A FRAMEWORK FOR MULTI-SENSOR POSITIONING AND MAPPING FOR AUTONOMOUS VEHICLES

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ABSTRACT:

Autonomous vehicles (AVs) are cars, buses or trucks that can travel with limited or no human intervention. They combine sensors, perception systems, and software to control, navigate, and safely drive the vehicle. AVs promise to improve the efficiency of our transportation system, reduce collisions and traffic congestion and improve mobility for our growing population. As the world continues to move toward a more efficient transportation system driven by AVs, there is a growing demand for new technologies that guarantee efficient and safe operation. Trust in AVs hinges on the reliability of autonomy, including the crucial task of positioning, which should be accurately provided at high precision everywhere for all environments. This paper introduces a framework for developing and deploying robust positioning and mapping systems for AVs at a submeter level of accuracy with high integrity. We introduce a new paradigm for the positioning and mapping of AVs that expands the capabilities of the present technologies and enables the processing of a broader range of complementary sensors and systems on a single platform. The target is to sustain this performance seamlessly everywhere in all operating and weather conditions relying on the suite of wireless and perception systems in addition to the vehicle's onboard sensors. Some sample results demonstrating the submeter level of positioning in various environments are discussed in this paper. This research will significantly impact the acceptance of and trust in AVs by enhancing safety and reliability and decreasing the failure rate in degraded environments.

1. INTRODUCTION

1.1 Background

Autonomous vehicles (AVs) promise to enhance safety, reduce emissions, and improve transportation system efficiency and reliability [1]. The growing demand for AVs is shaping the future of the automotive industry by transforming the in-vehicle experience and paving the way for large-scale implementation of autonomous driving [2]. AV technology requires onboard intelligence relying on a suite of sensors and systems such as global navigation satellite systems (GNSS), including GPS, vehicle motion sensors and remote sensing systems, including cameras, light detection and ranging (LiDAR) and radar. AVs capable of sensing the environment and navigating without human input require robust high, precision positioning at the decimeter level of accuracy under all operational environments [1-3]. The availability of the above sensors and systems in future AVs provides an attractive opportunity to increase the accuracy and reliability of the positioning system. Positioning services have long relied on GNSS, which cannot maintain an accurate vehicle position under bridges, around tall buildings and under tree canopies due to signal blockage or multipath [4,5]. AVs may rely on remote sensing systems to perceive the environment and provide accurate positioning [5,6]; however, they suffer from degraded performance in some environments, such as low visibility, rain or snow [7]. The North American AV market is projected to grow to 17.1% CAGR during 2023-30, to a value of $52.3B by 2030 [8]. Factors driving this growth include the need for safe and efficient driving, the evolution of AV technology, and increased R&D in the autonomous car sector. AVs hold great promise to provide safer roads, improve the transportation system's efficiency, and increase Canadians' mobility choices while creating new economic opportunities.

1.2 Problem Statement and Motivation

Since high-precision IMSS positioning is a recent and innovative concept, many highly pivotal gaps must be filled to achieve it at a large scale. Present land vehicles rely on GNSS receivers for positioning services. For AVs requiring a decimeter level of accuracy, GNSS receivers should operate on either differential mode (which requires a local reference station within 20km) or precise point positioning (PPP) mode [9-11]. The accuracy may deteriorate when travelling under overpasses or due to short GNSS outages and cycle slips [12,13]. Moreover, GNSS has other limitations in urban areas, such as multipath and signal blockage, where backup systems are necessary [14,15]. The proposed research will fill this GNSS-related gap by integrating the GNSS receiver with other onboard motion sensors and 5G wireless positioning technologies to sustain submeter accuracy. Vision-based positioning relying on cameras is based on processing camera frames (also known as visual odometry or VO), which performs well in textured and ambient environments [16,17]. VO is bound to errors due to the variations observed in the scene. Another serious research gap with VO is the inability to extract features in a degraded visual environment [17,18]. Present VO methods do not provide insight into the feasibility in downtown cores, areas where the vehicle travels through a tunnel, or in parking garages where parts of the scenes may have a complete absence of light [19,20]. LiDAR can operate in this degraded vision environment; however, it is generally more expensive, may cause design restrictions, and its 3D point cloud processing is computationally demanding [21]. Both cameras and LiDAR may fail to provide accurate positioning when operating under challenging weather conditions [7]. It is necessary to fill this critical gap by devising a weather-independent solution integrating electronic scanning radars (ESR) utilized for adaptive cruise control as an alternative to LiDAR to detect objects and provide range estimation [22]. Nevertheless, most

ESR-based positioning methods lack the target submeter level accuracy required due to insufficient range and resolution [23, 24]. We will address this open challenge through the integration of ESR with the onboard motion sensors (accelerometers and gyroscopes together with updates from speedometers, magnetometers and barometers) to provide changes in position, velocity and orientation relying on inertial navigation system (INS) algorithm [25,26]. However, the INS solution may drift rapidly over time due to inherent sensor errors [27,28]. Despite all possible updates from onboard sensors, INS cannot provide a reliable standalone solution for an extended duration [29-32]. It is obvious that no single technique is sufficiently versatile to address the challenge of precise positioning everywhere.

