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Permanent Link to Innovation: Not Just a Fairy Tale

2021/06/11

A Hansel and Gretel Approach to Cooperative Vehicle Positioning By Scott Stephenson, Xiaolin Meng, Terry Moore, Anthony Baxendale, and Tim Edwards MEET GEORGE JETSON. Those of us of a certain age will remember the animated TV sitcom The Jetsons, which featured George Jetson, "his boy Elroy, daughter Judy, and Jane, his wife." It portrayed life in 2062, 100 years after the series debuted in 1962. George and his family used many futuristic gadgets including robot maids, talking alarm clocks, flat-screen TVs, and flying automated cars. Many of those devices are already available, well ahead of schedule. But flying cars are not quite with us yet. However, asphalt-hugging automated vehicles are already here, albeit still in limited numbers. Google created a buzz recently with tests of its self-driving car. Google's cars were developed as an outcome of the Defense Advanced Research Projects Agency's 2005 Grand Challenge in which teams created autonomous vehicles and raced them through a challenging road course. Self-driving cars use a host of sensors to determine their position with respect to their surroundings and to navigate a chosen route legally and safely. Although wide-spread ownership of self-driving cars might still be a ways off, drivers of conventional vehicles will soon benefit from the research being conducted to provide them with positional awareness of other vehicles in their vicinity. This work may be characterized as part of the larger effort in developing intelligent transportation systems or ITS. What is ITS? In the words of ITS Canada, it's "the application of advanced and emerging technologies (computers, sensors, control, communications, and electronic devices) in transportation to save lives, time, money, energy and the environment." This definition applies to all modes of transportation, including ground transportation such as private automobiles, commercial vehicles, and public transit, as well as rail, marine, and air modalities. The term ITS includes consideration not only of the vehicle, but also the infrastructure, and the driver or user, interacting together dynamically. Just looking at ground transportation, there are many ITS developments underway, some of which are already implemented to some degree including systems for vehicle navigation, traffic-signal-control, automatic license-plate recognition, parking guidance, and road lighting to name but a few. An important aspect of ITS is cooperative vehicle

communication, which includes transmission of data vehicle-to-vehicle or vehicle-to-infrastructure (and vice versa — known by the abbreviation V2X). Data from vehicles can be acquired and transmitted to other vehicles or to a server for central fusion and processing. These data can include accurate real-time vehicle coordinates, which can be used to improve driver situational awareness and to monitor traffic flow for example. This use of V2X is known as cooperative vehicle positioning. Several technologies are being developed for accurate cooperative vehicle positioning including lidar, radar, image-based cameras, ultra-wideband, and signals of opportunity. But GNSS also has a role to play. In this month's column, team of British researchers turn to a children's fairy tale for inspiration in their development of a cooperative vehicle positioning approach using carrier-phase observations — another innovative application of real-time kinematic or RTK GNSS technology. "Innovation" is a regular feature that discusses advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley of the Department of Geodesy and Geomatics Engineering, University of New Brunswick. He welcomes comments and topic ideas. There is little doubt in the benefit gained from cooperative modes of road transport, as agents working together generally perform better. In simple terms, this is the holistic idea that the whole is greater than the sum of its parts, commonly known as synergy. On top of this clear advantage, the complex systems theory of emergence suggests that novel strategies will develop from the as-yet-undefined patterns and structures. It is clear, however, that to facilitate this development certain technological advances need to be achieved. In this case, individual road agents need to accurately identify their location, and communicate easily and safely with other agents. This is a shift away from protective and passive systems toward preventative and active transport safety. Cooperative driving, or vehicle-to-vehicle or vehicle-to-infrastructure driving (V2X), is proposed as the next major safety breakthrough in road transport. An example of the concept is shown in FIGURE 1. It involves agents in the road transport environment communicating on local and national levels in real time, to maximize the efficiency of movement, dramatically reduce the number of accidents and fatalities, and make transportation more environmentally friendly. □Figure 1. Vehicle-to-vehicle communications as envisioned by the United States Department of Transportation. In the U.S., the National Highway Traffic and Safety Administration has commented that connected vehicle technology "can transform the nation's surface transportation safety, mobility and environmental performance," with industry experts predicting the widespread uptake of the technology within five to six years. This provides an opportunity for road vehicles to share GNSS information. To an extent, this is possible with current technology. Communication is fairly pervasive and pretty robust, with the explosion in personal handheld mobile devices, using the GSM/GPRS, 3G, and 4G cellular communications networks. Positioning systems exist now that will provide a reasonably accurate and reliable location most of the time. However, the type of applications included in cooperative driving demand much higher performance from these positioning systems. For instance, as shown in the example in FIGURE 2, two vehicles approaching an intersection at relatively high speeds require accurate and reliable high output position information, and an ability to communicate with one another, in order to assess the likelihood of collision. Figure 2. Vehicles approaching

