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MULTI SENSOR DATA FUSION FOR AUTONOMOUS VEHICLES

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MULTI SENSOR DATA FUSION FOR AUTONOMOUS VEHICLES

By

SHASHIBUSHAN YENKANCHI

A Thesis

Submitted to the Faculty of Graduate Studies

Through the Department of Electrical &

Computer Engineering

In Partial Fulfillment of the Requirements for

the Degree of Master of Applied Science at

the University of Windsor

Windsor, Ontario, Canada

2016

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Multisensor data fusion for Autonomous Vehicles

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January 5, 2016

DECLARATION OF ORIGINALITY

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ABSTRACT

Multi sensor Data Fusion for Advanced Driver Assistance Systems (ADAS) in Automotive industry has gained a lot of attention lately with the advent of self-driving vehicles and road traffic safety applications. In order to achieve an efficient ADAS, accurate scene object perception in the vicinity of sensor field-of-view (FOV) is vital. It is not only important to know where the objects are, but also the necessity is to predict the object's behavior in future time space for avoiding the fatalities on the road. The major challenges in multi sensor data fusion (MSDF) arise due to sensor errors, multiple occluding targets and changing weather conditions. Thus, In this thesis to address some of the challenges a novel cooperative fusion architecture is proposed for road obstacle detection. Also, an architecture for multi target tracking is designed with robust track management. In order to evaluate the proposed tracker's performance with different fusion paradigms, a discrete event simulation model is proposed. Experiments and evaluation of the above mentioned methods in real time and simulated data proves the robustness of the techniques considered for data fusion.

DEDICATION

To my loving family:

Father: Ashoksingh Yenkanchi

Mother: Seema

Sister: Soumya

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CHAPTER 1

INTRODUCTION

In the past decade, one of the biggest breakthroughs in the automotive industry was to reduce the number of road fatalities and increase the comfort and safety applications in vehicles. The survey done by transport Canada shows that Canada was ranked 10th in terms of fatalities per billion vehicle kilometers traveled compared to other member countries of the organization for economic cooperation and development, shown in figure 1. The early innovations such as anti-lock brake system, seat belts, air bags, etc. are well accepted in industry and with all this considerable effort done, the demand is to further reduce the number of accidents on the road and make driving a comfortable experience for commutation rather than a threat to human life.

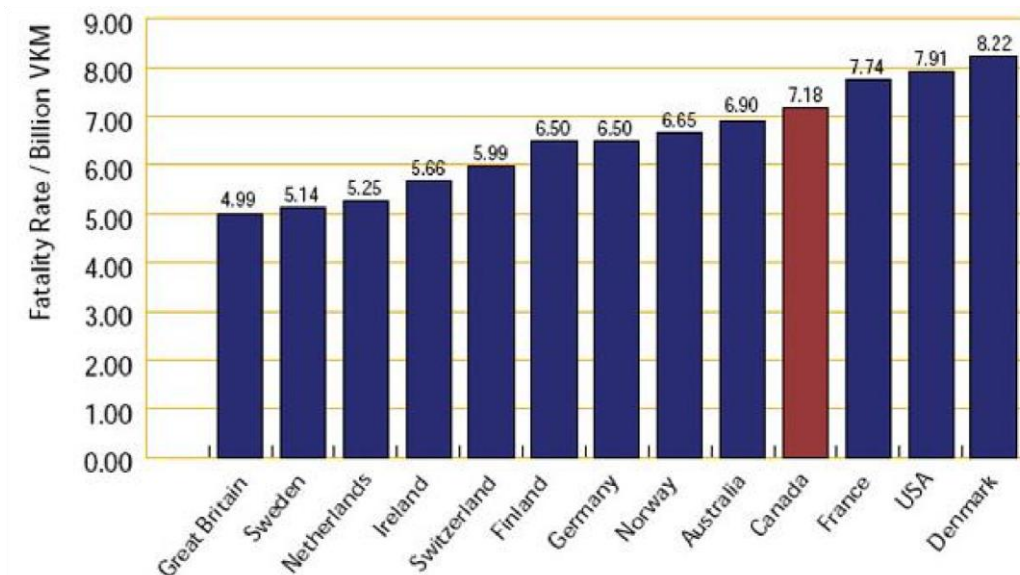


Fig. 1 Canada's 2008 Road safety ranking among OECD Member Countries [1]

Although, the developments so far has led to a lot of opportunities in terms of making reliable use of technology, the challengee still remains to keep this course

going by further increasing safety and many auto makers along with research projects such as Intelligent Car Initiative put forth by European Union are working to make extensive use of electronic devices such as sensors, micro controllers and the actuators to help the drivers in achieving what's called an extra eye on the road while driving to avoid dangerous driving situations. The way computers have been used for application of driver assistance systems today, The near future may experience a paradigm shift in advancement of technology in the way vehicles perceive the environment wherein, complete actions of drivers on the road will be taken care by the vehicle itself and the driver will just be a mere supervisor. The figure 2 illustrates one of such situations in traffic showing how the remote sensing devices can be utilized to provide safety and overcome dangerous situations caused by human negligence.

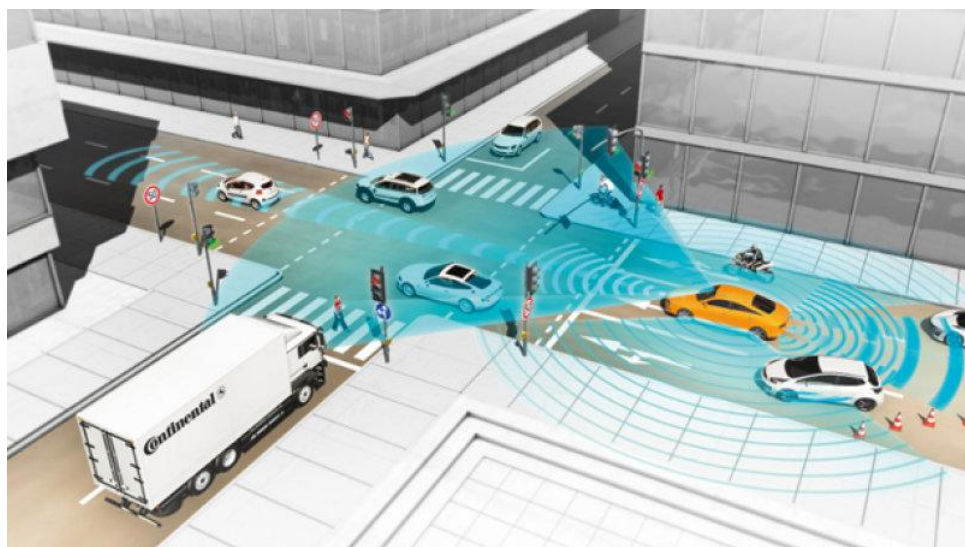


Fig. 2 Example of how remote sensing devices can be used for automotive safety applications¹

Currently, relying on these systems only the safety related and comfort applications such as an early collision warning, self parking aid, adaptive cruise

¹ Image courtesy- <http://www.autoblog.com/>

control etc. have been deployed in public use. Although, many autonomous driving projects initiated by groups like Defense Advanced Research Projects Agency (DARPA) and some of the major auto manufacturers have been put to test on the road, the challenges that need to be met in reality to make the autonomous vehicles (AV) available for everyone are still high. One of such challenge the engineers are facing today is to reduce the complexity of electronic systems and the infrastructure used for communication between them. Common understanding of the scene around the vehicle is required to use the overall sensory system. As of now, the level of understanding and strategies deployed are application specific. Say the forward collision avoidance may require a specific set up than a rear end collision or parking assist. This increase in the number of subsystems in turn will amount for a substantial increase in the cost of electronic devices used to build each individual functionality, compared to the overall cost of the vehicle itself. Apart from technological challenges, the AVs have to pass the legal issues concerning the law in terms of who is actually responsible if any disaster has to happen while driving autonomously.

