracy and precision of the identified locations, so that the HERON UGV can be effectively positioned relatively close to the road defect, before starting the automated maintenance procedure. To this end, by examining the relationship between the georeferenced points and the actual damage, road maintenance teams, and authorities can assess the alignment and make necessary adjustments to further enhance the precision. For instance, the initial positioning refinement of the HERON UGV could be achieved by an operator, who utilizes the HD cameras that are mounted on the UAV and/or UGV of the HERON sensing interface (see D2.2). These adjustments aim to align the georeferenced points with the road surface, resulting in increased accuracy and reliability for effective road maintenance and repair management.

Efficient road maintenance through utilizing a database with GPS coordinates (*Optional)*

Utilizing GPS coordinates enables the creation of a comprehensive database for storing and managing information on points of interest, supporting efficient road maintenance practices. This database serves as a centralized repository where various details related to road defects can be recorded and stored. Information such as the type of damage, severity assessment, photographs, and additional observations can be systematically documented, providing valuable insights for maintenance teams and authorities. By incorporating these data points into the database, road maintenance activities can be planned, prioritized, and executed effectively.

The availability of detailed information facilitates accurate resource allocation, targeted interventions, and timely repairs, ultimately improving road safety and prolonging the lifespan of the road infrastructure. Lastly, it is underlined that storing the GPS coordinates of the various PoIs can also assist the visual servoing as well as the actual maintenance process performed by the HERON system. For instance, regarding the geolocation of the traffic cones, storing the GPS coordinates of the HERON UGV in a database during the dispensing procedure, enables the platform to be aware of the exact location of the traffic cones during the removal phase. Hence, traffic cone removal becomes more straightforward and effective in terms of time and complexity. The specific functionality is illustrated in Figure 1 below.

Cone 1: 37.923600, 22.954858	Cone 2: 37.923605, 22.954740
Cone 3: 37.923595, 22.954610	Cone 4: 37.923595, 22.954492
Cone 5: 37.923600, 22.954381	Cone 6: 37.923620, 22.954232

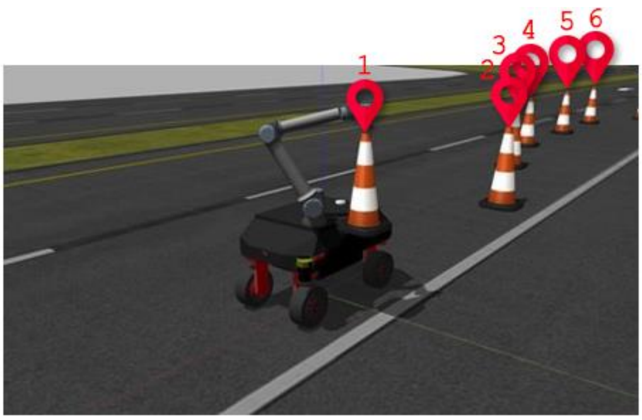

Figure 1: Georeferencing of the traffic cones by storing GPS data during the dispensing process.

3.1 Positioning from ground sources in HERON

In HERON the data coming from the ground come from the following types of sources:

1. CCTV cameras whose position is static and known
2. Data coming from patrolling vehicles that are moving and are using GPS sensors
3. Data coming directly from the HERON UGV

CCTV cameras are static points thus the geo-referencing of the captured visual information is done once offline. Any updates coming during monitoring or intervention operations will use this offline geo-referencing.

Data coming from patrolling vehicles will be georeferenced using the equipped GPS tracking. However, there are two main issues that might introduce errors in the georeferencing, (i) imprecise GPS coordinates due to the available sensors, and (ii) errors in the synchronization of the GPS and visual data streams. For the first issue, the HERON system will accompany these readings will additional monitoring patrols using UAVs equipped with centimeter-accurate RTK-GPS sensors as described in section 5. The second issue will be addressed with the installation of additional sensors and/or other infrastructure or again by accompanying patrolling vehicles with data coming from highly accurate sensors.

Finally, data coming from the HERON UGV will be equipped with appropriately accurate sensors to execute the intervention.

4 Precise localization of the HERON PoIs from aerial sources

This section discusses the analysis and georeferencing from aerial data sources. Similarly to what was noted in Section 3, the georeferencing of data from UAVs will take place mainly through the use of computer vision models developed in WP3 as well as the use of RTK-GPS sensors in the deployed UAVs. Supplementary techniques for increasing the georeferencing accuracy such as the analysis of remote sensing data or the integration with GIS systems will again take place as required.

Accurate detection through high-resolution drone imaging *(Mandatory)*

As already mentioned in Section 2, UAVs equipped with high-resolution cameras and GPS capabilities (see Section 2.1) offer remarkable possibilities for road defect detection by capturing detailed imagery from various angles, providing a comprehensive view of the road surface. These advanced drones enable the robotic platform, as well as the road maintenance teams and authorities to access a wealth of visual information that otherwise can be challenging to obtain (e.g., in areas of the road infrastructure that are difficult to access). Equipped with high-resolution cameras, drones capture images with exceptional clarity and detail, allowing for enhanced visualization and analysis of road defects. By flying at different altitudes and angles, drones can capture the road surface from various perspectives, providing a comprehensive view that aids in accurate defect identification and assessment.