a road intersection would benefit from V2X communication. These requirements are partly inter-linked, and can be mutually beneficial. For instance, communications methods can be used to share information to aid positioning, and some existing positioning systems can also be utilized to share information. Many recent solutions in vehicle tracking research have shifted the GNSS receiver to a supplemental role in the positioning system, favoring an inertial device as the core of the integrated solution. The clear advantage is that an inertial device operates continuously, although other sensors are required to achieve the required navigation performance. The GNSS receiver is demoted because of its inherent limitations, namely the requirement of a clear view of the satellites and the availability of correctional information. Most vehicle positioning research over the past two decades has focused attention on GNSS-centered systems, as evidenced by the abundant use of satnav devices used to assist in-car navigation. Despite its apparent monopoly over vehicle positioning in the commercial sector, the most successful systems developed to guide autonomous vehicles either relegate GNSS to one of a suite of sensors, or almost disregard it altogether. This is often due to its apparent lack of positioning accuracy or availability. Popular terrestrial positioning sensors include lidar, radar, image-based cameras, ultra-wideband (UWB), and signals of opportunity. Clearly, the combination of different complementary sensors is important, but it would be a mistake to discount the more advanced GNSS positioning techniques that are available, especially with the expansion of the four global GNSS services.

Cooperative Positioning The positioning of GNSS receivers relative to one another is a common application in transportation, such as during the aerial refueling of an airborne fighter jet by a tanker. In this case, it is important to know accurately the relative position of the two airplanes, but not necessarily their absolute position. Relative positioning of road vehicles is more complex. By their nature, road vehicles are almost always close to other vehicles or road infrastructure, and there are many separate agents in each scenario. Vehicles can also travel large distances, and in terms of GNSS positioning, this may mean vastly different atmospheric conditions. Hence, relative positioning in road transport is useful if all GNSS receivers relate to the same datum, which in most cases is effectively absolute positioning. Some previous work carried out by others concentrated on using GNSS code (pseudorange) and Doppler measurements for the relative positioning of vehicles, because it offers a simpler implementation method and is not susceptible to the cycle slips attributed to carrier-phase measurements. However, this means sacrificing the higher accuracy solution available from carrier-phase measurements. A major obstacle to GNSS positioning for V2X applications is the likely scenario of mixed receiver and antenna technology between vehicles. This has a major influence on the performance of relative positioning. By comparing various V2X relative positioning solutions, researchers found that an increase in positioning accuracy was typically accompanied by a decrease in availability and an increased demand for transmission bandwidth between the vehicles.

RTK GNSS Positioning. Real-time kinematic (RTK) GNSS positioning can be used to provide a solution at an accuracy of better than 5 centimeters (horizontal). This relies on the static reference receiver being located within 20 kilometers of the roving receiver, observing a good selection of common satellites with dual-frequency receivers. When RTK positioning is used, the distance to the reference station has a bearing on the successfulness of the integer ambiguity

