Tech *Notes*

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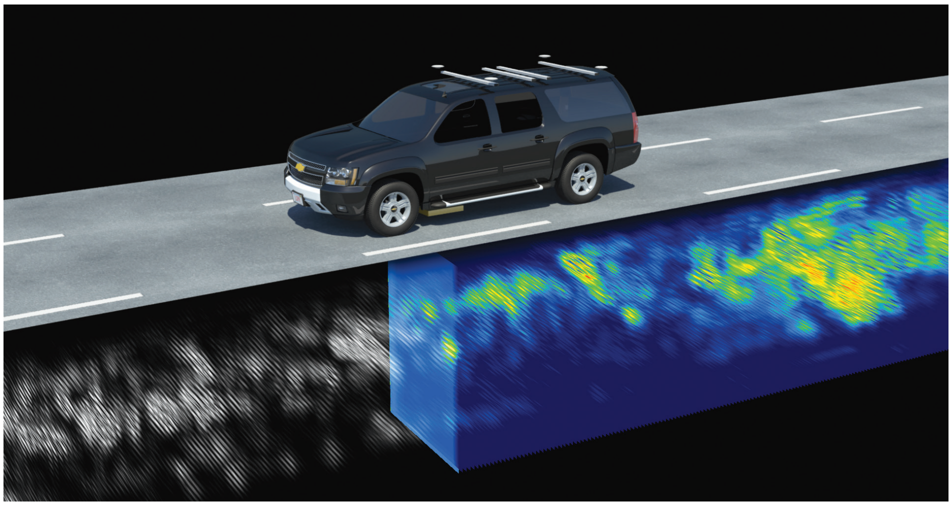
Localizing Ground-Penetrating Radar

Innovative ground-penetrating radar that maps underground geological features provides autonomous vehicles with real-time localization in all-weather conditions.

Autonomous vehicles aim to decrease the number of driver-caused accidents that result in over 30,000 deaths and an estimated 2.3 million injuries in the United States each year. Autonomous ground vehicles (AGVs) could be deployed for military or emergency operations in areas that pose risks to personnel. However, current AGVs are not mature enough for widespread adoption. Most AGV sensors cannot determine the vehicle's location when adverse conditions, such as heavy rain or fog, snow-covered roads, or lost GPS signals, hamper the functioning of their sensors because those optical sensors rely on traditional roadmap-based information (e.g., lane markers, stop lines).

MIT Lincoln Laboratory has developed a sensor that provides real-time estimates of a vehicle's position even in challenging weather and road conditions. The Localizing Ground-Penetrating Radar (LGPR) uses very-high-frequency (VHF) radar reflections of underground features to generate baseline maps and then matches current GPR reflections to the baseline maps to estimate a vehicle's location. The LGPR uses relatively deep subsurface features as points of reference because these features are inherently stable and less susceptible to erosion or damage over time. It utilizes VHF radio waves because they can penetrate rain, fog, dust, and snow.



The Localizing Ground-Penetrating Radar (LGPR) uses inherently stable subsurface features and their geolocation to locate the vehicle even in adverse weather conditions. The prior map can be seen in gray on the left, the current scan is shown in light blue under the vehicle, and the registered data is shown in blue and green behind the vehicle.

LGPR Methodology

For subsurface sensing, GPR is one of the most versatile and prolific sensing modalities today. GPR systems work by sending a pulse of electromagnetic radiation into the ground and measuring reflections that originate from scattering points below the surface. Reflections occur at the interface between objects that have different electromagnetic properties, such as pipes, roots, and rocks in the surrounding "dirt." However, it is not these discrete objects but rather the natural inhomogeneity in subterranean geology that often dominates GPR reflection profiles. Soil layers and variations in moisture content cause reflections in the data. Thus, GPR paints a fairly complete picture of the subsurface environment. With few exceptions, nearly every discrete object and soil feature is captured, provided that it is not significantly smaller than a wavelength and that it has sufficient contrast with the surrounding soil. The premise of GPR localization is that these subsurface features are sufficiently unique and static to permit their use as identifiers of the precise location at which their reflections were collected.