Automated detection of PoIs through drone-captured images and CV techniques (*Mandatory*)

As already mentioned in Section 4.6 of D3.1, drone-captured images provide a valuable resource for the automated detection of road defects through the utilization of various computer vision techniques (e.g., state-of-the-art object detectors, such as SSD and YOLO algorithms) [2]-[4]. By employing image processing algorithms, these techniques can analyze the captured images and identify various types of damage (e.g., potholes). Thereby the application of computer vision and deep learning allows for the automatic detection and classification of road defects, streamlining the defect identification process and enabling timely intervention. Moreover, the outputs of an automated defect detector can play a significant role in the georeferencing of HERON PoIs. More specifically, as presented in D3.1, when a trained YOLO model processes drone-captured images (or any other source of imagery, such as images that derive from a sensor mounted on the UGV), it generates bounding boxes around the detected road defects. These bounding boxes represent the spatial extents of the identified defects within the image. The coordinates of these bounding boxes, along with the associated confidence scores, provide crucial information for georeferencing the road defects. By integrating the outputs of the YOLO model with GPS coordinates and geospatial mapping techniques, the precise locations of the detected road defects can be determined. The bounding boxes provide the necessary spatial context, allowing for the alignment of the identified defects with the corresponding positions on the road surface. Consequently, his alignment is crucial for accurately georeferencing the PoIs and associating them with specific geographic coordinates.

Georeferencing through the integration of drone GPS data and captured images (*Mandatory*)

As already mentioned in the previous subsection, the integration of GPS capabilities significantly improves the effectiveness of drone-based defect detection, as it allows for precise georeferencing of the captured imagery. In other words, combining GPS data from the drone with the captured RGB images allows for precise georeferencing of detected defects. By associating GPS coordinates with each image frame, an accurate spatial reference is established, further enhancing the georeferencing process. Thus, the integration of GPS data and captured images enables a seamless connection between real-world geographic locations and the visual representation of the detected defects. This integration ensures that the identified road defects are not only visually documented but also precisely located within the road network to other components using a global and extensively used localization method. The GPS coordinates associated with each image frame provide a reliable and standardized spatial reference system, allowing for consistent and accurate mapping of the defects onto the road surface. Therefore, this integration of high-resolution drone imaging and GPS capabilities can revolutionize road defect detection and management, empowering road authorities with valuable data to prioritize repairs, optimize resources, and improve road safety, while in parallel an autonomous drone can coordinate maintenance works that are performed by the robotic platform as well as the pre/post-intervention phases.

Enhanced visualization through integrating drone imagery into GIS software (*Optional*)

The integration of drone imagery and corresponding GPS coordinates into GIS software offers a solution for enhanced visualization, analysis, and management of road defects and related data. By combining drone technology with GPS capabilities, high-resolution images captured by drones can be seamlessly integrated into GIS software platforms. This integration allows for a comprehensive view of the various PoIs, providing valuable insights for maintenance and repair operations. GIS systems enable the visualization of drone imagery, GPS coordinates, and other relevant data, such as the type and severity of defects. In parallel, it is noted that this visualization capability enhances decision-making processes by providing a clear and intuitive representation of road conditions.

Comprehensive aerial views through satellite imagery *(Optional)*

Satellite imagery services such as Google Maps or Bing Maps provide road operators with access to clear aerial views of under-inspection road areas. These services enable individuals to visualize the road network from a bird’s-eye perspective, offering valuable insights into the overall layout and condition of the roads. By utilizing the zoom function within these platforms, operators can further enhance their examination of road features and the surrounding environment. Zooming in on the satellite imagery allows for a detailed analysis of the road surface, including the identification of cracks, potholes, faded markings, and other points of interest. This level of scrutiny aids in accurately pinpointing the location of road defects and provides valuable context for effective maintenance and repair planning. Additionally, the ability to zoom in allows for a comprehensive assessment of the surrounding area, enabling stakeholders to consider factors such as nearby landmarks, intersections, and infrastructure that may impact maintenance operations or require attention.

4.1 Positioning from aerial sources in HERON

In HERON data coming from UAVs will be used as aerial imagery during infrastructure monitoring operations. For this purpose, ICCS will deploy a DJI Matrice 350 RTK UAV (see Figure 2) which is equipped with an RTK-GPS system. The use of this system and its benefits are elaborated in Section 5, but it is worth mentioning here that the RTK accuracy of this drone is 1cm + 1ppm (horizontal) and 1.5cm +1ppm(vertical).


Figure 2: DJI Matrice 350 RTK Drone.

5 Utilised positioning systems and real-time kinematic positioning

RTK stands for Real-Time Kinematic, which is a GPS positioning technique that provides highly accurate and precise real-time positioning data. RTK GPS systems utilize a base station, which is further analyzed in Section 5.1, and one or more rovers[1], to achieve centimeter-level positioning accuracy (see Figure 3). It is noted that RTK has various applications, such as for instance in land surveying, unmanned aerial vehicle navigation, and hydrographic surveying [5].

