Overview of Autonomous Vehicle Sensors and Systems

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ABSTRACT

This paper will identify the application of various technologies that enable autonomous vehicles and also explain the advantages and disadvantages associated with each autonomous vehicle sensor. Specific sensors and systems may show favorable results, but various factors can affect their real-world use. For this reason, each system will be reviewed for an understanding of their practical application.

INTRODUCTION

According to the NHTSA, 32,719 fatalities and 2.31 million injuries were caused by motor vehicle crashes in 2013. In similar motor vehicle accidents, the 1997 Tri-Level Study of the Causes of Traffic Accidents found that human errors were a definite or probable cause in 90-93% of the incidents examined. Autonomous vehicles have the capability of reducing and even eliminating the possibility of human error and could drastically change the dangers associated with motor vehicles. With the increased application of electronics in daily life and their increased use in the automotive world, it fosters improved safety, connectivity, and convenience.

The autonomous vehicle sensors and systems that will be discussed, but are not limited to, include RADAR, LIDAR, cameras (vision and thermal), ultrasonic, GPS, V2V, and the fusion of these signals [12]. To fully understand the architecture of autonomous vehicle design, a holistic view of the various sensors must be examined. By supporting various driver functions, each of these sensors and systems will be reviewed in their capacity for enabling autonomous vehicle design.

BACKGROUND INFORMATION

SENSOR CHARACTERISTICS

Before discussing the various sensors that exist within autonomous vehicle systems, it is important to describe the overall characteristics of these sensors from a high level prospective. The following technical characteristics play a key role in the selection of sensors in both individual and fusion applications [10]:

- *Accuracy*: The error between the true value and the sensor's reported measurement. This accuracy will be dependent on various factors including noise levels and external interference reduction parameters.
- *Resolution*: The minimum variance between two measurements, which is generally less than the actual accuracy of the sensor.
- *Sensitivity*: The minimum value that can be detected or measured.
- *Dynamic Range*: The minimum and maximum values that can be accurately reported.
- *Perspective*: This is generally conveyed as field of view.
- *Active vs. Passive*: An active sensor emits a form of energy to sense the environment, while a passive sensor relies on ambient conditions to provide information.
- *Timescale*: The refresh rate of the sensor and the frequency of the measurement bandwidth with time

- *Output Interface*: This can be understood as the output of the sensor which can be anything from an analog voltage, analog current, digital signal, serial, or network data stream.

SAFETY ADMINISTRATIONS

As manufacturers consider the application of various levels of autonomy into production vehicles, an important factor that weighs heavily on this decision are the mandates, guidelines and benefits the national and international safety administrations have placed. The two major agencies that have taken an approach to autonomous vehicles are the Euro NCAP, European New Car Assessment Programme, and the NHTSA, National Highway Traffic Safety Administration.

Euro NCAP

The Euro NCAP assesses the safety performance of new vehicles in the European market. With the acceleration of autonomy, they have developed a road map for autonomous vehicle systems and their expected capabilities. The safety assessments are broken up into two categories, ratings and rewards. In 2010, the reward system was created to compliment the rating system to provide an incentive for manufacturers to develop advanced safety systems. Many of these current rewards play a factor in scoring in the upcoming years. For additional information, see Figure 12 in the Appendix for the 2016-2020 scoring criteria. As of today, the following safety systems are given rewards by Euro NAP [5]:

- *Blind Spot Monitoring:* A system that alerts drivers based on camera, ultrasonic, or radar that there is another vehicle in their blind spot.
- *Lane Support Systems:* Any systems that aids in helping the driver stay in his or her lane. This is generally done utilizing vision systems or GPS. Lane departure warning provides either haptic, visual, or audible warning as the vehicle leaves the lane unintentionally, which is determined when turn signals are not used or no driver steering torque is felt. Lane keep assist take another step beyond lane departure warning by proactively providing steering torque to return the vehicle to its lane. However, most systems will only provide the torque for a small duration of time. If the lane keep system assesses the driver is not steering the vehicle for too long, it provides a more severe haptic and/or audible alert. These systems are not capable of providing a large amount of steering torque and are only meant to help guide the vehicle back into the lane if necessary.
- *Speed Alert Systems:* A system that visually displays the speed limit or even alerts the driver when the speed limit is exceeded. These systems utilize GPS information or in some advanced systems, they utilize cameras to detect traffic signs and report them to the driver. Advanced systems may even limit vehicle speed through adaptive cruise control or other means. Adaptive Cruise Control (ACC) is an adaption of the conventional cruise control system with the additional of modulating throttle and applying braking to vary the vehicle’s speed to follow the next closest in path vehicle.
- *Emergency Braking:* Utilizing radar, camera or LIDAR, this system detects potential collisions ahead and applies the brakes if necessary. Most systems utilize two levels of response. First, the system issues a visual and audible warning to the driver. If the driver does not respond by applying the brakes, the system intervenes and applies the brakes to reduce the severity of the detected accident.
- *Attention Assist:* Also known as drowsiness detection, this system alerts the driver if the driver appears tired. In current production systems, this detection is based on an algorithm of reoccurring lane departures, which requires at least a lane departure warning system for capability.
- *Automatic Emergency Call:* In an accident where the airbags are deployed, this system makes an automatic call to emergency services with the GPS location of the vehicle. This can save valuable time in accidents when every moment is crucial.
- *Pre-Crash systems:* These systems assess an imminent crash and take steps to ensure the occupants are optimally safe. This typically involves reducing slack in the seatbelt in varying degrees based on the predicted severity of the accident. Some systems can even adjust the seat position for optimal airbag deployment.
- *Vision Enhancement:* These systems take various steps to improve the vision of the driver in reduced visibility situations. Adaptive headlights vary the direction of the headlights around turns to provide

optimal lighting as the vehicle changes directions. Another example is night vision. Utilizing infrared light, night vision displays show the driver an amplification of objects based on thermal imaging.

- *Other Safety Systems:* For those systems that are not already quantified in the other categories, Euro NCAP takes the effort to still reward advanced safety systems with vehicle-specific endorsements.