In order to give the context of where the technology stands today, the trends in development of AVs have been classified into four levels of driving according to [2]. This can be summarized as follows:

- **Level 1-Function Specific Automation:** This deals with the automation of specific functionality such as adaptive cruise control, parking assist, lane guidance, etc. The driver is fully engaged and responsible for complete control of the vehicle.
- **Level 2-Combined Function Automation:** This deals with the automation of combined functionality in action, such as adaptive cruise control with

lane centering. The driver can partially disengage (hands off the steering wheel) only under certain conditions, while most of the time control is still under the driver and is responsible for monitoring the road.

- **Level 3-Limited Self-Driving Automation:** The driver can hand over the control to most of the safety-critical applications and rely on vehicle to monitor for changes in those conditions that will require transition back to driver control. The driver is not expected to constantly monitor the road.
- **Level 4-Full Self-Driving Automation:** In this level vehicle can perform all driving functions and can monitor traffic conditions for the entire trip and can be operated by the occupants who do not drive or without human intervention.

Currently, only level 2 has been made available for public use and most pilot projects put forth by major car manufacturers fall below level 3 which is state of the art now and requires more technological advancement in terms of reaching the goal of level 4 automation. The figure 3 below gives the overview of the timeline when the AVs will be made available for general public use.

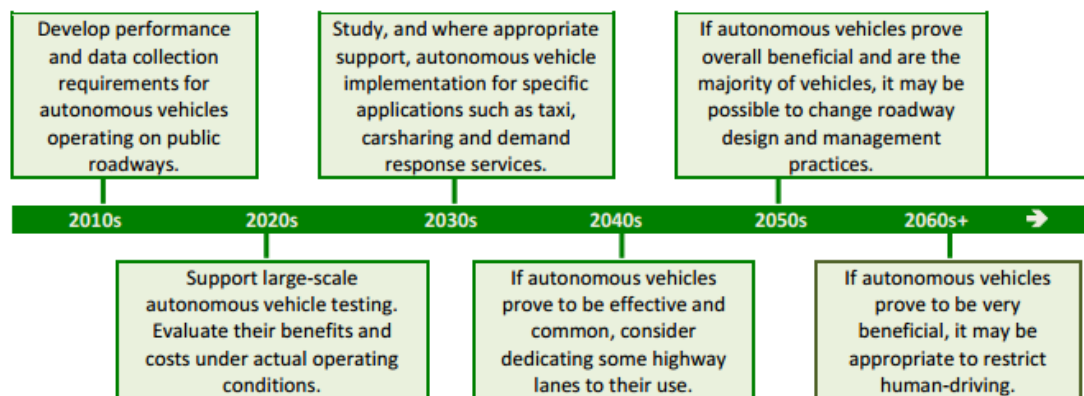


Fig. 3 Timeline summarizing the impact of autonomous vehicles on transport system [3]

This remarkable progress in the development of safety critical applications and extensive use of remote sensing devices in automotive industry has led to make use of tracking and information fusion methods that are largely in use for defense and surveillance related applications. With this the data fusion community has been working to develop applications based on the complete information derived from individual sensors to provide a more robust description of the environment to take better decisions. The goal of data fusion can be explained via the formal definition provided in [4].

“The basic problem in multi sensor systems is to integrate a sequence of observations from a number of different sensors into a single best-estimate of the state of the environment.”

Keeping this as a goal to find the best estimate from the different sensors used for AVs, this thesis introduces the key architectures used in order to achieve the fusion benefit. Chapter 2 introduces to the previous work done and state of the art, chapter 3 gives the overview of the types of sensors used. In chapter 4 some of the architectures used for data fusion are introduced, followed by chapter 5 which provides the insight to the proposed model. Further, chapter 6 shows some of the experiments conducted and the results obtained and finally chapter 7 concludes with some of the observations made and giving directions for future work.

CHAPTER 2

LITERATURE REVIEW AND SCOPE OF THESIS

With increased demand for safety and preventive comfort measures in the automotive industry, data fusion community is rapidly evolving. More focus is put forth to improve the existing solutions for fusion or to evaluate the test results of different case study setups. This chapter provides a rationale for proposed system architectures and entails, how this thesis contributes to the research in this area.

2.1 MOTIVATION

For Autonomous vehicles, to deal with preventive safety applications and to accurately judge the driving scenarios, the relevant information required is not only the state of the own vehicle but also the state of the traffic situation and the road condition. Many complex signal processing strategies are used to process the information perceived by the sensors which has been discussed in chapter 3. In literature, although some specific algorithms to perform this task are investigated since a decade, when it comes to automotive environment there are aspects which need specific attention. For example, the task of tracking is trivial, but in order to derive specific features of vehicle and pedestrian more specific algorithms are required depending on the types of sensors and the fusion methodology used. So, very less papers deal with this topic.

The important parameters to be considered here are the accurate detection of the obstacles and tracking them in the subsequent frames. The method used for this task has been discussed in chapter 5. It should be noted that this is not a trivial task. Many different algorithms have been proposed in literature to achieve this task,

therefore different system designs with corresponding advantages and disadvantages are possible. Also, it should be noted that the same algorithms may fail to perform and complexity varies depending on the factors such as the number of sensors used and changing weather conditions.

In literature one of the important aspects studied with respect to data fusion systems, in fact the most controversial one, can be termed as Fusion Paradigm. The ego vehicle's environment can be perceived by remote sensing devices and information from abstract raw sensor data can be transformed into high level description with help of signal processing algorithms. The steps involved to combine the information from several sensors into one joint description of the environment can vary depending on the fusion paradigms, low-level and high-level. Each has its advantages and dis-advantages in terms of performance of the overall system and its still an open ended question as to which architecture is superior over another.

2.2 LITERATURE REVIEW

Over the past decade, extensive research has been done in order to optimally combine the information from different sources for defense and surveillance applications. Although, most of the techniques are trivial, when it comes to apply them for automotive applications additional challenges are imposed due to unpredictable behaviors of obstacles on the road and changing weather conditions. This may alter the feasibility of specific techniques. Therefore, the rationale for further investigation on this topic is still high. Some of the early work that revolutionized the techniques to be used by the automotive industry includes the algorithms for advanced tracking [5], optimal filtering techniques [6], and techniques for fusion of multi-sensor data [7].