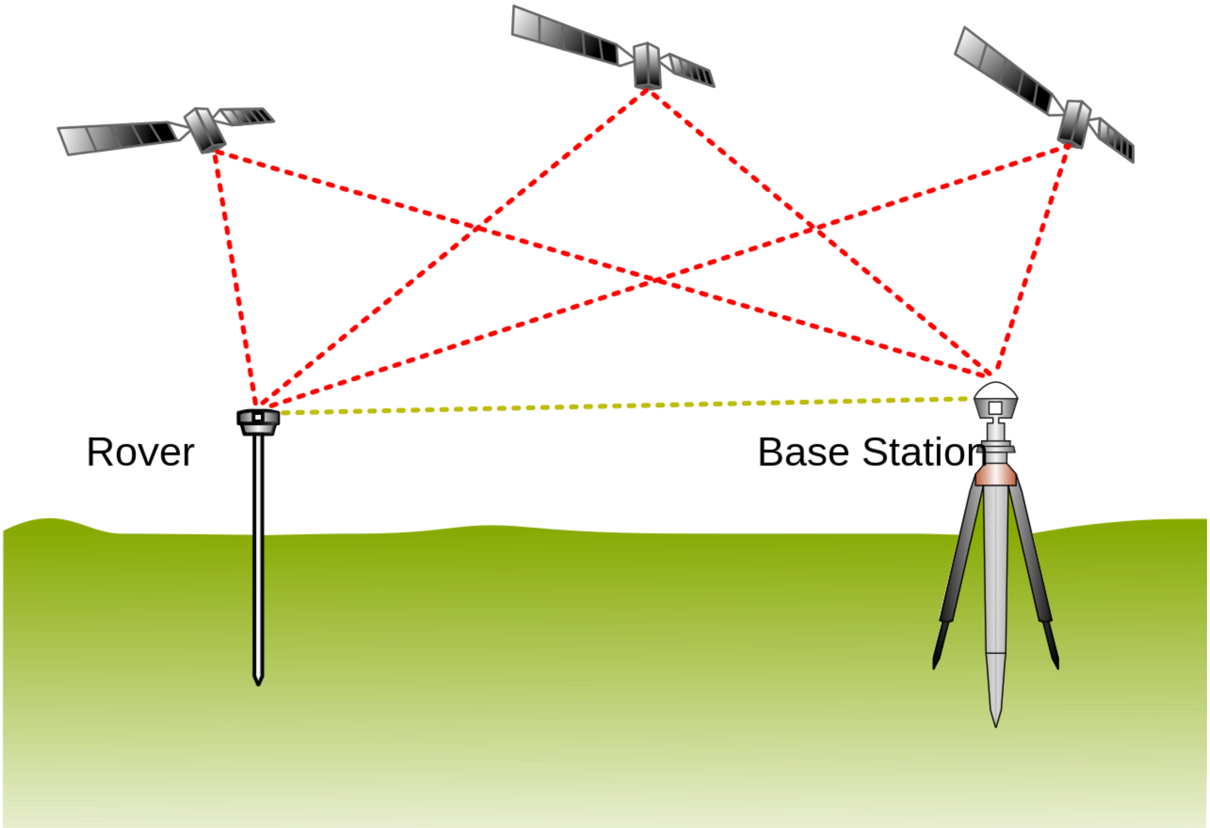

Figure 3: The RTK concept.

More specifically, in RTK GPS, the base station receives signals from multiple satellites and calculates its own position accurately. It then transmits correction data, including the difference between its known position and the measured position, to the rover(s) in real-time. Then, the rover(s) receive these corrections and apply them to their own GPS measurements, resulting in highly precise and accurate positioning information. RTK GPS relies on a technique called carrier phase tracking, which involves measuring the precise phase of the GPS carrier signals. Thereby, by comparing the phase measurements from the base station and rover(s), the system can determine the errors introduced by factors such as atmospheric interference and satellite clock inaccuracies. These errors are then corrected, enabling the rover(s) to achieve centimeter-level accuracy in real-time positioning. The RTK GPS system that will be utilized within the framework of the HERON project is depicted in Figure 4.

[1] The term "rover" refers to a mobile GPS receiver that moves around on the earth's surface. The rover receives signals from both the GPS satellites and a stationary, base GPS receiver (base station).

