# A Survey On Multisensor Data Fusion for Autonomous Applications

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***Abstract*—This is a survey paper on multisensor data fusion. First general sensor fusion principles and terminology are handled. Afterwards, the focus lies on the fusion of LiDAR and camera data for autonomous applications. This document is mainly an overview of the state of the art in the field of LiDAR and camera fusion.**

## I. Introduction

Modern autonomous vehicles use a large number of sensors. Besides LiDAR and radar, many also use on-board cameras to sense the environment. Every sensor has its own use case. However, sensors often provide information about the same features. For example, with data from a LiDAR sensor we can determine a distance between an object and the front of the vehicle. Alternatively, also radar data can be used for this. Knowing this, we can combine multiple sensors to compare the same features and improve the confidence in these features. Every sensor has its own advantages and disadvantages. The purpose of sensor fusion is to combine sensors in such a way the advantages of each sensor are combined and the disadvantages are suppressed.

This concept is not new as living organisms have the capability of using multiple senses to learn about the environment. The brain fuses all the information in order to perform a decision task. This concept is called multisensor data fusion. [1] In the world of sensor-fusion, authors distinguish two fusion classes: data fusion and decision fusion. In data fusion the fusion operates on the raw data from the measurements, and later a decision is made based on the fused output. In decision fusion the decision is directly made based on the different raw data channels from the measurements.

Joint Directors of Laboratories [1] defines multisensor data fusion as a ´multi-level, multifaceted process handling the automatic detection, association, correlation, estimation, and combination of data and information from several sources´. Data fusion is a multidisciplinary research area. It explores concepts from fields such as signal processing, information theory, statistical estimation and inference, and artificial intelligence. This is visible in earlier used methods based on central limit theory, Kalman filters, Bayesian networks, and convolution neural networks. This paper will first discuss general data fusion research. Afterwards, the subject will be narrowed down to the fusion of LiDAR, radar, and camera sensors.

## II. General Data fusion

A lot of research has already been done in the field of multisensor data fusion. Hall [2] states in his paper that in the 90's multisensor data fusion has received significant attention for both military and nonmilitary applications. This is the reason the Joint Directors of Laboratories (JDL) started to standardize terminology related to data fusion [3]. The JDL proposed a data fusion process which is a functionally oriented model of data fusion and is intended to be very general. Details about this process can be found in [2]. The essence is that data can be fused/processed on multiple levels.

- **Level one - object refinement:** Level one processing involves object refinement. In this level locational, parametric, and identity information is combined to achieve refined representations of individual objects.
- **Level two - situation refinement:** Level two processing is situation refinement. It develops a description of current relationships among objects and events. It is obvious the data from level one can be used for this.
- **Level three - threat refinement:** Level three processing deals with threat refinement. This is often seen as a prediction function. It projects the current situation into the future and draws inferences about threats and opportunities. A non-military example of this is the prediction of collisions in autonomous vehicles.
- **Level four - process refinement:** Level four processing involves process refinement. This means its objective is to refine the fusion process and monitor its performance.

Before any processing can be done on data a preprocessing step is needed. This preprocessing step analyses the input data and assigns it to the appropriate level. In [2] a list can be found with the JDL process levels and their commonly used techniques.

Khaleghi et al. [4] provide an excellent overview of data fusion methodologies, challenges, and recent advances in the field. The majority of their work is dedicated to low-level fusion. This means to the problems associated with the first level of the JDL model. They discuss the benefits of data fusion and as well as Hall [2] provide an overview of the methodologies which can be used.

An overview of data fusion approached from the viewpoint of signal processing can be found in the work of Mandic et al. [1]. A more image fusion focused overview of algorithms can be found in the work of Dong et al. [5]

## III. LiDAR and camera fusion

Efforts have already been made in the fusion of LiDAR and camera data. Zhang, Clarke, and Knoll [6] use these sensors for a vehicle detection system. They propose a method based on two phases: hypothesis generation and hypothesis verification. In hypothesis generation the image from the camera is cropped to the region of interest (ROI) where potentially an object can be found. Afterwards, these regions' coordinates are transformed to LiDAR coordinates to extract the LiDAR measurements. In hypothesis verification those measurements are used to estimate the objects contour and lastly the object is classified using a support vector machine. An important aspect of using two sensors is that they need to be well calibrated. This has already been achieved by Geiger et al. [7]

In their research, Zhang, Clarke, and Knoll concluded it is a challenge to detect vehicles robustly under various scenarios. Other road objects cause the results to deviate from the reality. They used camera data for generation and LiDAR data for verification. This is in contrast with other work where LiDAR is used for hypothesis generation and camera images are used for verification by classifying the proposed objects. Hwang et al. [8] achieved it this way, however, they concluded the performance of their system is low.

In other research Gohring et al. [9] have explored the fusion of radar and LiDAR sensors. The specific application they developed is car-following system for the German highways. They combine the advantages from both LiDAR and radar sensors. LiDARs are very accurate and are perfect for position estimation. Radars on the other hand are slower but can do precise velocity estimation. In their fusion algorithm a Kalman filter is used. Because their sensors did not have a hardware synchronization, they had to deal with Out-of-Sequence Measurements (OOSM). For this problem they refer to other research from Wang et al. [10] and Kaempchen, and Dietmayer [11].

Liang et al. [12] from Uber Advanced Technologies Group and the University of Toronto developed a 3D object detector using LiDAR and camera data to perform very accurate localization. Their approach consists of continuous convolutions and uses LiDARs and bird eye view images. The results of their research are very promising. Their evaluation on different benchmarks show significant improvements over the state of the art.

On the market side of things, interesting patents can also be found. In the United States a patent [13] exists for a method for fusing radar/camera object data and LiDAR scan points. The patented system is based on the hypothesis generation/verification principle earlier discussed. In the system the LiDAR data is used in response to an object being detected by the radar or camera. This is a clear example of level 1 processing of the JDL model since the method uses object files to represent the position, orientation and velocity of the detected objects.

## IV. Conclusion

The field of multisensor data fusion is a very mature field. There is already a lot a of research on multisensor data fusion for autonomous applications. Most research is focused on detecting objects and refine the properties of these objects. However, this is work situated only on the first level of the JDL model. The objects are refined by adding properties like position and velocity. In future work it would be possible to explore the use of higher level processes of the JDL model. Especially the threat refinement level is interesting.

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