resolution. A short baseline will benefit from a closer correlation of errors, due to the GNSS signals traveling through very similar parts of the atmosphere. Assuming each receiver is observing common satellites, this similarity will typically result in a higher success rate in the ratio test using the common Least Squares Ambiguity Decorrelation Adjustment, or LAMBDA, technique. This is particularly important following a GNSS outage. GNSS positioning of road vehicles using RTK or network RTK (where a network of reference stations replaces a single RTK reference station) can provide highly accurate (The transmission protocol of network RTK corrections is typically RTCM v3.0 or higher, and the composition of the correction information varies depending on the commercial service provider. The most common type of correction message format is that for a virtual reference station (VRS), although the most comprehensive and versatile method is the master-auxiliary concept (MAC). See references in Further Reading for details. In V2X and other intelligent transportation systems (ITS) applications, the position must be accurate, reliable, available, and continuous. Previous research has shown that network RTK GNSS positioning can deliver a highly accurate and precise solution in an ideal observation environment. In one test, more than 99 percent of the observations lay within 2 centimeters of the truth solution, with a very small number of anomalous results of up to 20 centimeters. The availability of a network RTK solution is determined by the availability of GNSS signals and the network RTK corrections. As network RTK positioning uses carrier-phase observations, GNSS outages and cycle slips significantly affect the performance of a receiver. However, the re-initialization of the fixed integer ambiguity resolution following a GNSS outage (such as caused by an overhead bridge) can be relatively fast. But from a cold start, the ambiguity resolution can take up to two minutes. This limits the widespread adoption of the technology for vehicle positioning. NGI Road Vehicle and Electric Locomotive Testbeds. We have carried out research at the Nottingham Geospatial Institute (NGI) using state-of-the-art testing facilities. These bespoke in-house facilities allow repeated controlled experiments, and are a useful tool in the development of ITS and V2X technology. To test the positioning performance thoroughly and under real-world conditions, we carried out experiments using the NGI's road vehicle, which is equipped with a collection of on-board ground-truth systems. Also, the roof of the Nottingham Geospatial Building (home of NGI) is the location of a remotely operated electric locomotive running on a 200-millimeter-gauge railway track. A photograph of the locomotive and plan of the track are shown in FIGURE 3. The locomotive can carry a selection of various positioning instruments, such as GNSS receivers, inertial navigation system (INS) devices, and tracking prisms, and can travel at a speed of over three meters per second. The position of the track is accurately known, and has previously been scanned at a resolution of 2 millimeters. □Figure 3. The NGB2 reference base station and electric locomotive track on the roof of the Nottingham Geospatial Building. Three control solutions are used to assess the performance of the cooperative positioning techniques in real-world tests: An RTK GNSS control solution provided by a local static continuously operating reference station (CORS); a network RTK GNSS solution based on the MAC standard; and a dual-frequency GPS/INS system. Each vehicle also can be independently tracked using survey-grade total stations or a proprietary UWB positioning system. Sharing Network RTK Corrections If vehicles could communicate with one another on the road, this would

help overcome the communication system limitation in network RTK positioning of road vehicles. For instance, if vehicle A has an external connection to a network RTK service provider (such as a mobile Internet connection) and a local connection to a second vehicle (B), then it could share its network RTK correction messages directly. Effectively, vehicle A would re-broadcast the correction information it has received from the corrections provider to the receiver on vehicle B. However, this would rely on the functional capability of the receiver of vehicle B, as network RTK real-time processing can be computationally intensive. Not all network RTK correction messages can be shared in this way, and the range over which the correction messages are still valid needs to be determined. As vehicles communicating with V2X devices are likely to be relatively close (a few hundred meters at most), the feasibility of sharing network RTK information is good. However, the network RTK VRS technique may offer more advantages. It is the most common form of network RTK used around the world, and requires significantly less bandwidth (approximately 10 kilobits per second at 10 Hz). The rover receiver is also less burdened by processing requirements. A VRS system operating on buses in Minnesota restricts the baseline to 2 miles, by updating the VRS location every 2 minutes. Correction messages typically have a lifespan of 10 seconds. After this time, the receiver determines the messages to be too old and does not compute a fixed-integer position. It can, however, use the information to calculate a differential GNSS (DGNSS) position. Therefore, the relayed message must arrive at the receiver on vehicle B well within 10 seconds. Previous trials at NGI found that the typical message latency of the original correction message reaching vehicle A via a GSM/GPRS connection is 0.85 seconds. The additional V2X communication to transfer the message to vehicle B should not add a significant delay.

