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Multi-Sensor Fusion and Sensor Calibration for Autonomous Vehicles

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Abstract - *Usage of Autonomous vehicles have grown in the recent years even though their safety records are still in question. While the manufacturers are adding more sophisticated sensors and technology to make them safer, there are still issues with cars classification and detection of objects around them. Automated sensors with the combination of automotive software and computers perform a vital role in autonomous driving as they monitor surroundings, detect obstacles, they allow the automation system to take over full control of the vehicle, thereby saving drivers a significant amount of time by doing tasks in much more efficient and safe ways and safely plan the routes and paths autonomously. While autonomous vehicle technology appears to be developing at a continual pace, so far no commercially available vehicles have yet passed the required level 4 ranking for road-safe autonomous vehicles as the contemporary autonomous vehicle (AV) systems face critical obstacles along the road to reaching the primary safety and reliability goals. There is still a huge amount of technology improvement that needs to be taken in order to ensure autonomous vehicle safety on the roads. This paper presents the current advancements of the autonomous vehicle driving technologies and points to the still existing performance challenges for the development of level 5 fully automated autonomous driving.*

Key Words: Autonomous vehicles, Advanced driver assistance systems, Autonomous driving, Automotive, Intelligent vehicles, LIDAR, Sensor Calibration, Sensor Fusion

1. INTRODUCTION

This year is supposed to be a remarkable year for self-driving cars where all major autonomous vehicle (AV) car makers have boldly declared years ago that this year the full automation autonomous driving and the permanent backseat driver status will be achieved. Even with extraordinary efforts from many of the leading auto makers, the fully autonomous cars are still out of reach and almost every one of the above predictions has been rolled back as the engineering teams of all these companies realized the complexity of the target and that this is going to be a much more incremental process. Possibly the major technical hindrance, is adapting human intelligence that enables car driving which was taken for granted to be easily replicated to autonomous driving systems proving previous predictions to be far too optimistic. There is an imminent gap, an important fact that current levels of vehicle autonomy are adequately low and the accountability for supervisory actions still resides with the drivers to operate the vehicles safely. There are welfare benefits of autonomous vehicles that could possibly eliminate emissions, increase traffic efficiency, improve road safety with accurate driving decisional problems associated with the human infirmities of fatigue, misperceptions, distractions and intoxication in the context of driving. As such there is a strong need to develop the autonomous vehicles to SAE level 5 to reap the outcome of this autonomous revolution.

2. AUTONOMOUS VEHICLE SENSORS

The classifications of autonomous driving are the adopted standards J3016 of the international engineering and automotive industry association, Society of Automotive Engineers SAE and U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA) are as follows

Level 0: Driver only: the human driver controls everything independently, steering, throttle, brakes, etc.

Level 1: Assisted driving: assistance systems help during vehicle operation (Cruise Control, ACC) – Year 2000

Level 2: Partial automation: the operator must monitor the system at all times. At least one system, such as cruise control and lane centering, is fully automated – Year 2013

Level 3: Conditional automation: the operator monitors the system and can intervene when necessary. Safety-critical functions, under certain circumstances, are shifted to the vehicle – Year 2018

Level 4: High automation: there is no monitoring by the driver required. Vehicles are designed to operate safety-critical functions and monitor road conditions for an entire trip. However, the functions do not cover all every driving scenario and are limited to the operational design of the vehicle – Year 2024

Level 5: Full automation: operator-free driving – Year 2030

2.1 Cameras

The most commonly used and primary sensors by all top and leading driverless technology developers are video cameras, radar sensors, ultrasonic sensors and lidar sensors. These sensors are further classified as active and passive, while active sensors send out energy in the form of a wave and detect objects based upon the information received such as radar sensors, the passive sensors simply receive information from the environment without emitting a wave, such as cameras. Camera/Image Sensors

Cars manufactured from 2018 already have the reverse cameras and the front cameras for lane departure warning system that detect road paint markings. Autonomous cars are externally equipped with video cameras and sensors at every angle to view and assess the objects on the road in 360° view and to provide a broader view of the traffic conditions around. The 3D cameras that are available now are used for detailed and realistic images between the vehicle and other cars, pedestrians, cyclists, traffic signs and signals, road markings, bridges, and guardrails, so the image data they produce can be fed to Artificial Intelligence, AI algorithms for object classification. Other than visible light cameras, there are also infrared cameras, which offer superior performance in darkness and additional sensing capabilities.

