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Form Approved
OMB No. 0704-0188

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1. REPORT DATE NOV 2014		2. REPORT TYPE		3. DATES COVERED 00-00-2014 to 00-00-2014	
4. TITLE AND SUBTITLE Localizing Ground-Penetrating Radar				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Massachusetts Institute of Technology, Lincoln Laboratory, 244 Wood Street, Lexington, MA, 02420				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

Tech Notes

www.ll.mit.edu

November 2014

Localizing Ground-Penetrating Radar

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

The development of self-driving vehicles is being pursued worldwide. The use of autonomous cars could improve the flow of traffic and also decrease the number of accidents caused by drivers' errors. The military is interested in deploying autonomous ground vehicles (AGV) for operations in areas that pose risks to personnel. However, current AGVs are not mature enough for widespread adoption. Most of the AGV sensors cannot determine the vehicles location when adverse conditions, such as heavy rain or fog, snow-covered roads, or lost GPS signals, hamper the functioning of their sensors, since those sensors rely on traditional roadmap-based information (e.g., lane markers, curbs, 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 predict a vehicle's location. The LGPR uses relatively deep subsurface features as points of reference because they 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.



Localizing Ground-Penetrating Radar (LGPR) uses relatively stable subsurface features and their geolocation to locate the vehicle even in adverse weather conditions.

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 fea-

ture 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 first 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 in order to estimate vehicle location on subsequent visits.

Tracking

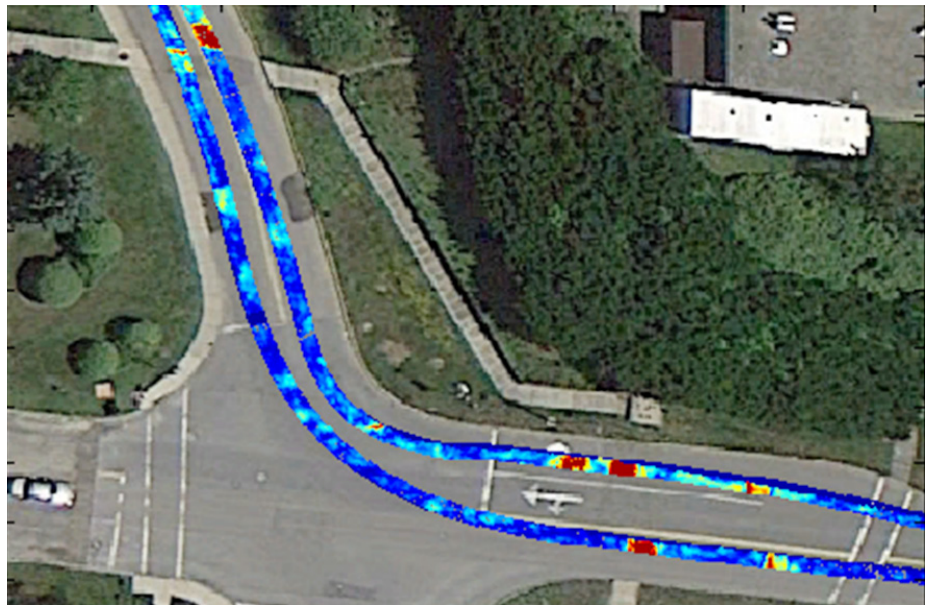
Next, online localization is performed in several steps. When the vehicle is in motion, data are periodically fetched from the database for matching. A $50\text{ m} \times 50\text{ m} \times 1\text{--}3\text{ m}$ three-dimensional grid of baseline data, centered on a GPS-defined initial location point 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 surrounding 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.

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

LGPR Design

The basic component of LGPR is a unique 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.



LGPR data are collected along the vehicle’s path. Note the diversity of subsurface radar responses in a region where the surface features are essentially the same. The colors along the vehicle’s path represent the depth of the anomaly in the subsurface region.

The LGPR array of 12 dipoles is linearly aligned within a reflective rectangular metal cavity with dimensions of $5\text{ ft} \times 2\text{ ft} \times 3\text{ in}$. 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.

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 underground features that are quite stable, it can provide position estimates even if it encounters severe weather, obscured or unpaved roads, disrupted or

altered roads, or GPS-denied areas.

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

In the future, fusing LGPR with lidar or other remote sensing methods may result in even more improved localization capabilities for autonomous vehicles. ■

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