NHTSA

NHTSA defines autonomous vehicles as "those in which at least some aspects of a safety-critical control function (e.g., steering, throttle, or braking) occur without direct driver input. Vehicles that provide safety warnings to drivers (forward crash warning, for example) but do not perform a control function are, in this context, not considered automated, even though the technology necessary to provide that warning involves varying degrees of automation (e.g., the necessary data are received and processed, and the warning is given, without driver input)." This paper will utilize a similar definition and will not go in depth on the HMI related to autonomous vehicles. NHTSA designated the following (abridged) levels of autonomy to clarify the topic for discussion [14]:

- *Level 0 – No Automation:* The driver is solely in control of the vehicle at all times. This vehicle never takes direct control of the vehicle controls (steering, throttle, or braking). The vehicle may have automated secondary controls such as wipers, headlights, turn signals, hazard lights, etc. Cruise control, because it simply holds a vehicle speed set by the user, is considered no automation as the user is still required to maintain control at all times.
- *Level 1 – Function-specific Automation:* Automation involving one or more specific control functions. If multiple control functions are utilized, they operate independently from each other. The driver has overall control, and is solely responsible for safe operation, but can choose to cede limited authority over a primary control (as in adaptive cruise control), the vehicle can automatically assume limited authority over a primary control (as in electronic stability control), or the automated system can provide added control to aid the driver in certain normal driving or crash-imminent situations (e.g., dynamic brake support in emergencies). The vehicle's automated system may assist or augment the driver in operating one of the primary controls – either steering or braking/throttle controls (but not both). As a result, there is no combination of vehicle control systems working in unison that enables the driver to be disengaged from physically operating the vehicle by having his or her hands off the steering wheel AND feet off the pedals at the same time. Examples of function-specific automation systems include: adaptive cruise control, automatic braking, and lane keeping.
- *Level 2 - Combined Function Automation:* This level involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions. Vehicles at this level of automation can utilize shared authority when the driver cedes active primary control in certain limited driving situations. The driver is still responsible for monitoring the roadway and safe operation and is expected to be available for control at all times and on short notice. The system can relinquish control with no advance warning and the driver must be ready to control the vehicle safely. An example of combined functions enabling a Level 2 system is adaptive cruise control in combination with lane centering. The major distinction between level 1 and level 2 is that, at level 2 in the specific operating conditions for which the system is designed, an automated operating mode is enabled such that the driver is disengaged from physically operating the vehicle by having his or her hands off the steering wheel AND foot off pedal at the same time.
- *Level 3 - Limited Self-Driving Automation:* Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions and in those conditions to rely heavily on the vehicle to monitor for changes in those conditions requiring transition back to driver control. The driver is expected to be available for occasional control, but with sufficiently comfortable transition time. The vehicle is designed to ensure safe operation during the automated driving mode. An example would be an automated or self-driving car that can determine when the system is no longer able to support automation, such as from an oncoming construction area, and then signals the driver to reengage in the driving task, providing the driver with an appropriate amount of transition time to safely regain manual control. The major distinction between level 2 and level 3 is that at level 3, the vehicle is designed so that the driver is not expected to constantly monitor the roadway while driving.

- *Level 4 - Full Self-Driving Automation:* The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. Such a design anticipates that the driver will provide destination or navigation input, but is not expected to be available for control at any time during the trip. This includes both occupied and unoccupied vehicles. By design, safe operation rests solely on the automated vehicle system.

INTERNAL VEHICLE SYSTEMS

Many of the inputs utilized by autonomous vehicle systems are based on already present sensors and systems. These signals are readily available on the vehicle's CAN and are utilized to provide vehicle information and are also utilized to generate responses based on autonomous vehicle sensors outputs. Because many of these systems and components are not generally designed for the additional load autonomous vehicle systems can add when they are more than just passively utilized, many of these sensors and systems require additional robustness to protect against the increased load. Some of these signals and interacting systems include [2]:

- *Wheel Speed Sensor:* This is typically a Hall Effect sensor that is located at each wheel and outputs a frequency that is then translated to a wheel speed. This can be understood as a form of tachometer that is utilized primarily by ABS and modern cruise control systems.
- *Yaw Rate Sensor:* This gyroscopic device is generally a piezoelectric device that utilizes the Coriolis force to identify vehicle rotation or also known as the angular difference between the vehicle's heading and actual movement direction. This is necessary for electronic stability control.
- *Lateral/Longitudinal Sensors:* These MEMS or piezoelectric sensors provide lateral/longitudinal acceleration and are utilized in modern vehicles for collision detection and electronic stability control.
- *Steering Inputs:* Autonomous vehicles utilized the signals and capabilities of electronic power steering to understand and demand various responses. The specific inputs monitored include steering torque sensor and steering wheel position.
- *Hydraulic brake booster/Hydraulic pump:* By apply brake pressure to control wheel speed, this is utilized by the driver via the brake pedal, by the ABS, traction control, and electronic stability control systems.
- *Driver Inputs:* Some of the driver inputs that are understood my modern automobiles include brake request, accelerator pedal, turn signals, steering torque, headlights, windshield wipers, and gear selection.
- *Transmission Outputs:* The utilized transmission output signals include current gear, gear state, and next gear selection.
- *Powertrain outputs:* Excluding the transmission, the remaining powertrain components output information including drivetrain speed, coolant temp, NOX levels, RPM, spark plug firing time, O2 levels, and much more that can utilized for autonomous vehicle control [1].
- *HMI:* This can range from a chime, to an onscreen message. Autonomous vehicle systems utilize current production HMI for numerous purposes to relay information to the driver.

EXTERNAL WORLD SENSING

GPS

GPS, or global position system, is based on the utilization of a receiver and antenna that communicate with various satellites to triangulate vehicle absolute position. Absolute position can be found based off of latitude-longitude-altitude, X-Y-Z Earth centered Earth Fixed, or UTM. This data when paired with a precise map can be utilized in autonomous vehicles to compute optimal routes, driving directions, topographic features, lane mapping, and even obstacle detection. Most modern vehicle systems utilize GPS for navigation, but do not have the accuracy required for a fully autonomous vehicle.

