GNSS-RTN Role in Transportation Applications: An Outlook

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ABSTRACT

Geospatial location service is not only used in measuring ground distances and mapping topography, but has also become vital in many other fields such as aerospace, aviation, natural disaster management, and agriculture, to name but a few. The innovative and multi-disciplinary applications of geospatial data drive technological advancement toward precise and accurate location services available in real-time. Although the RTN technology is currently utilized in a few industries such as precision farming, construction industry, and land survey, the implications of precise real-time location services would be far-reaching and critical to many advanced transportation applications. The GNSS real-time network (RTN) technology, introduced in the mid-1990s, is promising in meeting the needs of automation in most of the advanced transportation applications. This article presents an overview of the GNSS-RTN technology, its current applications in transportation-related fields, and a perspective on the future use of this technology in advanced transportation applications.

1. INTRODUCTION

In the past few decades, significant technological advances have been made in various spheres of the modern world. One good example is the global navigation satellite system (GNSS) which includes the GPS (U.S. global positioning system) and its counterparts: GLONASS (Russia), Galileo (Europe), and BeiDou (China). The GNSS has become one of the fastest-growing emerging technologies delivering location services to various industries. Geospatial data are not only used in measuring ground distances and mapping topography (Clark & Lee 1998), but it has found significant applications in various fields such as agriculture, construction, mining, safety and sustainability, structural health monitoring, natural disaster management (Nordin et al. 2009), and precise localization and accurate navigation (Jo et al. 2013). Among all these fields, geospatial technology plays a remarkable role in the transportation sector and has the potential to play an even more critical role in future transportation autonomous systems. Consequently, there is an ever-increasing demand for more ubiquitous, more accurate, and more reliable positioning and navigation solutions that partly led to the development of modernized location-based services (LBSs) known as GNSS-RTN. The use of this highly precise location technology (GNSS-RTN) would allow for transportation theories and ideas to be put to use. This article attempts to shed the light on the major existing GNSS-RTN transportation applications and provide an outlook of the future role this technology plays in advanced transportation applications.

2. GNSS RTN: STATE OF TECHNOLOGY

With the emergence of GPS Real-Time Kinematic (RTK) technology in the early 1990s, the use of GPS-RTK has become vital in various applications which require highly accurate positioning in real-time. However, the performance and accuracy of the traditional GPS-RTK are limited due to the distance between a reference station (a.k.a. base station) and a roving receiver (user device). The accuracy and reliability of the measurements degrade with the increase in baseline length (i.e., base-to-rover distance) due to distance-dependent errors such as ionospheric refraction, tropospheric refraction, and to some level, orbit errors. To achieve reliable and accurate results, specifically centimeter-level accuracy in positioning data, using the GPS-RTK technique, it is required that the roving receiver (rover) is located within the restricted range (typically in the order of 10 km) of the reference station (Wanninger 2003). To overcome the limitation of the baseline length of the traditional GPS-RTK technique and due to advancement in GNSS technology, GNSS-RTN concepts were introduced in the mid-1990s (Rizos 2002). The GNSS-RTN is a satellite-based positioning system using a network of ground receivers (also called base stations, reference stations, or continuously operating reference stations (CORSs)) as shown in Figure 1, to improve the precision of corrections. The network of reference stations extenuates and alleviates the spatially correlated atmospheric and satellite orbit biases (Rizos & Satirapod 2011), and improves the precision of geospatial positioning through real-time corrections sent from a central processing center to a rover. The utilization of ground sensors enables systems to have a range of 1 to 5 centimeters in accuracy, compared to a range of 1 to 10 meters when sensors are not utilized (Schrock 2006).

Since the 1990s, positioning technology has vastly improved. Whether that be with new constellations, new methods, or better hardware, GNSS and RTN improvements mean that the technology can provide positions more accurately than they were 25 years ago. New constellations increase the number of available satellites at any given time (Weber & Croswell 2012), new methods can account for error correction to yield more reliable results, and better hardware can increase accessibility to the system by decreasing the cost of entry.

