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Feature Article:

Navigation Systems Panel Report Navigation Systems for Autonomous and Semi-Autonomous Vehicles: Current Trends and Future Challenges

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NAVIGATION SYSTEMS FOR AUTONOMOUS VEHICLES

The world is abuzz with semi-autonomous and fully autonomous vehicles. From unmanned aerial vehicles (UAVs) to self-driving cars, integrating these vehicles into our daily lives will have astounding societal and economic impacts. As we endow these vehicles with higher levels of autonomy, the requirements on their navigation system become more stringent than ever before. Undoubtedly, navigation system failure for these vehicles could have intolerable consequences.

Navigation systems for future semi-autonomous and fully autonomous vehicles must possess the following attributes:

(1) Assured performance: specify the uncertainty associated with the navigation solution and alert the human to take over, when needed

(2) Tamper-proof: detect and recover from malicious attacks (e.g., jamming and spoofing)

(3) Redundancy: robustness to sensor failure and/or signal degradation

(4) High levels of accuracy: meet the accuracy requirement as dictated by the application; for example, achieve lane-level accuracy for self-driving cars

Navigation systems can be broadly categorized into:

(1) Sensor-based: provide a local navigation solution by utilizing dedicated on-board hardware that senses the surrounding environment (e.g., inertial navigation systems, cameras, lidar, etc.)

(2) Signal-based: provide a global navigation solution and rely on receiving external signals from either (i) dedicated transmitters (e.g., global navigation satellite systems (GNSS), eLoran, pseudolites, etc.) or (ii) nondedicated transmitters, also known as signals of opportunity (SOPs) (e.g., AM/FM, cellular, television, WiFi, communication satellites, etc.)

Current autonomous vehicle navigation system design trends fuse GNSS receivers with a suite of sensor-based technologies. By adding more and more sensors, designers are throwing "everything but the kitchen sink" to prepare the autonomous vehicle navigation system for the inevitable scenario when GNSS signals become unavailable or unreliable. High-grade sensors may violate cost, size, weight, and power (C-SWaP) constraints. Also, these sensors may not properly function in all environments (e.g., fog, snow, rain, dust, etc.) and are still susceptible to malicious attacks.

In what follows, future navigation system challenges brought forth by autonomous vehicles are discussed.

SENSORS

Recent decades have enjoyed rapid maturation of navigation alternatives to GNSS. Many of these advances

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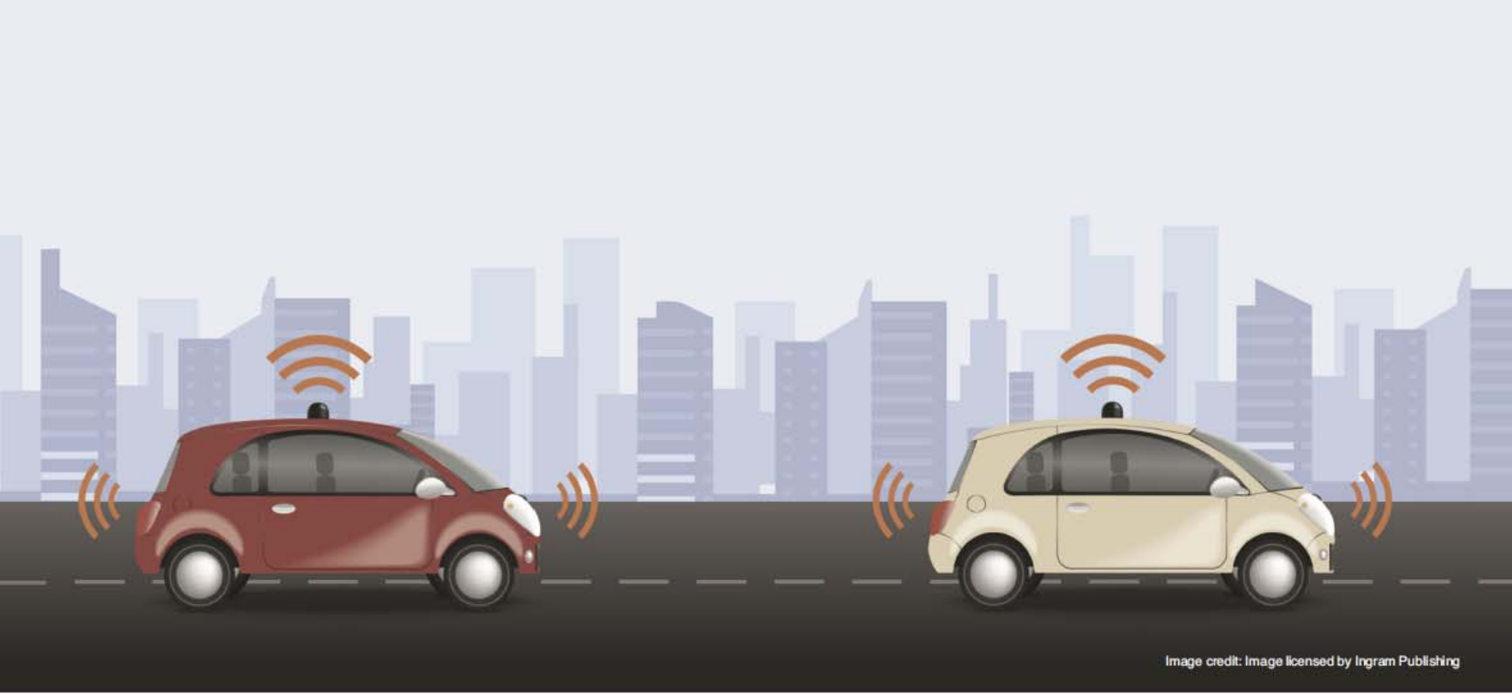