GPS technology is based on RF signal propagation. As an RF signal is sent by a satellite, this is picked up by the GPS antenna which then approximates the position anywhere in the sphere of the signal propagation. When two satellites are picked up by the antenna, the receiver approximates the position to the intersection of the two spheres which is generally a circle of intersection. This is why a minimum of at least three satellites is required for signal propagations. This leaves two possible points of the signal, one of which is negated due to its location off of the Earth's surface. Figure 1 below visualizes this concept:

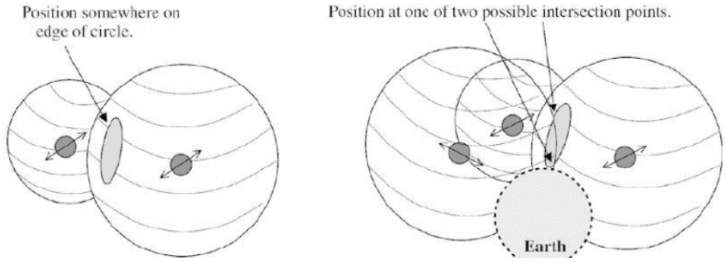


Figure 1 - Vehicle Position by Satellite Triangulation

A typical GPS receiver in a modern vehicle with poor visibility or limited satellite connectivity has an accuracy of approximately 5-15 meters. This accuracy is sufficient for providing route navigation, but is insufficient for assessing vehicle lane measurements. For this reason, correction signals are available from various sources including NDGPS, WAAS, and EGNOS [10]. These free sources provide signals to GPS receivers that improve positional accuracy to approximately 1-2 meters. This level of accuracy is capable of increased safety and reliability for route navigation, but is still not accurate enough to resolve lane boundaries.

More sophisticated correction sources have the capability of up to 1-2cm, but require much more expensive GPS hardware. Also, because these systems do not have the capability of detecting other vehicles, they still require camera and radar systems for use in uncontrolled environments. Omnistar HP is an example of one these high accuracy sources that is currently utilized in autonomous vehicles. Figure 2 shows an autonomous tractor utilizing differential GPS to control the movement and position of a tractor. However, in this case, the environment, the farm, is completely controlled with zero unknown obstructions or obstacles that the tractor has to avoid or overcome. A path is designated by the farmer, and the tractor precisely follows that path utilizing the GPS coupled with vehicle controls. This technology is mainly utilized it agriculture, aviation, surveying, and mining.

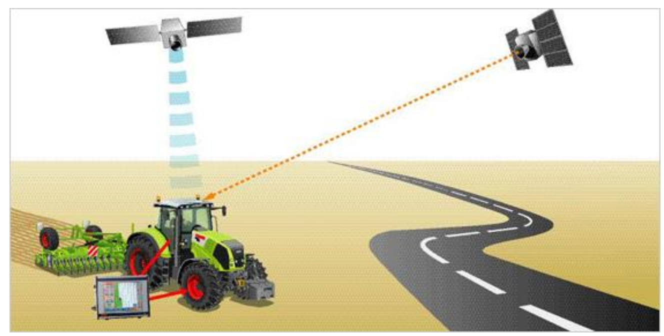


Figure 2 - Omnistar dGPS controlled tractor

At this time, a fully autonomous vehicle requires highly accurate GPS in conditions where other sensors may be blinded, but the higher cost of implementation has limited their application in production vehicles. Also, GPS systems have the capability to utilize vehicle internal sensors to provide data for confirmation or in cases of poor GPS visibility, but error factors exponentially grow as vehicle internal data is continuously utilized. The sensors utilized include yaw rate, lateral acceleration, longitudinal acceleration, and steering input. Utilization of 3 gyroscopes and 3 accelerometers is typically referred to as a vehicle's inertial measurement unit, or IMU. This is necessary for systems that require high fidelity understanding of vehicle motion in typical autonomous vehicles that heavily utilize GPS.

Although a primary use of GPS in autonomous vehicles is environmental sensing, many variables outputted by a GPS have applications in internal vehicle systems. These signals included, velocity, acceleration, and pulse-synchronized time. This data is utilized to verify internal vehicle sensor data and provide feedback to other vehicle systems.

RADAR

RADAR, or radio detection and ranging, is used in automotive applications for both near and far obstacle detection. Generally, the typical radar system is a tradeoff between range and field of view. For example a typical system used for adaptive cruise control has a range of approximately 150-meters and a field of view of approximately 20 degrees. Utilizing the Doppler Effect, they also provide speed as a direct output. Instead of using a rotating antenna, modern systems utilize a patch antenna with DSP-based pattern beam-forming methodology to measure azimuth angle.

Radar systems also function in a wide range of environmental conditions. Generally, they are immune to high luminosity, rain, fog, snow, and even dust. This capability along with lower cost compared to LIDAR systems have made them favorable in production vehicle applications.