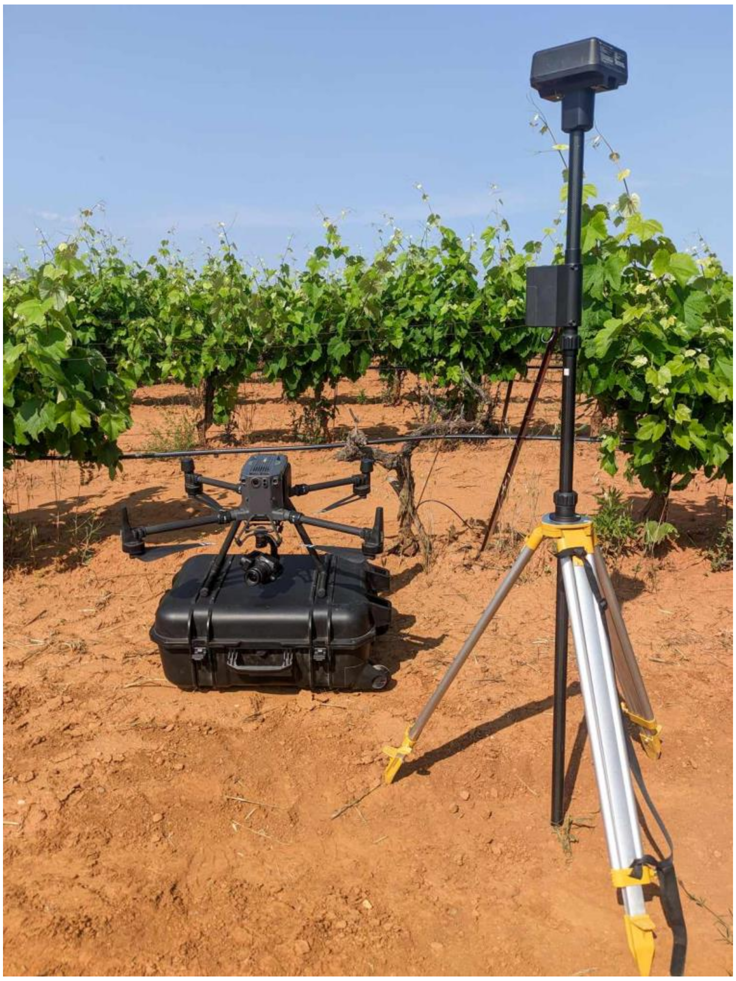

Figure 4: The RTK GPS that will be utilized by the HERON system to georeference and precisely localize the various PoIs.

5.1 Base stations

In RTK GPS, a base station is a fixed or stationary GPS receiver that serves as a reference point for providing correction data to rovers in the field. The base station's main function is to accurately determine its own position and then continuously transmit correction information to the rovers in real-time.

It is highlighted that the base station is typically set up at a known location with precise coordinates, and it remains stationary throughout the survey or data collection process. It is equipped with a high-precision GPS receiver capable of providing accurate positioning information. As already noted the base station receives signals from multiple GPS satellites and calculates its position using carrier phase tracking, which measures the precise phase of the GPS carrier signals.

Subsequently, once the base station accurately determines its position, it calculates the difference between its known coordinates and the measured position based on GPS signals. This difference is known as the “correction data”. The correction data contains information about various factors that introduce errors in the GPS measurements, such as atmospheric interference, satellite clock inaccuracies, and other sources of error.

The base station continuously transmits the correction data to the rovers in real-time using radio waves or other wireless communication methods. Rovers receive these corrections and apply them to their own GPS measurements, which allows them to achieve centimeter-level positioning accuracy.

It is also noted that the range of the base station's communication depends on the radio equipment used and the specific RTK GPS system. Typically, the base station's transmission range extends up to several kilometers, making it suitable for various applications that require precise positioning over larger areas.

Consequently, base stations are essential for the operation of RTK GPS systems, as they provide the reference data required to achieve highly accurate and real-time positioning. The stability and accuracy of the base station's position are crucial, as any errors in its coordinates will affect the quality of the correction data provided to the rovers. Surveyors and professionals ensure that base stations are set up on stable ground and use additional measures like ground control points or virtual reference stations to enhance accuracy in some cases.

Differences between ground base stations and virtual base stations

Two common types of base stations used in RTK GPS systems are ground base stations and virtual base stations. While both serve the purpose of providing correction data to rovers, they differ significantly in their implementation and applications.

Ground base stations

Ground base stations are physical, fixed GPS receivers placed at known and stable locations on the Earth's surface. Surveyors set up these base stations on secure foundations and use them as reference points to calculate correction data. The primary characteristics of ground base stations are as follows:

- **Stability:** Ground base stations are established on stable ground to ensure accuracy and consistency in providing correction data.
- **Transmission range:** Ground base stations typically have a limited transmission range, usually several kilometers, which restricts the area over which they can provide corrections to rovers.
- **Communication:** They transmit correction data via radio waves or other wireless communication methods to the rovers in real-time.
- **Deployment:** Setting up ground base stations requires physical effort and careful site selection to ensure optimal positioning for accurate correction data.

Virtual base stations

A virtual base station, also known as Network RTK or VRS (Virtual Reference Station), is a more modern and dynamic approach to RTK GPS corrections. Rather than relying on physical base stations, virtual base stations use a network of continuously operating reference stations (CORS) spread over a larger geographic area. The primary characteristics of virtual base stations are as follows:

- **Dynamic network:** Virtual base stations use a network of CORS that cover a larger area, allowing for more extensive coverage and flexibility in providing corrections to rovers.

- **Internet connection:** Instead of direct radio communication, virtual base stations use an internet connection to transmit correction data to the rovers.
- **Auto-adaptive:** The system automatically selects the most appropriate reference station(s) based on the rover's location, ensuring optimal accuracy and efficiency.
- **Ease of setup:** Virtual base stations eliminate the need for manual site setup, reducing the effort and cost associated with deploying traditional ground base stations.
- **Robustness:** Virtual base stations involve several CORS to compute the corrections, which means, if a ground base suddenly stops the data transfer, another will be used.