The target of this research is to set up a framework for a multi-sensor positioning approach capable of providing uninterrupted positioning at a submeter level of accuracy everywhere to enhance the ability of AVs to meet the growing demand for robust high-precision positioning to satisfy all levels of autonomy, focusing on: (1) multi-sensor fusion of all available AVs' sensors and remote sensing systems to provide continuous and robust positioning with high integrity; and (2) machine intelligence algorithms to manage and coordinate this heterogeneous set of sensors/systems into a robust positioning system to meet the demand for safety-critical autonomous driving.

1.3 Objectives

The availability of onboard sensors and remote sensing systems in future AVs provides an attractive opportunity to increase the accuracy of the positioning and guidance system. The ultimate goal of this research is to enhance the ability of AVs to meet the growing demand for robust high-precision positioning at decimeter level of accuracy to satisfy all levels of autonomy by adopting a novel intelligent multi-sensor system (**IMSS**) approach, focusing on the multi-sensor fusion of all available sensors and systems to provide continuous and robust positioning anywhere with decimeter level of accuracy with high integrity. Advanced machine intelligence (MI) based methods will be utilized to manage and coordinate this heterogeneous set of sensors/systems into a robust positioning system to meet the demand for safety-critical autonomous driving. The proposed research will overcome the limitations of current positioning technologies for AVs and expand their capabilities to operate seamlessly everywhere in all weather and operating conditions, even in degraded GNSS and vision environments, providing an 'uninterrupted everywhere' positioning with a decimeter level of accuracy. This paper aims to introduce and discuss an innovative framework for high-precision multi-sensor positioning of autonomous vehicles.

2. MULTI-SYSTEM POSITIONING FRAMEWORK

As shown in Figure 1, The proposed framework suggests exploring a computer vision-based module (relying on a set of onboard cameras and/or LiDARs) to produce a submeter level of positioning accuracy relying on centralized visual-inertial odometry supported by 3D maps (LiDAR and/or HD-Maps) aiding and a deep Learning-based outlier rejection to mitigate the effect of dynamic objects. The approach will be supported by hybrid wireless positioning methods based on the emerging 5G mmWave wireless technology in urban canyons together with multiple electronic scanning radars onboard AVs to support robust target detection and AV positioning in both denied GNSS and degraded vision environments. As shown in Figure 2, the proposed system will target a novel centralized IMSS for high-precision positioning that utilizes the onboard motion sensors as the primary source of position information supported by centralized multi-sensor integration with wireless technologies and perception systems. Furthermore, the proposed framework will manage and orchestrate AV's IMSS components using machine learning (ML) to adapt to different environments continuously, weather and operating conditions and AV dynamics.

