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Infrastructure Enhancements for CAV Navigation

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16. Abstract
This report presents a review of the main sensors used in connected and autonomous vehicles (CAVs). Radar, ultrasonic sensors, a global positioning system, radio-frequency identification, lidar, cameras, inertial measurement units, and capacitive–proximity sensors were detailed, listing their working principles, advantages, and disadvantages. Based on the review, potential measures to address their drawbacks and enhance control and guidance of CAV were proposed. The measures mainly consist of modification of electromagnetic, optical, and thermal properties of infrastructure materials in order for vehicles to communicate with the infrastructure.

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Autonomous Vehicles, Connected Vehicles, Guidance, Navigation, Sensors, Vehicle to Infrastructure Communications, GPS, Lidar, RFID, Radar, Ultrasonic Sensor, Camera, IMU

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CHAPTER 1: INTRODUCTION

BACKGROUND

Connected and autonomous vehicles (CAVs) are poised to revolutionize the way goods, services, and passengers are transported. There are numerous benefits of CAVs, with the most relevant being driver/passenger safety, increased roadway capacity, reduced congestion, and potential reduction in emissions. Regarding safety, CAVs can eliminate the possibility of human error, which causes 94% of accidents (NHTSA, 2017). In addition, under the control of sensors and algorithms, the lateral and longitudinal distance between vehicles can be safely reduced with a faster perception-reaction time, thus allowing more vehicles in the same space. Finally, application of CAVs such as truck platooning can decrease frictional drag and increase fuel economy. CAV technology also disproportionately benefits younger, older, and disabled people by providing access to transportation means currently out of reach (Atkins, 2016) and increases safety for this demographic. The list of benefits is reflected in the projected demand for CAVs. The demand for CAV technologies is projected to reach $37 billion in the United Kingdom (UK) by 2035. In addition, there will be 6,000 direct and 3,900 indirect additional jobs in the production of CAV technologies in the UK (Catapult, 2017).

There are issues that need to be addressed before CAV technologies can be impactful. A recent survey of leading automakers, suppliers, startups, investors, and technology companies (Foley & Lardner LLP 2017) listed the key factors affecting the development of connected cars and autonomous vehicles. According to the survey, 35% of the respondents indicated safety is the biggest obstacle for the growth of autonomous vehicles. The survey also found 39% of the participants thought that the inability of road infrastructure to support autonomous features is the primary issue in developing or implementing technologies for CAVs.

To take full advantage of CAVs' benefits requires implementation by government agencies, which are responsible for transportation policy for the public. The government needs to establish a regulatory framework, as well as keep track of evolutions in CAV technologies, so that the owners of the built infrastructure can maintain the roadway and roadside in an appropriate condition. Maintaining infrastructure in good condition can facilitate the deployment of CAV, for instance, by not having to account for unexpected situations caused by deteriorated infrastructure. Beyond keeping infrastructure in good condition, CAV implementation may require modifications to road markings, signage and signalization, lane width and road capacity, and access management. Newly constructed infrastructure needs to ensure security of data transmission and maintenance through detailed maps, devices that receive and transmit data, traffic-signal controllers, traffic-management centers, and secure communication networks (PSC and CAR, 2017).

Consequently, research efforts focused on driver/vehicle safety and vehicle to infrastructure (V2I) communication can have tremendous impact on the implementation of CAVs. This report reviews the sensors and safety issues associated with the operation of AVs and then proposes potential ideas to the roadway that will result in safety enhancement and improved performance of connected and autonomous vehicles.

OBJECTIVE AND SCOPE

The main objective of this study is to review current technologies for CAVs and to propose enhancements to the roadway and roadside infrastructure to elevate the safety of vehicle guidance and navigation systems. The potential roadway/roadside adjustments will aim at increasing vehicle guidance reliability, minimize the added cost of CAVs, and continue to move toward implementation on all classes of roads.

OVERVIEW OF THE REPORT

This report is divided into four chapters. Chapter 2 presents a review of the most common sensors employed by connected and autonomous vehicles to control, maneuver, and navigate roadways. The chapter describes the working principle of each sensor, its advantages, disadvantages, and potential limitations for safe operation. Chapter 3 focuses on ideas for modifying roadway- and roadside-infrastructure components that would enhance the performance and safety of connected and autonomous vehicles. Chapter 4 summarizes the findings and suggested ideas.

CHAPTER 2: SENSORS IN AUTONOMOUS VEHICLES

Connected and autonomous vehicles have multiple sensors that take advantage of various technologies to improve driving safety. The sensors are located at different locations in the vehicle, so that the CAV's surroundings can be covered and allow for safe vehicle control, guidance, and navigation. Figure 1 summarizes the most relevant sensors that allow for the operation of CAVs, along with their main functions. The following section details each sensor, along with its working principles, advantages, disadvantages, and limitations.

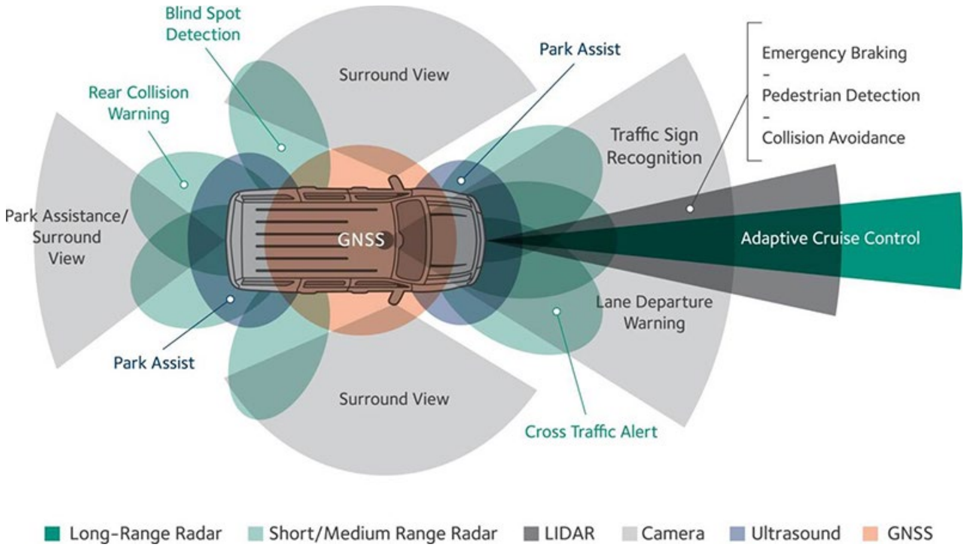

Figure 1. Photo. Main sensors in autonomous vehicles (Novatel, 2018).

RADAR

Radio detection and ranging (radar) is a system that uses radio waves to determine the range, angle, and velocity of targets. As demonstrated by German physicist Heinrich Hertz in the late nineteenth century, radio waves are reflected by solid objects. German and Russian scientists first applied this principle in the early 1900s to detect ships in dense fog without knowing their distance (James, 1989), and the US Navy introduced the term RADAR in 1940. The modern use of radar includes air-traffic control, antimissile systems, ocean surveillance, meteorological monitoring, aircraft anti-collision systems, and geological exploration using ground-penetrating radar.

In a radar system, the transmitter produces radio waves or microwaves that are transmitted using an antenna. Reflected waves are received by the same or a different antenna and analyzed to determine the target's position and properties. The antenna emits electromagnetic waves that travel at the speed of light, strike a target or object of interest, and reflect back to the receiving antenna. If any reflected waves are received, the time difference between wave emission and reception can be used to compute the range between source and object. Special radar antennas can focus these waves in a desired direction so that they travel mostly in a straight line.

Automotive radar sensors use two types of wave modes: pulse and continuous wave. In the pulse-wave mode (Charvat, 2017), short pulses are sent at regular intervals to determine distance by measuring the time delay between the transmitted and received signal. In the continuous-wave mode, such as frequency-modulated continuous waves (FMCW) (Iovescu & Rao, 2017), the signal is linearly modulated. The distance is then determined based on the difference in the transmitted and received frequencies (Figure 2).

$$Range\ for\ pulse - wave\ mode = \frac{1}{2} speed\ of\ light \times time\ of\ flight$$

Figure 2. Equation. Range for pulse wave mode radar.

Both radar modes have advantages and disadvantages. Pulsed radar has a blind spot on short distances (between 50 and 100 m), which is not an issue for continuous radar. However, pulse radar can measure the relative target speed of a moving target. For continuous radar, the movement of the object creates the Doppler effect, shifting the frequency of the transmitted waves. This trait is problematic because distance is measured using the frequency shift, which is further affected by the Doppler effect.

Automotive industries have used radar systems since the late 1990s. Radar is integrated into adaptive cruise control, blind-spot detection, and more accurate parking sensors (Charvat, 2017). Radar also helps in direct acquisition of the range and velocity of objects (Wenger, 2007). Moreover, radar is robust in bad weather, so it is more insensitive than other automotive sensors to adverse weather (Wenger, 2007; Wenger & Hahn, 2007; Gresham et al., 2004; Kato et al., 2002; Wu et al., 2009). Another advantage of radar is its low cost, which allows the installation of numerous small radar sensors for real-time decision-making (Charvat, 2017). In addition, for aesthetic purposes, an automobile can have invisibly mounted radars behind electromagnetically transparent materials, such as a plastic bumper (Wenger, 2007). The size of radar sensors is expected to decrease further in the coming years. Due to spectrum regulations and standards development in Europe and the United States, automotive radar systems are shifting from 24-GHz to 77-GHz bandwidth by the year 2022 (Iovescu & Rao, 2017). This shift in bandwidth will decrease the size of the antenna to one-third of today's and improve resolution and accuracy threefold.