With the technological evolution and advancement in satellite systems, the use of GNSS-RTN technology for the correction of positioning data has developed into commercially viable systems available today. The advent of GNSS-RTN made it possible to achieve highly accurate positioning over a distance of 70-100 km (reference station spacing should generally not exceed 70-100 km) from the base station (Feng & Li 2008). Schrock acknowledged that, although the GNSS-RTN technology was reasonably new, it had already had a significant impact on many fields and showed a tremendous increase in popularity. In the U.S., there were 18 systems at the beginning of 2005 and 40 in 2006 (Schrock 2006). Currently, the National Oceanic and Atmospheric Administration (NOAA) CORS Network (NCN), managed by NOAA and the National Geodetic Survey (NGS), is the cornerstone of the geometric component of the National Spatial Reference System (NSRS) with observations from over 2800 stations nationwide. These CORSs are part of subnetworks operated by 239 public and private entities. Each network operator/owner shares its GNSS/GPS positioning data and metadata with NGS, which are analyzed and made freely available to the public for postprocessing and applications in Receiver INdependent EXchange (RINEX) format (National Geodetic Survey 2021). In addition, several private companies are offering GNSS-RTN products and location-based services (LBSs) with Leica Geosystems, Trimble, and Topcon being the three most pervasive providers of GNSS-based services and products around the globe (Lorimer & Eric 2008). Leica has a SmartNet GNSS-RTN system comprised of over 1500 CORSs in many states across the United States as shown in Figure 2 (Leica 2021b). Leica offers centimeter-level accuracy under conditions of good satellite coverage, good geometry, and low multipath environments. Furthermore, Topcon operates its private network called TopNET Live. Figure 3 shows the coverage of TopNET Live North America. TopNET Live Global has over 5000 reference stations in the Americas, Europe, Asia, China, and Russia. Topcon incorporates privately owned (third party) CORSs in TopNET Live and provides free subscriptions to the private owners of CORSs.

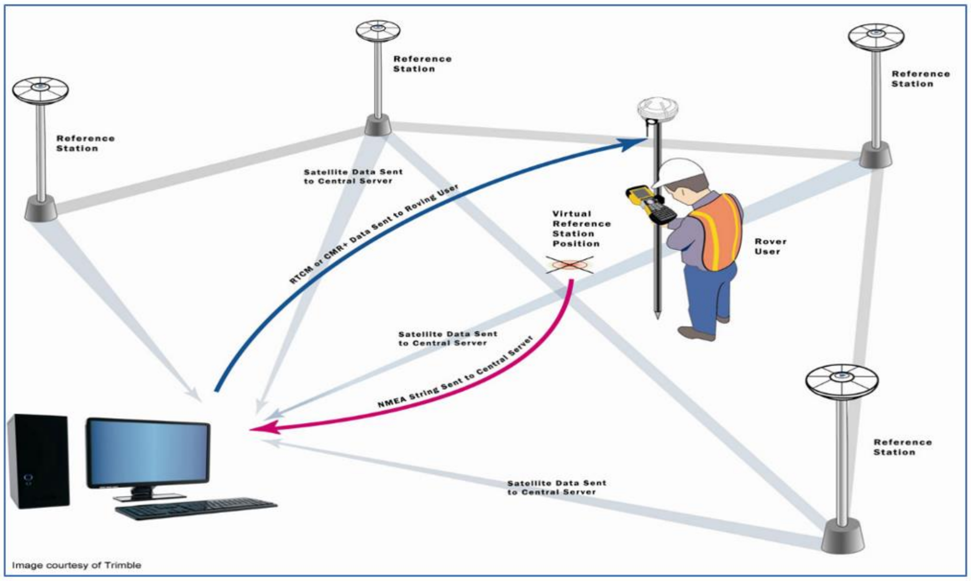

Figure 1. Data Flow in RTN and Configuration of a VRN (Courtesy of Trimble)

The GNSS-RTN system comes with many benefits but has certain limitations. Benefits include eliminating the need to establish a base station for each task, reduced labor cost, continual accuracy and integrity monitoring by GNSS-RTN, no distance correlated error, and a common reference coordinate system for geospatial data. Limitations included the high cost to establish and maintain such a system and accuracy being limited by the poor quality of the cellular phone connection (Henning 2007; Huff 2019).

