Advancements and Limitations in Sensor Fusion for AI-Controlled Vehicles

Enzo Paesano
Gulliver Prep, FL

Abstract

People's dreams of self-driving cars navigating the streets of their city are getting closer and closer every year. Regardless, we are still far from reaching that goal due to some hurdles that Artificial Intelligence (AI) needs to clear like visibility and detection of surroundings. This paper gathers and summarizes the advancements in sensor technology and data fusion that contribute to the safety, reliability, and limitations of self-driving cars. Sensor technology is the core for self-driving, as it uses multiple sources to collect information so that the cars do not present a danger to others. As of now, the perception stage of the automobiles is still under development. Data fusion is essential to self-driving, as it combines data from the outside world and is able to translate it into information to which the AI can interpret and respond. Recently, newer, compact cameras have been able to capture more information with better resolution. Although this is a positive for self-driving, cameras still have their limitations. Natural obstacles and harsh conditions (frequent problems on the road) affect the camera's visibility and detection capacities. Along with having to battle these conditions, long-term exposure to real-world environments cause harm to the camera's ability to function as intended. I am writing this paper to convey the knowledge we need in order to make this large advancement in the automobile industry. In order for this to be possible, camera technology must become stronger, more reliable, and more affordable. The combination of the three will represent the qualitative change that needs to happen before self-driving cars become the norm.

Introduction

This study focuses on the use of sensor fusion in autonomous vehicles. Sensor fusion was originally created as a solution to the technologically challenged single-sensor system (Galar & Kumar, 2017). Today, it has made its way into the automotive industry, acting as an assistant to human drivers. However, this paper discusses the ability and flaws of fully autonomous cars.

According to Google, the automotive industry is one of the most influential in the world. At first, cars would simply take someone from one place to another. Once this practice was normalized, comfort was added to make it more pleasant. Faster modes of travel, such as airplanes, were invented, but the simplicity and accessibility of cars would allow them to remain a primary mode of transport. As the industry progressed, car innovation shifted from maximizing driver experience to making sure driving is a safe mode of transport. This can be attributed to debates over which mode of transport is the safest, where cars continue to be one of the more dangerous ones. The idea of having autonomous vehicles on the roads is to have safe and efficient transport.

There can be different situations where a person does not feel their best but feels that they are obligated to drive (e.g., when tired or intoxicated). Autonomous vehicles would be able to escort that person to and from their destination, without them having to do anything, serving as a personal chauffeur. This would be Level 4 Automation, where the AI has complete control over the car and is able to efficiently drive people around, while being mindful of other AVs and human drivers (Hanna, 2015, p. 8). This future would hope to lower accidents where a person is intoxicated or tired. These reasons provide the need for implementation of AVs.

Fundamentals of Sensor Fusion

The use of artificial intelligence (AI) requires many moving parts to come together. Most importantly, it relies on data fusion and sensor fusion. Ideally, artificial intelligence should mimic the actions of humans when completing a non-physical task. Data fusion, a concept which was created around the 1960s, is used to make data collection more reliable. It relies on the collection of data from multiple sources and of the synthesis of all the information into one data point. Data fusion effectively communicates clear data and is able to give accurate information to the car's perception block. Data fusion became popular due to its being more accurate than simply collecting one piece of data and basing actions off of one test (Fawole & Rawat, 2024).

Sensor Fusion Basics

Sensor fusion is the combination of multiple sensors or cameras in order to gather data, and can be a critical part of data fusion. Some examples of devices that utilize sensor fusion are Radio Detection and Ranging (RADAR), Light Detection and Ranging (LiDAR), camera, and ultrasonic sensors. These sensors all use a combination of waves to detect any objects surrounding the sensors, except for cameras. Engineers are able to mount sensors and cameras onto the exterior of cars. The sensors and cameras are constantly capturing and processing information. But if the sensors all utilize similar methods to capture information, why are there so many different types of sensors? Well, that comes down to not being able to capture everything at once in the matter of milliseconds. An example of this is the RADAR sensor, which measures speed and distance, while cameras take photos to classify different objects. As a result, there are multiple devices that each capture their own individual information, and relay it as fast as they are able to (*What Is Sensor*, n.d.).

Sensor Fusion Applications in AI-controlled Vehicles

Cameras:

One of the most well-known and easily recognizable sensors are cameras. Cameras take photos of their surroundings through a transmission of light through the camera lens. Utilizing these photos, the AI system filters and identifies the objects seen in the photos. They are able to recognize many surroundings, such as traffic signs or objects. The information can be critical at moments, being able to detect pedestrians or objects in the way. If the sensors send information that something is in the way, the camera is then able to verify whether there is something in the way. When the camera identifies an object or person into which it is about to collide, the AI will use the information from sensor fusion to send a signal to the vehicle for a full emergency stop. Another important ability cameras have given us is an easier way to park. By utilizing a camera with sensors and guiding lines, sensor fusion has made parking easier than ever (figure 1).