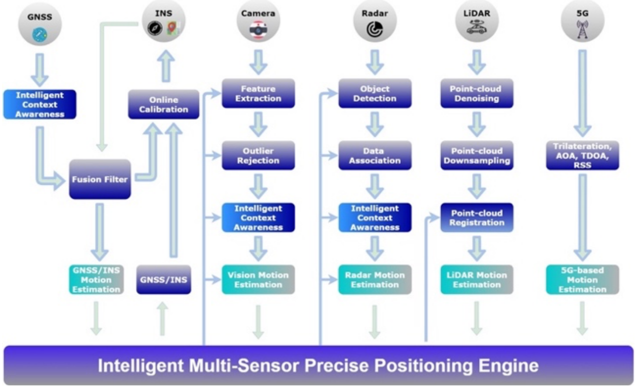

Figure 1. Overall System Architecture

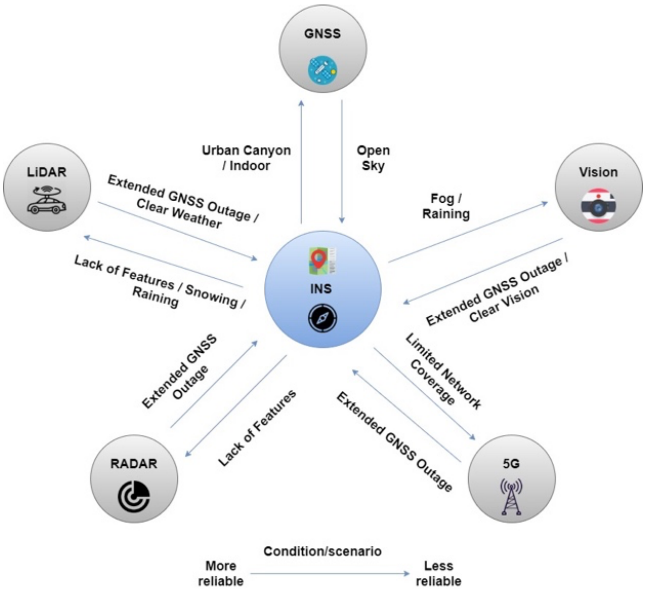

Figure 2. INS-based core positioning.

3. 5G-BASED INTEGRATED WIRELESS POSITIONING

This research track is related to utilizing the newly emerging 5G mmWave wireless technology to solve critical challenges faced by AV's positioning in challenging and denied GNSS environments (urban areas and parking garages) and in degraded visual environments. The large bandwidth and the massive multi-input-multi-output (MIMO) capabilities of 5G technology provide the potential of fine time resolution and high precision spatial diversity, enabling accurate positioning even in the challenging urban environment of multipath and signal fading. In Figure 3, we demonstrate the performance of 5G mmWave-based wireless positioning developed as part of this research with respect to widely used high-precision positioning provided by GPS-based precise point positioning (PPP). It can be depicted from Figure 3 that the 5G-based solution was able to sustain lane-level positioning with an accuracy of less than 50 cm. The GPS-PPP solution failed to provide the same level of accuracy due to the overpass bridge that blocked the GPS signal. The results in Figure 3 is part of a complete trajectory performed in Don Valley Parkway (Toronto), for 15 Km at an average speed of 100km/hr. Table 1 summarizes the performance compared to the benchmark solution based on GPS PPP. The ground truth was provided by NovAtel's PWRPAK7, integrating a high-end GNSS receiver with a high-end IMU (KVH1750) and postprocessing using the inertial explorer software.

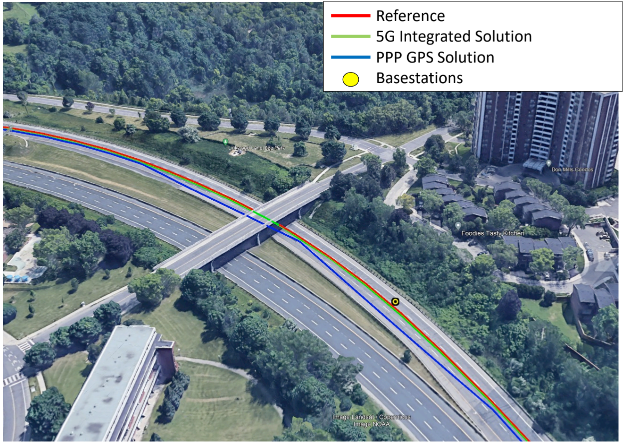

Figure 3. 5G wireless positioning performance versus GPS PPP in Don Valley Parkway, Toronto, ON.

Table 1. Comparison to GPS PPP.

	PPP GPS	5G Integrated Solution
RMS Error	**1.3m**	**0.40m**
Max Error	**2.5m**	**1.4m**
Sub-1m	**48%**	**99%**
Sub-30cm	**17%**	**88%**

The integrated 5G solution fusing the 5G-based mmWave wireless positioning with the onboard motion sensors (OBMS) has also outperformed the 5G standalone solution in dense urban environments. In Figure 4, we showcase the performance in downtown Toronto for a small part of a long trajectory of more than 2 Km long. For the whole trajectory, the integrated 5G/OBMS positioning solution achieved a submeter level of positioning accuracy 95% of the time, while the standalone 5G failed to achieve more than 90%.