One of the first systematic approaches to combine data from multiple sensors

for preventive safety applications in the automotive industry was carried out by a research group ProFusion 1 and 2, which is a part of the European Union funded integrated project *PReVENT* (2008) [8] which aims at providing intelligent integrated safety to drivers on the road to avoid accidents. The ProFusion sub-project was dedicated to evaluate and design the implementation of data fusion systems for effective crash mitigation strategies. They extensively worked on different fusion paradigms by collaborating with some of the parallel sub-projects of *PReVENT* to improve driver assistance systems and increase safety as illustrated in figure 4. Major findings from this project claim that low-level fusion is beneficial in terms optimally handling the combined effect of sensors, where as high-level approaches have advantages in terms of modularity, scalability and are efficient in handling the communication load. Sensors like radar, laser scanner and cameras, Infrared Cameras were used.

















Fusion Approaches Use Cases	Early Fusion 	Multi-Level Fusion 	Grid-Based Fusion 	Track-Level Fusion 
PF2 COMPOSE  				
PF2 INSAFES  				
PF2 SASPENCE  				
PF2 APALACI  				
PF2 COMPOSE & SAFELANE Truck  				

Fig. 4 Illustrations of different fusion paradigms adopted by ProFusion group [8]

Some of the objectives that were achieved by *PREVENT* group were through the following sub-projects that include: *SASPENCE* which focused on speed management and headway control and *WILLWARN* whose concept was based on adhoc networks for V2V communication and vehicle positioning. These two sub-projects assisted driver in longitudinal control of the vehicle. For lateral safety the projects designed were *LATERAL SAFE*, that decrease risk of collision in lateral and rear end of the vehicle. The *SAFELANE*, which constantly monitors driver's attention by checking for drowsiness, fatigue and distraction in order to keep the driver active and concentrated while driving. In order to provide safety for drivers at the intersections and avoid collisions while turning another sub-project came up called *INTERSAFE*. Here the driver warning was based on bidirectional V2I communication along with path prediction of host and other vehicles. For vertical safety and protection of vulnerable road users another two sub-projects came up called *APALACI*, whose main application was semi-autonomous braking followed by *COMPOSE*, whose application was autonomous braking concerned about vehicle's immediate vicinity. Most of these projects provide a protective shield around a vehicle and this can be seen in figure 5 below.

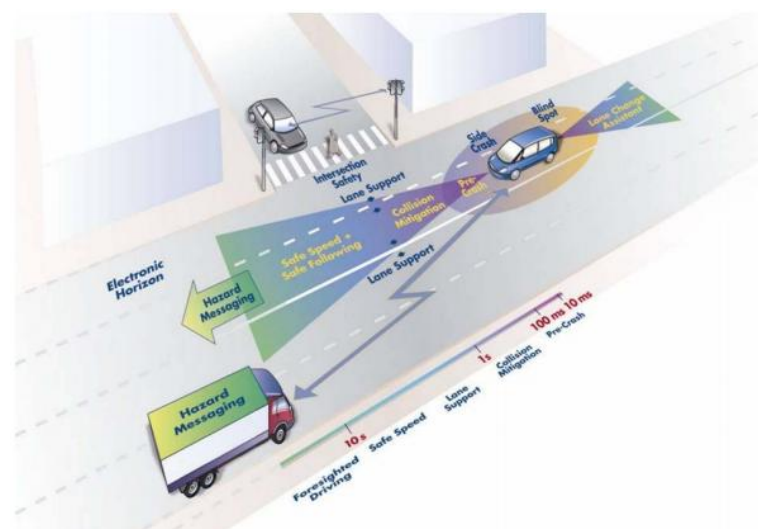


Fig. 5 Illustrations of PREVENT safety Objective [8]

Inspired by the above projects one more integrated project was started *SAFESPOT* (2010) [9]. This project focused on cooperative systems for road safety with smart vehicles on smart roads. The main objective is detection in advance of potentially dangerous situations to extend in space and time driver's awareness of surroundings. There are eight different sub-projects that are put together to achieve these objectives. One of the interesting sub-project to look at is *INFRASENS* [10]. This sub-project aims at creating an infrastructure based platform which focuses on the acquisition of data from roadside and combine with on-board sensors located on the vehicles. A cooperative fusion was proposed in order to combine data from laser scanners, digital maps and V2V/V2I technologies. More on assessments of the overall project can be found in [11]. They claim that the cost of the components and infrastructure are too high and more work is required in reduction of complexity of the system. The figure 6 below illustrates one of the scenarios involving working on this project.

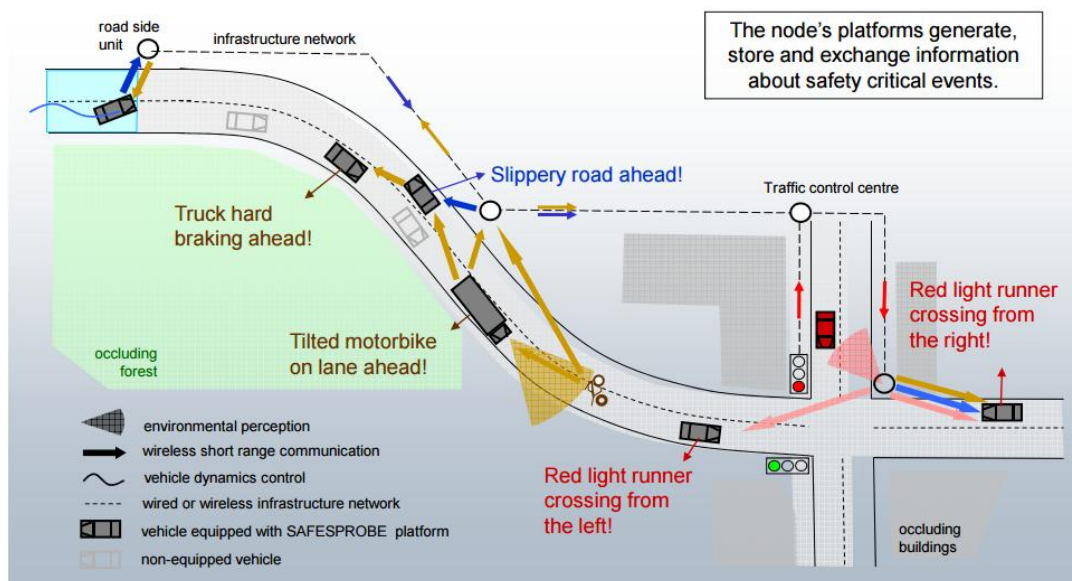


Fig. 6 Illustrations of SAFESPOT safety Objective [10]

Another integrated project that gained a lot of attention is *HAVEit* (2011) [12]. This project aims at the long term realization of highly automated driving for intelligent transport. The highly automated driving brings the next generation Advanced driver assistance systems for increased road safety by letting the vehicles drive by itself, however, keeping the driver still in control of the vehicle whenever it is necessary. There are five sub-projects which aim at safety architecture implementation, joint driver co-pilot system and highly automated driving applications separately. The paper [13] examines in detail the problem of multi sensor data fusion for target tracking and road environment perception in automated vehicles. Fusion was done at central level and sensor level. The important claim they make with their experimental outcomes is that central level tracking yields better results than sensor level tracking. One of such architectures featuring joint system-driver co-system can be seen in figure 7 below.