Radar implementation comes with several challenges. For instance, radar lacks high lateral resolution (Kato et al., 2002; Wu et al., 2009), so it needs a large number of sensors for better coverage. In addition, electromagnetic shielding such as copper and metal sheets/screens can interfere with the signal. Furthermore, signals are blocked, reflected, and attenuated by any electrical conductor. Some objects are electromagnetically transparent and do not reflect enough energy, making them difficult to detect. There is also a chance of cross talk between signals from different automotive radars.

Even though radar is less prone to the effects of weather conditions, it is not fully independent. During rainy and snowy conditions, an accumulation of a water film in the electromagnetic waves' path acts as a signal attenuator, thus leading to partial or total obstruction of radar signals in the millimeter-frequency range. Water-film formation on the surface of an antenna lens causes issues in automotive long-range radar performance. However, an ice layer has a negligible absorption coefficient and exerts generally less influence on the performance of automotive radar sensors (Arage et al., 2006). Therefore, moisture in the air reduces the range of the radar equipment but not necessarily its accuracy.

ULTRASONIC SENSOR

Ultrasound is a mechanical pressure wave with a frequency typically higher than what the human ear can detect, e.g., 20 kHz. Ultrasonic devices use frequencies from 20 kHz to several GHz and are commonly used to detect objects and measure distances.

Mechanical waves have been studied from as early as the sixth century. Langevin performed the first application of ultrasound technology to detect submarines and icebergs in 1917. Discovery of the piezoelectric effect in 1880 allowed the fabrication of transducers that generate and detect ultrasonic waves in different mediums like air and water (Pollet, 2012). Application of ultrasound technology is made for detection and ranging of objects, imaging of objects, acoustic microscopy, in high power for physical therapy, and many biomedical purposes.

Typically, an ultrasonic transducer converts an electric signal into high-frequency mechanical waves, or vice versa. Such sensors generally work in pulse-echo mode, acting as both transmitter and receiver. A voltage pulse excites the transmitter, causing an ultrasonic wave to be emitted. When the wave strikes the target, an echo is reflected to the same sensor, which now acts as a receiver (Polaroid Corp., 1984; Bozma & Kuc, 1991). The time difference between emission of the wave and arrival of the echo is known as the time of flight. The range between the source and the target is obtained by the formula in Figure 3:

$$Range = \frac{1}{2} speed\ of\ sound\ in\ medium \times time\ of\ flight$$

Figure 3. Equation. Range for ultrasound sensor.

Ultrasound is a widespread and well-researched technology. Commercial automotive sensors typically operate at frequencies between 40 and 60 kHz and detect obstacles from 30 to 450 cm away (Nordevall, 2015). Wide-area coverage and detection of close vehicles and obstacles give an advantage to ultrasonic sensors (Aeberhard et al., 2015). However, ultrasound-wave propagation depends on pressure and temperature, and it can be affected by high-speed winds. Detection of an object depends on its distance, shape, and size. The presence of a reflective surface at a shallow angle produces poor results (Parallax, 2018). In addition, the beam pattern of an ultrasonic sensor is not uniform in all directions, as shown in Figure 4. The signals are strongest in the orientation of the sensor. Objects at larger angles from the sensor orientation are either not detected or must be closer than the maximum range of the sensor to be detected (Parallax, 2018).

LIDAR

Light detection and ranging (lidar) is a sensor that emits certain wavelengths of light to detect objects. Lidar measures the time it takes for the beam of light to be reflected back to the sensor from the object (the reflector). Lidar works similarly to radar, with the main difference being the use of light waves instead of radio waves to detect the objects. Using the travel time of light, the angle at which the light was emitted, and the sensor location, the three-dimensional coordinates of the object are determined (NOAA, 2012). The pulses of light have significantly smaller wavelengths than radio waves (1 µm vs 1 cm), which allows lidar to detect smaller objects (Schwarz, 2010). Lidar can also be combined with other sensors to obtain more reliable data. For instance, lidar combined with radar improves the precision of speed data (Göhring et al., 2011).

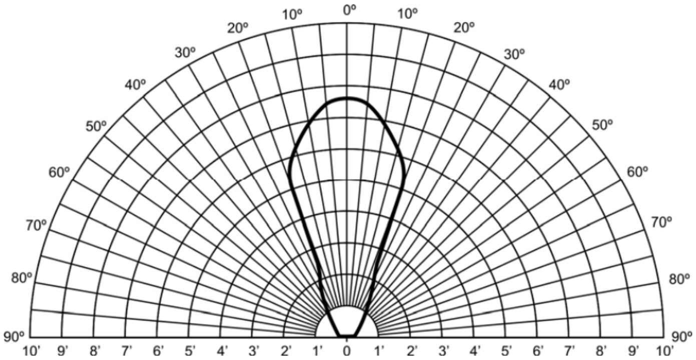

Figure 4. Photo. Nonuniform beam-pattern sample of an ultrasound sensor for the detection of a cylindrical target of 3.5 in. (8.9 cm) diameter and 4 ft (121.9 cm) height (Parallax, 2018).

Lidar was initially used for collecting elevation data at high speed. Example of current lidar applications include building extraction, 3D-asset collection, mapping, robotics, surveying, autonomous navigation, security, manufacturing, automotive safety systems, flood-insurance-rate maps, forest and tree studies, and costal change mapping (NOAA, 2012; Schwarz, 2010). In the transportation industry, lidar has been used to classify vehicles in traffic analysis (Lovas et al., 2004); to detect the road-surface profile and road edges (e.g., curbs) (Zhang, 2010); and more recently, by autonomous vehicles to detect objects. Airborne lidar, one of its initial types, can be processed to create surfaces, which, at the same time, can be used to create contour lines and include intensity values among other attributes (NOAA, 2012).

In road transportation, a highway network can be planned, designed, constructed, and maintained with measurements from a lidar attached to a vehicle moving at highway speed (called mobile lidar). The most important traits of data for this kind of application are accuracy and point-cloud density (Olsen et al., 2013). For the cloud of points, there are requirements regarding accuracy and density. Density refers to the quantity of points per unit area (FHWA, 2016). There are three types of accuracy: (1) network accuracy, which is the difference with respect to the geodetic datum; (2) absolute accuracy, or accuracy without using geodetic datum; and (3) local accuracy, the uncertainty in coordinating the points with respect to each other.

In autonomous vehicles, lidar use can be grouped in three categories: perception, localization, and navigation (Eldada, 2017). Lidar can be used for lane-keeping, parking assistance, blind-spot detection, adaptive cruise control, traffic-jam assistance, front–rear collision avoidance, cross-traffic alert, intersection-collision avoidance, autonomous emergency braking, emergency steering assistance, object detection, object tracking, object identification, scene capture, and accident reconstruction.

When applied to autonomous vehicles, lidar is called a mobile lidar system (MLS), which is different from an airborne lidar system (ALS). First, the uniformity of the point cloud density is greater in an ALS. However, the closer distances in AV applications (around 100 m) allow for higher cloud density. Even though ALS has a larger laser footprint, MLS can measure in locations difficult to access, such as under bridges and in tunnels; and it can better identify steep terrain (Olsen et al., 2013).

Despite its numerous advantages and high potential, lidar has also drawbacks including its high cost. One of the most significant limitations is that the light lidar emits can be distorted by environmental effects such as clouds (important for aerial applications), rain, and dense haze (NOAA, 2012). In addition, objects not in the line of sight cannot be captured, not to mention that very reflective objects located at short distances can be hard to capture. This drawback is observed, for example, with dark surfaces at long distances because they do not reflect light very well. The quality of lidar measurements is also compromised when the pavement is wet and where refraction is an important factor (e.g., the presence of steam, precipitation, or heat rising from surfaces). Finally, MLS cannot penetrate water; and it is limited to a narrow window of operation, with a range between 50 and 100 meters (Olsen et al., 2013).

CAMERAS

Cameras capture images from the surrounding environment in AVs. Compared to commercial cameras, AV cameras have a larger pixel size to enhance sensitivity to low light and have lower resolution and faster responses (Tummala, 2017). Some approaches in AV technology claim that a car can “see” using only cameras. However, the most common approach is to complement cameras with other sensors such as lidar and radar (Quinn, 2017). Cameras are the most advanced technology for object classification because they can capture texture, color, and contrast. In addition, cameras’ resolution keeps increasing at a high rate, making them very cost-efficient (Osman, 2017). The field of view of a camera determines its range, with medium-range cameras having a horizontal field of view between 70° and 120°.