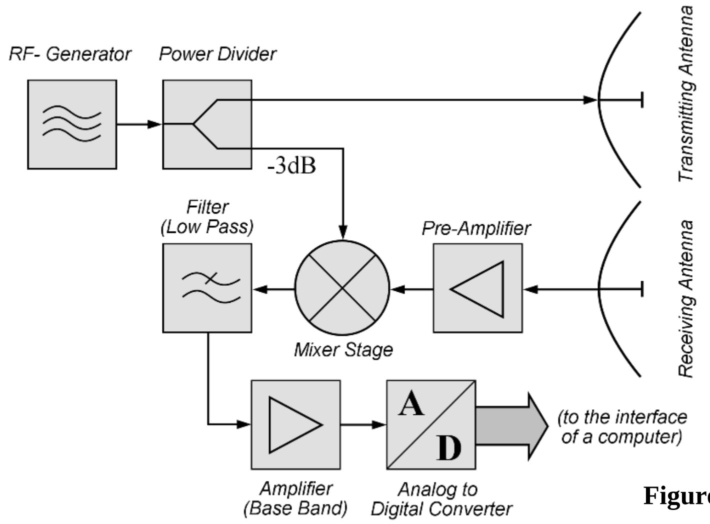


Figure 3 – RADAR System Block Diagram

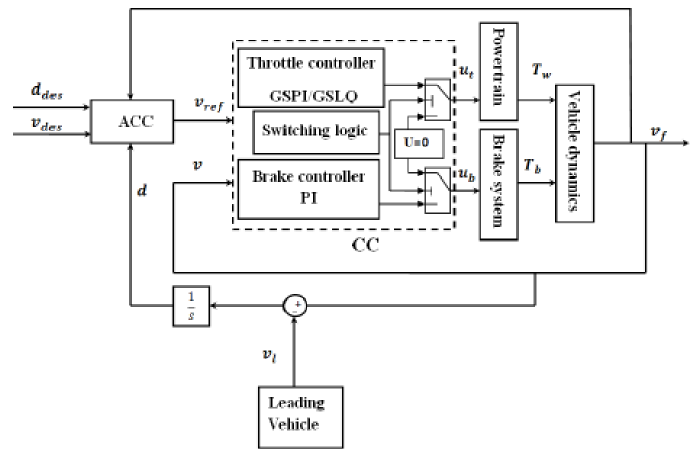


Figure 4 - Sample ACC Switching Algorithm

The block diagram shown in Figure 3 illustrates the basic design of a radar system. Utilizing a radio frequency generator it outputs a wave in the 76-77GHz range band. The return wave is then picked up by the patch antenna, which is amplified and filtered for noise. This is then passed through an A/D converter and is sent to the processing unit for computation [4].

Adaptive cruise control typically utilizes a radar because of its dynamic ability to detect object distance and also speed. Utilizing typically a RADAR for object speed and position information, the host vehicle is able to vary cruising speed to safely follow the next approaching vehicle. A sample ACC system with a switching algorithm is shown in Figure 4. Utilizing switching logic, it derives the necessary control algorithm for proper functionality. If the target vehicle is outside of the range or speed threshold, the system works as a conventional cruise control system. When the switching logic exists within the defined ACC parameters, the requested speed is reduced as necessary. This speed reduction is done utilizing the brake controller and throttle input. These controllers are then tuned for optimal performance.

LIDAR

LIDAR, or laser range finder system, utilizes a beam of light typically with an infrared laser diode that is reflected off of a rotating mirror. As the light hits non-absorbing objects the light is reflected back to a sensor that creates a map similar to the radar block diagram shown previously. To overcome semi-porous materials and various weather conditions, higher-end LIDAR systems utilize multiple beams to provide multiple distance measurements simultaneously. Also this multi-beam approach is utilized in higher fidelity applications where approximating 3 dimensions are required [10].

Although LIDAR systems tend to be more accurate than RADAR, they typically have higher costs and require additional packaging space that prohibit their use. For example, the spinning LIDAR system used in Google's autonomous vehicle costs approximately $70,000. Also, LIDAR systems are typically not as accurate as RADAR systems for detecting speed. This is due to the inability to utilize the Doppler Effect compared to RADAR. For this reason, the Google vehicle utilizes both LIDAR and RADAR sensors which can be seen in Figure 13 in the appendix.

Some automotive suppliers have made available low speed LIDAR systems, like Continental AG, which utilizes typically 4 beams of light, but the system used by Google for full autonomy, from Velodyne Inc., utilizes 32-64 beams for higher fidelity measurements. Many industry analysts expect LIDAR to become increasingly favorable because of its capability of producing much more accurate measurements as the automotive industry demands increased autonomous capability.

CAMERA

Camera systems are used in almost all autonomous vehicles. Current production vehicles utilize them for lane departure and lane keeping algorithms. Also, camera systems are being developed for road sign reading applications.

Camera systems absorb light that bounces off of an object similar to how the human eye functions. The beam of light is separated into the colors red, blue and green, and this is then fed into a complementary metal oxide semiconductor (CMOS) or a charge coupled (CCD) sensor. The light is converted into an electric charge, and this is how a digital camera interpret an image. CCD sensors typically create higher quality images, but utilize much more power than CMOS sensors. Most vehicle applications are based on CCD sensors due to the level of maturity and availability of the sensor. For higher resolution, 3 separate sensors are utilized. Another method is to take in the light and sequential rotate each color filter, and this is then fed into the single sensor that overlays each of the colors on top of one another [9]. This method is not favorable for a moving images, which leaves them impractical in automotive applications. The most economically and common form of capturing the various colors is to utilize a single filter that is separated into various colors where each cell can only take in specific colors, as shown in Figure 5.

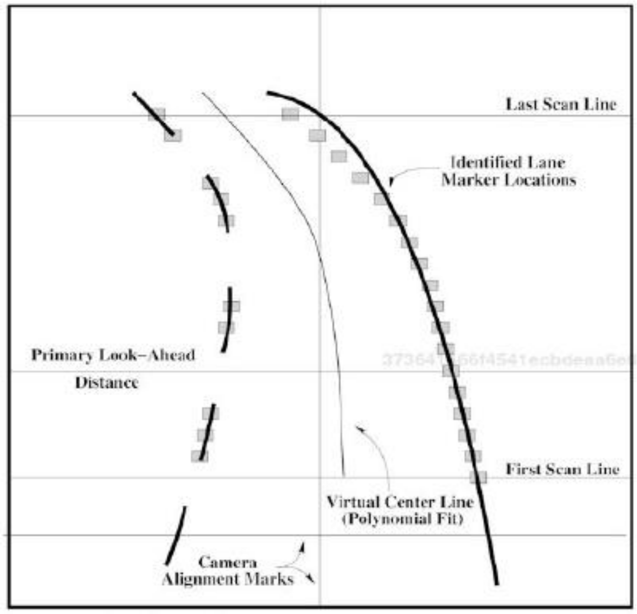
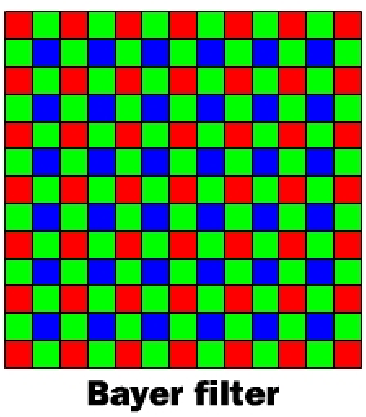


Figure 5 - Single Bayern Color Filter



Works

The most common utilization of a camera system in a current production autonomy is lane detection. The basic algorithms utilizes a dynamic range to create an optimal contrast difference between the black in the road and the white or yellow in lane markings. This is also fed forward to help predict future lane markings and trajectory calculations. Assuming parallel lane markers, a polynomial is fit to the lane that utilizes far ahead detections. This overall interpretation is typically utilized to create a bird's eye view for vehicle path. The curve fitting analysis helps account for roads with dashed lines and has the capability to make approximations for short durations of missing lane lines. A typical system relies and being able to at least decipher one side of the vehicle's lane. An example of this technique is shown in the Figure 6 below.