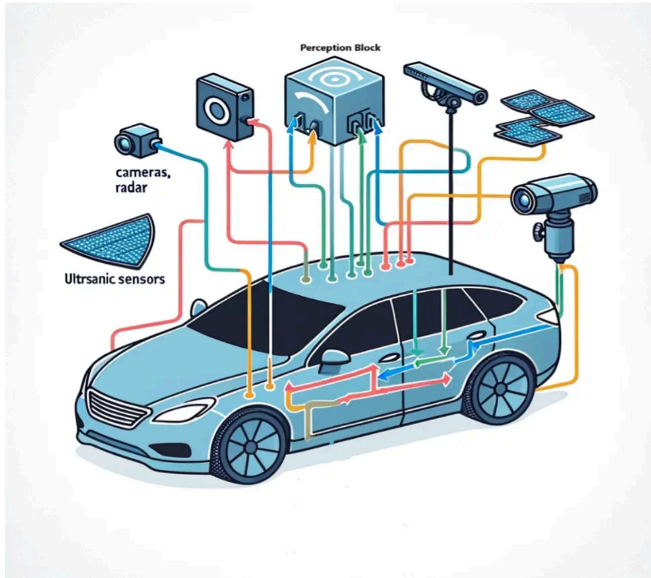

Figure 1
Data gathering in perception block
Note: The image, from *Sensor Fusion Techniques in Autonomous Vehicle Navigation: Delving into various methodologies and their effectiveness* (Arefe, 2024), illustrates the flow of data from the car's sensors to the perception block.

LiDAR:

LiDAR is another sensor which is often used as a supplement to cameras. Originally used to map aeronautical terrain, it is now widely seen in autonomous vehicles (figure 1). This is due to its functionality in processing up to 200,000 data points per second. The data transmitted can be in either a one-dimensional, two-dimensional, or three-dimensional format. In 1D, only the distance between the surroundings and the car are measured. To capture data in 2D, LiDAR also measures an angular displacement of objects. Measurements in 3D are gathered with an additional elevation measurement.

Sensor Calibration:

Sensor calibration is the foundation block for sensor fusion and data fusion, as well as a crucial step in processing, which either happens before sensor fusion or is used in autonomous driving (AD) applications (figure 2). Sensor calibration adjusts the response of a sensor to make sure that the output and input are accurately aligned (*Sensor Calibration*, n.d.). Because of this powerful feature, sensor calibration is integral for advanced sensor fusion.

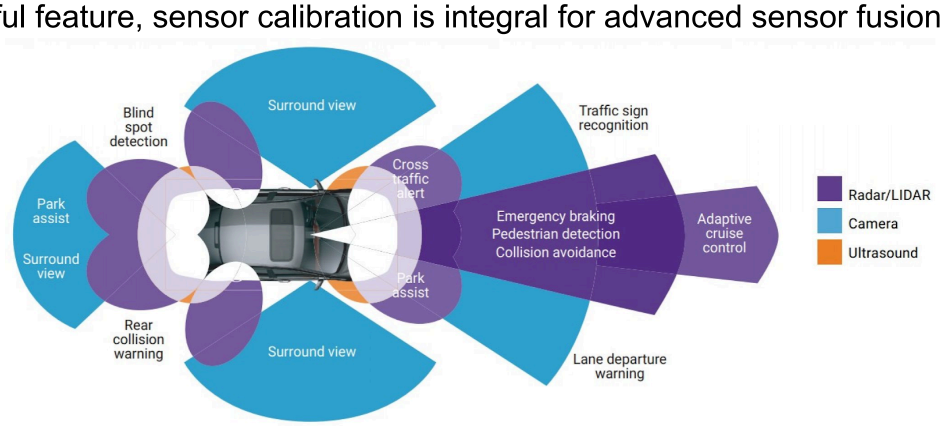

Figure 2

Numerous sensor technologies with varying capabilities can find use in autonomous vehicle designs

Note: Figure 6 from *Multi-sensor Fusion for Robust Device Autonomy* (Multi-sensor Fusion, 2019), shows the different sensor technologies and their uses in an autonomous car design

Limitations of Sensor Fusion

Weather is a variable that cannot be controlled nor exactly predicted. It is possible that, while driving, rain, hail, or snow may fall. Rain adds an obstacle to a camera's visibility, disrupting the clear view from the system. In addition to raindrops falling in the view of the camera, there can also be rain dripping onto the camera itself. If it comes to the point where the harsh weather is able to damage a part of the sensors in any way, the driver is to interrupt the trip and disengage the car immediately. Ultimately, sensors will have to be equally capable (if not better than humans) at detecting the car's surroundings in rain, hail, or snow, in order for AI cars to be widely accepted.

