Sensors and Sensor Fusion in Autonomous Vehicles

Jelena Kocić, Nenad Jovičić, and Vujo Drndarević

***Abstract* — In this paper, we are presenting a short overview of the sensors and sensor fusion in autonomous vehicles. We focused on the sensor fusion from the key sensors in autonomous vehicles: camera, radar, and lidar. The current state-of-the-art in this area will be presented, such as 3D object detection method for leveraging both image and 3D point cloud information, moving object detection and tracking system, and occupancy grid mapping used for navigation and localization in dynamic environments. It is shown that including more sensors into sensor fusion system benefits with better performance and the robustness of the solution. Moreover, usage of camera data in localization and mapping, that is traditionally solved by radar and lidar data, improves the perceived model of the environment. Sensor fusion has a crucial role in autonomous systems overall, therefore this is one of the fastest developing areas in the autonomous vehicles domain.**

***Keywords* — Autonomous vehicles, camera, fusion, lidar, radar, sensors, sensor fusion.**

I. Introduction

AUTONOMOUS vehicles, also known as self-driving vehicles, are recognized as a current trend in research and development, where many major research centers, automotive companies, and academic institutions are contributing to this field on a daily basis. The aim of this paper is to make an overview of the current state-of-the-art of the sensors and the sensor fusion in autonomous vehicles. As the sensors are the key components of the self-driving vehicles, the fusion of the information from the sensors and their proper interpretation followed by control of the vehicle has the central point in the autonomous driving.

The autonomous vehicle system can be divided into four main categories as it is shown in Fig. 1. The vehicle is sensing the world using many different sensors mounted on the vehicle. These are hardware components that gather data about the environment. The information from the sensors is processed in perception block whose components combine sensor data into meaningful information. Planning subsystem uses the output from perception block for behavior planning and for both short and long-range path plan. Control module ensures that the vehicle follows the path provided by the planning subsystem and sends control commands to the vehicle.

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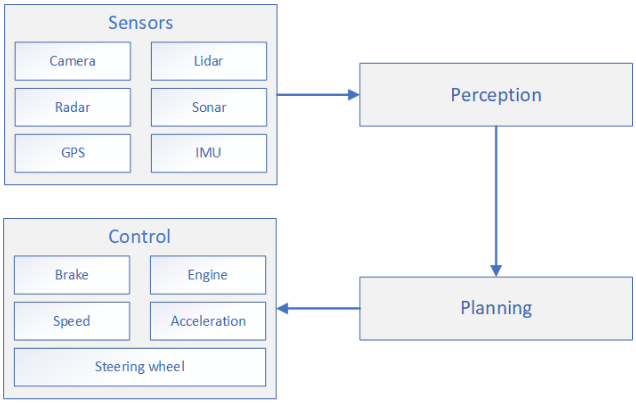

Fig. 1. Block diagram of the autonomous vehicle system.

The first successful attempts in the development of the autonomous vehicles started in the middle of the last century. The first fully autonomous vehicles were developed in 1984 at Carnegie Mellon University [1], [2], and in 1987 by Mercedes-Benz and the University of Munich [3]. Since then, many companies and research organizations have developed prototypes of autonomous vehicles and are intensively working on the development of full autonomy of the vehicles.

Significant breakthrough in the field of autonomous vehicles is done during the Defense Advanced Research Projects Agency's (DARPA) challenge, Grand Challenge events in 2004 and 2005 [4]-[5] and Urban Challenge in 2007 [6] where is demonstrated that machines could independently perform the complex human task of driving. In 2007 DARPA Urban Challenge, six of the eleven autonomous vehicles in the finals successfully navigated an urban environment to reach the finish line, which is considered a landmark achievement in robotics.

Current challenges in autonomous vehicles development are scene perception, localization, mapping, vehicle control, trajectory optimization, and higher-level planning decisions. Novel trends in autonomous driving include end-to-end learning [7]-[9] and reinforcement learning [10]-[11].