Key differences and advantages

The most important differences between the aforementioned types of base stations used in RTK GPS systems are listed below:

- **Coverage:** Ground base stations are limited in their coverage area, whereas virtual base stations can cover larger regions, making them particularly advantageous for wide-area applications and surveying projects that span vast territories (e.g., road infrastructures).
- **Flexibility:** Virtual base stations offer greater flexibility since rovers can access multiple CORS in real-time, providing seamless transitions between regions and mitigating issues caused by obstructions or signal degradation.
- **Setup and maintenance:** Virtual base stations require minimal physical setup and maintenance compared to ground base stations, making them cost-effective and efficient solutions.
- **Robustness:** Ground base stations may be affected by environmental factors or local disturbances, while virtual base stations benefit from a distributed network that is generally more robust and reliable.

In conclusion, both ground base stations and virtual base stations play crucial roles in RTK GPS technology, providing correction data to rovers for achieving centimeter-level accuracy in positioning. The choice between the two depends on the specific requirements of the application, the geographic area to be covered, and the available resources. Ground base stations offer stability and precision in localized areas, making them suitable for small-scale projects, whereas virtual base stations excel in providing widespread coverage and adaptability in dynamic environments. As RTK GPS technology continues to advance, both ground and virtual base stations contribute to the broader goal of accurate and efficient positioning solutions across various industries and applications.

5.2 Key advantages of RTK GPS for HERON

The Real-Time Kinematic (RTK) Global Positioning System (GPS) holds significant implications for the HERON platform, a robotic system **requiring high precision** and **real-time positioning** data for effective and efficient operation. The primary utility of RTK GPS lies in its centimeter-level accuracy, an attribute critical to the successful identification, targeting, and repair of road defects such as potholes, cracks, and faded markings by the HERON platform.

RTK GPS' **real-time positioning** is another invaluable feature, offering immediate corrections and up-to-date positioning information. For the HERON system, this translates into the robotic platform's ability to optimally plan its path according to shifting road conditions, ensuring swift defect location and targeted repairs while circumventing potential hazards.

Moreover, RTK GPS contributes to **increased efficiency** by streamlining workflows and negating the need for time-consuming manual surveys. In the context of the HERON platform, the efficiency enabled by RTK GPS facilitates quicker defect detection and repair cycles, ultimately minimizing road disruptions and enhancing overall road quality.

The combination of **high precision and real-time capabilities** of RTK GPS not only boosts productivity by reducing errors and rework but also optimizes resource allocation. Consequently, the HERON platform can benefit from expedited response times, improved road safety, and cost-effective maintenance operations, underlining the improved productivity enabled by RTK GPS.

Importantly, RTK GPS integrates seamlessly with Geographic Information System (GIS) platforms, enabling accurate georeferencing and data integration. This integration empowers the HERON robotic system with accurate, real-time geospatial data, enabling efficient defect prioritization, resource allocation, and maintenance planning.

Finally, RTK GPS systems are designed with future-proofing in mind. They can be upgraded and adapted to accommodate advancements in technology, ensuring the HERON platform remains current, and benefits from improved accuracy and faster data processing, enabling efficient defect identification and repair

RTK GPS within the HERON system

The HERON system utilizes the aforementioned functionalities (see Sections 5.1) and advancements from the RKT technology (see Section 5.2) in order to precisely georeference the detected regions of interest (see D3.1-D3.3 for more information). In particular, the georeferencing system (see Figure 4) consists of:

- A base station (as described in Section 5.1), whether it is a ground base station located on-site (i.e., close to the road infrastructure), or a virtual base station (Networked Transport of RTCM via Internet Protocol - NTRIP). The base station is depicted in Figure 5(a).
- RTK antennas mounted on the HERON UAV and/or UGV, which will play the role of the rover (as described in Sections 5.1). The rover receiver is depicted in Figure 5(b).

(a) (b)

Figure 5: The base station (a) and the RTK antennas mounted on the HERON UAV (b), which will act as the rover receiver of the georeferencing system.

The operating steps of the RTK GPS, which will act as the flagship of the HERON georeferencing system, are listed below:

- The base station [see Figure 5(a)] communicates with GPS signals in the sky.
- The rover(s) [see Figure 5(b)], whether is the drone or the robotic system, is then going to get the signals from the base station.
- The base station is then going to send the rover its correctional position data.
- For the RTK service to work on the UAV and/or UGV, the rover also must have a direct line of sight with the satellites in the sky as well, from which it gets the GPS signal.
- Consequently, when both signals go to the rover, the RKT service works, and thereby it is possible to effectively georeference the HERON drone and/or robotic platform as well as precisely localize the PoIs.

The aforementioned functionalities are also illustrated in Figure 6 below.