Accuracy of sensors are critical to the safety and effectiveness of autonomous cars. The sensors and cameras cover different ranges and areas (figure 2). All the devices used for detection are connected to the perception block. This block processes all the information given and removes any uncertainty in the data collection. After this, the information is fed to the AI, so the system can determine what action to take based on how it is programmed to perform (figure 3). All of this technology combined onto a car's surface can be costly, as well as ruin satisfying designs.

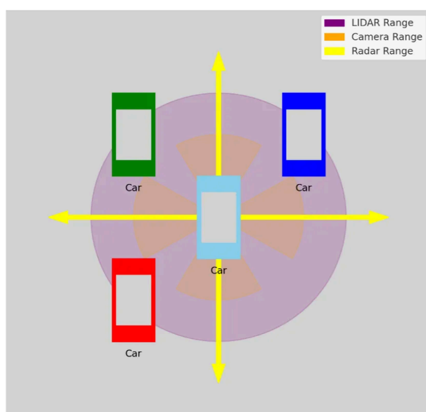

Figure 3

Sensing the surroundings through sensor fusion

Note: This image, from *Sensor Fusion Techniques in Autonomous Vehicle Navigation: Delving into various methodologies and their effectiveness* (Arefe, 2024), depicts an autonomous vehicle's sensors working to navigate around other cars, as well as the ranges and abilities of each of the sensors.

Driving safely on conventional roads means being able to react to the environment. In signs and streetlights, colors help drivers anticipate what is coming and follow road rules. For example, a streetlight changing from green to yellow lets a driver know that they should begin to slow down as the light is beginning to turn red. If a fully artificial intelligence system were to be controlling the car, cameras with highly detailed processors would be required to be able to identify different light waves, which are then connected to an action that the car should perform (figure 3).

Sensor Fusion Process Challenges

When it comes to connecting sensors to the artificial intelligence system, transceivers are a strong option which are commonly used. Digital Signal Processors (DSP) allow for optimization of data quality over optical fiber networks. The DSP removes hiccups along the transmission by adjusting the amplitude and phase of the received data in the optical fibers. This allows for maximum information to be received with limited errors. There are some times when the data is not suitable for transmission through optical fibers, so the system uses modulation. In this process, data is encoded into analog signals that are able to go through the optical fibers. In order for all the receivers to work at the optimal performance, adaptive algorithms are created to monitor the quality of the received signals and make sure the parameters are working accordingly. Tremendous amounts of computing power have to be used in order for photos to be analyzed (figure 4). This is a requirement to function, and may be disrupted or stagnate the flow of data to the AI information. (Pudliszewska, n.d.).

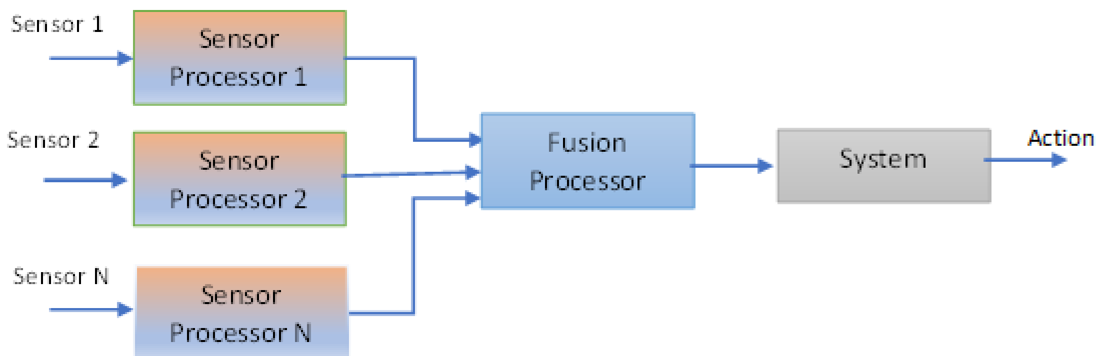

Figure 4

Process of Sensor Fusion

Note: In *Sensor Fusion with Deep Learning* (Jusuf, 2022), the centralized scheme can be regarded as a special case of the distributed scheme where the sensors communicate every scan to each other.