II. Sensors in Autonomous Vehicles

The key components of autonomous vehicles are the sensors. The sensors that can be part of autonomous vehicles are cameras, lidar, radar, sonar, a global positioning system (GPS), an inertial measurement unit (IMU), and wheel odometry. Sensors in automotive vehicles are used to collect data that is analyzed by the computer in the autonomous vehicle and used to control

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the steer, brake, and speed of the vehicle. In addition to the automotive sensors, the information from environmental maps stored in the cloud and data uploaded from the other cars are used to make decisions about vehicle control.

A. Camera

While perception in autonomous vehicles is achieved with many sensors and sensor systems, cameras were one of the first types of sensors to be used in driverless vehicles and are currently the main choice for car manufacturers. Novel vehicles have dozens of different cameras mounted on vehicles. Cameras enables an autonomous vehicle to literally visualize its surroundings. They are very efficient at the classification of texture interpretation, are widely available, and more affordable than radar or lidar. The downside of the camera is the computational power needed for processing the data. The latest high-definition cameras can produce millions of pixels per frame, with 30 to 60 frames per second, to develop intricate imaging. This leads to multi-megabytes of data needed to be processed in real-time.

Since the camera is an indispensable sensor in autonomous driving, the applications of camera usage in self-driving vehicles are endless [12]-[16]. The domain of application includes perception, semantic segmentation, end-to-end autonomous driving, and many others. Cameras can be also used inside of the vehicle for the human-machine interaction [17].

B. Radar

Radar stands for Radio Detection and Ranging. Radar is sensor integrated into vehicles for different purposes like adaptive cruise control, blind spot warning collision warning and collision avoidance. Even a radar is a mature technology, it still gets improved especially for application of autonomous driving [18]-[19]. While other sensors measure velocity by calculating the difference between two readings, radar uses the Doppler effect to measure speed directly. Doppler effect is important to sensor fusion because it gives the information about velocity as an independent measure parameter, and it makes the fusion algorithms converge much faster.

Long-range radar is microwave radar at 77 GHz, has a low resolution but can measure speed and detect vehicles and obstacles to 200 m away. Short/medium range radar is mature and inexpensive technology in 24 GHz and 76 GHz bands. This sensor can detect velocity and distance, but broad beams and long wavelengths limit resolution and produce complex return signals.

Although radar is more efficient than cameras and lidar in select situations like bad weather, radar has less angular accuracy and generates less data than lidar. Unlike cameras, radar does not have any data-heavy video feeds to process but has lower processing speeds needed for handling data output compared to lidar and cameras.

Radar can be used for localization by generating radar maps of the environment, can see underneath other vehicles, and spot buildings and objects that would be obscured otherwise. Of all the sensors on the car, radar is the least affected by rain or fog and can have a wide field of view, about 150 degrees, or a long-range, over 200 meters. Compared to lidars and cameras, radars have a low resolution, especially in the vertical direction.

C. Lidar

Lidar stands for Light Detection and Ranging (LiDAR). Lidar uses an infrared laser beam to determine the distance between the sensor and a nearby object. Most current lidars use light in the 900 nm wavelength range, although some lidars use longer wavelengths, which perform better in rain and fog.

In the most present lidars, a rotating swivel scans the laser beam across the field of view. The lasers are pulsed, and the pulses are reflected by objects. These reflections return a point cloud that represents these objects. Lidar has a much higher spatial resolution than radar because of the more focused laser beam, the larger number of scan layers in a vertical direction, and the high density of lidar points per layer. This type of lidars cannot measure the velocity of objects directly and have to rely on the different position between two or more scans. lidars are more affected by weather conditions and by dirt on the sensor.

On the other hand, lidars with a MEMS (Micro-Electro-Mechanical System) vibrating micromirrors have a possibility to scan the laser beams. Instead of mechanically moving the laser beam, a similar principle to phased array radar can be employed. Dividing a single laser beam into multiple waveguides, the phase relationship between the waveguides can be altered and thereby the direction of the laser beam shifted.