The main advantage of cameras lies in the ability to process a lot of information related to lane markings and road signs because cameras can process colors. Machine learning is used to expand this capability to applications such as differentiation between cars and pedestrians. In addition, cameras are cheaper than lidar. The ability to process a huge number of images obtained by the cameras comes at the cost of high computational efficiency. Another disadvantage of cameras similar to lidar is the susceptibility of a camera’s reading to various weather conditions like rain and fog. In addition, cameras have difficulty in capturing an object under poor lighting conditions (Quinn, 2017; Tummala, 2017).

Multiple advancements in connected and autonomous vehicles have been made possible by cameras. For instance, some adaptive cruise controls rely on cameras for detecting and classifying different vehicles (cars, trucks, and motorcycles) and driver behaviors (brake lights and turn signals). The classification has been possible because of the evolution of cameras and algorithms that process the information captured by cameras. Similarly, the ability of traffic-sign recognition to read posted speed limits and of a lane-keep system to detect lane markings is from cameras (Osman, 2017). Tesla's autonomous vehicles are equipped with eight cameras that provide a 360-degree view and a range up to 250 m (Lambert, 2016). The camera locations include rearward-looking side, wide-forward, main-forward, narrow-forward, and forward-looking side cameras (Figure 5).

One of the approaches using cameras to identify objects is edge detection. In this approach, edges of an object are identified based on the change of color from one pixel to another one adjacent to it. In the case of autonomous vehicles, this approach can be used to determine the presence of a truck or a pedestrian by drawing its outline. There are two disadvantages to edge detection. First, if the light conditions are low, the edges become almost impossible to identify because the pixel-to-pixel difference is not significant. Second, the information collected requires a lot of computational effort to be interpreted and translated into an action quickly (Tufts, 2017). Edge detection can be improved using algorithms to classify images. For instance, the algorithm can identify road signs and the type of road sign. Such classification is achieved by comparing the image from the camera to a set of known images stored in the computer (Tufts, 2017).

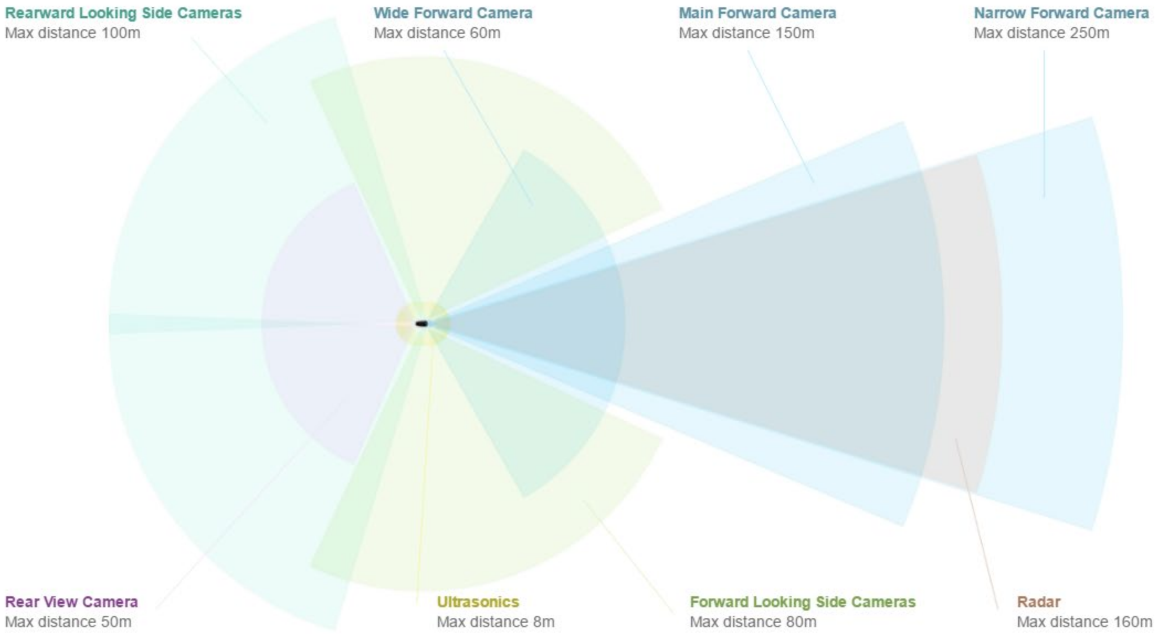

Figure 5. Photo. Tesla's camera system (Lambert, 2016).

Cameras require high computational power because the central control unit processes raw data from four to six cameras. In some situations, additional hardware is required for accelerating computations. However, these systems have the disadvantage of causing high power loss. Also, some data-compression methods are used to help image processing, but they require a large storage capacity. Due to these challenges, approaches that distribute image processing between the cameras and an engine-control unit are expected to dominate by 2020 (Rudolph & Voelzke, 2017).

In summary, cameras can improve CAV navigation at a lower cost than lidar. However, it poses challenges such as higher computational cost and sensitivity to low-light conditions.

GLOBAL POSITIONING SYSTEM (GPS)

The global positioning system (GPS) is a satellite-based positioning system that provides users with a precise location in three dimensions. GPS is one of the global navigation satellite system (GNSS) that is operated under the Department of Defense (DoD) by the U.S. Air Force. The GPS started as a test program using ground-based transmitters at the U.S. Army Proving Ground at Yuma, Arizona, in 1973. The first satellite was launched in 1978; and in July 1995, GPS met all the requirements for full operational capability, with 24 satellites in orbit (Dana, 1997; GPS, 2018).

DoD defines three segments of GPS: control, space, and user segments. The control segment consists of a global network of ground-monitoring stations located in various regions of the world, as shown in Figure 6. When the GPS satellite passes overhead, these stations provide command and control of the GPS constellation, compute the precise location of the satellites, and ensure the constellation accuracy, as well as its health. In addition, these stations also perform maintenance and anomaly resolution for the satellites (GPS, 2018).

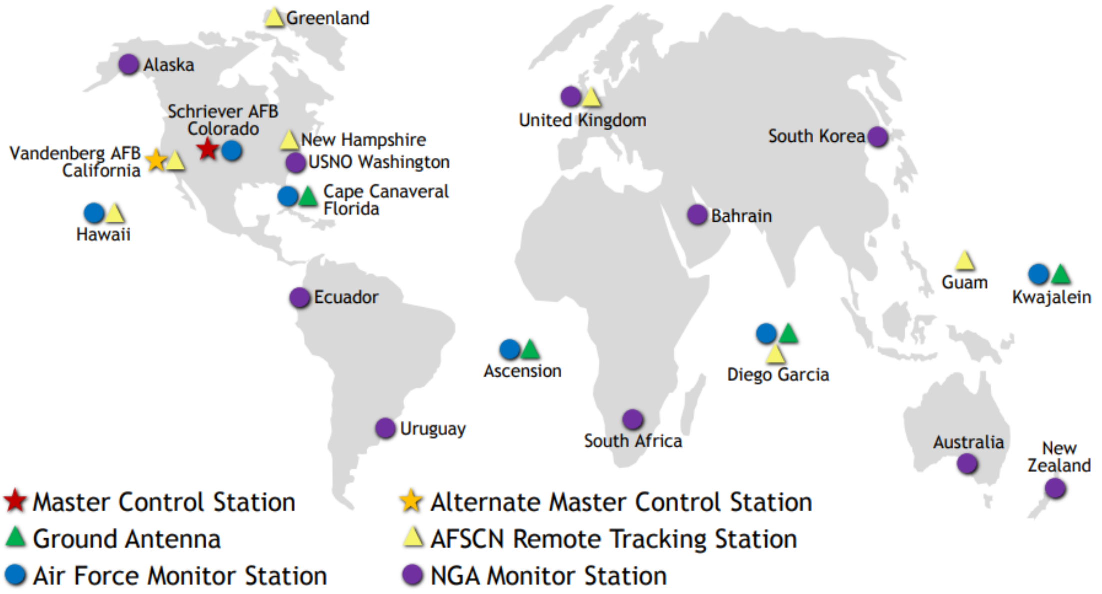

Figure 6. Photo. GPS control segment (GPS, 2018).

The space segment currently consists of 31 satellites about 12,550 mi (20,200 km) above the earth's surface. These satellites revolve around the earth in six quasi-circular orbit planes inclined at a 55-degree angle, forming a GPS constellation, as seen in Figure 7. The constellation provides worldwide coverage, with at least five satellites visible from any point on the earth. Each satellite revolves around the earth in 12-hr intervals (Dana, 1997; GPS, 2018). Each GPS satellite continuously broadcasts signals at two microwave frequencies in the L-band: L1 (1,575.42 MHz) and L2 (1,227.6

MHz). Satellites encode signals using pseudorandom noise (PRN). The navigation message also consists of orbital data and satellite-clock offset.

The user segment is composed of the receivers used by agencies or individuals. Civil, commercial, and scientific users have access to the standard-positioning service, while the US military has access to secure GPS precise-positioning service. In May 2000, the US government ended the use of selective availability that intentionally degraded civilian accuracy on a global basis. Consequently, the user-range error of GPS signals is the same for civilian and military.