Advancements in Sensor Fusion

AI can see the world through four main components: detect, segment, classify, and monitor. The combination of autonomous vehicle technologies and sensors allow the car to make quick decisions to change its route based on other cars on the road. The space around the car and objects/other cars in the road are a part of the detect section, where the car uses the sensors and cameras in order to scan the environment. LiDAR sensors are used to detect road markings and the road itself by using the speed of light. This process provides multiple data points which are fused together into point clouds (*What Is Sensor*, n.d.).

Many of these moving parts translate into even more devices and software to achieve autonomous driving (figure 4). Global Navigation Satellite Systems (GNSS) help AI familiarize itself with its surroundings as well as connect with satellite technology to pinpoint the exact location of the car (*Driving Towards*, n.d.). Technology has been able to get it within the range of centimeters of the car's real time location. The GNSS is updated every few hours in order to receive new information (Chen et al., 2023).

What should the AI system be programmed to do if it detects something that is not recognizable in its system? Should it keep on going? Should it fully brake? Should it slow down until it can make the "correct decision"? Experts have been debating this idea and developing different systems for these scenarios. For example, Cruise, Tesla, and Waymo have decided to implement a feature which practically shuts down the car. It waits, idle, until an AV specialized team can come to the car to resolve the situation (Cummings, 2023).

Scale-invariant feature transform (SIFT) algorithms interpret objects through their distinct features. Mindy Support gives us an example involving a traffic sign. For background context, “Mindy Support is a global provider of data annotation for LLM and customer service, trusted partner for Fortune 500 and GAFAM companies” (*Top Ranking*, n.d.) As a car approaches a sign, the sign’s corners are entered into the system as its features. From this information, the system is able to identify which type of sign it is. There are various programs performing different types of identification. AdaBoost, “a widely used machine learning algorithm that combines many weak classifiers to form a strong classifier by adjusting the weights of training samples” (Cheng & Han, 2016), categorizes the data into different sections in order to find a single, high-performing classifier. With this information, there can be more efficient decision-making. TextonBoost, an extension of AdaBoost’s framework (Shotton et al., 2006), conducts similar functions. Histogram of oriented gradients (HOG) analyzes the picture of an object to determine how the car should respond to it. YOLO (You Only Look Once) helps group objects into specific categories (e.g., tall and slim can be humans, while short and long can be dogs). These features are all significant for machine learning in cars. (*HOW MACHINE*, 2020).

Future of Sensor Fusion

A self-driving car’s AI system is a complex thing that attempts to mimic the actions of human drivers. Because it is a system, it gathers more information as more data is provided, and is unable to learn new information on its own. This is one of AI’s biggest weaknesses. With environments constantly changing for drivers, depending upon their desired destination, systems would have to be regularly updated. Different objects used in detours or construction and other situations have to be added into the system by humans in order for the AI to adapt to the new surroundings. Only then, the AI would be able to mimic the appropriate actions. This constant maintenance will definitely cause trouble in self-driving cars’ integration into society (Cummings, 2023).

Objects and data points in our environment such as weather, glare, location and terrain (Yeong et al., 2021) account for large amounts of data which have to be implemented into the system. . Difficulties in having the most up-to-date data arise when companies resist collaborating and sharing data with one another, due to fear of losing their competitive advantages. The quality of the data being implemented into the system is also important. The better the data, the better the care will perform. Being that in order to drive autonomously the car is being powered by computers and technology, it is susceptible to being hacked (Fawole & Rawat, 2024). These are problematic flaws that, until fixed, restrict the mass implementation of AI into vehicles.

Conclusion

This paper presented an overview of current AI vehicle systems and technologies. First, the general abilities of sensor fusion were discussed, explaining how the sensors are able to gather data via the use of cameras or sensors. In the case of autonomous vehicles, the information is then sent to a central processing unit, where the information is analyzed and processed. The amount of sensors in the system can vary depending on the capabilities of the central processor. The sensor methods talked about include cameras, LiDAR, and sensor calibration. Also presented was the limitations of sensor fusion: factors which are restricting it from becoming as powerful of a resource as it could be. Weather conditions can interrupt the sensor’s vision as well as distort the image of objects around it. The accuracy of sensors also needs to improve when detecting new objects or linking colors with a command for the car to make. Finally, in the last parts of the paper, sensor fusion is broken down to analyze what advancements need to be made to make autonomous driving feasible and safe.