Coherent lidars can measure velocity directly. High resolution is valuable for identifying objects. Lidars can map a static environment as well as detect and identify moving vehicles, pedestrians, and wildlife. Currently the limit is high cost, however, the technology is moving forward in the direction to down-size the cost and the size of the sensor. A novel research and development in the space of automotive lidar applications are [20]-[24].

III. Sensor Fusion

Sensor fusion is an approach for combining data delivered from disparate sources such that the coherent information is created. The resulting information is more certain than it would be possible when these sources were used individually. This is especially important when different kind of information are combined. For example, on the autonomous vehicle, it is important to have a camera in order to clone a human vision, but the information of the obstacle distance will be the best gained through the sensors as lidar or radar. For that reason, sensor fusion of camera with lidar or radar data is very important since there are complementary. On the other hand, combining information from lidar and radar will provide more certain information about the distance of the obstacle ahead of the vehicle or general distance of the objects in the environment.

A. Sensor Fusion for 3D object detection

Current trends in autonomous vehicles development showed increased usage of the lidar. Sensor fusion from camera and lidar data gives an optimal solution in terms of hardware complexity of the system, only two types of sensors are integrated, and the system coverage, camera for vision and lidar for obstacle detection complement each other. Here the image data is fused with 3D point cloud data, and as a result, 3D box hypothesis and their confidence are predicted. One of the novel solutions for this problem is the PointFusion network [25]. This method has application in 3D object detection.

Novel approaches in achieving sensor fusion using neural networks tend to treat each signal with a different neural network, then to integrate the resulting representations into a new neural network and have a high-level fusion, as shown in Fig. 2. The first benefit of this solution is avoiding lossy input predictions, by firstly having low-level processing of each signal individually. The second benefit is having a conceptually simple solution, which is current and future trend in neural network development, under the moto “small neural nets are beautiful” [26].

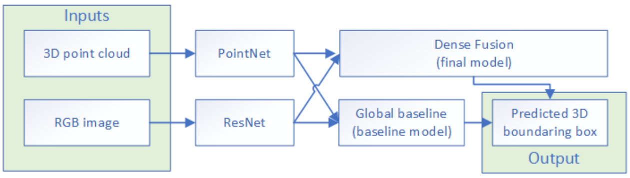

Fig. 2. Block diagram of 3D object detection form image and 3D point cloud data, [25].

B. Sensor Fusion for occupancy grid mapping

Occupancy grid mapping is used for navigation and localization of autonomous vehicles in dynamic environments, Fig. 3. For solving this problem, sensor fusion from cameras and lidar is used. Sensor fusion process each sensor complementary of others, where the camera provides high-level 2D information as color, intensity, density, edge information, and lidar provides 3D point cloud data. The usual approach in occupancy grid mapping is to independently filter all grid cells. However, the new trends are in direction of using superpixels to the grid map, where the grid cells occupied by an obstacle are not omitted [27].

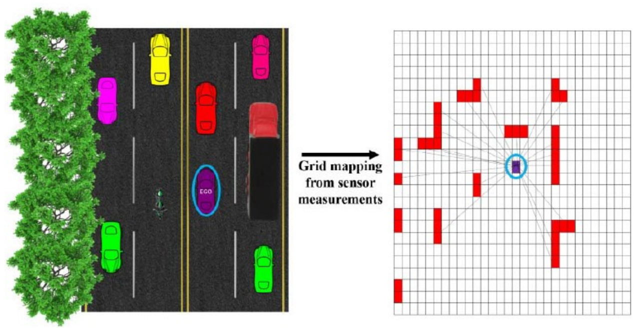

Fig. 3. Occupancy grid mapping, [27].