Capturing Network RTK Messages. To demonstrate the potential benefit of sharing network RTK messages between vehicles, network RTK messages were captured on board a vehicle and shared with a second vehicle. Vehicle A is the NGI van, and vehicle B is the NGI electric train. Most off-the-shelf network-RTK-enabled GNSS receivers are designed to communicate directly with the network RTK server using a connected communication device (GSM modem, UHF/VHF radio, cell phone, and so on), which typically provides a stable connection to minimize data loss. To intercept the network RTK correction message, the GNSS receiver was set up to simply accept the correction message from a smartphone via Bluetooth. In this case, the connection to the network RTK service provider is established between the smartphone and the network RTK server. An application running on the smartphone (as shown in FIGURE 4) requests information from the network RTK server, logs the data, and passes the message directly to the Bluetooth-connected GNSS receiver on vehicle A. By intercepting the correction message, it can also be forwarded on to a second receiver, in this case on vehicle B.

□Figure 4. Flowchart showing the capturing and sharing of network RTK correction messages (left), and the NTRIP client program running on an Android smartphone (right). **Sharing Messages with Second Receiver.** FIGURE 5 shows the positioning solutions generated by a shared-network-RTK correction message. The original message was captured by the smartphone application operating on board vehicle A (the NGI van), and applied to GNSS observations made by a receiver on vehicle B (the NGI train). The baseline between the two vehicles was less than 100 meters, and the location of the VRS requested from the network RTK server was the NGI building

(in geodetic coordinates to three decimal places). As Figure 5 clearly shows, the shared VRS corrections are equally valid for any receiver operating in the vicinity of the VRS. The thick red line is the fixed position of the train track, and the thin blue line represents the positions generated by the GNSS receiver using the shared network RTK corrections. □Figure 5. Sharing the network RTK message from vehicle A to vehicle B. The VRS message type was chosen because it requires much less bandwidth, takes less processing capacity, and is prevalent among legacy receivers. Network RTK users typically require download speeds of 1.8 kilobits per second (VRS) and 5.6 kilobits per second (MAC). This is well within the typical speeds available from cellular wireless communications, which offer 80 kilobits per second downlink speeds from 2.5G systems to beyond 40 megabits per second for recent 4G systems. The GNSS receiver on vehicle B is operating in an ideal location, with a clear view of the sky and a high number of visible satellites, which improves the probability of successful RTK ambiguity resolution.

Generating Pseudo-VRS Corrections

The potential benefit to GNSS positioning of using V2X communication between various road vehicles and infrastructure can be expanded by the implementation of pseudo-VRS positioning. This system resembles the children's fairy tale Hansel and Gretel, where in order to help remember the route through a forest that guides them back to their home, Hansel drops markers along the path (in separate cases small white pebbles, and then breadcrumbs). By using the markers, the children can navigate their way through the forest, but without them they are left lost and disoriented. The pseudo-VRS system uses a similar principle, where vehicle A marks its path by leaving behind small packets of information that can be used by other nearby vehicles. The small packets of information are VRS-like, and are broadcast using V2X communication devices and technology. Like the breadcrumbs in the fairy tale that are eaten by birds shortly after being dropped by Hansel, these VRS-like packets of information have a short lifespan.

VRS Requirements

It has been long established that a short baseline between reference and rover receivers leads to more accurate and successful relative GNSS positioning. A short baseline can effectively deal with satellite orbit and atmospheric errors, which become difficult to deal with as the baseline length grows, and is the reason why RTK GNSS positioning is typically limited to baselines shorter than 20 kilometers. A typical RTK baseline may be between 1 and 10 kilometers long, but it is still beneficial to reduce the baseline further, particularly if there is a large difference in elevation. This is enabled by the VRS network RTK technique. By using the observation data from several permanent reference stations that surround the rover location, a virtual reference station is created close to the location of the rover, including virtual observation measurements and position. This VRS information is transmitted to the rover, and the rover receiver treats the information like that of a real reference station. This technique can deliver better than 5-centimeter accuracy up to 35 kilometers. The principle builds on the transfer of measurements made at the real reference stations to the VRS. The carrier-phase measurement at the real reference station (), shown in Equation 1, is made up of the geometric distance between the receiver and satellite (), the integer ambiguity (), and the receiver and satellite clock bias (). The key to the VRS technique is that the integer ambiguity and the receiver and satellite clock bias are not location dependent, so they can be transferred directly to the virtual reference station from the real reference station. (1) By differencing the