The findings from researching this paper were able to provide insightful knowledge on how sensor fusion in cars works, as well as why autonomous vehicles are barely seen out on the open road. Understanding the function and abilities of sensor fusion is critical to improve it. The future looks bright, as many companies like Waymo, Tesla, Zoox, Cruise are competing to release a fully autonomous vehicle for the public. The most significant advancements recently have been seen with Waymo's ride service offered to the public and Tesla's robo-taxi, unveiled at their most recent event. Current issues are complex and require innovative thinking to overcome them. Yet, sooner or later, the future of the automotive industry will arrive.

Bibliography

Arefe, Chaklader Asfak. "Sensor Fusion Techniques in Autonomous Vehicle Navigation: Delving into Various Methodologies and Their Effectiveness." Medium. Last modified January 1, 2024. https://chaklader.medium.com/sensor-fusion-techniques-in-autonomous-vehicle-navigation-delving-into-various-methodologies-and-c95acc67e3af.

Chen, Liang, Fu Zheng, Xiaopeng Gong, and Xinyuan Jiang. "GNSS High-Precision Augmentation for Autonomous Vehicles: Requirements, Solution, and Technical Challenges." MDPI. Last modified March 17, 2023. https://www.mdpi.com/2072-4292/15/6/1623.

Cheng, Gong, and Junwei Han. "Adaboost Algorithm." Science Direct. Last modified 2016. https://www.sciencedirect.com/topics/computer-science/adaboost-algorithm.

Cummings, Mary L. "What Self-driving Cars Tell Us about AI Risks." IEEE Spectrum. Last modified July 2023. https://spectrum.ieee.org/self-driving-cars-2662494269.

"Driving towards Autonomy." NOVATEL. https://novatel.com/industries/autonomous-vehicles#:~:text=High%20precision%20Global%20Navigation%20Satellite,the%20localization%20solution%20is%20correct.

Fawole, Oluwajuwon A., and Danda B. Rawat. "Recent Advances in 3D Object Detection for Self-Driving Vehicles: A Survey." MDPI. Last modified July 25, 2024. https://www.mdpi.com/2673-2688/5/3/61#B100-ai-05-00061.

Galar, Diego, and Uday Kumar. "Sensor Fusion." ScienceDirect. Last modified 2017. https://www.sciencedirect.com/topics/engineering/sensor-fusion.

Hanna, Katherine L. "OLD Laws, NEW Tricks: DRUNK DRIVING AND AUTONOMOUS VEHICLES." *Jurimetrics* 55, no. 2 (2015): 275-89. JSTOR.

"HOW MACHINE LEARNING in AUTOMOTIVE MAKES Self-driving CARS a REALITY." MINDY SUPPORT. Last modified 12 2, 2020. https://mindy-support.com/news-post/how-machine-learning-in-automotive-makes-self-driving-cars-a-reality/.

Jusuf, Suad. "Sensor Fusion with Deep Learning." RENESAS. Last modified July 25, 2022. https://www.renesas.com/en/blogs/sensor-fusion-deep-learning.

"Multi-sensor Fusion for Robust Device Autonomy." Edge AI + Vision. Last modified January 29, 2019. https://www.edge-ai-vision.com/2019/01/multi-sensor-fusion-for-robust-device-autonomy/.

Pudliszewska, Marianna. "High-Speed Data Meets Ai: The Evolution of Transceivers and DSP in AI Clusters." STORDIS. Accessed July 5, 2024. https://stordis.com/the-evolution-of-transceivers-and-dsp-in-ai-clusters/.

"Sensor Calibration." MPS. https://www.monolithicpower.com/en/learning/mpscholar/sensors/advanced-topics-in-sensing/sensor-calibration#:~:text=Definition%20and%20Importance,input%20by%20a%20recognized%20standard.

Shotton, Jamie, John Winn, Carsten Rother, and Antonio Criminisi. "TextonBoost: Joint Appearance, Shape and Context Modeling for Mulit-Class Object Recognition and Segmentation." Microsoft. Last modified January 2006. https://www.microsoft.com/en-us/research/publication/textonboost-joint-appearance-shape-and-context-modeling-for-mulit-class-object-recognition-and-segmentation/.

"Top Ranking AI and Customer Service Company." Mindy Support. https://mindy-support.com/about-us/.

"What Is Sensor Fusion for Autonomous Driving Systems? – Part 2." RGBSI. https://blog.rgbsi.com/sensor-fusion-autonomous-driving-systems-part-2.

Yeong, De Jong, Gustavo Velasco-Hernandez, John Barry, and Joseph Walsh. "Sensor and Sensor Fusion Technology in Autonomous Vehicles: A Review." MDPI. Last modified March 18, 2021. https://www.mdpi.com/1424-8220/21/6/2140.