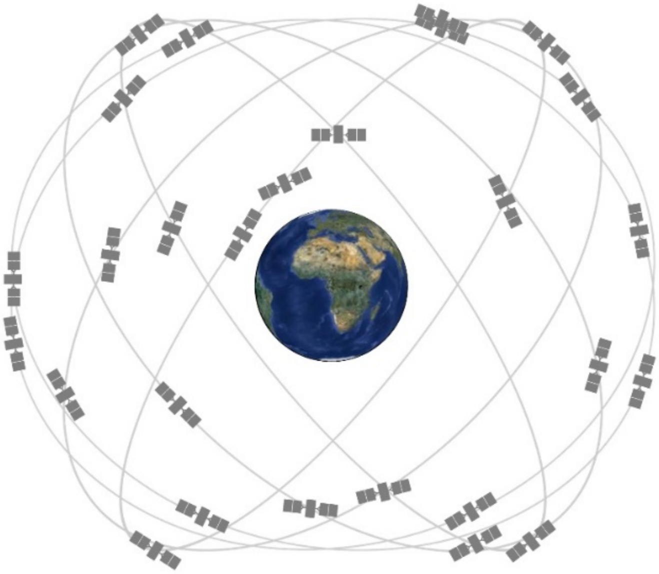

Figure 7. Photo. GPS constellation (GPS, 2018).

GPS satellites broadcast radio signals with information about their exact locations and precise time of broadcast (*t*1) from an onboard atomic clock. These GPS radio signals travel at the speed of light (c) through space and are received by the GPS receiver device. The GPS receiver notes the exact time of arrival (*t*2) and uses these two times to compute the distance from each satellite in view simultaneously. Distance is computed as a product of the speed of light and the travel time (given by *t*2 – *t*1) of the radio signal. Four satellites are used to solve for the position and exact travel time, correcting for the influence of the ionosphere on transmission-path delays.

Using the distance from each satellite, a range sphere is computed around the satellites. The intersections of these spheres give the receiver’s location (see Figure 8). Based on the broadcast message, the satellite position (as well as the receiver’s position) can be estimated as latitude, longitude, and elevation (Dana, 1997; Parkinson & Spilker, 1996).

The biggest advantage of GPS is the ability to enable real-time positioning within a few centimeters due to the implementation of dual-frequency receivers and/or augmented systems (GPS, 2018). In vehicles, differential GPS aids in localization of the vehicle to find its position in the road lane (Aeberhard et al., 2015). In addition, the government commits to broadcast signals that limit user-range error to less than 7.8m (25.6 ft) with 95% probability. On May 11, 2016, the average global user-range error was less than 0.715 m (2.3 ft) with 95% probability (GPS, 2018). However, the accuracy depends on the receiver capability of using dual-frequency, which is more expensive than a single-frequency receiver. In addition, signal blockage due to weather conditions, poor receiver condition; faulty software; radio interference; a gap in coverage due to satellite maintenance; signals reflected from buildings and other structures; and the presence of large obstacles like buildings, bridges, trees, and tunnels cause inaccuracy in the measurements (Dana, 1997; GPS, 2018; Rodríguez-Pérez, 2007).

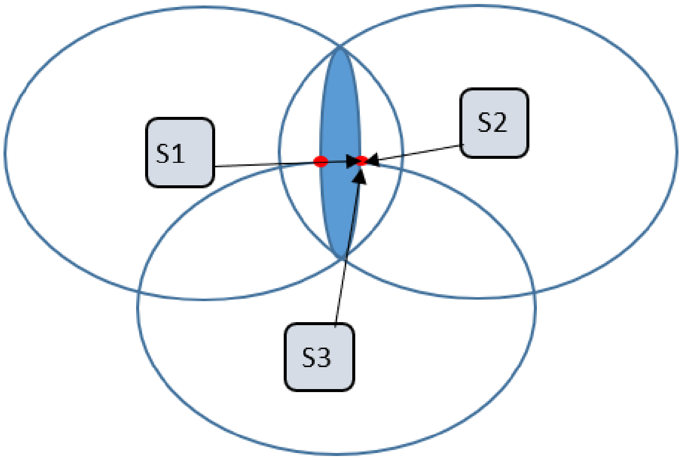

Figure 8. Photo. Three satellites (S1, S2, and S3) with range spheres. Intersection of two range spheres form a plane denoted by an elliptical blue area, and the intersection of three range spheres forms points denoted by red dots.

INERTIAL MEASUREMENT UNITS

An inertial measurement unit (IMU) measures the type, rate, and direction of motion in the vehicle; and it is composed of accelerometers and gyroscopes. The accelerometer, as its name indicates, measures the nongravitational acceleration of a body. When the body vibrates, the force created is measured. Because the mass is constant, the acceleration can be determined (Hazry et al., 2009).

IMU's main advantages stem from its light weight, portability, and ease of use. In addition, IMU does not need another sensor such as a camera to provide an accurate reading (Oberlander, 2015). IMU monitors the vehicle's movement in the environment where it is traveling, which changes continuously. IMUs also provide information to other sensors in the autonomous vehicle to improve accuracy and reliability. Some other functions of IMUs in autonomous vehicles include determination of location, position in the road, direction, orientation, and velocity (OXTS, 2016).

Accelerometers can be open- or closed-loop. In the open-loop type, the mass in the accelerometer can be displaced; so, the motion is measured directly. In the closed-loop type, the mass cannot move; and the force to prevent movement is recorded (Oberlander, 2015). The gyroscope measures the orientation based on the earth's gravity. The IMU can be designed to measure the translational and rotational motion in the six degrees of freedom by manipulating the amount, location, and alignment of the accelerometers and gyroscopes (Hazry et al., 2009; Starlino, 2009).

Some IMUs also incorporate magnetometers to enhance the accuracy of the readings coming from the accelerometer and the gyroscope. The magnetometer is a sensor that is sensitive to the magnetic field and provides the orientation of an object with respect to the earth's magnetic north. The orientation of the object instrumented with IMU is obtained from the measurements of the magnetometer and the accelerometer. This first step is performed while there is no translation. After motion begins, the gyroscope updates the orientation of the object. The size of the IMU can affect accuracy and resolution. If the IMU is too small, accuracy and resolution can be compromised. Sometimes, this drawback is overcome by having redundant measurements (e.g., multiple accelerometers and gyroscopes) and implementing robust sensory fusion (Technaid, 2004).

RADIO-FREQUENCY IDENTIFICATION (RFID)

Radio frequency identification (RFID) is a technology that wirelessly detects and responds to electromagnetic signals. RFID consists of three main components: (1) transponder, (2) reader, and (3) antenna. Transponders contain unique information stored in a microchip. Usually, the transponder is passive when it is not within the interrogation zone created by the reader. When the reader supplies the power necessary to activate the transponder in an interrogation zone, the transponder is activated. The reader usually consists of a radio-frequency modulator (transmitter and receiver) and a control unit. The reader also includes a system to communicate data to the computer or other system. Both transponder and reader have antennas to establish communication. Performance of the system depends on the size of the antennas (Finkenzeller, 2003; Domdouzis et al., 2007).

RFID dates back to the origin of radar technology. During World War II, the Allies used the identify-friend or foe (IFF) transponder developed by the British to identify friendly aircraft. Such aircraft were equipped with transponders that responded appropriately to the interrogating signal from a base station (Domdouzis et al., 2007; Chawla & Ha, 2007; Dobkin, 2012). Decades of research, especially in the 1960s and 1970s, lead to commercial use of such systems in the 1980s, including traffic--management systems and electronic toll collection. Commercialization expanded in the 1990s and 2000s with diverse applications such as supply-chain management, retail systems, oil refineries, construction sites, and tracking of buried objects (Domdouzis et al., 2007; Chawla & Ha, 2007).

RFID can be divided into two main classes, based on how the energy supply of the transponder works: active or passive (see Figure 9). Active transponders have their own energy supply in the form of a battery or solar cell. A built-in power supply increases the range of the system, as the tags do not depend solely on the electromagnetic field created by the reader to be activated. In addition, signals can be transmitted even when they are not in the reader's range (Finkenzeller, 2003; Domdouzis et al., 2007; Chawla & Ha, 2007). Active tags can also have additional sensing capability, as well as operate in harsh environments. By contrast, passive transponders do not have any power-supply source, which increases their flexibility and longevity. The reader's electromagnetic field provides the energy for operating the transponder and sending the data. If the transponder is outside the reader's range, the transponder is not able to send a signal due to a lack of power (Finkenzeller, 2003; Chawla & Ha, 2007; Want, 2006).