3. GEOSPATIAL DATA REQUIREMENTS

Published by the US Departments of Transportation, Defense, and Homeland Security, the Federal Radionavigation Plan represents the official US policy on position, navigation, and timing (PNT) (U. S. Government 2019). The plan contains positioning requirements for various communities and use cases. For example, pilots flying over the ocean may only require ten nautical mile accuracy while pilots in a terminal area may require one nautical mile accuracy. Meanwhile, positive train control requires one-meter accuracy and collision avoidance on highways requires 0.1-meter accuracy. For marine use cases, inland waterway navigation typically requires two meters while ocean navigation requires one nautical mile at best. However, the plan is careful to note that the accuracies and needs are included for reference only. The Plan states that while the government will try to accommodate as many use cases as possible, it is under no obligation to fulfill every use case. For ground transportation, most of the plan’s stated accuracies could easily be met and enhanced by nationwide GNSS-RTN. The

Federal Radionavigation Plan also outlines inland water transportation use cases that could see improvement with better PNT based on GNSS-RTN services. Currently, inland water operations are limited in suboptimal weather conditions such as reduced visibility due to fog. It is possible that improved PNT could enable all-weather operations and also improve capacity in inland waterways and harbors by increasing the efficiency of the facilities.

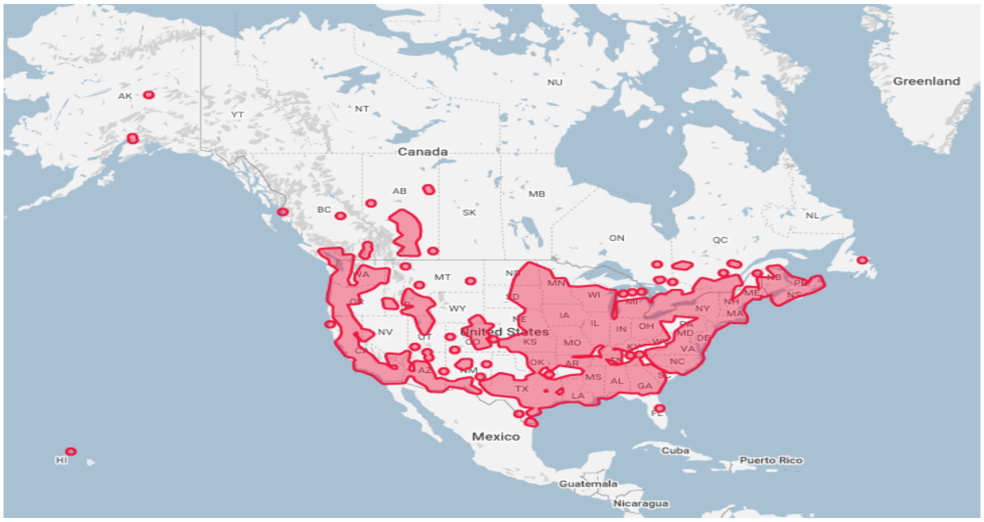

Figure 2. SmartNET Coverage in North America (Courtesy of Leica)

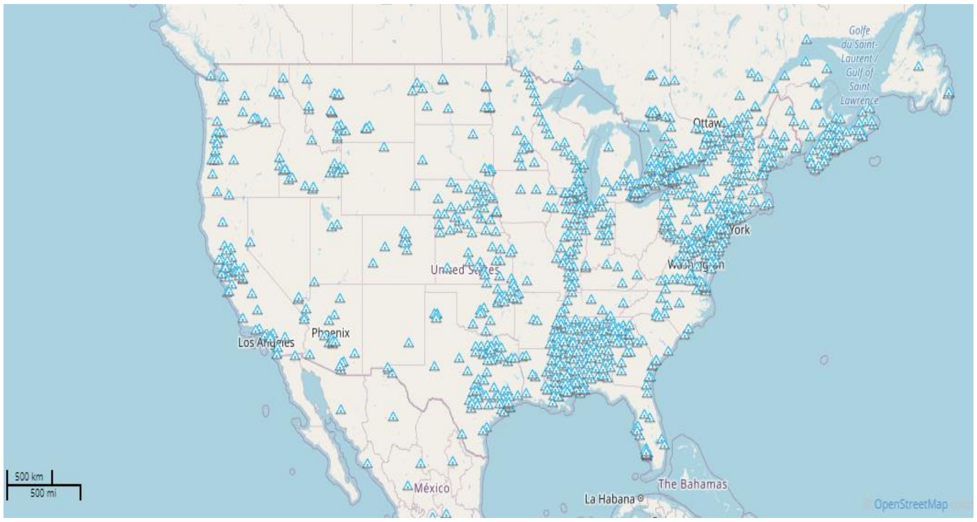

Figure 3. Coverage of TopNET Live in North America (Courtesy of TopCon)