carrier-phase equation of the real and virtual reference stations (and , respectively), the ambiguity and clock errors are canceled. The result is shown in Equation 2. (2) By combining the carrier-phase measurement equations at the real and virtual reference stations, only two unknown terms remain. The first includes the position of the VRS (), which is, in principle, arbitrary and is typically the approximate location of the rover receiver. The second is the observable of the VRS (), which can now be obtained without actually measuring it. (In practice, the technique is a little more complex, as satellite orbit and atmospheric errors and biases need to be modeled for the VRS position). The VRS information can then be packaged using the RTCM standards and delivered to the rover receiver to enable network RTK VRS positioning. Pseudo-VRS. Using the established VRS techniques and standards described above, we propose to use the GNSS observations and subsequent position information to simulate the existence of a VRS (see FIGURE 6). Imagine vehicle A carries a GNSS receiver together with the means to calculate its position accurately (for instance, it is also receiving differential corrections or has other positioning devices on board). So long as the receiver can successfully resolve the integer ambiguity, it can also produce each component required to describe a VRS. Clearly in this case, the receiver on vehicle A is a “real” reference station, but the existing VRS standards can be exploited to transfer this information to other local GNSS receivers. For instance, a receiver operating on vehicle B can use the information as a local real-time differential correction service. □Figure 6. The flow of data during the generation and sharing of pseudo-VRS data. Because the VRS technique is well established (the most popular form of network RTK positioning), legacy receivers are able to take advantage of this pseudo-VRS information. RTCM standards are also well defined for the transfer of GNSS information in this form. The pseudo-VRS information is valid for several seconds, so the delays introduced in transferring the information from one vehicle to a second can easily be accommodated. Like any communication device based on radio waves, V2X communication devices are likely to be subject to a level of delay and message loss that requires redundancy in the system. It is important that during one epoch the whole pseudo-VRS message is delivered, as there is little similarity between one epoch and the next. The original reference receiver is likely to be on a moving vehicle. Effectively, the pseudo-VRS imitates the VRS in Equation 2 by providing the virtual reference station coordinates and carrier-phase observable. The information is also delivered to the second receiver in the same format RTCM message. A slight difference here is that only one-way communication is needed — the original coordinates of the VRS do not need to be supplied by the second receiver. The pseudo-VRS processing is carried out using the RTKLIB open source software. RTKLIB has limited options to vary the position of the base station during RTK positioning, so the program is seeded with customized configuration files and run independently for each epoch. This creates an additional feature: The processing of each epoch has no effect on any other. Vehicle-to-Vehicle Communication. As we just consider the exploitation of V2X devices in this article, the nature of the communication medium is not under test. For this reason, off-the-shelf wireless routers (2.4 GHz) were used to communicate between vehicles, using fixed local IP addresses. However, the performance of the routers under cooperative driving tests is limited by range, multipath, and signal obstruction. Real-World Tests To generate

significant test results, some of the following tests use recorded and replayed data.

Test Setup. To test the performance of a pseudo-VRS positioning system, and the success of different configurations, real-world tests were carried out at the Nottingham Geospatial Institute. Two vehicles were used. Vehicle A was the NGI's road vehicle, and vehicle B was the NGI's electric locomotive. As the position of the locomotive test track is very accurately known, this can be used to measure the performance of the pseudo-VRS system. Vehicle A was equipped with six GNSS receivers, a tactical-grade INS system, and a wheel odometer, and tracked using a total station and 360° prism. This provided multiple position solutions to ensure significant results. Vehicle B was equipped with a GNSS receiver, and tracked using a proprietary UWB system for related V2X tests. Also, on the roof of the NGB, and lying inside the track perimeter, is the NGB continuously operating reference station. This hyper-local reference station allows local RTK solutions, and acts as a barometer of GNSS activity when tests are episodically carried out. FIGURE 7 shows an aerial image of the test scenario. The Google background shows the NGB to the west, and surrounding roads to the south and west (still under construction during the image acquisition). The thin yellow line is a ground distance of 100 meters. The red dots signify the position of vehicle A (in the east), and the purple dots show the position of vehicle B (on the roof of the NGB building). The accuracy of the Google image is unknown, and is used here purely for illustrative purposes. □

Figure 7. Aerial image of the test.