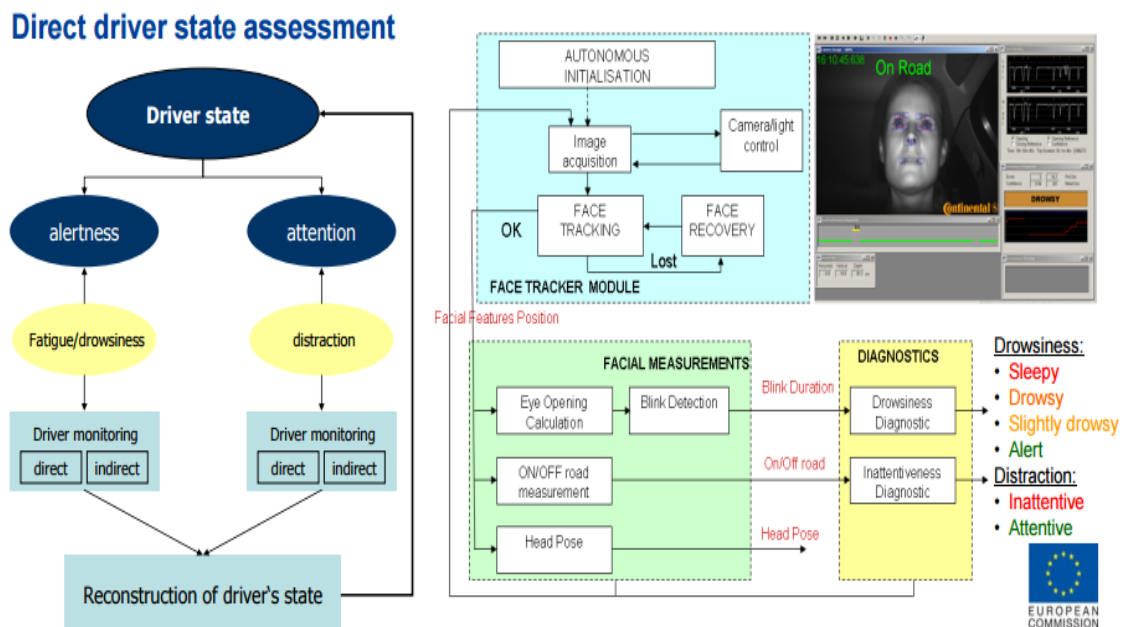


Fig. 7 Illustrations of HAVEit joint system-driver co-system [12]

The project *InteractIVe* (2010-2013) [14], inspired by *PreVENT* again, aims at developed intelligent and integrated high performance ADAS applications to enhance the safety of the driver. This project more specifically aimed to design, develop and implement three groups of functions which include continuous driver support, collision avoidance and collision mitigation with demonstrator vehicles consisting of six passenger cars of different class and one truck. There are seven sub-projects out of which the *Perception* project works specifically on developing advanced multi sensor data fusion approaches and processes by integrating a range of sensors, digital maps and wireless communication in order to advance the safety requirements by active intervention and multiple integrated functions. Some of the interesting research activities that go in this project module can be seen in figure 8 below. The major claim that could be used for this thesis is that High-level fusion is better than low-level fusion paradigm while designing safety and time critical applications. More on the techniques can be read in [15], [16], [17].

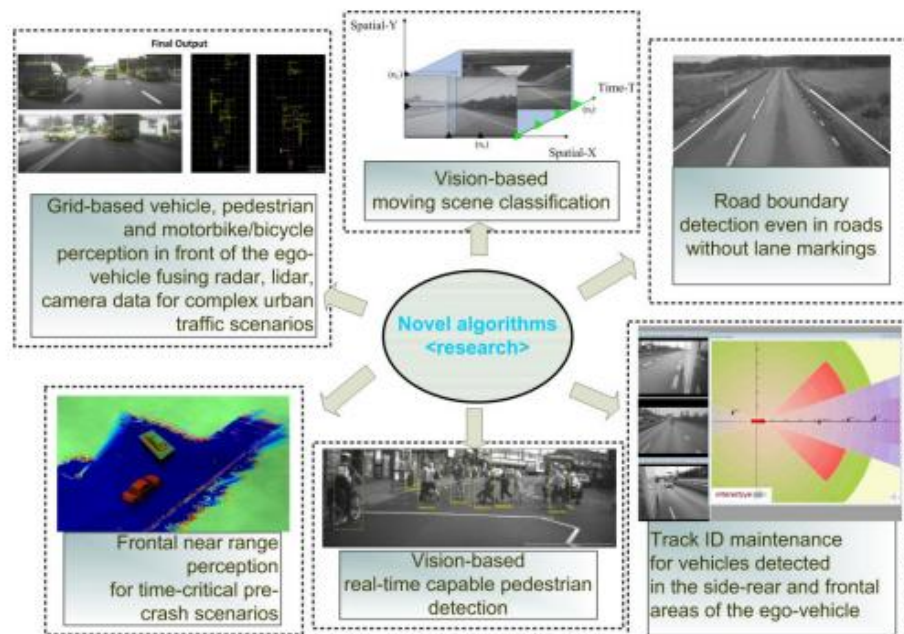


Fig. 8 Research activities in perception module of interactIVe project [14]

The current state of the art in technology is focused on *AdaptIVe* (2014-2017) [18] project. This is the predecessor of the previous project *InteractIVe*. The project develops, tests and evaluates automated driving applications for passenger cars and trucks in daily traffic consisting of eight demonstrator vehicles in close distance, urban and highway scenarios. Main objective focuses on strategies for system-driver interaction. The figure 9 below illustrates some of the areas of current research activities. Interesting work to follow are [19], [20].



Fig. 9 Research activities in AdaptIVe project [18]

Some of the other interesting parallel projects that need to be looked at are DESERVE (2012-2016) [21], which aims at developing embedded ADAS applications in order to reduce the complexity and cost of existing systems. The project Autonet2030 (2013-2016) [22] aims at developing and evaluating algorithms for cooperative automated driving in the year 2030 focusing on technologies like V2X

in order to enhance safety. In order to provide safety for vulnerable road users the project PROSPECT (2015-2018) [23] aims at developing and testing autonomous emergency braking system (AEB) to provide proactive safety for pedestrians and cyclists. The project RobustSENSE (2015- 2018) [24] aiming at robust and reliable environment sensing with situation prediction. The main goal of this project is to use data fusion strategies to improve the perception and to overcome the situations wherein, the sensors fail to operate due to harsh weather conditions and other adverse conditions.