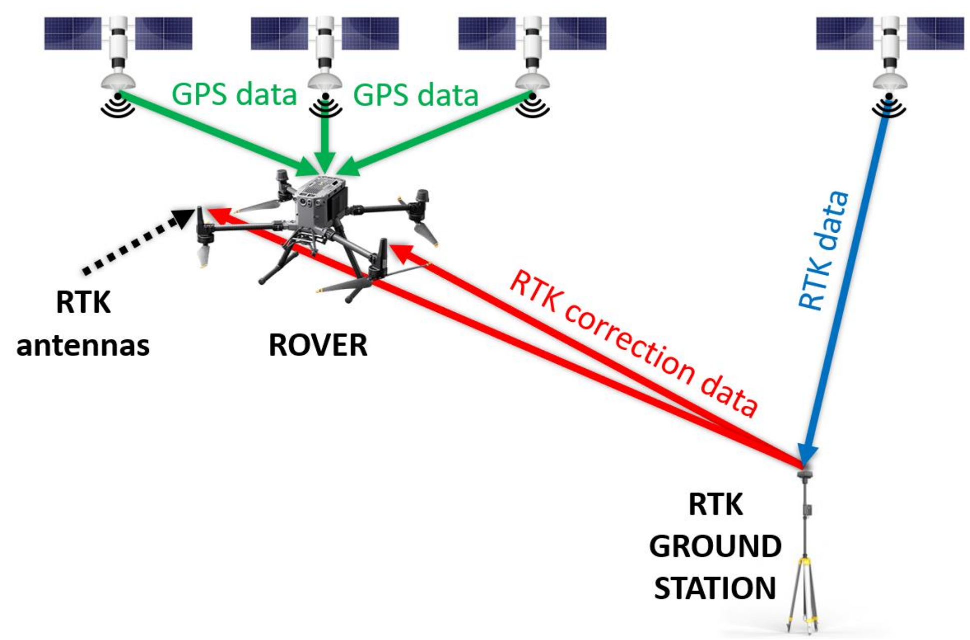

Figure 6: HERON georeferencing system.

5.3 Utilized positioning systems

As already mentioned in Section 5.1, within the context of the HERON project, the choice between using a virtual base station or a ground base station for RTK GPS corrections can significantly impact the efficiency, flexibility, and overall performance of the robotic system. While both types of base stations offer precise positioning data, virtual base stations hold several distinct advantages over ground base stations, making them the preferred option for this specific application. These are listed and analyzed in the following subsection.

Key benefits of utilizing virtual base stations in the HERON system

Wider geographic coverage

A crucial advantage of virtual base stations is their extensive coverage area compared to individual ground base stations. Virtual base stations utilize a network of continuously operating reference stations spread across large regions. This widespread coverage can enable the HERON platform to access real-time correction data over vast areas, facilitating continuous and uninterrupted positioning during automated road defect maintenance tasks. In contrast, ground base stations have limited transmission ranges, which may require frequent relocation or deployment of multiple base stations for comprehensive coverage, resulting in increased setup and maintenance efforts.

Flexibility and dynamic adaptability

Virtual base stations offer greater flexibility as they automatically select the most suitable reference station(s) based on the rover's location (i.e., the precise location of the HERON AUV and/or UGV). This dynamic adaptation ensures that the robotic platform continuously receives the most optimal correction data, regardless of its position, even when crossing between different regions with varying ground base station availability. This adaptability eliminates the need for manual intervention and allows the robotic platform to seamlessly navigate through diverse terrains and road conditions without interruption, enhancing its overall reliability and operational efficiency.

Ease of setup and cost-effectiveness

Setting up and maintaining ground base stations can be time-consuming and resource-intensive. On the other hand, virtual base stations eliminate the need for physical site selection and setup, reducing setup time and cost. The use of internet connections for data transmission instead of dedicated radio links further simplifies the setup process, making virtual base stations a cost-effective solution for automated road defect maintenance platforms.

Robustness and redundancy

Virtual base station networks are designed with redundancy in mind. The network's distributed nature ensures robustness, as the robotic platform can access multiple CORS simultaneously or switch between them seamlessly, minimizing the impact of potential communication disruptions or station outages. This redundancy adds a layer of reliability and robustness to the system, reducing the risk of downtime or positioning inaccuracies during critical road defect maintenance operations.

Continuous data availability

The continuous operation of virtual base stations allows the robotic platform to access real-time positioning data at all times, ensuring uninterrupted data flow and precise positioning. It is noted that this continuous data availability is vital for maintaining accurate control and navigation during automated road defect maintenance, as it minimizes interruptions and enhances the platform's ability to address defects promptly and efficiently.

In conclusion, for the HERON system, a virtual base station can offer significant advantages over a ground base station. Its wider geographic coverage, dynamic adaptability, ease of setup, and continuous data availability make it a superior choice for supporting the precise positioning and georeferencing requirements of such an advanced automated system. Thereby, by leveraging the benefits of a virtual base station, the UGV can achieve enhanced reliability, flexibility, and efficiency in detecting and repairing road defects.

The ground base station alternative

While virtual base stations offer numerous advantages that are analyzed in the previous paragraphs, there may be situations where a ground base station becomes necessary due to the unavailability of a virtual base station network in a specific area. In such cases, ground base stations can still provide valuable correction data for the robotic platform's real-time positioning needs. Ground base stations can be strategically placed at key locations close to the road infrastructure, in order to cover the immediate area of interest. Although this approach may involve more manual effort in setting up and maintaining the ground base station, it can still offer precise positioning for localized road defect maintenance operations. In other words, ground base stations may be preferred in remote or sparsely covered regions where establishing a virtual base station network may not be feasible. Additionally, ground base stations can act as backups in case of internet connectivity issues or other technical challenges that may affect the availability of virtual base station corrections. In a nutshell, while ground base stations may not offer the same level of flexibility and coverage as virtual base stations, they can serve as reliable alternatives to support the robotic platform's critical positioning requirements when virtual base stations are not available.