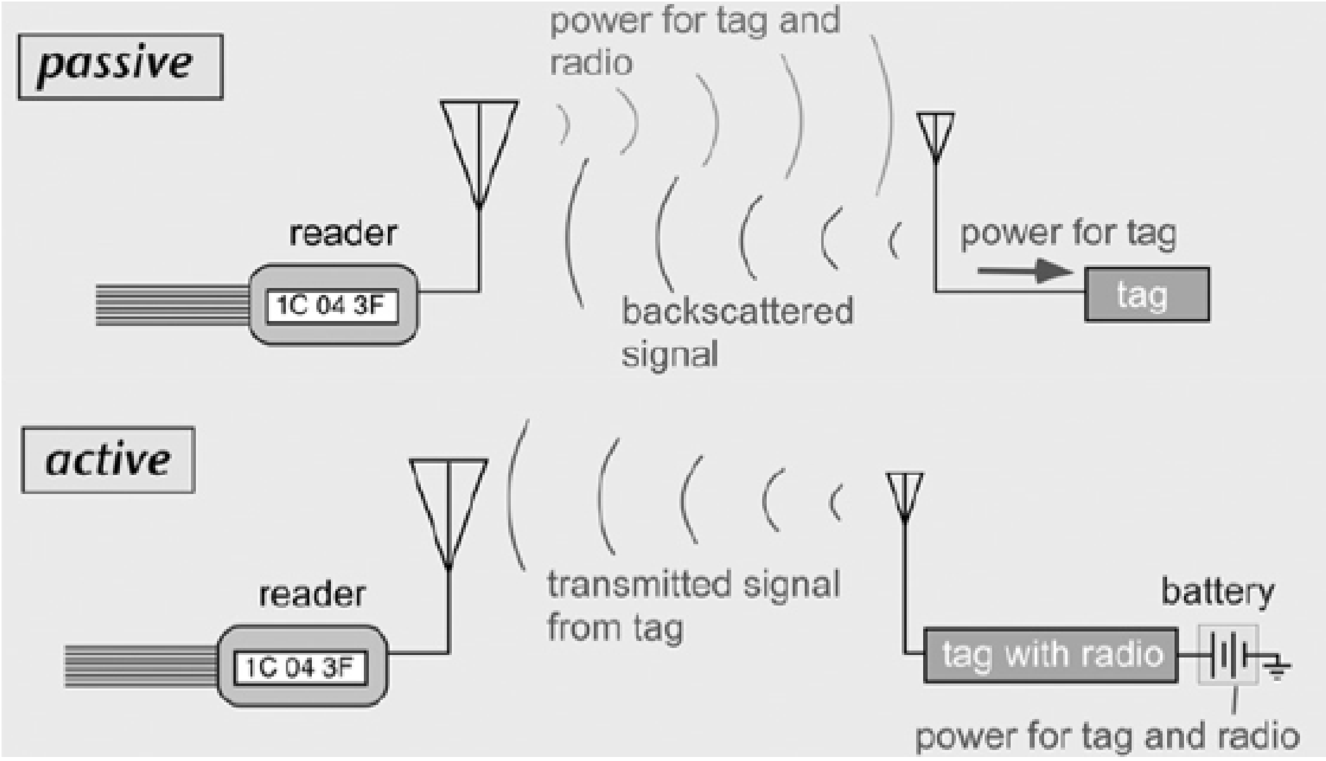

Figure 9. Photo. Passive and active powering of tags (Dobkin, 2012).

In addition to tag type, two approaches are based on the power transfer from reader to tag: near-field RFID and far-field RFID. Both approaches transfer power to a remote tag to sustain the operation of the tab, using electromagnetic properties associated with radio-frequency antennas. Far-field operates on frequencies greater than 100 MHz and typically in the ultrahigh frequency (UHF) range (such as 2.45 GHz). The domain of near-field coupling is below these frequencies.

Near-field coupling is based on Faraday's principle of magnetic induction (Figure 10). A reader passes an alternating current through the coil to generate an alternating magnetic field around it. As the tag approaches this alternating magnetic field, an alternating voltage is induced in the coil of the tag. When such alternating voltage is rectified and stored in capacitor, a charge reservoir that powers the tag chip is created. Current flow in the tag coil creates a small magnetic field around it that opposes the reader's field. Because the current is proportional to the load applied to the tag's coil, the process is known as load modulation. By encoding the signal as small variations in the magnetic field of the tag coil, the reader can recover the signal and detect the tag ID.

Far-field coupling uses electromagnetic waves from a reader's dipole antenna (Figure 11). The tag receiver captures the energy as alternating potential difference between the arms of the dipole antenna. A diode rectifies this potential and stores it in a capacitor. After enough energy is accumulated, the stored energy is used to power the electronics. The process of backscattering is used for communication, as the tags are beyond the range of the reader's electromagnetic field. The antennas are designed with precise dimensions and are tuned to a particular frequency to absorb most of the energy at that frequency (Want, 2006). However, if an impedance mismatch occurs at this frequency, the antenna reflects little energy toward the reader. By changing the antenna impedance over time, the tag reflects the signal in a pattern that is encoded in the tag ID.

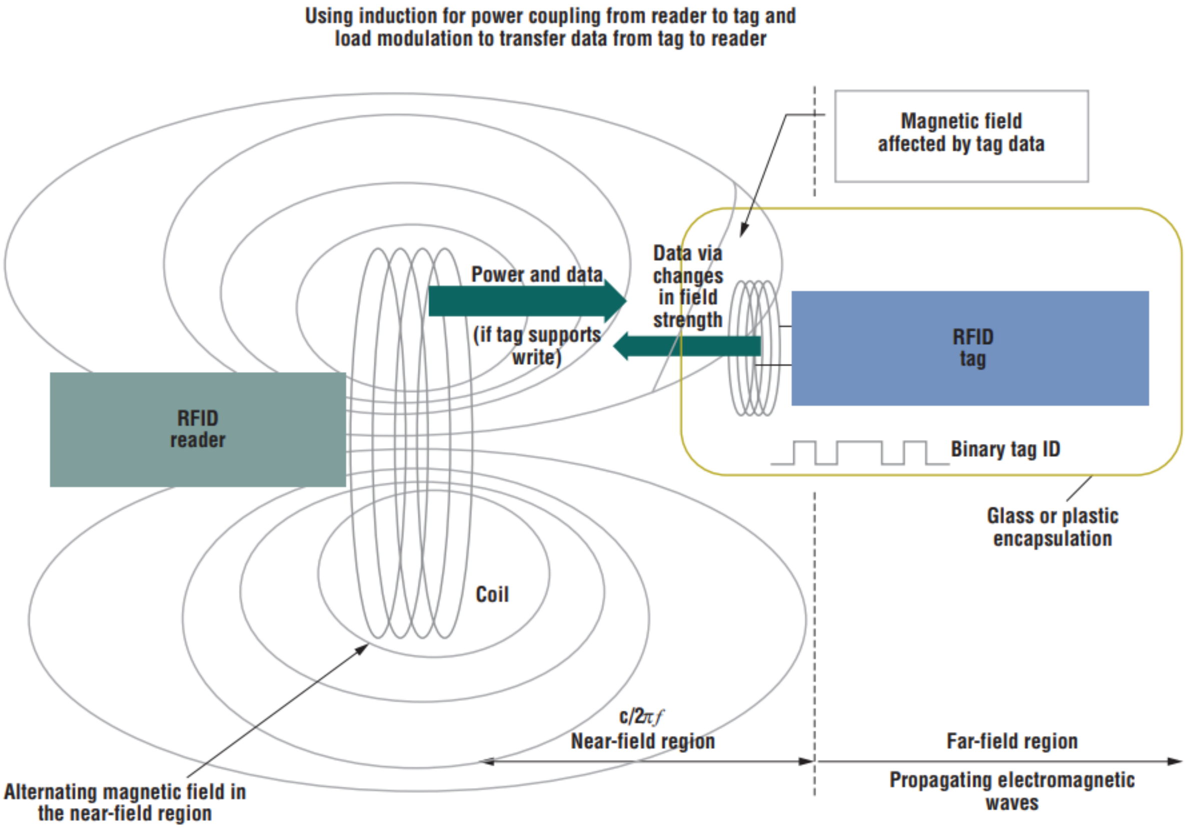

Figure 10. Photo. Near-field communication mechanism for RFID tags at less than 100 MHz (Want, 2006).

RFID has significant potential due to the development of inexpensive radio receivers and decreases in the power requirement for the tag at a given frequency as a result of the shrinking feature size of semi-conductor manufacturing. The lower power requirement also helps in reading at greater distances. A typical far-field reader interrogates tags that are 3 m away, with some companies claiming a 6-m range (Want, 2006). These features allow RFID applications such as toll collection (Dobkin, 2012).

There are some limitations of near-field and far-field coupling. The range of operation is limited by the frequency and amount of energy received by the tag, as well as the sensitivity of the radio receiver to the received signal. Signals are attenuated at a higher rate when the distance increases (Want, 2006). Moreover, for automotive applications, there are challenges of reading collocated tags, debris or metal interference, difference in stationary and in-motion reading conditions, and the presence of water or snow during adverse weather conditions.