Test Results. These tests are designed to show the performance of a pseudo-VRS system using a V2X communication system. However, the results shown here were created using recorded raw data. The test results will help to design the correct RTCM message to share between vehicles in future tests. To simulate the operation of a pseudo-VRS system, vehicle A must share its known absolute position and some raw RINEX information for each epoch with vehicle B. Vehicle B can then use this information, together with its own observed RINEX data, for the same epoch to calculate its known absolute position. In practice, there will be a slight delay in the delivery of the information from vehicle A (much like in a traditional RTK system), so that information from concurrent epochs are unlikely to be used. The RTKLIB software cannot directly handle the variation of a base station's coordinates (and output an absolute solution), so a small separate script was designed to utilize the processing capability of the software in a pseudo-VRS system. FIGURE 8 shows the results of pseudo-VRS positioning. During dual-frequency tests, 99.67 percent of observations achieved fixed ambiguity (1197/1201). During single-frequency (broadcast ionosphere) RTK, 61.45 percent (738/1201) observations achieved fixed ambiguity. The ratio test threshold was 2.0. Around the area of 454930E 339708N, the number of common visible satellites dropped from eight to seven, and then again from seven to six three seconds later. This caused each of the three solutions to degrade slightly. The dual-frequency RTK solution briefly lost its fixed ambiguity solution (for two epochs, or 0.1 seconds), before regaining the fixed solution. The single-frequency RTK solution could not achieve a fixed ambiguity solution again until the number of common visible satellites returned to seven (five seconds after the initial satellite was lost). The DGNSS solution saw a similar degradation in its solution during this period. □

Figure 8. Results from pseudo-VRS positioning. The mean coordinate errors for the three solutions are 0.054, 0.707, and 0.323 meters (1 standard deviation, 3D), as shown in Table 1. This is compared to a solution

calculated using the local CORS base station. The error in horizontal and vertical follows the typical ratio of 1:2. Test results were also completed using a lower pseudo-VRS update rate. At 1 Hz, the results prove even better. Although the latency of the correction is up to 1 second (positioning is calculated epoch by epoch), the results were better than updates at 20 Hz. The dual-frequency RTK solution achieved a fixed ambiguity at every epoch (100 percent), and when compared to the known track position appeared correctly fixed. The single-frequency RTK solution achieved a fixed ambiguity for 70.02 percent (897/1201) of the observations; a slight improvement over the 20-Hz results. Table 1. Results from pseudo-VRS positioning. Table 2 shows the performance of the pseudo-VRS system under different latency scenarios. This is important because a message transmitted by vehicle A may be delayed or newer messages may be disrupted. Once the latency of the correction message reaches 8 seconds, the performance of the positioning solution begins to drop. The number of fixed ambiguity solutions falls, and the resulting positioning accuracy also decreases. However, the solution can still deliver 20- to 30-centimeter accuracy with a message latency of up to 30 seconds. Table 2. Effect of message latency on positioning quality.

Conclusions This article has outlined the potential benefit of V2X technology to cooperative vehicle positioning. A vehicle that knows its absolute position accurately can assist a second vehicle to position itself using established GNSS techniques. The pseudo-VRS base-station location must have reasonably accurate coordinates. Without this, the correct integer ambiguity cannot be resolved, and there is the risk of an incorrect resolution giving false success. This requires good reliability and integrity of the position of vehicle A, a characteristic that can be provided by network RTK positioning but likely needs further support from alternative positioning solutions.

Acknowledgments The authors acknowledge Leica Geosystems for the provision of an academic license for the SmartNet network RTK service. We thank Yang Gao and Qiuzhao Zhang of the University of Nottingham for their assistance and detailed discussion during the experimental tests. The work was supported by the U.K.'s Engineering and Physical Sciences Research Council. This article is based on the paper "A Fairy Tale Approach to Cooperative Vehicle Positioning" presented at the 2014 International Technical Meeting of The Institute of Navigation held in San Diego, California, January 27-29, 2014.

Manufacturers For our tests, vehicle A (NGI's road vehicle) was equipped with six Leica Geosystems AG GS10 GNSS receivers with individual AS10 antennas, an Applanix Corp. POS RS with Honeywell International Inc. CIMU tactical grade INS system, and was tracked using a Leica Nova TS50 total station. Vehicle B (NGI's electric locomotive) was equipped with a Leica GS10 GNSS receiver and AS10 antenna.