5.4 EUREF Permanent GNSS Network

The EUREF Permanent Network (EPN) is a network of continuously operating reference stations spread across Europe, primarily established for geodetic and geophysical applications. EUREF stands for “European Reference Frame”, and the network is managed and coordinated by the EUREF Technical Working Group, which is part of the International Association of Geodesy (IAG).

The main objectives of the EPN are to provide precise and consistent GNSS data for geodetic research, positioning, and monitoring purposes. The network is designed to support a wide range of applications, including surveying, mapping, land deformation monitoring, tectonic plate movements, atmospheric research, and satellite orbit determination. The map below depicts the EPN stations set up to stream real-time data through at least one of the EPN broadcasters [9].

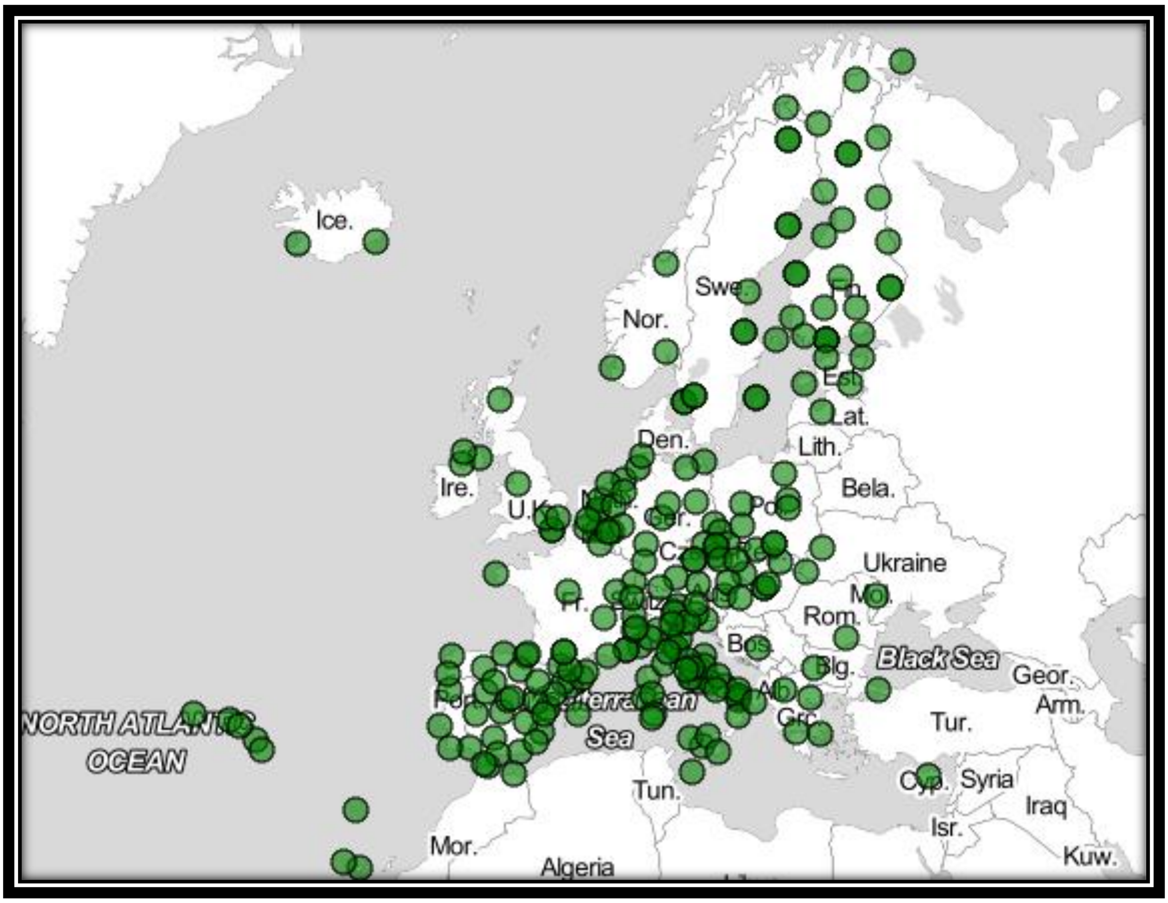

Figure 7: EPN stations set up to stream real-time data through at least one of the EPN broadcasters.

Key features of the EUREF Permanent GNSS Network include:

- **Continuously operating reference stations:** The EPN consists of permanently installed GNSS reference stations equipped with high-precision GPS (Global Positioning System) and GLONASS (Global Navigation Satellite System) receivers. Some stations may also support other GNSS systems like Galileo or BeiDou.
- **Real-time data transmission:** The GNSS data from the EPN reference stations are continuously transmitted in real-time through data streams, making the corrections available for users in real-time positioning applications.
- **Wide geographic coverage:** The network covers a vast area across Europe and neighboring regions, providing extensive spatial coverage for positioning and geodetic research.
- **High data quality and accuracy:** EPN stations are carefully calibrated and maintained to ensure high data quality and accuracy. The data from these stations are processed using precise geodetic algorithms to provide reliable positioning information.
- **Open access:** The EPN data is publicly available for scientific, academic, and commercial use, fostering collaboration and knowledge exchange in the geodetic community.
- **Support for various applications:** The EPN supports a diverse range of applications, including reference frame maintenance, crustal deformation monitoring, Earth's rotation studies, ionosphere and troposphere research, and GNSS satellite orbit determination.