In summary, most of the research done so far claims that the development of ADAS applications and automated driving has been a process without any uniform practices. Most researchers predict this may hinder the fast market applications ADAS and may pose safety threats and legal consequences in the event of ADAS technical malfunctions and failures. SO, more research is required in this blooming field of Multi-sensor Data Fusion (MSDF).

2.3 SCOPE OF THESIS

The future architecture of Autonomous Vehicles will have to comply with increasing amount of complex electronic devices in an information perception subsystem. In order to support for increasing advancement in technological developments, evaluation of the nature of sensory systems and signal processing strategies with respect to requirements of dependability on safety applications is necessary. With the knowledge of prior research low-level fusion paradigm has proved to be effective in terms of fusion benefit, whereas high-level accounts for scalability and better communication load. The quality of environmental perception is not only dependent on these two architectures, but also on different subsystems such as varying sensor

sets, type of algorithms chosen and fusion objectives. Therefore, estimation of how these subsystems perform is of remarkable importance.

Since the exact structure of information perception system may vary with increasing advancements in technology, it is not feasible to evaluate every possible design in real time experimental setup. In order to fill this gap, the scope of this thesis is to design effective hybrid cooperative fusion architecture and Multi target tracking system and do a statistical data analysis of proposed fusion architecture, keeping in mind to answer the research question “*what fusion paradigm is suitable with respect to the application and to what extent simulation can be used to evaluate the system*”.

CHAPTER 3

SENSORS USED FOR AUTONOMOUS VEHICLES

This chapter gives the overview of some of the sensors that are commonly used by AVs for the environment perception. Due to the nature of electronic devices, it is common to have a certain degree of error with respect to physical phenomenon measured by the individual sensors. While designing safety critical applications, the degree of reliability on these sensors is high and should be accurate enough to make the decisions that humans fail. This chapter also gives the overview of driver assistance systems that are in use and some of the strengths and weakness of these sensors are depicted relevant to this thesis.

3.1 TYPES OF SENSORS

Most of the sensors used for automotive applications can be classified into two types Active sensors and passive sensors, based on the physical phenomenon they measure either by actively probing the environment or passively perceiving the environment. Active sensors tend to send the radiations in order to detect the objects around and eliminate the noise by comparing the time-of-flight information between the emissions. Whereas, passive sensors perceive the information based on the illumination of the environment. Passive sensors are less expensive compared to the active sensors in a way of mechanism they are generally built. Some of the active sensors that are used are laser based, radar and ultrasonic sensors. While, passive sensors can be vision based such as cameras. Some of the important properties of these sensors are reviewed below with advantages and disadvantages.

3.1.1 LASER BASED SENSORS

Laser based sensors include Laser Scanner and Light Detection and Ranging (LIDAR). Laser based sensors work on the technology that emit the light impulse of electromagnetic waves. The wavelength of the electromagnetic spectrum includes near infra-red (800 – 950nm) or in the ultra violet above (1500nm). The distance of the object is calculated by time-of-flight information taking the difference between emission and received pulses. The relative velocity of the object cannot be directly obtained while it is derived by taking the derivative of the range with respect to the time when the object is observed for multiple frames. This makes it possible for these kind of sensors to track multiple targets. However, the drawback of this class of sensors is they are vulnerable to dirty lenses and poorly reflecting targets and also another draw back is they are sensitive to changing weather conditions. Applications like automatic parking, collision mitigation rely on these kind of sensors.

3.1.2 RADAR SENSORS

The Radar Stands for Radio Detection and Ranging. Just like Laser based sensors, the radar sensors emit strong radio waves and receiver collects the reflected signals back. The range of obstacle is calculated by time-of-flight information. Also, one more advantage is the velocity of the object can be directly calculated from the frequency shift between the emitted signal and Doppler echo. These kind of sensors was heavily used in defense and aviation industries to map the movement of the aircraft and derive the information as in range and velocity. This property of these kind of sensors made them popular to use for automotive applications. Usually there are two types of radars that are popular in automotive sector one is Long range radar (LRR) which operates at

77-81 GHz spectrum and second is a Short range radar (SRR) that operate at short range 21.65-26.65 GHz. The range properties include 120-150 meters for LRR and 20-60 meters for SRR. These kind of sensors are vulnerable to extreme weather conditions as in thick fog and may sometimes fail to distinguish between target and clutter. Applications like collision mitigation, adaptive cruise control are popular that rely on these kind of sensors.

3.1.3 VISION BASED SENSORS

These kind of sensors falls under passive sensor category as they do not emit any ray instead perceive the environment based on the different wavelength spectra such as color, grey scale and infra-red. Vision based sensors include monocular cameras and stereo vision camera. Unlike the above mentioned active sensors, they cannot derive range and velocity of the targets while the information can be derived by applying some sophisticated signal processing strategies. The availability and affordability makes these kind of sensors largely applicable for automotive applications. Also, the other advantage is, the camera can actually distinguish between the objects based on physical properties and can be used for applications like traffic signal analysis, lane change assist etc. The drawback includes vulnerability to weather conditions like rain, thick fog and also most of the cameras fail to operate in dark unless it is night vision equipped sensor.

With advancement in technology, the number of sensors being used in order to make cars more intelligent is immensely large. There are also many other types of sensors being used such as Photonic mixer device (PMD), Closing Velocity (CV) and also another class of sensors include V2V, V2X technologies along with GPS and

digital maps. The in depth analysis and use of these sensor types is out of the scope of this thesis. Table 1 below summarizes the different sensors with their properties and applications mentioned above.

	Distance	Velocity	Applications
Laser Based	Time-of-flight	Indirectly via range derivative	pre-crash collision mitigation, Automatic parking assist, etc.
Radar	Time-of-flight	Frequency shift	Forward Collision warning, Adaptive Cruise control, etc.
Vision Based	Indirectly via model parameters	Indirectly via range derivative	Lane change assist, Traffic signal analysis, etc.

Table. 1 Summary of the types of sensors used for AV

3.2 ADVANCED DRIVER ASSISTANCE SYSTEMS

The Advanced Driver Assistance systems (ADAS), include the most of the current existing technologies that assist drivers on road to rely on applications such as Adaptive cruise control (ACC), Forward collision mitigation, Automatic parking, Lane change assistance and many more. Currently, all these applications are built to support partially to the driver. The dependability of these driver assistance systems is high not only on the current state of the vehicle, but also on the environment that is constantly changing with respect to time. These conditions are subjected to the type of sensors used for a particular application. In future, ADAS applications are expected to rely more on the safety of the passenger by autonomously taking control of the vehicle as in, autonomous emergency braking, collision avoidance while steering autonomously and intelligent decision making to take control of the vehicle during

negligence of the driver. Also, what's more important is the reliability of these systems built. As the sensors in nature are not accurate a validation system is required in order to mitigate the false activations of any of the applications whenever they are not required to function. This may lead to more substantial problems, which account for the safety of the passenger. More on the ADAS developments and current state of the art can be found in [25]. The figure 10 below shows some of the existing applications with the types of sensors used in ADAS.