4. GEOSPATIAL DATA USE IN TRANSPORTATION APPLICATIONS

Since the GPS became open to civilian applications around three decades ago, geospatial data has increasingly found applications across industries and sectors, including agriculture, construction, transportation, and aerospace, to name but a few. This section aims to provide a brief overview of the use of GPS technology in some of the major established transportation applications.

Vehicle Navigation Systems:

The availability and accuracy of the LBSs and positioning data (GPS) offer improved efficiencies and safety for all surface transportation systems. The GPS navigation systems are available as built-in devices in most of the newer models of vehicles, as standalone navigation devices, as well as in almost all recent smartphones as built-in applications. However, the GPS location service has a positioning error up to several meters. Currently, GPS data has been used in land-vehicle-navigation (LVN) and fused with Inertial Navigation System (INS) data to obtain a relatively accurate position of the vehicle (Liu et al. 2010). However, these technologies still rely on GPS signals and only work well in areas where GPS reception is not weak or compromised by substantial multipath issues. In GNSS-challenged environments such as urban canyons and forested streets, or even driving in congested traffic adjacent to several vehicles, these technologies may not function well. INS in vehicles can extend GPS coverage beyond areas of accuracy but not for substantial distances before the loss of required accuracy. Toledo-Moreo et al. investigated challenges for navigation systems such as lane-level positioning, map matching, and the quality of the navigation system. Measurements from a GNSS receiver, an odometer, a gyroscope, and data from enhanced digital maps are combined in the proposed system. The proposed system showed good results in terms of positioning, map matching, and integrity (Toledo-Moreo et al. 2010). Maaref et al. investigated the use of LiDAR data combined with pseudo ranges drawn from unknown cellular towers to overcome GNSS-challenged environments. The study considered a vehicle-mounted LiDAR sensor that enters an environment where GNSS signals are of no use. An extended Kalman filter is used to fuse the pseudo ranges produced by the receiver equipped in the vehicle to cellular towers, aid the LiDAR odometry, and estimate the vehicle's 3-D position. Simulated and experimental results found a 68% reduction in the 2-D root-mean-square error over solely LiDAR odometry (Maaref et al. 2019).

Vehicle Fleet Management:

In today's world, GPS is widely used for in-vehicle navigation systems and enables Automatic Vehicle Location (AVL) service. Most of the issues associated with the routing and dispatch of commercial vehicles (e.g., trucks) such as delays and high operating costs are significantly reduced or eliminated with the help of the GPS. GPS services also help in the management of mass transit systems, road construction and maintenance crews, and emergency vehicles. Specifically, geospatial data and LBSs are playing a vital role in public transit around the globe. Most of the public transportation agencies have implemented GPS systems within their fleets and monitor the schedules and operations on available routes. Transit GPS devices come with many exciting and practical features that are extremely useful in managing transportation fleets. A GPS-enabled bus routing software provides the utility of better maintaining the buses on time. It also provides the most up-to-date information to riders about ongoing trips of the buses or metro trains such as accurate arrival times at different stops on route. For bus transit, AVL services track and monitor the movements and locations of every bus on the road. The public transit operators can receive alerts about potential issues impacting routes, delivery, and fleet workflows. In the Twin Cities metro area in Minnesota, transit buses are allowed to use shoulders designated as bus-only shoulders under certain conditions. In 2011, Pessaro and Van Nostrand investigated the use of a driver assist system (DAS) on buses for the

Minnesota Valley Transit Authority (MVTA) to encourage more shoulder use and to assist during suboptimal driving conditions. Differential GPS (DGPS), LiDAR, and maps were used to assist drivers in collision avoidance and lateral (shoulder) positioning. The study found that 95 percent of customers were satisfied with the on-time performance of buses equipped with the DAS and that most drivers found driving on the shoulder safer and less stressful with the DAS enabled (Pessaro & Nostrand 2011). Along with safety, one of the major benefits of positioning services for public transportation operators is lower operational costs.