Stereo vision is the application of two or more cameras to provide the fidelity necessary to distinguish depth and height of objects. The typical configuration utilizes two cameras separated by a horizontal distance. This distance is correlated to a desired depth of field and resolution. The concept is similar to the position of a person's eyes. By providing two different prospective of the same object, depth can be distinguished. The difficulty of this technique in camera systems is the capability to detect the same object in each camera. Various techniques exist including, corner detection, identifying recognizable features, dimensioning, and utilizing reference objects. The procedure for interpreting stereo vision systems can be broken down into the following steps [10]:

1. Corrections for camera and lens-based image distortions
2. Rectification of both images to a common reference plane
3. Identification of features visible in both images and measuring the displacement in order to compute disparity
4. Using camera and mounting parameters, the disparity is converted into a height or depth map

Another application of visions systems utilizes thermal imaging. By utilizing or creating light above the range of human sight, in the infrared, these systems provide greater resolution in low lit conditions. This technology is the primary enabler to night vision systems in vehicles.

In a passive infrared system, the thermal radiation of emitting objects is captured in a thermographic camera. This black body radiation is captured on a sensor similar to a typical camera that captures visible light. The sensors utilized in thermographic cameras are based on pyroelectric or ferroelectric materials that produce an electrical charge that is correlated to pixels with a varying temperature gradient image [7].

In an active infrared system, additional light is added to the environment in the infrared spectrum to provide increased resolution of particularly inanimate objects. Figure 7 shows a night vision display in the BMW 7 series.

ULTRASONICS

Figure 6 - Vision based Lane Marking

Utilizing sonar, sound navigation and ranging, above the range of human hearing, a sound wave is reflected from various objects in range, and the frequency of the return pulses is utilized to indicate the distance away. A piezoelectric material is charged with an alternating electrical voltage causing it to fluctuate and produce a sound wave. As the sound wave travels through the air, the pressure difference created resonates through the air transferring the energy from each particle of the air until the wave is dissipated or reflected. The reverse of the process is generally how the return wave is deciphered. Similar to a microphone, as the diaphragm fluctuates due to a sound wave, the electrical charge produced by the piezoelectric material is converted to an A/D signal. This is the ideal function of an ultrasonic system [13].

Figure 8 - Chrysler 300 Ultrasonic Reverse/Parking Sensors [3]

Propagation of a sound wave requires a medium for the wave to travel. Without a medium, the energy cannot be transferred to continue resonation. As the wave travels through the medium, various changes can occur that effect the wave. Reflection is the return of a wave as it meets a medium with a greater density than that of the original medium. Ideally, all of the sound wave is reflected back to the source. However depending on the medium that is met by the sound wave, the return wave will have varying degrees of phase change and amplitude modulation when reflected. When the wave is not reflected back to the source, the ray can be classified as being refracted, diffracted or absorbed. Refraction is the change in angle of a ray as it passes through various mediums. As a wave passes on the fringe of two mediums where only a portion of the wave is bent, this is called diffraction. Absorption is the characterized by the exponential decrease in amplitude of the wave as it passes through a material. This energy is absorbed by the atoms of the traversed medium. This technology is available by every OEM today. Figure 8 shows a Chrysler 300 with this system.

Ultrasonic systems tend to be cheapest of the technologies discussed. However, they are effected by blockage or disturbances typically more than RADAR systems based on the physics of operation described above. Because they can only operate in a medium unlike an electromagnetic wave, they are heavily influenced by the medium of the sound wave propagation. As the temperature, humidity, and environmental conditions of the medium varies, so do the sensing capabilities of the ultrasonic sensor. To accommodate for changes in temperature, many sensors utilize an algorithm that adjust readings based on ambient temperature. With these limitations and to remain cost effective, ultrasonic sensors are generally used for parking sensors or other close range applications. Also, of the systems described, ultrasonic sensors tend to be the most accurate in closer proximity situations.

V2V / V2I

Vehicle to vehicle communications (V2V) is the direct communication between multiple vehicles. Utilizing a vehicle’s internal network, this can be done with minimal vehicle modifications. However, this capability would be limited to a short range via RF communication due to the dynamic velocity of each vehicle. Utilizing GPS can help synchronize and coordinate each vehicle signal, but this is also dependent on GPS dynamic availability.

The communication between vehicles is typically designated as either single hop or multihop. Single hop is communication between neighboring vehicles of close proximity. This can be utilized with a string of capable vehicles, but is extremely dependent on a perpetual chain of vehicles with V2V possibility. To overcome this requirement, multihop involves the communication of multiple vehicles utilizing intermediate nodes or longer range communication.

Research has been conducted to resolve the latency and range limitations of multihop. High vehicle velocities causing Doppler shifts, urban signal noise disturbances, and inherent traffic interferences have limited range capabilities. The most favorable result shown with up to a few hundred meters of range utilized IEEE 802.11b, operation in the 2.4 GHz band, for V2V and V2I. However, this requires large scale market acceptance for V2V. Without large scale market acceptance, the technology will provide erratic data until another V2V capable car is within range. V2I faces similar hurdles, but has the additional requirement of infrastructure creation. This requires a large level of government support and deployment of roadside infrastructure systems [10].