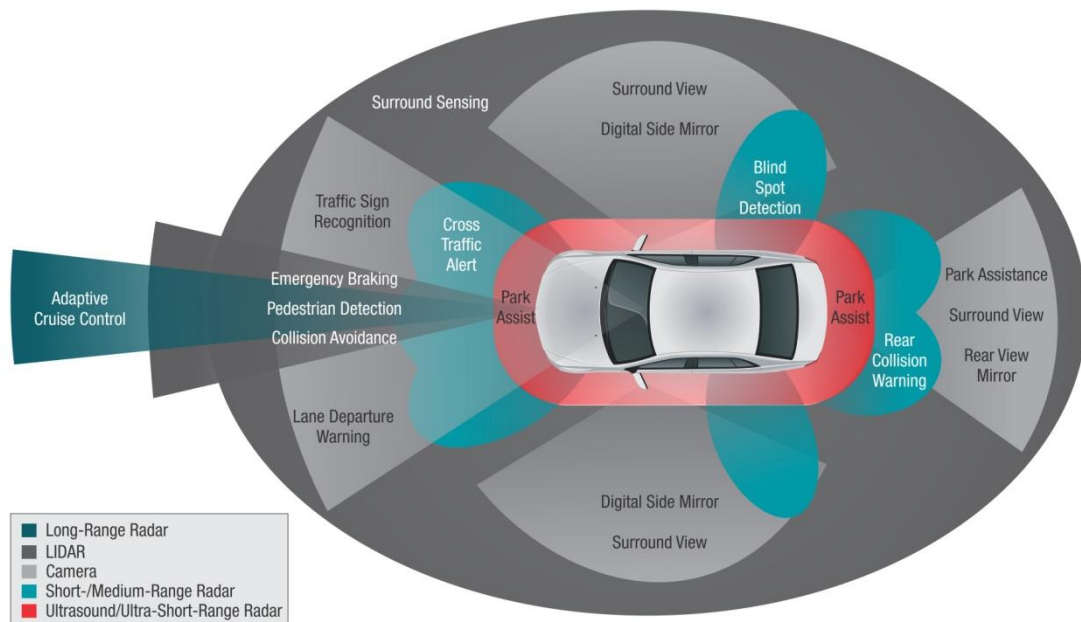


Fig. 10 ADAS applications in use with the different types of sensors ²

² Image Courtesy-millionstartups.com

CHAPTER 4

MULTI SENSOR DATA FUSION

Most of the techniques pertaining to the information fusion were derived from defense and surveillance applications in the automotive industry. The challenge was to make the environment perception more robust with increasing confidence and reliability in order to meet the unpredictable demands of the constantly changing nature of the AV's surroundings. Yet, the challenges that are to be met impose few additional constraints depending on the cost, architectures and types of sensors used. This chapter introduces to some of the architectures that are commonly accepted by the data fusion community followed by some of the advantages of using these methods.

4.1 ARCHITECTURES OF MULTI SENSOR DATA FUSION

Due to the vast majority of applications exist for multi sensor data fusion some to mention in the field of robotics, defense applications, virtual reality and air traffic control, the methodology of fusion techniques used is diverse. Many models have been proposed to achieve this task over the years. Out of all these one of the highly cited models that is still followed today is the model proposed by U.S based defense research foundation named Joint Directors of Laboratory (JDL). This model is widely studied and revised in 2004. The figure 11 below shows the revised JDL model for data fusion [26].

The JDL model takes into account the abstraction of data at different levels with respect to fusion. The data can be abstracted at a very early stage as in signal level to the highest possible impact level often termed as decision level. This also

comprises of integration of information from different sources such as sensors, databases and different layers of data processing called fusion domain along with an interface for decision system. In automotive industry the fusion domains inherited from this model can be implemented to achieve the robust description of the environment. However, there are constraints with respect to cost and complexity of the design.

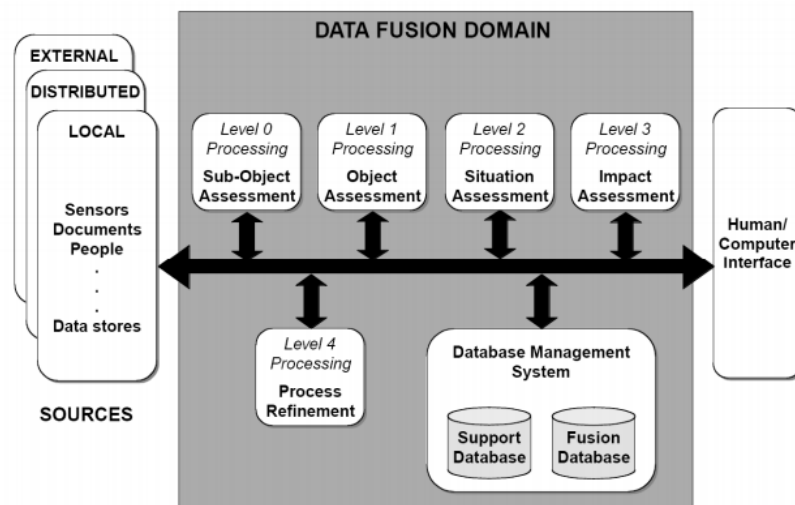
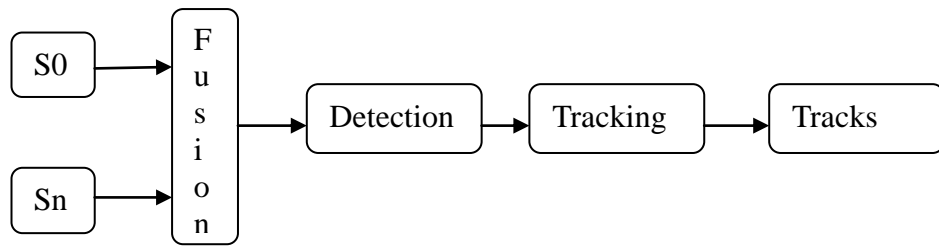


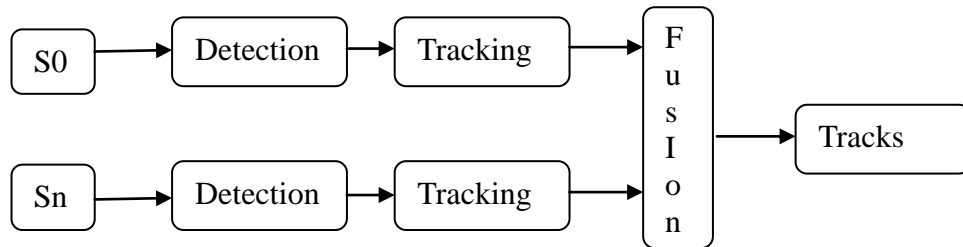
Fig. 11 JDL process Model for Data Fusion [26]