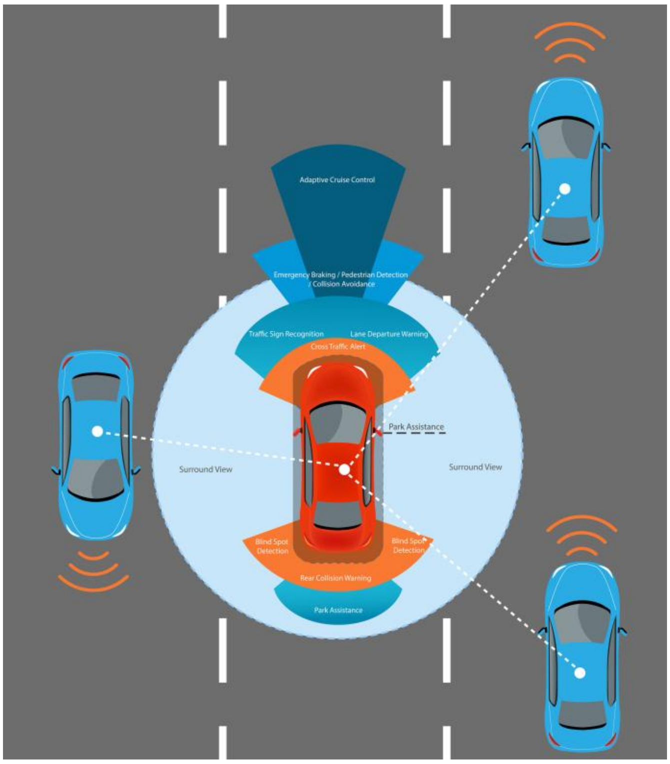

Fig -1: Autonomous Vehicle sensors communications

2.2 Radar Sensors

Many ordinary cars already have radar sensors as part of their driver assistance systems such as adaptive cruise control. The Radio Detection and Ranging, Radar sensors are vital sensors for the overall function of the autonomous driving to detect object distance and speed in relation to the vehicle in real time.

The short-range radar (SRR) sensors that are 24GHz permit blind spot monitoring, lane keeping assistance and parking aids while the long-range radar sensors (LRR), 77 GHz does automatic distance control and brake assistance. The Radar sensors are reliable when identifying objects during fog or rain unlike camera sensors.

Fig -2: Long Range Radars (LRR)

2.3 Ultrasonic Sensors

Since 1990s Ultrasonic sensors are used in the cars as parking sensors, these sensors are best for low-speed cars to provide additional sensing abilities due to their limitation of short distance sensing. Another downside of the Ultrasonic sensors is the high cost.

Fig -3: Ultrasonic Sensors

2.4 Lidar Sensors

Lidar Sensors, the Light Detection and Ranging sensors is a laser-based system that measures the distances to several objects on the road and creates 3D images of the objects and maps of the surroundings. They create a full 360-degree map around the vehicle rather than relying on a narrow field of view. The laser beams hit objects in the environment and bounce back to a photodetector then the returned beams are brought together as a point cloud creating a three-dimensional image of the surroundings. Many well-known autonomous vehicle manufacturers use Lidar systems. They work very similar to the Radar Sensors other than they use Lasers instead of Radio waves.

Lidar sensors provide highly valuable information of their surroundings environment (temperature, solar radiation, darkness, rain, snow) and are powerful sensors which are very expensive. There have been recent research technologies which are less expensive such as solid-state sensors that can be used as a replacement for Lidars.

Fig -4: Lidar Sensor on Autonomous car

2.5 Thermal Cameras

Thermal sensors are well-suited for nighttime driving and seeing through glare and most fog. Compared to visible-light cameras, Thermal sensors are better in low or challenging light conditions by detecting objects from the infrared energy they emit. They are good at detecting people by distinguishing living things from inanimate objects, which complements the driver-warning and enhance driving safety. Thermal sensors offer the autonomous vehicle industry a way to fill its sensor gap and improve car intelligence which brings the industry one step closer to fully autonomous vehicles.

2.6 GNSS

Global Navigation Satellite System (GNSS) technology provides the accuracy, availability and reliability that a vehicle requires to be self-driving. A fully autonomous vehicle needs an accurate localization solution paired with the confidence that the localization solution is correct. GNSS technology is capable of providing decimeter-level accuracy to ensure a vehicle stays in its lane or a safe distance from other vehicles. The technology solutions for autonomous vehicles include GNSS receivers that use multiple frequencies and multiple GNSS constellations, Synchronous Position Attitude and Navigation (SPAN) technology, GPS Anti-Jam technology and interference mitigation, and correction services to provide the positioning and sensor integration that autonomous vehicles need.