Although these technologies face significant hurdles for large scale implementation, the benefits to utilizing these system leapfrog automotive safety by improving the following factors:

- *Emergency Responders:* By connecting vehicles and infrastructure, you allow faster response times as all motorists are alerted of approaching emergency vehicles. Also, this can be applied to quicker alert times for motor vehicle accidents.
- *Traffic Flow*: By tethering vehicles, traffic flow can be optimized by syncing vehicle speed and braking. This would apply the 'platooning' vehicles concept. This concept drastically improves traffic conditions by platooning numerous vehicles closely behind one another utilizing communicated speeds, braking, acceleration, and steering. As vehicle merge and exit, the various vehicles could predictively accommodate and optimize traffic flow. This not only improves traffic flow, but it also drastically reduces vehicle drag by utilizing drafting which improves vehicle efficiency and fuel economy. Drafting is the technique of following a lead vehicle close enough to reduce drag by exploiting the lead vehicle's slipstream or wake of air.
- *Obstacle Avoidance*: As an obstacle is first identified, this information can be relayed to all other approaching vehicles. This can be anything from construction, traffic accidents, foreign objects, pot holes, to slippery roads. This has the capability to advise drivers of alternate routes and accident prevention. Coupled with the traffic flow example above, this would automate steering and braking to assist emergency services to re-route traffic autonomously.

Although there are numerous advantages far beyond the above list with V2V and V2I, current infrastructure and vehicle architectures require a high level of cost for mainstream implementation. As the cost of the enabling technologies decreases, perhaps this may have future potential.

FUSION

By leveraging the strengths of individual sensors to negate individual pitfalls, fusion is critical for fully autonomous vehicles. Individually, all the systems discussed have inherent drawbacks, but by fusing sensor data a fully autonomous vehicle becomes possible. For example, utilizing a vision system synced with LIDAR or RADAR can provide not only object detection, but also empty space and image processing. This same concept can be applied to GPS and RADAR/LIDAR. A highly accurate GPS system for lane keeping, would have the added capability of understanding obstacles.

The major reasons for utilizing sensor fusion involve accuracy and data availability. The calibration and accuracy of all sensors can be questioned in worst case conditions. By leveraging the use of numerous sensors, the overall vehicle accuracy and reliability of data drastically improves. Inherent errors that grow with sensor aging or failure modes can be detected by using these numerous data sources. Although accuracy is an important factor to autonomous vehicle systems, the main reason for the use of various sensors is based on data availability. Various sensors are blinded by different factors. This can be due to interference, signal outages, and environmental conditions. For example, as a GPS experiences short-term loss of signal, the use of a vehicle's inertial measurement unit (IMU) can approximate vehicle travel in the interim. A sample environmental sensing system is shown in Figure 9.

With understanding of the environment, an accurate understanding of the vehicle state is also crucial. This is typically derived from the internal vehicle outputs along with GPS, IMU, and or a magnetic compass as shown below:

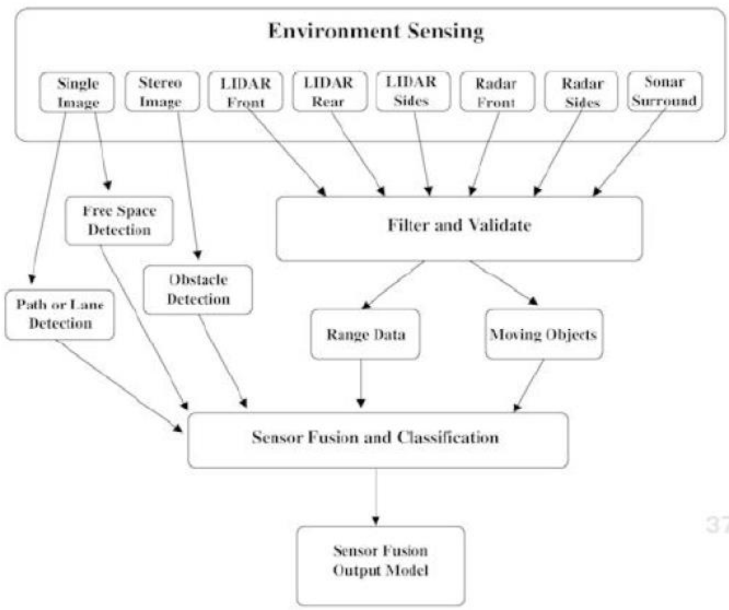


Figure 9 - Example Environmental Fusion System

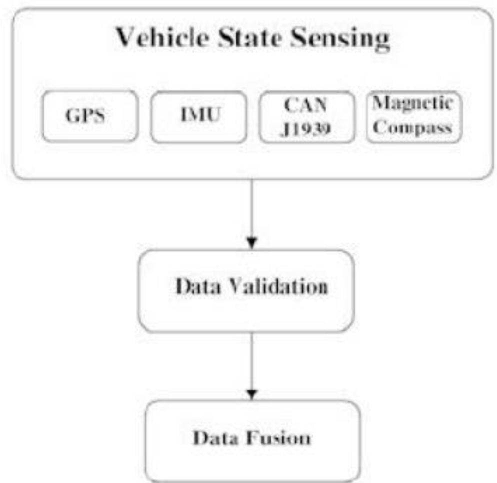


Figure 10 - Vehicle State

APPLICATION

Application of autonomous vehicles requires a careful understanding of both the vehicle and environment in a controlled state. For this reason, autonomy may exist completely in only controlled environments, or NHTSA Level 3, but full autonomy may be far too expensive for the mainstream domain. A few possible autonomous environments are described below:

- *Highway Conditions*- This environment can be controlled due to distinct road edges, no traffic lights, and limited access to only compliant motor vehicles. Baring catastrophic accidents, an autonomous vehicle would have the capability of navigating a highway with the capability of alerting the driving of an upcoming event that require his or her attention. Utilizing a vision system, LIDAR/RADAR, and GPS input, this system could be implemented in the mainstream market with limited costs to the customer.
- *Specific Operations*: As a vehicle enters an environment that can be controlled, scenario specific autonomy becomes possible. This can range from parking, lane changes, to intersection maneuvering. A system could approach a possible autonomous event and either alert the driver of system readiness or engage via HMI.
- *Off-Road applications:* This could be anything from a washed off road to true off-roading. In this situation camera systems have limited capability and require accurate GPS and object detection (ultrasonic, LIDAR, and RADAR). Also, an accurate understanding of vehicle dynamics is crucial to navigating the terrain. As specific sensors may have partial blockage, sensor adjustments will be required based on fusion data and vehicle dynamics. The difficulties associated with off-roading also encapsulate a lot of the obstacles faced with adverse weather conditions. All of the sensors discussed based on their general operating principles are not immune to icing, torrential downpours, sandstorms, and other extreme weather conditions.