For automotive applications two types of fusion paradigms are possible depending on the level of data abstraction [6]. The low level fusion or signal level fusion that utilizes the raw sensor data and the high level fusion or so called the decision level fusion which uses the processed data for fusion of information. There is the third kind of fusion that takes in the advantages of both high level and low level called the hybrid fusion or feature level fusion. Each of these fusion paradigms has certain advantages and disadvantages based on the application and types of sensors utilized for integration of the information to perceive the environment. The figure 12 below shows the block diagram of each of these fusion paradigms that are in use.

a)



b)



c)

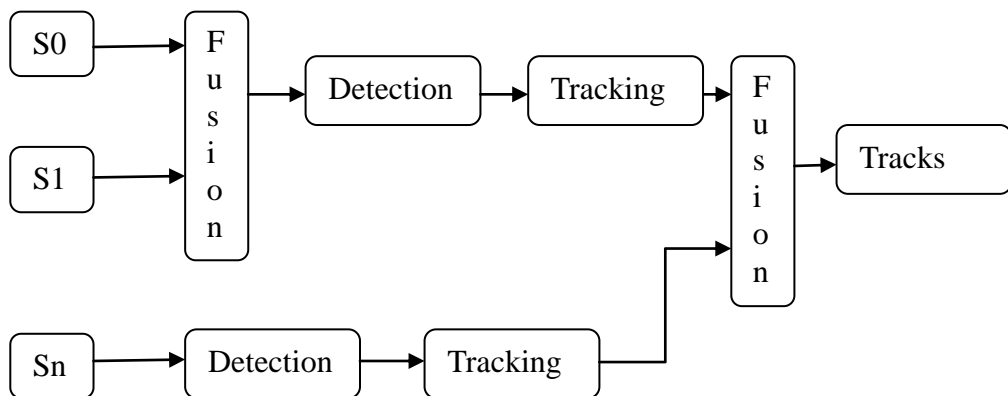


Fig. 12 a) Low-level fusion b) High-Level Fusion c) Hybrid Fusion

4.2 ADVANTAGES OF MULTI SENSOR DATA FUSION

The design and implementation of data fusion architectures vary from application and the types of sensors used. Also the field of application is diverse as in data fusion is used for defense and surveillance, aviation industries, Robotics and Virtual reality apart from the automotive sector. According to [6], There are nine benefits of data fusion aiming at two objectives of increased system's availability and increases system's authenticity that define the exactness of the objects perceived. The sensor arrangements vary in accordance with the objectives. There can be three different classes of sensor arrangement as shown in figure 13.

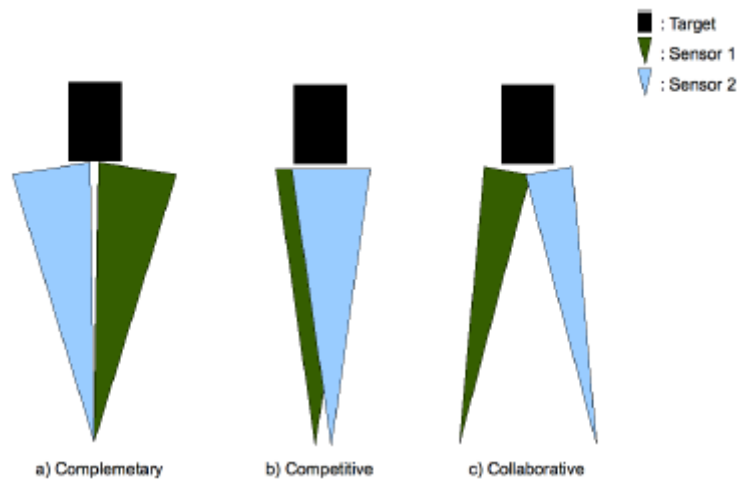


Fig. 13 Different classes of sensor arrangements [27]

The following arrangements for fusion objectives are:

- Complementary Arrangement: The sensors perceive complimentary information with advantages of extended spatial coverage, extended temporal coverage and improves detection.
- Competitive Arrangement: The sensors perceive the same area of coverage,

providing redundant data with the advantages of increased dimensionality, improves system reliability and enhanced spatial resolution.

- Collaborative Arrangement: The sensors perceive the environment collaboratively by providing information that single sensor cannot derive. The advantages are increased dimensionality and enhanced spatial coverage.

CHAPTER 5

PROPOSED METHOD

This chapter gives the overview of the proposed model used for the study mentioned in the scope of this thesis. Since in literature the problem of MSDF technique is not uniquely designed however, is studied separately addressing multiple problems as tracking with detection while few tend to deal with specific problem as obstacle detection. In the first part of this work a novel technique to detect the road obstacles for AVs using laser scanner and camera is designed. The second part focuses on data association and state estimation often termed as multi target tracking (MTT) with robust track management. In order to estimate the performance of proposed MTT in terms of different fusion paradigms with varying sensor combinations, a discrete event simulation analysis model is proposed in the third part.

5.1 OBSTACLE DETECTION USING COOPERATIVE FUSION OF LASER SCANNER AND CAMERA

In this section the architecture proposed for the cooperative fusion between laser scanner and camera sensors is considered. The block diagram given in figure 14 below explains the steps taken towards obstacle detection on road for AV. There are many sophisticated methods available in literature to do this task considering single sensor such as camera alone, however the motive here was to explore the techniques available for laser scanner processing and with the help of this extract the potential ROIs in the image plane as a form of binary mask. Further, in future

work the advantages of this method are discussed with relevant techniques in order to extend this work. Further sub sections in this part explain each important block in the proposed architecture.

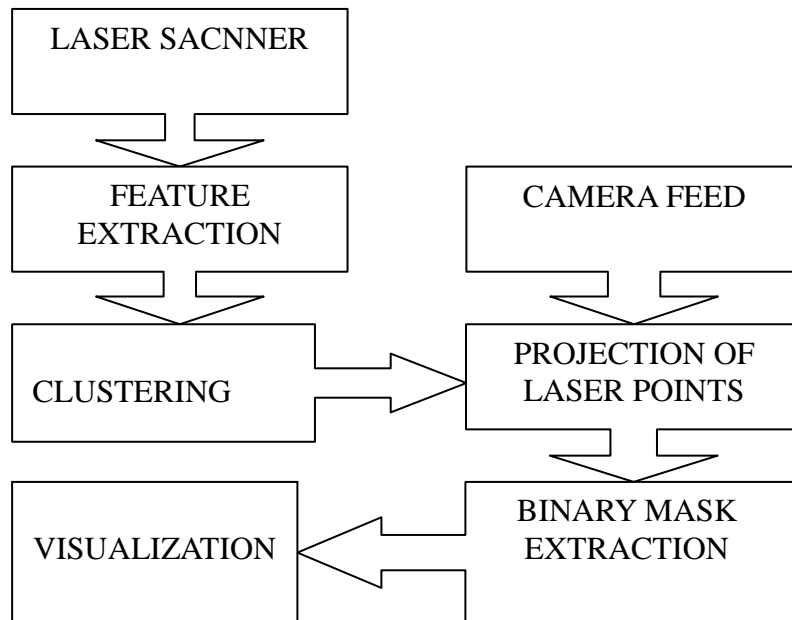


Fig. 14 Block diagram for cooperative fusion of laser and camera

5.1.1 FEATURE EXTRACTION

Since the objects in world around AVs are made of primitive geometric shapes, due to the property of laser scanner the reflections of ground objects have information about local saliencies such as surface normal and curvature at each of the corresponding 3d location in sensor space. The first preprocessing step involved in order to make sense of point cloud data obtained is to remove the points belonging to the road surface by fitting a planar surface which requires estimating of above mentioned saliencies in each step.