2.7 IMU

In contrast to camera, LiDAR, radar and ultrasound sensors, the IMU is a sensor that requires no information or signals from outside a vehicle. The IMU measures the forces of acceleration (gravity and motion) and the angular rates of the vehicle. When combined with a GNSS receiver, the IMU can provide a complete positioning solution to accurately determine a vehicle's position and attitude. When the GNSS signal isn't available, the IMU measures the vehicle's motion and estimates its position until the GNSS receiver can again access the satellites and recalculate the position.

3. SENSOR FUSION AND CALIBRATION

Autonomous vehicles need to sense the environment around them safely to drive, detect other vehicles on the road, stop for pedestrians, and handle any unexpected circumstances they may encounter. To properly view the road an autonomous vehicle (AV) need the sensors and technologies required for data fusion and redundancy to validate the information for perception, localization, mapping and controls. Since the Radars, Cameras and other sensors has its own limitations and the fusion of them would contribute to improved Advanced driver assistance systems (ADAS) functions including cross traffic support and obstacle avoidance. Whilst camera systems are ideal for identifying roads, reading signs and recognizing other vehicles, LiDAR applications are superior when it comes down to accurately calculating the position of the vehicle, and radars perform better at estimating speed. The sensor fusion is when you bring two types of sensors with each of the sensor with its own strengths and weaknesses in terms of range, detection capabilities, and reliability to compare and calibrate the data to give the autonomous vehicles an all-inclusive and full 360-degree view of the environment.

Sensor fusion data processing can happen two ways, centralized processing or Distributed Processing. In centralized processing all decisions and processing are handled by the central processing unit after data is fed into it from all the sensors. While in a fully distributed processing system, the data is processed at the sensor level with only metadata sent back to a central fusion Electronic Control Unit (ECU). The advantages of central processing unit are it has more data as no data is lost in pre- processing or while compressing in the sensor module and as the sensors modules only capture data and transmit them, they are small, cheap, and consume less power, the disadvantages are that the ECU needs to be capable of receiving higher bandwidth data and also requires greater processing speeds and wider bandwidth is required to handle the amount of sensor data in real-time. The advantages of the distributed processing is that the ECU consumes less power and requires lesser processing capability and the sensors only send metadata to the ECU, low bandwidth cables can be used to interface between the ECU and the sensors, thereby cutting down on costs, the disadvantage is that the sensor modules become costly as they need an application processor and end up being bigger in size.

The importance of sensor fusion techniques are

- Reduction in Uncertainty: Multi-sensor data fusion techniques reduce the uncertainty by combining data from numerous sources. It is therefore imperative to compensate using other sensors by fusing their data together using data fusion algorithms.
- Increase in Accuracy and Reliability: Integration of multiple sensor sources will enable the system to provide inherent information even in case of partial failure.
- Extended Spatial and Temporal Coverage: Area covered by one sensor may not be covered by the other sensor,

therefore the coverage or measurement of one is dependent on the other and this complements each other.

- Improved Resolution: The resolution resulting value of multiple independent measurements fused together is better than a singular sensor measurement.

- Reduce System Complexity: System where sensor data is preprocessed by fusion algorithms, the input to the controlling application can be standardized autonomously of the employed sensor kinds, consequently simplifying application implementation and providing the option of modifications in the sensor system concerning number and type of employed sensors without alterations of the application software.

Sensor Calibration is the most critical to mapping, localization, perception, and control of an autonomous vehicle (AV) but yet still very less discussed. The typical AV sensor suite consists of cameras, LiDARs, radars, and IMUs which needs to be calibrated to high level of accuracy. The goal of the calibration is to recover the lens distortion of the cameras, the accelerometer and gyroscope of the IMU. These are essential input to perception, mapping, localization, and control modules of the AV. The perception system identifies the objects on the road, such as cars, pedestrians, dogs and cyclists. This data is combined from multiple sensors like Lidar and Camera, calibrated to obtain a high-precision output needed to support the AV accuracy. The calibration of the mapping which contains lane boundaries, traffic lights, stop signs is very critical for the safety of the AV which are again calibrated from combined data fusion of LiDAR, camera, and IMU. If the calibration were to be off by just a few degrees, the AV could potentially confuse the lanes and signal lights which could cause a disaster. For the high-quality localization, the data fusion and correlation of data between IMU, LiDAR(s), wheel odometry, and cameras are obtained for calibration and precise position of the vehicle on the HD map.