Another interesting application of GPS during snow emergencies is locating and tracking snowplows. To ensure that snow removal is efficient and that plows and salt trucks are dispatched timely, these vehicles are equipped with GPS and connect to a central facility. Routes that have been plowed are mapped and updated to show the latest information. With the availability of GNSS-RTN accurate position service in real-time, it would be even feasible to identify which lane of a multilane highway has been plowed. The Alaska Department of Transportation uses positioning data from real-time kinematics (RTK) for a special fleet of snowplows known as smart snowplows. These plows are outfitted with GNSS receivers and receive corrections from an RTK base station. Combined with collision avoidance technologies and GIS, snowplows can alert the driver visually and haptically through vibrations in the seat when the snowplow is drifting outside of a lane (AK-DOT & PF 2012). The RTK corrections are accurate within five centimeters at most. Given that most pavement markings in the United States are four inches at a minimum, this gives the driver confidence that they can stay within the lane. While snowplows are not able to operate at high speeds, the technology allows for safe operation in conditions where visibility may be otherwise extremely limited (AK-DOT & PF 2018).

GPS applications are also used in other fleet management services (FMSs) (Hu et al. 2015; MELE 2005). Fleets of trucks (Karp 2014), couriers, taxis, and other commercial vehicles can be managed using a positioning system and two-way communications between vehicles and a central control center. This way, companies can improve scheduling, reduce operating costs, enhance effective distribution, thus saving energy (Hu et al. 2015; Theiss et al. 2005). Besides, traffic violations such as abnormal driving behavior, speeding, driving illegal routes, etc. can be reduced with a successful implementation of GPS-based FMSs (Hu et al. 2015). Moreover, use of geospatial-based FMS along with an incident management system (IMS), emergency vehicles can be dispatched and monitored efficiently. Furthermore, geopositioning services can be used in electronic toll collections based on vehicle miles traveled on the toll highways such as the TollCollect system for heavy vehicles with weight over 12 tons that is used in Germany (Blau 2005; Rangwala & McClure 2004).

Transportation System Management:

Traffic congestion is a serious problem, especially in urban areas. For detecting, monitoring, and controlling traffic congestion, the most important factors used in Integrated Traffic Management Systems (ITMS) are travel time, speed, and delay. GPS data can be used to determine travel time, speed, and delays, and thus can be utilized for ITMS. The main advantage of monitoring congestion using GPS data is that real-time information on travel time and speeds can be obtained in an accurate, economical, and timely manner (Baria & Samant 2011; Faghri & Hamad 2002). This system can be utilized for daily congestion management in real-time based on GPS data or for annual congestion monitoring based on periodic GPS data collection during a particular season or infrequently throughout the year. In addition to monitoring traffic operations during congestion, the system can also precisely locate incidents that occur on the freeway (Faghri & Hamad 2002).

Geospatial techniques and data are also used in transportation asset management. Some state DOTs utilize GPS along with various imaging technologies to determine pavement condition down to as fine a scale as needed (CalTrans 2019; MnDOT 2019; Smith 2019). To establish an inventory of roadway networks along with attributes, LiDAR along with integrated GNSS and INS (LBSs) are used on a mobile platform or a vehicle, known as mobile LiDAR system, to capture roadway markings, assets, and cross-sections (Zeybek 2021). GPS is also utilized to collect locations for ADA pedestrian infrastructure (MnDOT 2019), guardrails, culverts, and bridges (Cambridge Systematics & Meyer 2007). GPS is an ideal positioning solution for asset management because it can be referenced to locations in pre-existing databases. The Ohio DOT divided its road network into 1.9 million 0.01-mile segments to integrate data for legacy systems, newer web applications, and GPS (Cambridge Systematics & Meyer 2007). In addition, GNSS technology along with other sensors such as LiDAR, vehicle vibrations, and digital cameras, are utilized in the automated survey of pavement surface conditions (Eriksson et al. 2008; Koch & Brilakis 2011; B. X. Yu & Yu 2006). In this regard, commercially available systems from companies such as Fugro and Dynatest offer solutions integrating GPS and imaging systems that can be mounted onto a cargo van for pavement evaluation (Dynatest 2021; Furgo 2021). GPS technology allows creating an inventory of the various roadside structures (signs, guardrails, etc.) much faster than was done in old days (Arnold 1998). For instance, the Montana Department of Transportation undertook an effort to survey railroad crossings in the state to create a GIS map of the crossings with information about their condition.