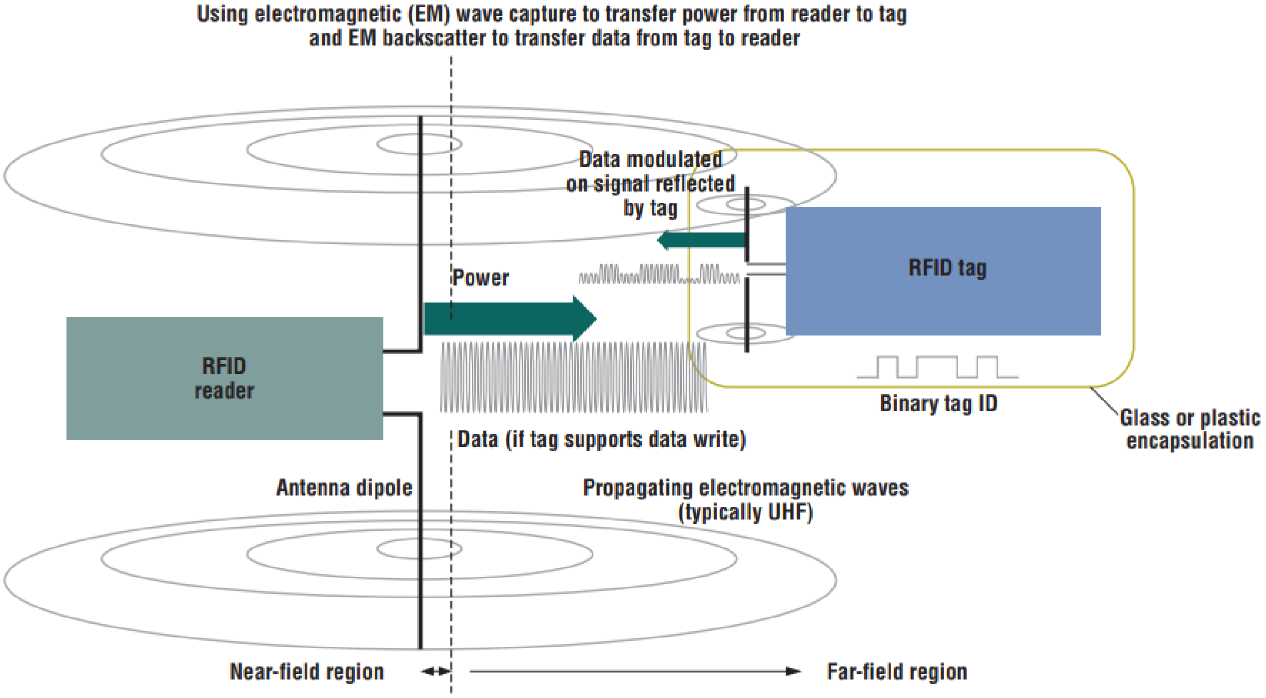

Figure 11. Photo. Far-field communication mechanism for RFID tags at great than 100 MHz (Want, 2006).

CAPACITIVE PROXIMITY SENSOR (CPS)

Capacitive proximity sensors (CPS) are mostly used for contactless function activation in the interaction between vehicle and driver, and they belong to a larger group of sensors called proximity sensors. Proximity sensors are of four main types: inductive, capacitive, ultrasonic, and optical (Rajan, 2015). The main component in a CPS is a capacitor, a device that stores electrical energy or charge in two plates for a prolonged time. The capacitor is characterized by the amount of charge it can hold for a given voltage, which is called the capacitance (Terzic et al., 2012). The plates are electrodes separated by a dielectric, which is a nonconductor. The ability of the CPS to detect an object depends on the dielectric constant of the object: the higher the dielectric constant of the object, the easier it is to detect. The presence of an object is detected by a CPS without any contact by reading changes in the returned signal that the CPS emits. The maximum distance at which a CPS can detect an object can be designed, and it varies between 5 and 40 mm.

The main advantages of CPS include low cost, low power consumption, and the fact that it can detect metallic and nonmetallic objects (Rajan, 2015). In addition, CPS has high reliability and a long life because it does not have mechanical components; and it does not need physical contact to operate (Terzic et al., 2012). By contrast, as in the case of the other sensors discussed, its main disadvantage lies in the fact that it can be affected by environmental conditions such as temperature and humidity (Rajan, 2015).

In AV, the main application of CPS is found in human–machine interface. CPS is used to activate an audio panel based on proximity of the hand, responding to specific 3D gestures, such as scrolling or sideways wiping, and a keyless entry system (Noopuran, 2014). In addition, CPS can replace switches; and it can monitor liquid levels in the vehicle, such as fuel, brake fluid, and coolant (Arora & Verman, 2011).

Table 1 presents a summary of the sensors considered, listing their main advantages and disadvantages.

Table 1. Advantages and Disadvantages of Various Sensors Already Used or Applicable in AV

Sensor	Advantages	Disadvantages
Radar	• Provides an object's distance and velocity • Less sensitive to weather conditions such as rain and snow but not fully weatherproof. • Moisture in the air reduces the range of detection. • Low cost. • Can be mounted behind an electromagnetically transparent material for aesthetic purposes.	• Low lateral resolution, so a large number of sensors is needed for better coverage. • An electric conductor can block or shield the signals. • Communication interference is possible, due to cross talk between sensors. • Blind to electromagnetically transparent objects.
Ultrasonic	• Well-researched and -applied technology • Very good for close-range object detection, therefore useful for slow-speed movement and parking.	• Wave propagation depends on pressure and temperature, so it is affected in areas of high wind. • Detection depends on the distance, shape, and size of the object.
Lidar	• Provides very precise distance • Helps in multiple safety features, such as lane-keeping, front–rear collision avoidance, blind-spot detection, cross-traffic alert, and object-tracking.	• Very high cost. • Waves are distorted by environmental conditions such as rain or dense haze. • Objects should be in line of sight. • Difficulty in dark condition for long distance.
Camera	• Processes information about lane marking, road signs, etc., to help safe navigation. • Advancement of machine-learning and deep-learning algorithms help detect vehicle types, pedestrians, and other road features.	• Data processing is computationally expensive. • Susceptible to weather conditions such as rain, fog, and poor light conditions.

Sensor	Advantages	Disadvantages
GPS	- Real-time accurate positioning of vehicles within a few centimeters accuracy with appropriate device.	- Signal blockage due to weather conditions, faulty software, poor receiver condition, radio interference, lack of satellite coverage, or signal obstruction causes error in reading or no reading.
IMU	- Weather-independent - Not affected by any dynamic driving condition, such as other vehicles, pedestrians, etc. - Provides redundant location information based on movement of the vehicle, from internal readings.	- Does not interact with dynamic environment and assists the navigation by internal reading based on movement of the vehicle.
CPS	- Mainly applicable in human–machine interface where human gestures can control various actions. - Reduces human distraction.	- Not entirely applicable in navigation safety.
RFID	- Can improve readings in adverse weather conditions at the expense of power from the vehicle to read information stored in transponders. - A technology widely in use in other applications.	- A new type of sensor that is not currently used in AV. - A large number of transponders need to be embedded within the pavement. - Information stored in the transponder might need to be modified in different locations, making it very difficult for large-scale implementation.

CHAPTER 3: MODIFICATIONS FOR VEHICLE–INFRASTRUCTURE COMMUNICATION

Communication between infrastructure and vehicles is important for successful deployment of autonomous and connected vehicle at a large scale. However, current infrastructure does not provide assistance for the vehicles to control, guide, and navigate safely and efficiently if inclement weather occurs or primary navigation features fail. The physical infrastructure should be modified so that sensors in autonomous vehicles can detect the roadway and roadside in a way that improves the safety of the vehicle under all conditions.

In the specific case of pavements, the control, maneuver, and lateral positioning information can be delivered to the vehicle by modifying pavement's material properties or by using passive sensors. Magnetic, conductive, thermal, and optical properties of the pavement can be modified to assist in safe navigation by placement of aggregates with distinctive dielectric and magnetic properties. By contrast, passive sensors do not require extra electric power; and they can be embedded in the pavement to be interrogated by readers on the AVs. For instance, sensors such as passive RFID can be embedded to provide an extra layer of safety during adverse weather conditions such as heavy rain, fog, and snow. These modifications can be implemented during construction of new roads or while retrofitting existing pavements.

MATERIAL MODIFICATIONS

Aggregates influence most of the paving material's properties. In conventional pavements, aggregates with same properties are used throughout the depth and width. Strategic modification of pavement by placement of aggregates with certain dielectric or magnetic properties can create a signature (e.g., electromagnetic or thermal) that can be read by autonomous vehicle sensors to find the edge or center of the road. Detection of pavement boundaries can help in lateral positioning CAVs during driving. In addition, systematic location of such signatures during pavement construction also reduces the computational effort to detect road boundaries. These modifications can be implemented during the construction of new pavement, whereas existing pavements can be milled and filled with appropriate material to provide the distinctive properties that are different from those of standard paving materials. Distinct materials can be placed on either the boundary or the center of the lanes, as noted in Figure 12.

The distinctive material can consist of modification to electromagnetic, thermal, and optical properties of the pavement. Details of each type of property are discussed further in this chapter.