- *Urban Applications* – This capability would require tracking of numerous objects simultaneously. Pedestrians, bicyclists, merging traffic, exiting traffic, and various signal interferences exist in this extremely dynamic environment.

Off-roading and urban applications can be considered the extremes of autonomous vehicle capabilities. This capability requires a large amount of processing and numerous sensors for data integrity. However, highway and scenario-specific systems are already in production. All of the systems given rewards by Euro NCAP are based on current production systems. Beyond production vehicles, numerous examples have proven that given the right price point the possibility of fully autonomous vehicles is possible. Many of these technologies have existed for years, but are only recently resurfacing as market interest and price have made these technologies more advantageous. In 1992, Mitsubishi first offered lane-keeping support on the Mitsubishi Debonair. The 1995 Mitsubishi Diamante had the first ACC system. The 2000 Cadillac Deville had the first night vision.

Beyond current production, large scale autonomous vehicles became reality due to the DARPA Grand Challenge. DARPA, Defense Advanced Research Projects Agency, to foster research in autonomous vehicle design began awarding prizes in numerous competitions for autonomous vehicle applications starting in 2004. The initial 2004 DARPA Grand Challenge awarded a $2M prize to whomever could complete a 150 mile route autonomously in the Mojave Dessert. None of the competitors were able to complete the challenge. The following year, five teams were able to complete the course. Stanford's vehicle, Stanley came in first place and was awarded $2M [11].

Figure 11 - 2005 1st Place DARPA Winner (Stanley)

Google's autonomous vehicle has no steering wheel or pedals. At a price of $150,000 the vehicle utilizes LIDAR, RADAR, cameras, wheel position sensors, IMU, and GPS. Figure 13 in the appendix shows Google's Autonomous Car with detail of the external sensors [15].

CONCLUSION

This paper introduces and explains the sensors, systems, and various factors that play into autonomous vehicle design. Although a single sensor cannot provide all the information necessary for autonomy, the fusion of the sensors discussed have proven the possibility of fully autonomous vehicles. In fact, vehicles like the DARPA Urban Challenge competitors or the Google autonomous vehicle have made this a reality. Numerous automakers have already made the commitment. Current production vehicles have already proven Level 2 autonomy as defined by the NHTSA. As government agencies reinforce the need for additional safety and various technologies become more cost effective, autonomous vehicles become not only feasible but a proven possibility.

REFERENCES

1. Automotive Control Systems For Engine, Driveline, and Vehicle 2nd Edition by U. Kiencke and L. Nielsen
2. Automotive Electronics Handbook, 2nd Edition, R. Jurgen, McGraw Hill, 2000.
3. "Chrysler 300 Parking Sensors." Chrysler Group LLC., n.d. Web.
4. "Continuous-wave Radar." Wikipedia. Wikimedia Foundation, n.d. Web. 22 Apr. 2015.
5. "Euro NCAP Advanced Rewards." Euro NCAP. N.p., n.d. Web. 1 Apr. 2015.
6. Kim J, Rajkumar R, Jochim M. Towards dependable autonomous driving vehicles: a system-level approach. ACM SIGBED Review. 2013;10:29-32
7. Meyrowitz AL, Blidberg DR, Michelson RC. Autonomous vehicles. Proceedings of the IEEE. 1996;84:1147-1164
8. Mubashir Ahsan, K S Alimgeer. Autonomous Ground Vehicle. International Journal of Technology and Research. 2013;1:96

9. Nice, Karim, Tracy V. Wilson and Gerald Gurevich. "How Digital Cameras Work" 29 November 2006. HowStuffWorks.com. <http://electronics.howstuffworks.com/cameras-photography/digital/digital-camera.htm> 22 April 2015.
10. Ozguner U, Acarman T, Redmill K. Autonomous Ground Vehicles. Artech House; 2011
11. "Robot Car "Stanley" Designed by Stanford Racing Team." Robot Car "Stanley" Designed by Stanford Racing Team. Stanford University, n.d. Web. 22 Apr. 2015.
12. Sun Y, Xiong G, Song W, Gong J, Chen H. Test and Evaluation of Autonomous Ground Vehicles. Advances in Mechanical Engineering. 2015;6:681326-681326
13. Terzic, Jenny. "Chapter 2 Ultrasonic Sensing Technology." Ultrasonic Fluid Quantity Measurement in Dynamic Vehicular Applications. Place of Publication Not Identified: Springer International Pu, 2013. N. pag. Print.
14. "U.S. Department of Transportation Releases Policy on Automated Vehicle Development ." U.S. Department of Transportation Releases Policy on Automated Vehicle Development. N.p., 30 May 2013. Web. 1 Apr. 2015.
15. Waldrop MM. Autonomous vehicles: No drivers required. Nature. 2015;518:20-23

BIOGRAPHY

Jaycil Z. Varghese is an electrical engineering graduate student of the University of Michigan, Dearborn, USA, and an engineer in the CIE Program at Fiat-Chrysler Automobiles. He also earned his B.S. in Electrical Engineering at the University of Michigan. The Chrysler Institute of Engineering (CIE) Program is highly selective with a limited number of openings each year. Only the best and brightest college graduates are chosen. Trainees embody strong work ethic while maintaining a sense of purpose and modesty throughout the program. During the first two and a half years of work, participants in the CIE Program will receive challenging rotational assignments while completing a Master's degree (MSEE). The program begins quickly to build skills and knowledge through a series of work assignments. The variety of assignments gives trainees an overall perspective of what working at Chrysler is all about. It helps identify what job would properly balance the trainee's career goals and the needs of the corporation. Each CIE candidate completes seven, four month rotations within the corporation getting the chance to experience areas such as vehicle integration, engine calibration, or brand marketing. Jaycil has a graduation date from the CIE Program and his M.S.E.E. of December 2015.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