The EUREF Permanent GNSS Network plays a significant role in European geodetic and geophysical research, contributing to the establishment and maintenance of a stable reference frame for accurate positioning and monitoring purposes. The network's real-time data streams and wide coverage area make it a valuable resource for real-time kinematic applications, supporting precise positioning for surveying, mapping, and navigation in Europe. Additionally, the continuous monitoring of GNSS data helps researchers and scientists to better understand geophysical processes, such as tectonic plate movements and crustal deformations, contributing to advancements in geoscience and disaster monitoring.

The EUREF Permanent GNSS Network can be crucial for the HERON robotic platform due to its high-precision and continuously available GNSS data. The network's wide geographic coverage across Europe ensures that the robotic platform can access real-time positioning information with centimeter-level accuracy throughout its operation. This level of precision is essential for the robotic platform to navigate precisely along the road, identify road defects with great accuracy, and execute maintenance tasks efficiently. Additionally, the network's open-access policy allows the robotic platform to integrate seamlessly with the GNSS data, enabling reliable and up-to-date positioning, even in dynamic road conditions. Leveraging the EPN's data ensures that the robotic platform stays on track, performs targeted maintenance, and enhances the overall safety and effectiveness of automated road defect maintenance operations, contributing to well-maintained and safer road infrastructure.

5.5 HEPOS - Hellenic Positioning System

Regarding the Greek pilot, the Hellenic Positioning System (HEPOS) will be utilized, which is a system that enables precise positioning services, using all existing satellite positioning systems (GPS, GLONASS, GALILEO, BEIDOU). It was installed in 2007 and since then it has been operating 24/7 and 365 days a year [10].

The Hellenic Positioning System HEPOS is a genuinely innovative infrastructure project, which allows high-accuracy satellite-based positioning, utilizing the existing Global Positioning System (GPS). Thus, homogenous and accurate topographic measurements are achieved nationwide in a faster and more cost-effective way [11].

HEPOS was developed in-house by NCMA S.A. for the development of the Hellenic Cadastre. Yet, it can be used for a great number of other applications in the fields of Topography, Geodesy, Cartography, Construction Engineering, etc., in which accuracy at a centimeter-level is of high importance. Consequently, HEPOS is addressed to a wide range of interested parties, such as Public Services and Bodies, Surveying Engineers, and generally professionals of geosciences, private engineering contractors, constructors, academic and research institutions, etc. It also emphasized that HEPOS can be used both for real-time and post-processing applications. Consequently, it can be beneficial for the georeferencing and precise localization of the various HERON PoIs.

HEPOS consists of a total of 98 permanent reference stations (see Figure 8) covering the whole country and a Control Centre [12]. The Control Centre processes the reference stations' data and sends the data needed for the accurate positioning of their location to the users.

(a) (b)

Figure 8: Typical reference stations of HEPOS.

The stations are located 50-70 km apart and cover:

- The continental country as a whole by two sections (networks) defined mainly by the absolute magnitude of the movement of the reference stations, due to geological phenomena
- Crete, with a network of 8 reference stations
- The island country, with 11 individual reference stations

HEPOS provides both real-time positioning services via the internet or dial-up connection and post-processing via a web interface. The provided accuracy varies according to the user's wish from 1m (DGPS) to a few centimeters (RTK, PPK). Finally, it is underlined that with the use of the system, homogeneous and accurate topographic measurements are achieved throughout the country, faster and more economically.

6 Conclusions

The exploration presented within this deliverable report, D3.4 "Point of Interest Georeferencing and Precise Localisation Software", has sought to illuminate the intricacies and the potential of the innovative strategies and solutions incorporated within the HERON project.

Starting from the broad outline of our approach to georeferencing points of interest in Chapter 2, the proposed functionalities not only address the central needs of the project but are also adaptable and flexible according to changing priorities and scenarios.

The distinct approaches towards localizing points of interest from ground sources, presented in Chapter 3, and aerial sources, discussed in Chapter 4, reinforce the versatility and inclusivity of our methodology. We have planned to capture, process and interpret data from a range of sources and platforms, thereby ensuring the comprehensive and efficient functioning of the HERON system.

Chapter 5's exploration of the various positioning systems and particularly the in-depth discussion on RTK-GPS affirmed the crucial role of advanced and precise localization techniques in achieving our end objectives. The incorporation of these cutting-edge systems greatly enhances the efficacy of our project and sets a high standard for future developments in this field.

In conclusion, the ambitious scope and developed methodologies of the HERON project are mirrored in this deliverable report. The precise georeferencing and localization software detailed herein facilitates the creation of comprehensive and effective solutions for infrastructure maintenance. As we move forward, these findings and insights will serve to guide, inform and refine our future efforts.

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