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### **384. Automated high-resolution ground-penetrating radar prospection with an uncrewed ground vehicle at an archaeological site**

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Although large progress has been made in geophysical data acquisition, the survey of large areas together with a high spatial resolution remains time-consuming even when using multiple sensors in parallel. In order to overcome this problem, one possibility is the use of uncrewed aerial vehicles. Tests with drone-borne electromagnetic induction instruments and magnetometers have been conducted.

Air-launched ground-penetrating radar (GPR) surveys were also tested, but result in decreasing reflection amplitudes (and therefore reduced penetration depth) and lower spatial resolution (Diamanti and Annan 2017, 1694). Therefore ground-based methods should also be explored.

A small, four-wheeled Clearpath Robotics Husky uncrewed ground vehicle (UGV), with a maximum speed of ~1 m/s and a payload of up to 75 kg, was tested to investigate its suitability for automated GPR prospection (Verdonck 2021, 220). It is equipped with wheel encoders, an inertial measurement unit (IMU), and a GNSS receiving corrections from permanent reference stations via mobile internet. Additional position measurements were obtained by tracking a prism placed on top of the Husky using a robotic total station. These allow the UGV to estimate its position, orientation and velocity, through data fusion by means of an extended Kalman filter, which is part of the Robot Operating System (ROS), an open source framework structured as a large number of small programs or 'nodes' (Quigley, Gerkey and Smart 2016).

In July 2021, the Husky was tested at the Roman town Falerii Novi (Italy), which was surveyed previously with a GPR array towed by an all-terrain vehicle. The UGV pulled two 500 MHz GPR antennae, covering an area of 1600 m<sup>2</sup>. The objectives of the survey were to investigate (1) how accurately the robot can follow predefined survey lines; (2) if the robot can independently reach a series of predefined goals; (3) how well the UGV can avoid obstacles; (4) which sensors are essential for localization and navigation; and (5) possible interference between UGV and GPR.

The accuracy of the UGV when following predefined lines was tested at speeds of 0.3–0.9 m/s. Although there were cross-line errors of up to 0.2 m, for all speeds the errors were relatively consistent within and between traverses. As a consequence, the survey area was evenly covered, and sample density approximated theoretical requirements for 500 MHz GPR antennae. This resulted in time slices of the same quality as the ones collected with the human-driven GPR platform. Three manual interventions were necessary, when the UGV could not reach a waypoint, mainly because of wheel slippage in the shifting sand covering parts of the test site.

The UGV's ability to avoid obstacles was tested in two ways. A Velodyne VLP-16 LiDAR mounted in the front of the Husky allowed it to successfully avoid an obstacle of ~0.5 m x 0.3 m x 1 m. At the same time, long vegetation caused the LiDAR to identify a number of false positives, which made the Husky deviate from its path. This occurred more often when plants had thick stems, and less in the case of grass. Also, after having avoided the obstacle, the robot often did not return to the predefined transect line, but followed a parallel path to reach the next waypoint. This is because the ROS planner finds a path with minimal cost. This cost is only based on the distance from the target and from obstacles, not on the proximity from the original predefined

line. Alternatively, the position and dimensions of the obstacles can be measured with a GNSS before the start of the survey, and additional waypoints can be given to the UGV so that it can avoid the obstacles without using a LiDAR. This is more time consuming but led to good results at Falerii Novi.

Another question is which sensors are vital for the UGV to navigate. In order to obtain a precise position estimate, the wheel encoders (whether in combination with the IMU or not) were not sufficient, but RTK GNSS or the tracking total station were essential. To investigate which sensors are necessary to reliably calculate the robot's orientation, several sensor combinations were tried: GNSS–wheel encoders, GNSS–wheel encoders–IMU, and GNSS–wheel encoders–tracking total station. It was found that the UGV performed equally well using only GNSS–wheel encoders, and that the use of extra sensors such as IMU or tracking total station was not essential. At the moment, it is being investigated how accurately this single GNSS instrument can predict also the coordinates of the GPR antennae pulled behind the robot.

When measuring interference between the sensors mounted onto the UGV and the GPR antennae, the most important source of noise was the 900 MHz transmitter of the wireless emergency stop. It had to be kept at a distance of at least a few metres not to interfere with the GPR receiver.

After each transect, raw GPR data are automatically transferred from the notebook on the UGV to a base station computer for quality control in the field. A simple data processing flow was developed, including dewow, time zero correction, gain, background removal, conversion of GNSS coordinates to a projected coordinate system, calculation of individual antenna coordinates, and the creation of horizontal slices. Currently, the use of semi-automated interpretation algorithms based on convolutional neural networks is being investigated, both for rapid visualisation of the results as they are transferred by the UGV, and as an aid in the final delineation and interpretation.

## References

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