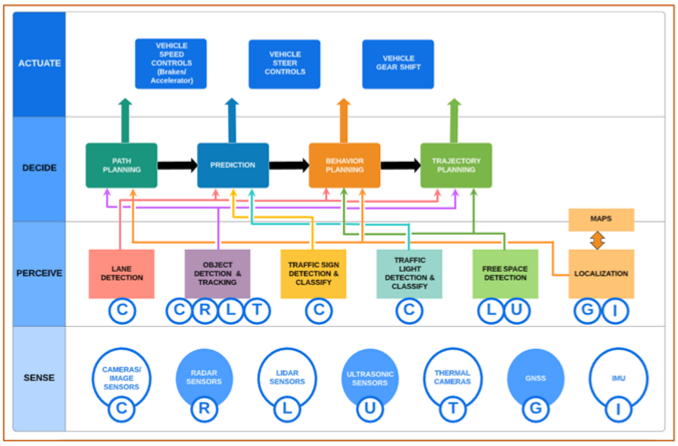

Fig -5: Data Flow Architecture in Autonomous Driving system

To detect and eliminate calibration errors, and perform independent quality calibration, each AV uses multiple cameras, LiDARs, radars, ultrasonics, IMU and GNSS by breaking down the entire calibration process into paired sensor calibration by first calibrating each individual sensor's essential parameters and then independently calibrate their relative to the top LiDAR [4]. A high-quality, fully automatic process needs to be developed to independently conduct the calibration process in a repeatable manner on the drive to keep the calibration accuracy over time from temperature and vibration variations. This needs the online, self-correcting calibration algorithms development to identify any errors in calibration and to be able to calibrate vehicles at a higher reliability and faster rates while maintaining calibration in a wider variety of operating environments.

4. PERFORMANCE CHALLENGES

The autonomous vehicles to this day did not deliver the safety confidence as they are still challenges in the vision in bad weather where cameras can be foiled by glare, radars can have a bad visibility, ultrasonic sensors can only view the nearby objects, Lidars have the distance limitations, map stability issues and vision challenges during rain. Following are the areas of improvement of sensors of an autonomous vehicle (AV).

4.1 Radar Sensors

The 2D Radar sensors currently being used in autonomous vehicles (AV) only correctly identify 95% of the objects which does not make them safer. They do not determine the height of the object due to its horizontal scanning and do not have the ability to classify objects other than metal.

4.2 Camera Sensors

Bad weather conditions such as rain, fog, or snow can prevent cameras from clearly seeing the hindrances on the roadway, which can rise the probability of accidents. Moreover, there are often conditions where the images from the cameras are not of good quality for a computer to make a timely decision for the vehicle to take control actions. Similar to human eyes, visible light cameras have limited capabilities in conditions of low visibility. The solution for this is to use multiple cameras creating multiple video data to process, which needs significant computing hardware.

4.3 Lidar Sensors

Lidar Sensors used in autonomous vehicles (AV) are very expensive than radar sensors as made out of rare earth metals. Even then the problem is that snow or fog can sometimes block lidar sensors and negatively affect their ability to detect objects in the road.

To bridge the gaps, Infrared and Thermal cameras have come to spotlight to detect objects that are invisible to the naked eye in extremely challenging conditions by detecting wavelengths below the visible spectrum that indicate heat.

4.4 Multimodal data

In spite of the crucial developments in Autonomous vehicles, several challenges persist. The Unique and significant issue is the multimodality of data at an acquisition and data source level. The sensors physical units of measurement are different, in sampling resolutions, and in spatio-temporal alignment. The ambiguity in data sources also poses challenges that include noise relating to calibration errors, quantization errors or precision losses; differences in reliability of data sources, inconsistent data and missing values. Due to the inherent uncertainty of traffic behavior, autonomous vehicles need to consider multiple possible future trajectories of the surrounding actors in order to ensure safe and efficient ride [5]. In case of LiDAR and camera sensor fusion, it is tough to deal with the spatial misalignment and resolution difference in heterogeneous sensors.