- *A/D:* Analog to Digital
- *ABS:* Anti-lock Braking System
- *ACC:* Adaptive Cruise Control
- *CAN:* Closed Area Network
- *CCD:* Charge Coupled Device
- *CMOS:* Complimentary Metal-Oxide Semiconductor
- *DARPA:* Defense Advanced Research Projects Agency
- *EGNOS:* European Geostationary Navigation Overlay Service
- *ESC:* Electronic Stability Control
- *Euro NCAP:* European New Car Assessment Progamme
- *GPS:* Global Positioning System
- *HMI:* Human Machine Interface
- *IMU:* Inertial Measurement Unit
- *LIDAR:* Laser Range Finder System
- *MEMS:* Microelectromechanical Systems
- NDGPS: National Differential Global Positioning System
- *NHTSA:* National Highway Traffic Safety Administration
- *RADAR:* Radio Detection and Ranging

- *SONAR:* Sound Navigation and Ranging
- *UTM:* Universal Transverse Mercator
- *V2V:* Vehicle to Vehicle
- *V2I:* Vehicle to Infrastructure
- *WAAS:* Wide Area Augmentation System

APPENDIX

Summary points tables

Adult Occupant Protection

Test	2016	2017	2018	2019	2020
Frontal ODB / Mobile barrier	8	8	8	8	8
Frontal FW	8	8	8	8	8
Side MDB	8	8	8	8	8
Side pole	8	8	8	8	8
Whiplash front	2	2	1.5	1.5	1.5
Whiplash rear	1	1	0.5	0.5	0.5
AEB City	3	3	4	4	4
Total	**38**	**38**	**38**	**38**	**38**

Child Occupant Protection

Test	2016	2017	2018	2019	2020
Dynamic performance	24	24	24	24	24
Vehicle-CRS compatibility	12	12	12	12	12
Vehicle based assessment	13	13	13	13	13
Total	**49**	**49**	**49**	**49**	**49**

Pedestrian Protection

Test	2016	2017	2018	2019	2020
Headforms	24	24	24	24	24
Upper Legform	6	6	6	6	6
Lower Legform	6	6	6	6	6
AEB VRU-Pe	6	6	6	6	6
AEB VRU-Cy			6	6	6
Total	**42**	**42**	**48**	**48**	**48**

Safety Assist

Test	2016	2017	2018	2019	2020
ESC	-	-	-	-	-
SBR	3	3	3	3	3
SLD/SAS	3	3	3	3	3
AEB (Interurban)	3	3	3	3	4
LDW/LKD/LSS	3	3	4	4	4
Junction Assist					2
Total	**12**	**12**	**13**	**13**	**16**

Figure 12 – Euro NCAP 2016-2020 Scoring Table

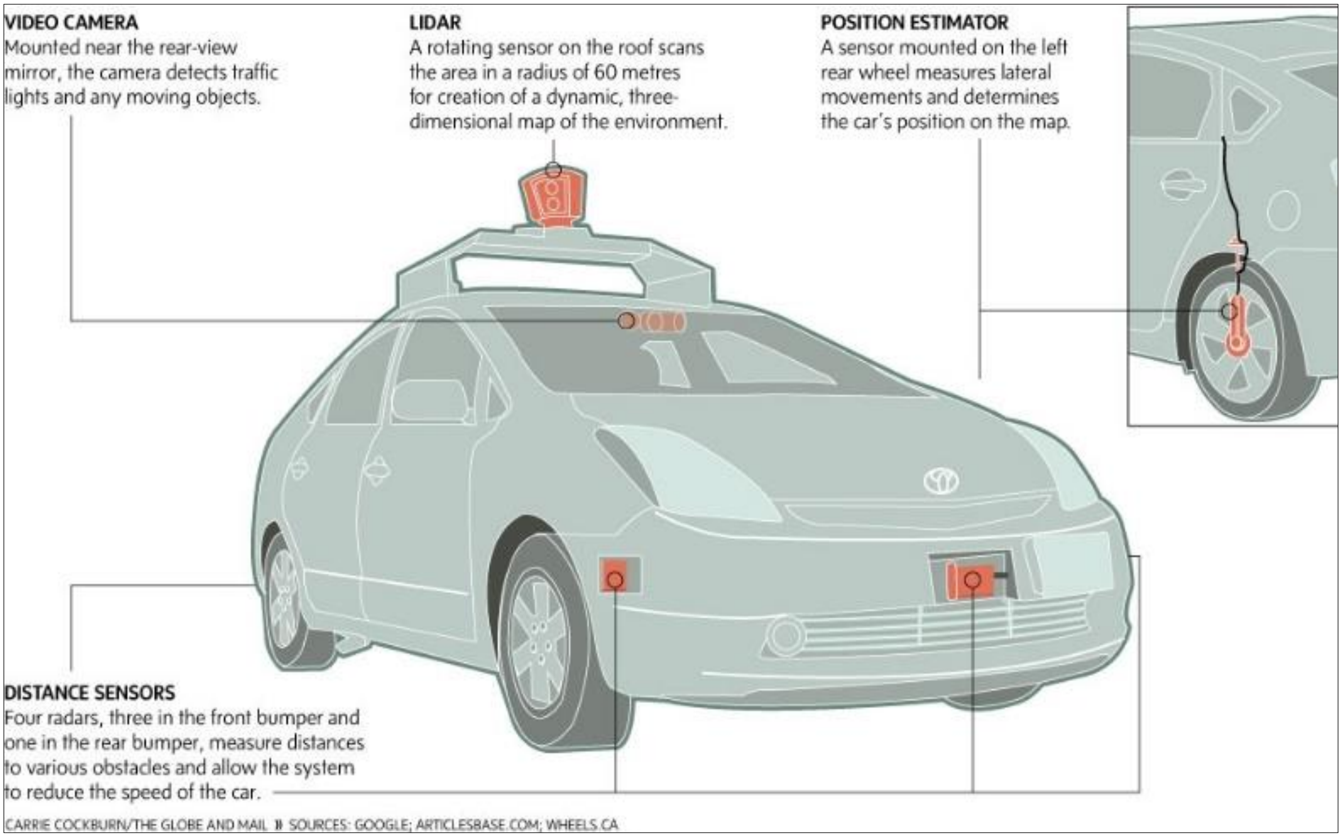


Figure 13 - Google's Autonomous Vehicle