The GPS can also be used in autonomous structural health monitoring. For example, the GPS has been used to monitor the integrity and deformations of bridges using RTK technology in real-time to within a few millimeters (ASHKENZAI & Roberts 1997). Accuracy can be improved further with the introduction of pseudolites in order to augment the at times geometrically weak satellite constellation (Barnes et al. 2003). The Bridge Engineering Center (BEC) at Iowa State University developed the Bridge Engineering Condition Assessment System (BECAS), a suite of hardware and software that aims to eliminate the subjectivity of visual bridge inspections and provide continuous bridge condition evaluation. The hardware of BECAS includes the strain and temperature sensors and GPS antennas. In a financial justification for the BECAS system, the BEC concluded that the service life of a case study bridge was increased by 37 years, therefore justifying the cost of the system 85.2% of the time (Lu & Phares 2018).

Highway Construction:

GPS is widely utilized in the construction industry and for infrastructure projects and mapping. With the availability of DGPS, it is now possible to survey a large area quickly and efficiently to create a digital map of a highway network. Alabama Department of Transportation (ALDOT) used GPS technology for the first time in 1988 to establish a statewide survey network set with GPS techniques. The survey was completed in 1995 and sent to NGS which made it available to the public (FHWA 2000).

An Automated Machine Guidance (AMG) system relies on geospatial technologies, such as GNSS, to guide or control heavy construction equipment such as dozers, motor graders, excavators, pavers, and more. The Oregon and Iowa Departments of Transportation are considered pioneers in the implementation of AMG – both agencies began using AMG over 15 years ago. Some of the benefits of an AMG system are better control of quantities, increased productivity, increased accuracy and precision, more uniform surfaces, fuel savings, and optimized efficiency in surveying (Mallela et al. 2018; Torres et al. 2018). Uniform asphalt density is an important characteristic in pavement performance. Intelligent compaction (IC) aims to solve this problem by outfitting compactors with sensors such as accelerometers, temperature sensors, GPS receivers, and on-board computers to calculate and display asphalt density in real-time. The Federal Highway Administration has found that IC is effective in not only reaching the target density but also achieving a more uniform density (FHWA 2014; Xu & Chang 2013). IC can also be used to determine compaction curves, which could make the compaction operation more efficient by potentially calling for fewer passes. GPS data is used for tracking the compactor as it moves along the project and for mapping the results onto the onboard computer for easy viewing and post-processing in software such as Veta (FHWA 2014). In addition, IC technology is also tested and implemented for compaction of embankment sub-grade soils and aggregate base layer in pavement construction (Chang et al. 2011; Gallivan et al. 2010). Adoption of this technology is actively taking place; a 2018 memo from the Minnesota Department of Transportation expected that full preliminary implementation of IC technology in its projects would be completed by the end of the 2018 construction season (Embacher 2018).

Furthermore, many private companies offer GPS technology for more accurate and efficient dozer operations. Caterpillar’s Grade with 3D technology uses GPS on dozers to, as Caterpillar claims, increase operational accuracy and productivity and reduce operator inputs. GPS is used on the dozers to adjust the blade tilt and lift as the dozer moves across the project site (Caterpiller 2021). Leica offers a similar solution for dozers branded as iCON iGD3. iCON uses two blade-mounted GNSS antennas to, as Leica claims, boosts productivity, performance, and machine utilization (Leica 2021a). Trimble also offers a solution capable of measuring blade tilt and lift using a dual-GNSS solution which can, as Trimble claims, offer millimeter accuracy on finished grades and improve accuracy while decreasing costs (Trimble 2021).