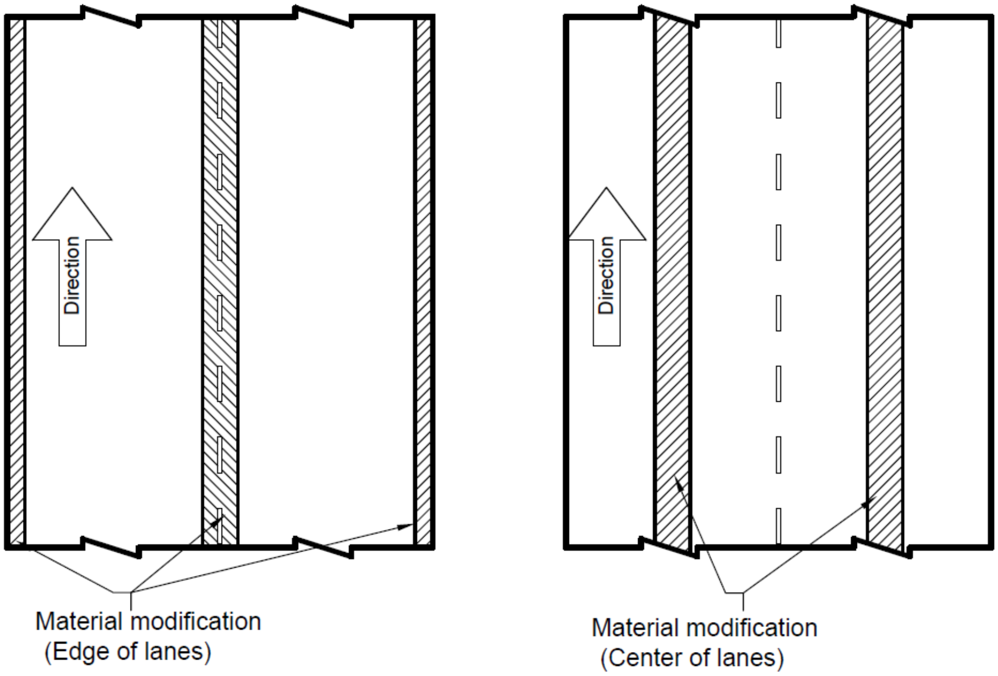

Figure 12. Photo. Material modification on the edges of the lane (left) and the center of the lane (right).

Electromagnetic Properties

Various approaches can be adopted for modification of electromagnetic properties in pavement such as (1) use of aggregate with distinct electromagnetic properties such as steel; (2) use of steel-fiber-reinforced concrete; (3) electrification of rebars in some pavement types, such as continuously reinforced-concrete pavements; (4) use of magnetic epoxy; and (5) installation of thin metallic strips or magnetic tape embedded in the pavement that creates an eddy-current effect to provide the electromagnetic signature that assists in vehicle maneuvering.

The electromagnetic property can be detected by radar. Alternatively, eddy-current technique or magnetometers can be used, which are potential future sensor for CAVs. Array of multiple sensors at different widths of the vehicle could be used to receive the signal from the modified material. Locations with a distinctive electromagnetic material reflects higher energy or affects magnetic field around it, as compared to normal pavement material, as shown in Figure 13. Using the eddy-current method creates a varying magnetic field that induces eddy currents in materials such as magnetic epoxy or other electromagnetic material embedded in the pavement, as shown in Figure 13. The higher reflected signal or the disturbance of the magnetic field helps to localize a vehicle upon the pavement.

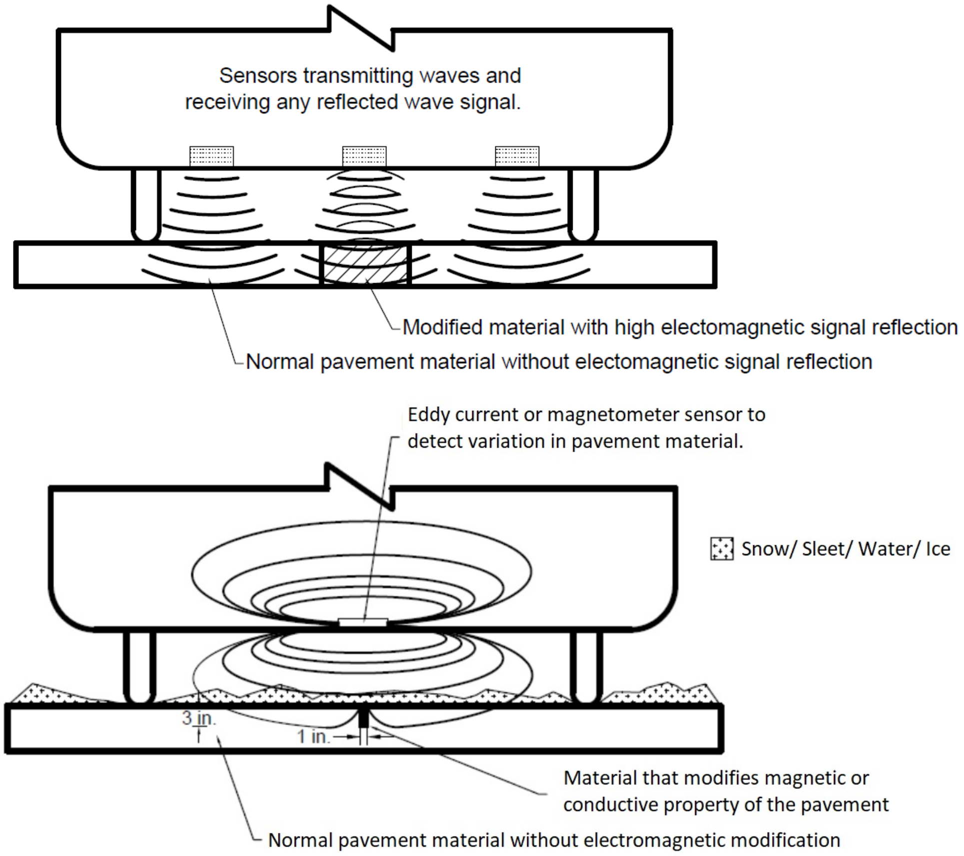

Figure 13. Photo. Use of radar (on top) and eddy-current or magnetometer method (bottom) to detect various materials of different electromagnetic properties in the pavement.

Optical Properties

Optical properties of the pavement can be also changed to help the vehicle maneuver safely and determine its lateral position in the lane. Transparent/translucent concrete mix or epoxy can be used strategically to help the vehicle. A notch can be made and filled with transparent/translucent concrete that allows light to pass through. Lidar or laser device array can be used to determine the location by measuring the depth from the vehicle to the pavement surface, as demonstrated in Figure 14.

Thermal Properties

Similar to its electromagnetic and optical properties, pavement’s thermal properties can be used to determine the location of a vehicle. Strategic location of the aggregates with different thermal diffusivities can help to distribute the heat at different rates throughout the pavement. The heat map can be identified by a thermal camera to determine the location of the vehicles.

Specifically, asphalt concrete (AC) and Portland cement concrete (PCC) have different thermal diffusivities. This difference can be exploited to create a thermal pattern composed by a patch of asphalt along the boundaries of a concrete pavement, as seen in Figure 15. The resulting heat map can be used to enhance CAV navigation. The difference in thermal properties is also helpful when it is snowing and before the temperature of the pavement equilibrates. However, when the temperature of the pavement reaches a constant, for instance after a long winter, the heat map would not be able to differentiate between locations with different thermal properties.

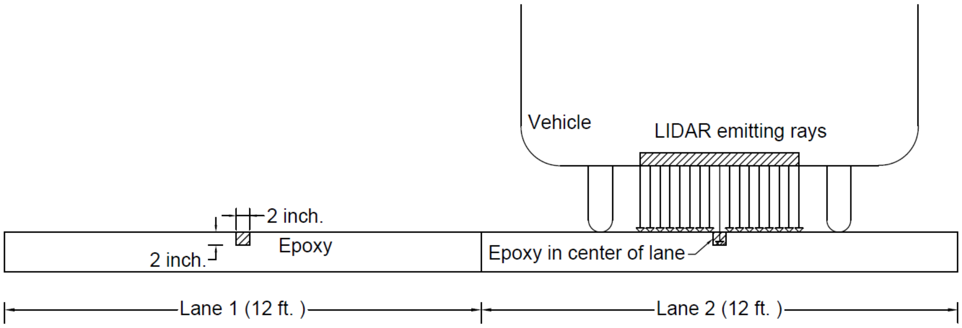

Figure 14. Photo. Two-lane road with a notch in the center of the lane, filled with transparent epoxy.

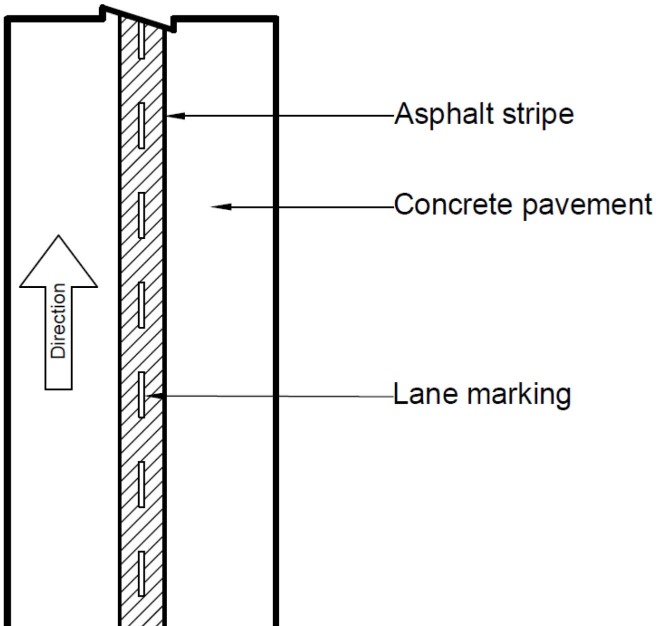

Figure 15. Photo. Asphalt patch on a concrete pavement, making sections of different thermal diffusivities.