C. Sensor Fusion for moving object detection and tracking

Moving object detection and tracking is one of the most challenging aspects of autonomous vehicle domain. Since solving this problem is crucial for autonomous driving, the ratability and performance of the solution are very important. Hence it is usual that all existing sensors mounted on the vehicle are used. The most common is sensor fusion of camera, radar and lidar data.

Earlier approaches in moving object detection and tracking are focused on fusing sensor data, which follow tracking along with additional information from a simultaneous localization and mapping (SLAM) module. Additional fusion was done on the track level to have an overall perception of the environment.

A new approach in this field performs detection at the radar and lidar level, then sending regions of interest from the lidar point clouds into the camera-based classifier, and then fused all this information together. The information from the fusion module is feeding the tracking module, for the list of moving objects. By including the object classification from multiple sensors detections, the perceived model of the environment is improved. Block diagram of the multiple sensor perception systems [28] is presented in Fig 4.

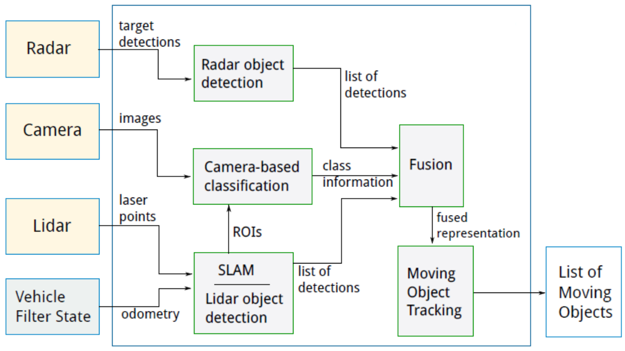

Fig. 4. Multiple sensor perception system, [28].

In sensor fusion from a camera, radar, and lidar data, it is usual to apply the low-level fusion on radar and lidar data that has been pre-processed, but not otherwise run through any type of model to extract features or object information. Then this fused information is part of a high-level fusion block that considers camera inputs as well. In this context, low-level fusion is solving localization and mapping, while the detection and classification are results of high-level fusion. Combining low-level fusion as an input to high-level fusion may be considered as one of the trends in perception in autonomous vehicles.

The improvement of the performance of data association and movement classification can be done by using vision object class and shape information for choosing the method for object detection. Based on the distance of the object from the vehicle, a tracking system can be switched between a point and a 3D box models [29]. This leads to the conclusion that information gained from a camera is critical in localization and tracking tasks too, and the future trends are exploring contextual information about urban traffic environments to improve the tracking system capability.

IV. CONCLUSION

One of the main aspects of motivation for autonomous vehicles development was to lower the number of traffic accidents and to reduce a human factor as a cause of the accidents. The idea was to have an autonomous vehicle that will be more reliable than a human. In order to achieve this high-demanded task, vehicles have not to only imitate human behavior, but to achieve a better performance. The reliability of the sensors and the sensor fusion system has the crucial role in this process. The vehicles must have not only cameras that will clone the human sight, but the sensors as radar and lidar as well to sense the obstacle, to map the environment, and all them together to be fully autonomous.

In this paper, we analyzed current state-to-the-art in the research and development of sensor fusion in autonomous vehicles using signals from the camera, radar, and lidar. It is shown that by increasing the number of different sources of the signals (sensors), the perception models are improved, and higher reliability of the autonomous vehicle is achieved. An addition of different types of sensors to the autonomous vehicle system leads to better understanding of the surveillance, where it is crucial not only to have detailed information about other road users, dynamic objects but also about stationary objects.

Current trends in sensor development are showing that the biggest breakthrough is expected form lidar with MEMS micromirror that can provide high-density point cloud at the high frame rate and downsize the size and the cost of the sensor. Achieving this is important since the main obstacle to the integration of lidar in autonomous vehicles for mass use are the size and the cost of the sensor. Current challenges in sensor fusion in autonomous vehicles are determination the drivable corridor, path planning and obstacle avoidance, and estimation of the position with respect to the reference frame, landmark-based localization, and including contextual information about urban traffic environments.

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