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READING • Authors' Conference Paper "A Fairy Tale Approach to Cooperative Vehicle Positioning" by S. Stephenson, X. Meng, T. Moore, A. Baxendale, and T. Edwards in Proceedings of ION ITM 2014, the 2014 International Technical Meeting of The Institute of Navigation, San Diego, California, January 27-29, 2014, pp. 431-440. • Intelligent Transportation Systems Proceedings of IEEE ITSC 2013, the 16th International IEEE Conference on Intelligent Transportation Systems, "Intelligent Transportation Systems for All Modes," The Hague, The Netherlands, October 6-9, 2013. Overview of Intelligent Transport Systems (ITS) Developments in and Across Transport Modes by G.A. Giannopoulos, E. Mitsakis, and J.M. Salanoca, Joint Research Centre Scientific and Policy Report EUR 25223 EN, Institute for Energy and Transport, Joint Research Centre, European Commission, 2012, doi: 10.2788/12881. "How Google's Self-Driving Car Works" by E. Guizzo in IEEE Spectrum Blog, October 18, 2011. "Elbow Room on the Shoulder: DGPS-Based Lane-Keeping Enlists Laser Scanners for Safety and Efficiency" by C. Shankwitz in GPS World, Vol. 21, No. 7, July 2010, pp. 30-37. "Driverless Cars" by R. Murray in Computing and Control Engineering, Vol. 18, No. 3, June-July 2007, pp. 14-17. • GNSS and Inertial Navigation Systems "GPS and Inertial Systems for High Precision Positioning on Motorways" by J.E. Naranjo, F. Jiménez, F. Aparicio, and J. Zato in Journal of Navigation, Vol. 62, No. 2, April 2009, pp. 351-363, doi: 10.1017/S0373463308005249. • Vehicle-to-Vehicle and Vehicle-to-Infrastructure Technologies "Implementation of V2X with the Integration of Network RTK: Challenges and Solutions" in Proceedings of ION GNSS 2012, the 25th International Technical Meeting of The Satellite Division of the Institute of Navigation, Nashville, Tennessee, September 17-21, 2012, pp. 1556-1567. DOT Launches Largest-Ever Road Test of Connected Vehicle Crash Avoidance Technology, National Highway Traffic Safety Administration press release, August 21, 2012. "Relative Positioning for Vehicle-to-Vehicle Communication-enabled Vehicle Safety Applications" by C. Basnayake, G. Lachapelle, and J. Bancroft in Proceedings of the 18th ITS World Congress, Orlando, October 16-20, 2011. "Can GNSS Drive V2X" by P. Alves, T. Williams, C. Basnayake, and G. Lachapelle in GPS World, Vol. 21, No. 10, October 2010, pp. 35-43. • Network RTK "Network RTK for Intelligent Vehicles" by S. Stephenson, X. Meng, T. Moore, A. Baxendale, and T. Edwards in GPS World, Vol. 24, No. 2, February 2013, pp. 61-67. "A Comparison of the VRS and MAC Principles for Network RTK" by V. Janssen in Proceedings of IGNS2009, the 2009 Symposium of the International Global Navigation Satellite Systems Society, Gold Coast, Queensland, Australia, December 1-3, 2009. "Introduction to Network RTK" by L. Wanninger, IAG Working Group 4.1: Network RTK (2003-2007). Online article. Last modified June 16, 2008. RTCM Standard 10403.1 for Differential GNSS (Global Navigation Satellite Systems) Services - Version 3, developed by RTCM Special Committee No. 104, Radio Technical Commission for Maritime Services, Arlington, Virginia, October 27, 2006. "Accuracy Performance of Virtual Reference Station (VRS) Networks" by G. Retscher in Journal of Global Positioning Systems, Vol. 1, No. 1, 2002, pp. 40-47. "An Overview of Multi-Reference Station Methods for cm-Level Positioning" by G. Fotopoulos and M.E. Cannon in GPS Solutions, Vol. 4, No. 3, January 2001, pp. 1-10, doi: 10.1007/PL00012849.

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