Mapping

The first step in the LGPR process is to develop a map of the environment below the road. In this step, the GPR data of subterranean "objects" are simply collected along with GPS tags to form the initial database of subsurface features. This subsurface map is then used as a reference dataset to estimate vehicle location on subsequent visits.

Tracking

Next, online localization is performed in several steps. When the vehicle is in motion, data are periodically fetched from the database for matching. A 50 m × 50 m × 1–3 m three-dimensional grid of baseline data, centered on a GPS-defined initial location point that is determined by the latitude, longitude, heading, and roll (or tilt) of the sensor, is placed in memory for matching. When the vehicle nears the edge of this grid, it requests a new grid of the same size centered on its new position. In this way, a local grid of baseline data is always maintained.

- A search region around the initial location estimate contains "particles" (points on the grid) representing candidate locations and orientations. An algorithm iteratively evaluates the particles to narrow the search for the maximum correlation within the vehicle's five-dimensional space (easting, northing, height, roll, and heading).
- After several iterations, the highest-correlation particle is chosen as the most likely estimate of the vehicle's current location and orientation.
- The search region is updated and either expanded or shrunk to reflect this new estimate.

LGPR Design

The basic component of LGPR is a unique waterproof 12-element antenna array that uses a custom VHF stepped-frequency continuous-wave radar. The VHF system penetrates deeper than typical GPR systems; thus, it captures deeper, more stable geological features. Also, because VHF frequencies are inherently insensitive to small objects (e.g., a small soda can on the surface will be ignored because of its small VHF radar cross section), their use ensures that new reflections are from the types of geological features cataloged in the baseline data.

The LGPR array of 12 dipoles is linearly aligned within a reflective rectangular metal cavity with dimensions of 5 ft × 2 ft × 3 in. Several key modifications to traditional GPR were fundamental to the design:

- The cavity depth of 3 inches was designed for under-vehicle mounting.
- The spacing between array elements is approximately one-tenth of a center-frequency wavelength. This resolution is finer than typically seen in GPR arrays and enables high-fidelity matching to baseline data.
- All elements in the array have identical near-field patterns. This requirement allows path retraversal to resolve pass-to-pass offset or misalignment.

The Autonomous Systems Mobile Testbed vehicle has the waterproof localizing ground-penetrating radar array mounted underneath. Additional sensors, such as lidar, camera, and GPS/INS units, are used for verification and studying sensor fusion.

Demonstrated Capability

The LGPR system was tested over 100s of miles on paved and unpaved roads in four U.S. states and was used by the U.S. military to navigate multiple AGVs over more than 1000 miles in Afghanistan's very demanding environments. The LGPR method showed robust performance in these trials.

The article titled "Localizing Ground Penetrating RADAR: A Step Toward Robust Autonomous Ground Vehicle Localization," published in the January 2016 issue of the *Journal of Field Robotics*, describes Lincoln Laboratory's demonstration of 4 cm cross-track localization achieved by a vehicle driven at 60 mph under fair weather conditions. Recent work demonstrated real-time centimeter-level, highway-speed, nighttime localization during a snowstorm that had obscured all lane markings.

Benefits of LGPR

For an AGV to maintain awareness of its surroundings and location, it is equipped with a suite of sensors. The main advantage of adding the LGPR to such a suite is its ability to operate under conditions that incapacitate other localization sensors, such as optical or infrared systems. Because the LGPR deduces location on the basis of stable underground features, it can provide position estimates even if it encounters severe weather, obscured or unpaved roads, altered roads, or GPS-denied areas. Fusing LGPR with lidar or other remote sensing methods may provide improved localization capabilities for future autonomous vehicles.

Furthermore, data from below-road features that the LGPR captures can be useful for infrastructure inspection, such as finding underground sinkholes or detecting structural weaknesses in bridges. Because the LGPR compares the data it collects against prior scans of the terrain, changes in the scans (e.g., subsurface deterioration) can be readily detected. ■

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