4. LIDAR MAP REGISTRATION FOR URBAN NAVIGATION

This research track is related to utilizing the LiDAR technology and 3D high-accuracy maps to limit the navigation state errors generated by the vehicle sensory dead reckoning (VSDR) solution in GNSS challenging environment. Our approach utilizes a scan matching algorithm, commonly known as registration, for estimating a transformation (translation and rotation) between point cloud data obtained from the LiDAR mounted on the AV and reference point cloud data constructed from an available city-scale 3D maps database. The estimated transformation from the LiDAR to Map Registration (LMR) module is then used to correct the position and attitude navigation states computed by the VSDR algorithm. A sample performance of the LMR/VSDR is shown in Figure 5 from downtown Kingston, Ontario. The LMR/VSDR solution used a 3D LiDAR map for the city of Kingston and was able to achieve an RMS position error of 60cm and maintained submeter level of positioning accuracy more than 95% of the time.

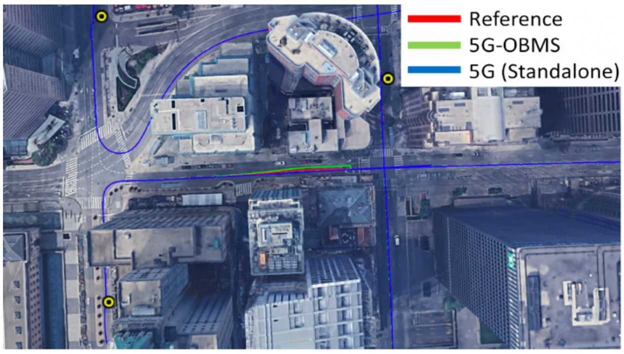

Figure 4. 5G integrated wireless positioning performance versus 5G standalone in downtown Toronto, ON.

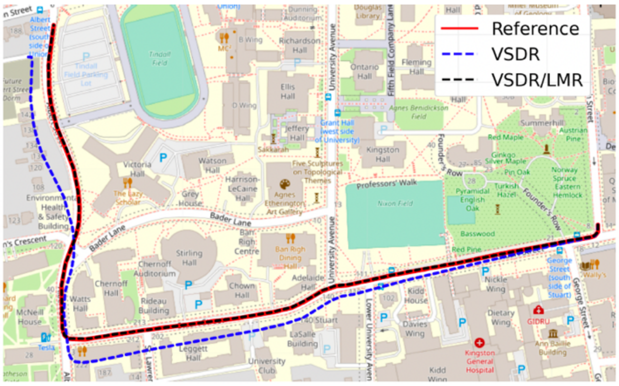

Figure 5. LMR/VSDR integrated positioning performance versus VSDR standalone in downtown Kingston, ON.

5. ESR MAP REGISTRATION FOR CHALLENGING GNSS AND VISION ENVIRONMENTS

In complete GNSS signal blockage and degraded vision environments (mostly experienced in covered parking garages), our research explores the use of mmWave automotive radars (ESR) integrated with the available 2D or 3D maps of the environment to provide reliable and continuous positioning information for AVs. Figure 6 shows the positioning performance in a covered parking garage.

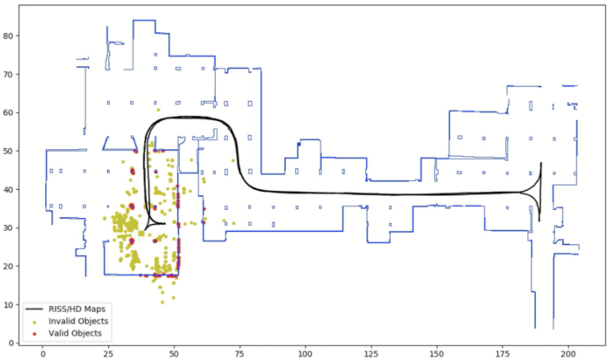

Figure 6. ESR integrated positioning performance inside a covered parking garage environment.

The available 3D LiDAR map of the parking garage in Figure 6 was utilized by our ICP-based algorithm to register the ESR scans and provide accurate positioning at high precision. The method we developed integrates ESR with the available dead reckoning sensors from the vehicle to enable radar scan aggregations and bridge any gaps in the sparse radar scans. The outcome is a reliable positioning performance capable of achieving a submeter level of positioning accuracy 100% of the time and errors less than 30 cm more than 95% of the time.

6. CONCLUSIONS

At this stage of the research, we have demonstrated the ability to integrate new emerging wireless technology based on mmWave wireless networks with the vehicle onboard motion sensors to sustain a submeter level of positioning accuracy along highways and downtown environments. We have also shown the ability to integrate LiDAR or ESR with the available 3D maps of the environment to provide the same level of accuracy in degraded GNSS and vision environments. In the future, it is among the objectives of this research to manage and orchestrate AV's multi-sensor/multi-system components using machine learning (ML) to adapt to different environments continuously, weather and operating conditions and AV dynamics.

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