have been driven by the proliferation of better sensing technology, such as higher grade low C-SWaP micro-electromechanical systems (MEMS) inertial measurement units (IMUs) with integrated magnetometers, three-dimensional (3-D) lidar, RGB-D cameras, and better and smaller visual/thermal cameras.

Very small MEMS IMUs are approaching tactical-grade and are at the core of alternative navigation systems. When properly integrated with pseudo-measurement constraints (e.g., zero-velocity updates, nonholonomic constraints, etc.), useable navigation for short periods is becoming possible. Much alternative navigation advances have been largely centered on the use of visual-inertial [1], 3-D lidar, and simultaneous localization and mapping (SLAM) [2]. This technology has matured to the point that nowadays, in well-structured environments, lidar or camera-based 3-D SLAM has basically become an off-the-shelf capability. Likewise, low-cost RGB-D cameras have now enabled very dense SLAM at a weight scales suitable for UAV applications [3].

A current challenge facing sensor technologies is their inability to provide long-term autonomy, given practical C-SWaP limitations of memory footprint. Without returning to known/stored locations (i.e., key-frames) over-time (i.e., loop-closures), their navigation solution suffers from the accumulation of drift, making them amenable to integration with GNSS- and SOP-based systems, which provide an absolute position estimate that helps overcome such drift.

GLOBAL NAVIGATION SATELLITE SYSTEM

GNSS have become a commodity when it comes to developing location-based services. In fact, GNSS is the technology of choice for most position-related applications, when it is available [4]. Virtually all smartphones and many gadgets are equipped with a GNSS chipset. Some of the reasons for GNSS popularity include (1) dedicated and constantly maintained infrastructure, (2) continuous global coverage, and (3) meter-level (standalone mode) and centimeter-level (differential mode) navigation solution, in open sky conditions.

A GNSS receiver relies on signals from a constellation of satellites to estimate a set of pseudorange measurements from which it computes its position. GNSS is a general term encompassing several international systems, such as U.S. GPS, European Galileo, Russian Glonass, and Chinese Beidou. Although these systems are operational, their space segment is going through continuous renovations and enhancements (e.g., signal redesign, constellation upgrading, and launching new satellites) in order to meet the demands of current applications. Recently, the advent of connected and autonomous vehicles is pushing the limits of GNSS technology in terms of accuracy, availability, integrity, and robustness [5]. There is a rich literature addressing GNSS challenges [6] and other known security vulnerabilities, such as jamming and spoofing attacks [7], [8].

SIGNALS OF OPPORTUNITY

Motivated by the plenitude of ambient radio frequency SOPs in today's environment, a new navigation paradigm to exploit these signals has emerged over the past decade [9]. Even though SOPs are not intended as navigation sources, researchers have shown incredible navigation performance with such signals in (1) a standalone fashion [10], [11], achieving meter- and submeter-level accuracy on UAVs [12], [13] and (2) as an aiding source to dead reckoning sensors, bounding the sensor's error in the absence of GNSS signals [14], [15].

SOPs enjoy several attributes: (1) they are ubiquitous: dozens of potential transmitters are found in most locales of interest; (2) they are transmitted at a significantly higher power: their effective radiated power can be 40 dB higher than GNSS; (3) they are diverse in frequency and direction: signals are transmitted at different frequencies and high bandwidth, and their transmitting antennas are geographically distributed; and (4) they are free to use: no deployment cost or operating expenses are incurred to use them, since their infrastructure already exists and they are already being transmitted for other purposes. These attributes (1) make SOPs usable in environments where GNSS signals are not usable or reliable (e.g., indoors and deep urban canyons), (2) yield a more accurate navigation solution, and (3) improve redundancy, bringing navigation system robustness to malicious attacks (e.g., jamming and spoofing).

However, because SOPs are not intended for navigation, one must address a number of challenges before they can be exploited as reliable and accurate navigation sources. These challenges include (1) the transmitters' locations are generally unknown, (2) their timing may not be known and is not necessarily synchronized, (3) in contrast to GNSS, their reference oscillator stability is generally not of atomic standard, and (4) receivers capable of producing a navigation solution with these signals are not prevalent- they are proprietary and in specialized research laboratories. These challenges have been the subject of extensive research recently [10]–[16].

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