EMBEDDED-SENSOR MODIFICATIONS

Pavements can be modified by embedding sensors that relay information to CAVs. Ideally, the sensors should be suitable for long-term use, while minimizing maintenance and construction associated with costly sensors. A sensor that does not require any external source of power would be optimal for vehicle and infrastructure communication. In addition, sensors that actively broadcast messages during adverse climatic conditions such as snow or heavy rainfall could also be mounted on roadside infrastructures like stop signs or traffic lights to enhance the safety of CAVs.

RFID Sensors

Passive RFID sensors embedded in the pavement can store information about the surrounding location to help CAVs navigate. The RFID sensors can have tags that read certain value, which can correspond to any particular method of determining the location of a vehicle in the transverse direction. In the example presented in Figure 16, the readings along the center of the lane correspond to the value 0, the reading on the right sensors increase by 1 ft, and the readings on the left sensors decrease by 1 ft. For a 12-ft-wide lane, there are 13 sensors per lane, which read from −6 on the left +6 on the right edge of the lane.

As most of the pavements are of standard width, such series of RFID can be mass produced with standard information stored and arranged in a sticklike fashion. The arrangement can be embedded in the joints or notched sections of pavements, which can be sealed after installation. When conditions become adverse, the vehicle can interrogate the RFID sensors by creating an influence zone, as seen in Figure 17. Table 2 presents a sample calculation of how such RFID sensors can help a vehicle navigate. Assuming two RFID readers on two wheels of the autonomous vehicle, the blue cells on the table represents the values read by each tire. For instance, the first reading indicates that the left wheel reads −6, while the right wheel reads 0 from the RFID sensors. When the average of these values are computed, the approximate center of the vehicle can be obtained.

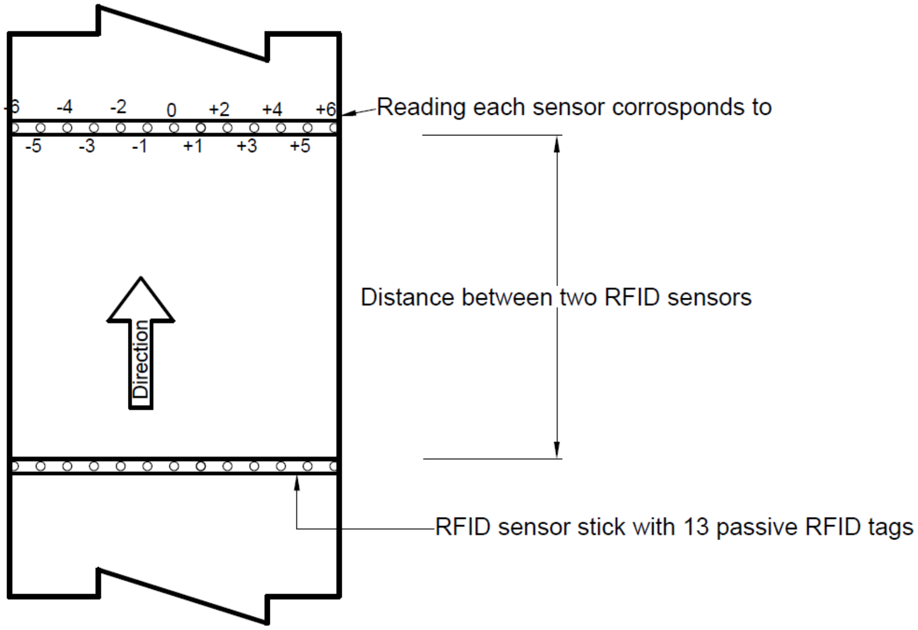

Figure 16. Photo. Plan view of RFID sensors embedded in the pavement.
Two RFID sensor sticks, with readings corresponding to each sensor in the stick.

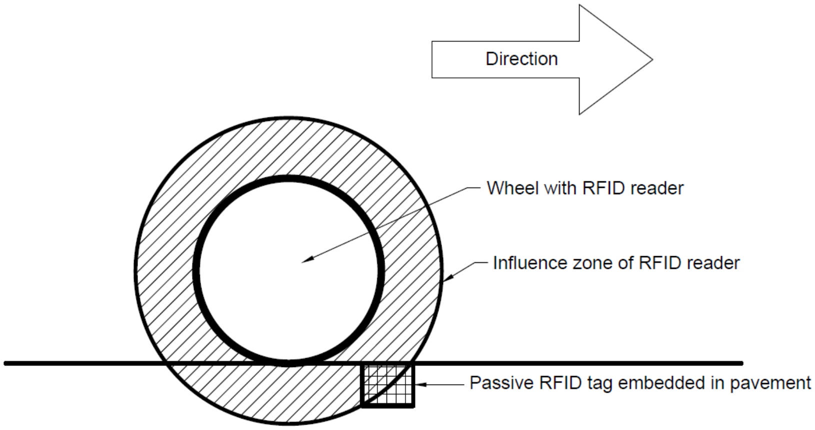

Figure 17. Photo. Side view of RFID sensor embedded in the pavement and influence zone created by RFID reader.

Table 2. Sample Calculation of How RFID Sensors Can Determine the Center of Vehicles, Using the Reading from Standard RFID Sensors Embedded in the Pavement

Distance of sensor from left edge of the lane														
0	1	2	3	4	5	6	7	8	9	10	11	12		
Values assigned to RFID sensor in transverse direction														
−6	−5	−4	−3	−2	−1	0	1	2	3	4	5	6		
Readings by RFID sensors in wheel (in blue) and center of the vehicle (yellow)													Sum of two wheel readings	Average (center of vehicle)
−6			🟨			0							−6	−3
	−5			🟨			1						−4	−2
		−4			🟨			2					−2	−1
			−3			🟨			3				0	0
				−2			🟨			4			2	1
					−1			🟨			5		4	2
						0			🟨			6	6	3

Table 3 summarizes the main ideas discussed in this chapter.

Table 3. Advantages and Disadvantages of Pavement-Material Modifications and Sensors

Properties/Sensor	Advantage	Disadvantage
Electromagnetic properties	• Radar/eddy-current methods are less affected by rain and snow. • Components (aggregates, rebar, fiber) already used in pavement construction	• Quality control during construction should be robust.
Optical properties	• Can be retrofitted in existing pavement by milling and pouring epoxy	• A problem if covered by snow or dust
Thermal properties	• Components already used in pavement construction.	• Sensor currently not used in AV; thermal camera needed • Less effective when equilibrium temperature is reached in a long winter/summer
RFID	• Communication during adverse weather like heavy rainfall or snow • Saves computational power for AV by providing exact information • Vehicles provide power, so passive sensors in pavement	• Extra cost during construction • Complexity can increase, depending on the information stored.

CHAPTER 4: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The most common sensors in connected and autonomous vehicles were reviewed, along with types of passive and active sensors that may be placed in the pavement. Finally, limitations of CAV sensors, especially during inclement weather were noted; and modifications to the pavement were proposed to enhance the navigation capabilities of AVs when their primary control, maneuvering, and navigation components are not functioning.

Eight sensors were reviewed: radar, ultrasonic sensor, global positioning system, radio-frequency identification, lidar, cameras, inertial measurement unit (IMU), and capacitive–proximity sensor. Each sensor uses a specific type of signal. Radio signals are used by radar and GPS to detect objects and determine location, respectively. Lidar and cameras are used to identify surrounding objects through light waves. Lidar uses beams of light for detection, while cameras provide functionality by processing images. RFID is mostly used for transferring information using electromagnetic signals that can be powered with an external reader. Finally, ultrasonic sensors use higher-frequency sound waves to calculate distance between objects; and IMU monitors vehicles' movements. Of the eight sensors, IMU is the only one not involved in CAV navigation, as it is mostly used for contactless function activation in the interaction between vehicle and driver.

A common drawback among all sensors was the sensitivity of their measurements to adverse weather conditions like fog, rain, ice, and snow. Several potential solutions were proposed based on infrastructure modifications, which can be divide into two broad categories. The first involves modification to pavement electromagnetic, magnetic, optical, and thermal properties. The second alternative is the use of RFID tags along the pavement to transfer infrastructure information to the CAV.

Based on the information collected, the following conclusions can be drawn:

- Adverse environmental conditions are among the main factors preventing the massive implementation of CAV for all roadway classifications and geographic locations in the United States.
- Magnetic and conductive properties modification of some existing infrastructure materials, such as aggregates, rebars, and fibers, can make specific regions in the pavement more identifiable beyond current optical camera techniques (e.g., lane edges).
- Modification based on optical properties can be implemented not only on new pavements but also on existing ones by milling and pouring epoxy. Potential issues that would cause technology not to function would be excessive snow and ice on the road.
- Asphalt concrete and Portland cement concrete are widely used infrastructure materials with different thermal diffusivities and reflectance properties. The difference can be exploited, so that a specific road region, such as the centerline, can be detected easily by its temperature and rate of temperature change.

- RFID can provide communication during adverse weather conditions like heavy rainfall or snow. In addition, RFID saves computational power; and CAV can provide power to passive sensors inside the pavement. These benefits would have to overcome the extra construction cost and maintenance.

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