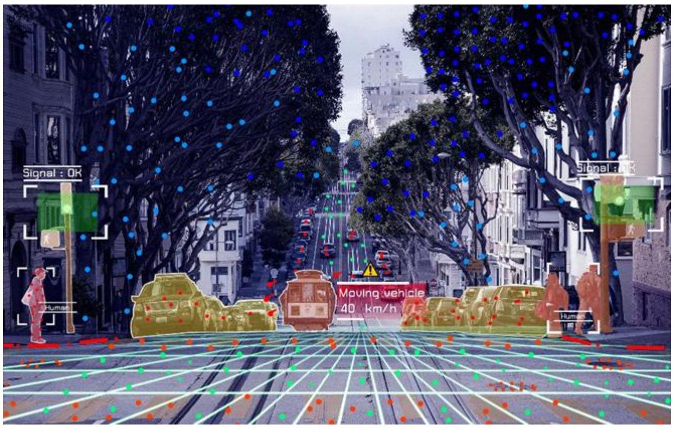

Fig -6: Autonomous driving concept showing Lidar, Radar and Camera sensor signal system

The robust approaches for data fusion are still in works, due to which the uncertainty in the fusion algorithm, and data fusion algorithms that work with minimal calibration since extrinsic calibration methods might be impractical due to exchange of data between all the sensors. Moreover, fusing data from different sources comes with other challenges, such as the difference in data resolution. LiDAR output is significantly lower compared to the images being processed by a camera. Therefore, the next stage of the data fusion algorithm is calculated to equal both the resolutions of LiDAR data and imaging data through an adaptive scaling operation. For the case of collision avoidance, these processes become critical, so the real-time collision avoidance sensor systems designed not to drive into objects or individuals, utilizing a scanning LiDAR and a single RGB camera are still in challenging developments.

4.5 Level 5

Unlimited number of cameras, radars and lidars assembled to the AV still provide limited competences for driverless cars compared that of human visual perception, regardless of producing far more visual data for software to interpret. Human drivers, in reality, identify and respond to objects much farther ahead than permitted even by the current radar, cameras and lidar, effectively making plans in response to things happening. The crashes of the AVs involved so far cautions the overreliance on technology, a reflection of the insufficient hardware and software on board. For self-driving cars furnished with an assortment of camera, radar, and LiDAR sensors the scenario of safety dividers, clearly marked lanes, reflective road markers, speed limit signs, and high visibility signs are comparatively easily sensed and processed. Steering, Speed, braking, and acceleration are all relatively easy to control because every car on the highway is traveling at close to a uniform speed and there are no sharp turns or sudden obstacles to avoid. While a country road with random traffic, no clear dividing lanes with multiple asymmetrical intersections is much tougher to sense and control when a bad weather presents poor visibility.

Level 5 vehicle would need to be able to handle a much more complex city environment, and to respond not only to pedestrians, cyclists, motorcyclists and other vehicles, but also complex traffic lights and lane markings in various weather and light conditions, and with various complicating factors, such as being forced to drive behind a other vehicles, their ability to navigate from behind something and respond to objects not within their line of sight is an ability that's only now being developed. The major issues that must be resolved before autonomously driven cars are ready for fully autonomous are efficient and precise sensors, high performance and redundant software, advanced maps, improved vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. On the technical side, while verification of simple communication protocols for connectivity is somewhat studied, the verification of a large Vehicle-to-everything (V2X) system will require new modelling formalism to enable scalability. Another challenge is the verification of learning-based components (e.g. neural networks), which are already widely used in perception algorithms. In particular, how these components affect the overall system-level safety properties or how to pose verification questions with respect to datasets used in training these algorithms are open problems [6]. With these limitations of narrow applications, we could be in a very long era of Level 3 and Level 4 of autonomous driving until sensor technologies become cheaper to produce and the software become more reliable.

5. CONCLUSIONS

Despite great strides being made in AV technologies, universal Level 5 driving remains challenging due to the real-world driving scenarios are much more complex than the existing navigation technology can progression. The big companies are also shifting their focus away from level 5 and instead concentrating on level 4 high automation that operates within specific geographical areas and weather conditions. This paper summarizes the remaining clear gaps in the existing systems and technologies. There is a need to be able to calibrate vehicles at a higher reliability and faster rates while maintaining calibration in a wider variety of operating environments, disagreements on optimal sensing modality for localization, mapping and perception need to be settled, algorithms with high accuracy need to be developed, consistent road conditions are yet problematic, Vehicle-to-vehicle (V2V) communications are still in its initial stages due to the complex infrastructure required, reliability of sensors in uncontrolled weather conditions is still not achieved. These challenges present great opportunities to explore new system designs and try cutting-edge techniques in computer vision, deep learning, and robotics to master the level 4 and work towards level 5 full automation driving.

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BIOGRAPHIES

Smitha Gogineni has 18 years of experience in Instrumentation and Controls engineering in Oil & Gas and Semiconductor industries she also served as an Editorial board member for International Society of Automation ISA's Intech journal, reviewed technical articles for many publishers and is an active Senior member of ISA.