Aviation and Marine Transportation:

In the National Airspace, GPS has enabled the creation of waypoints without needing to establish a physical infrastructure. This has resulted in increased efficiency and safety (O’Brien 2006). However, in the vicinity of certain airports, GPS data can be supplemented with a system the Federal Aviation Administration (FAA) calls a Ground-Based Augmentation System (GBAS). While not explicitly stated, GBAS operates as a GNSS-RTN for capable aircraft. A very high frequency (VHF) antenna broadcasts corrections to nearby aircraft two times per second using post-processed data received from terrestrial antennas that help in the safe operation of the aircraft. Aircraft also need to have the equipment necessary for receiving and processing the corrections (FAA 2000).

In the ocean, it is near impossible to establish physical wayfinding infrastructure due to the depth of the water. GPS provides marine operations a safe and effective way to determine the location, speed, and heading of a vessel. This allows vessels to operate efficiently and safely, especially in tight areas such as harbors (Xue 2006).

These innovative and diverse applications drive the technological advancement towards precise and accurate measurements that the nationwide GNSS-RTN system would produce. In the following sections, some of the emerging and future applications of GNSS-RTN in transportation are discussed.

5. GNSS-RTN: EMERGING TRANSPORTATION APPLICATIONS

GNSS-RTN has been increasingly used in the U.S. and around the world for many applications where high-precision geospatial data are needed. Continuously operating reference stations (CORSs) were long used as a source of differential GPS (DGPS) and RTK corrections, mainly for surveying and mapping applications.

The promise of the GNSS-RTN technology in transportation applications is perhaps one of the most obvious of all other potential applications of the GNSS-RTN. The current evolution of automated transportation systems, which constitute the most important development since the advent of the automobile, is one good example of the role this technology could play in future transportation systems. Auto manufacturers and technology companies have been working tirelessly in developing autonomous vehicles that would revolutionize the way mobility is used in societies. Thus far, the premise of automated vehicles is to use advanced sensors such as lidar, radar, and cameras (among other sensors) in sensing the environment thus acquiring input data needed for vehicle control. This approach is reasonable in urban environments and particularly on higher class highways and streets where the road is well paved and delineated with appropriate signage and markings. However, in rural areas, many highways are built to lower standards, lack appropriate signage and markings, and maybe unpaved. This presents a difficult challenge for the use of automated vehicles, currently being developed and experimented, in rural environments. The use of high precision GNSS-RTN location data provides a promising approach in addressing complex rural environments. Further, LiDAR and other sensors are prone to failure when used in suboptimal weather conditions such as snow, rain, and fog. Such conditions have no impact on GNSS technology, making it a highly reliable complement to lidar and sensors on AVs, therefore improving the safety of AVs (Joubert et al. 2020). High-level precision in positioning is necessary to guarantee the safety of AV users. The location precision provided by GNSS technology is high, but its availability was scarce when the technology was first introduced due to the few navigation satellites in orbit. Today, there are at least 125 operational navigation satellites. The higher number of satellites in orbit allows for more reliable use of GNSS technology by improving error correction. It has been found that GNSS technology, as it is today, is accurate enough to provide, with high confidence, lane-determination – one of the biggest concerns with automated vehicles (Joubert et al. 2020). Besides, GNSS-RTN technology would enable connected and automated vehicles (CAVs) to send (broadcast) and receive accurate location information of traffic conditions, breakdown incident alert, road traction conditions sensed by sensors, crash incident position, and specific road restrictions.

By combining positioning technology with systems that can display geographic information or with systems that can automatically transmit data to display screens, a new dimension in surface transportation is realized. In a white paper for Swift Navigation, Joubert et. al discussed how advancements in GNSS and corrections networks such as GNSS-RTNs will enable more advanced localization in autonomous vehicles. Localization is the process of the vehicle setting itself into its surroundings. This is done with many data sources such as radar, LiDAR, cameras, GNSS, and GNSS corrections networks such as GNSS-RTN (Joubert et al. 2020). The most recent studies highlighted in the white paper demonstrated 95th percentile horizontal accuracy of 0.14 m in an urban environment using network-RTK (GNSS-RTN). A fixed solution was available for 87 percent of the study interval. This comes close to the stated required accuracy of 0.1 m in urban environments (Humphreys et al. 2018, 2019).

Another important emerging application of the GNSS-RTN technology is to support the smart cities concept by providing precise location data. The technology can significantly impact urban environments by allowing for a more sustainable transportation system and improving the social, economic, and environmental issues that surround it. The network can be incorporated in an Intelligent Transportation System (ITS) and facilitate the path for Smart Cities. A proposed location-based service Galileo EnHancement as BoOste of the Smart CiTies (GHOST) uses the European GNSS high precision positioning to monitor road deterioration, police irregular parking, and report street lighting anomalies. The GHOST concept promises to increase the performance and efficiency of a city's infrastructure while reducing its monitoring costs (Tadic et al. 2016). GNSS technology and Wi-Fi signals were used to develop a platform designed to test and assess the positioning of navigation technologies with the European project HANSEL. The platform processes GNSS snapshots transmitted from smartphones. The processed data is then shared through Wi-Fi Access Point Location Service to all smart city users (Minetto et al. 2020).

The level of precision of the GNSS-RTN location data and the lack of latency would open the door for other automated processes in preserving and managing the transportation system infrastructure. One such application is lane striping operation and rumble strip installation where location data could be used to automate the process, thus increasing the efficiency, and reducing the costs involved in the traditional human-controlled processes.

In transportation infrastructure, bridges are considered crucial links in the transportation network and are important to the national economy. Most of the time bridges are failed due to continuous loadings (normal and abnormal loadings). Monitoring bridge deformation continuously and regularly is an essential task in bridge maintenance and management. Recently, GPS technology has been used in structural health monitoring of bridges (Benoit et al. 2014; Kaloop & Li 2011; Manzini et al. 2018), however, other sensors or a DGPS network are used along with GPS for accurate measurement of movements or deformation. The University of Nottingham, U.K. proposed the use of the network-based real-time kinematic (NRTK) GNSS technique to monitor the dynamic response of bridges. Laboratory and field experiments were conducted in the study. The four-stage methodology proposed uses a designed wavelet filtering scheme to recognize GNSS noise in the static data collected by the CORS. The study compared the performance of RTK and the NRTK-GNSS techniques and found the latter to have a potential cost savings of 80%, validating its use (J. Yu et al. 2016).

Safety at road construction sites is a serious issue in transportation. A construction site is a complex system consisting of workers, machines, materials, activities, and facilities. In recent years, leveraging the rapid advancement in technology, the construction industry has put forward an innovative management model, known as smart construction sites, which shifts the construction industry from labor-intensive ways to automation and data-driven ones. At the construction site, tracking of the construction equipment and machinery is central for the monitoring of safety, productivity, and sustainability-related practices (Langroodi et al. 2021). LBS, one of the technologies deployed in smart construction sites, is used to track the operations of heavy machinery (Akhavian et al. 2018; Axelsson & Wass 2019). High accuracy in positioning service using GNSS-RTN would make the construction industry safer, and enhance productivity and efficiency.

6. CONCLUDING REMARKS

This article provided an overview of the GNSS-RTN technology and the use of geospatial data in some of the established transportation applications as well as a perspective on some of the emerging and future applications of the GNSS-RTN technology in the transportation field.

From unmanned aerial vehicles (UAVs) to AVs, all modern-day transportation relies on a steady stream of signals and information from external sources for localization, route planning, perception, and general situational awareness. This includes reliance on positioning, navigation, and timing (PNT) information. A highly accurate positioning service is essential both for short-range driving control and long-range navigation and planning. The role of the GNSS-RTN system will only be increasing in the future especially with the advent of automated transportation systems. Although more than half of the states have already established statewide GNSS-RTN systems, the geographical coverage of all the states is a major hurdle. This makes a national GNSS-RTN essential for seamless access to accurate geospatial data in real-time. In addition to technological difficulties, the deployment of a highly accurate positioning network on a nationwide scale requires significant government support and funding. For such a network, it may be worth looking into a system that uses a lower density RTN augmented with satellite positioning in certain locations if local-scale RTN station density turns out to be cost-prohibitive. If a single national system is not created, the federal government could publish and provide technical assistance on system interoperability standards to allow for an effective national network.

As confirmed by recent studies, the benefits of a GNSS-RTN, within existing applications, far outweigh the implementation costs of such a system, not to mention the potential of technology in supporting many of the future transportation applications. GNSS-RTN has the potential, through providing accurate data in real-time, to enhance vehicle safety and operations, automate road construction and maintenance, and examine the pavement surface condition for pavement management and rehabilitation.

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