In the field of computer vision literature, methods like Least squares, Principal Component Analysis (PCA) and Random Sample Consensus (RANSAC)

are well known, and are still cited algorithms in order to achieve this task. Some of the recent works can be found in [28] [29], wherein the work done by nurunabbi et al gives the analysis of the above mentioned techniques for ground plane detection and removal. RANSAC is a re-sampling technique which iteratively generates the candidate solutions into inliers and outliers by using the minimum number of observations required to estimate the model parameters that fit a plane. If the fraction of the number of inliers over the total number of points in set exceeds the predefined threshold T , then the model parameters are re-estimated considering all the identified inliers and process is terminated. Simple illustration of this method for 2d line fitting can be seen in figure 15 below.

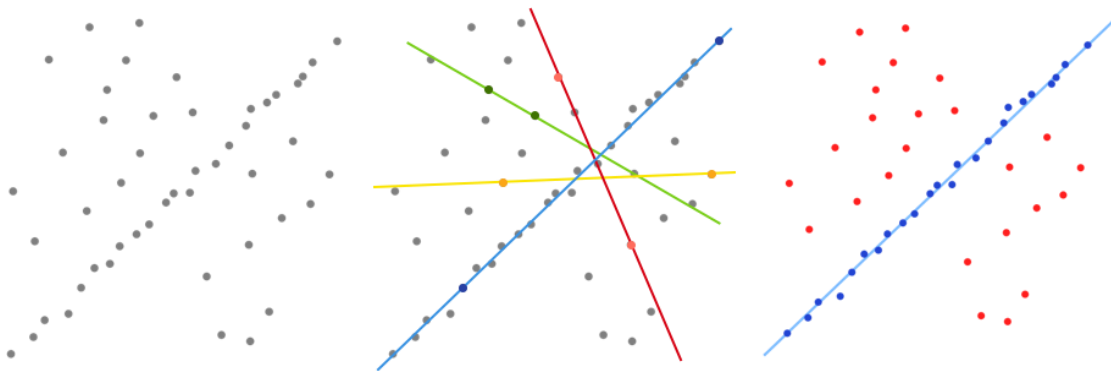
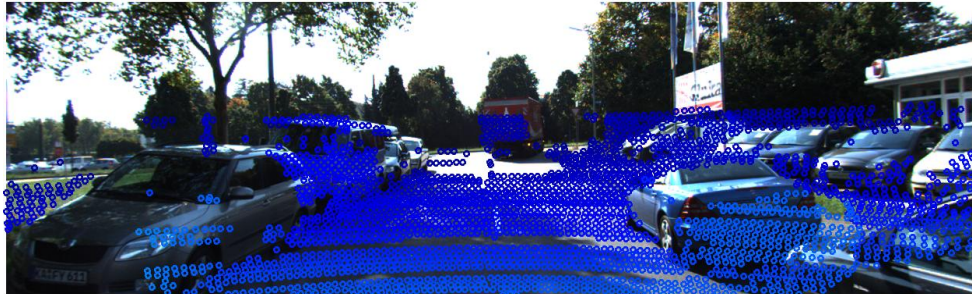


Fig. 15 Illustration of 2D line fitting technique

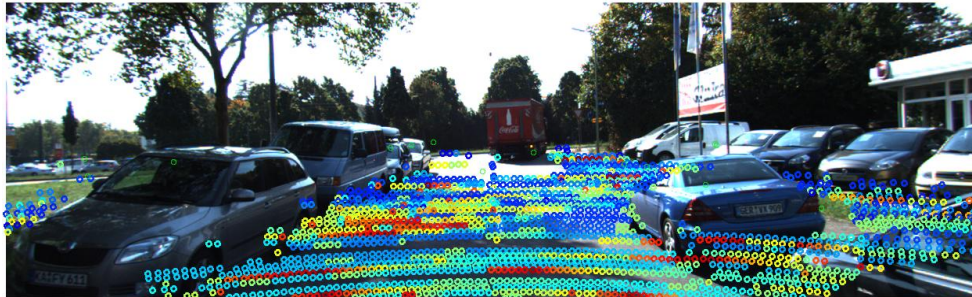
Much later in [30], Torr and zisserman showed that in RANSAC if the threshold T for considering the inliers is set too high then the robust estimate can be very poor. To over come this they proposed a new estimator called MSAC which takes as support the log-likelihood of the solution taking into account the distribution of outliers and uses random sampling to maximize this. Vosselmen and Klien [31] showed the advantages of using MSAC over RANSAC algorithm for this purpose. This work uses MSAC algorithm for Road surface estimation and removal of points

belonging to corresponding plane. Figure 16 below illustrates some of the results applied to the point cloud data.

a) Raw laser point cloud projected on an Image



b) Ground plane detection on the horizontal plane in point cloud data



c) Ground plane removal and projection of laser points on vertical surfaces



Fig. 16 Illustration of Ground plane Detection and removal from point cloud data

5.1.2 CLUSTERING

Once the ground plane is removed, the remaining point clouds belong to road obstacles which may be coming from vertical plane surfaces such as cars, walls and clutter objects such as poles and bins on the road. The next step is to classify the points belonging to the vehicles and the rest of the objects. This task of grouping

points coming from same objects into one is called clustering. The 3D points coming from laser for each frame may differ in orientation based on the arbitrary shapes. In order to cluster the data of this type most promising clustering methods include Graph-theoretic methods which cluster the data based on the neighboring points [32]. In this work one of the kind belonging to this class of methods called DBScan proposed by Ester et al [33] is used.

The advantage of using this algorithm is it does not take into account the prior initialization of a number of clusters to be formed as in Kmeans. It takes just two parameters as input specified by the user. The parameters include the search radius θ and the minimum number of neighboring points Mp to be considered while clustering. An illustration of working of this algorithm is shown in figure 17. The algorithm starts with arbitrary point A and looks for the Mp points in θ neighborhood. The new cluster is started if condition is satisfied by marking A as cluster center and all other points in neighborhood belong to this cluster core. In the next step Mp neighborhood of all these points is checked and cluster is grown arbitrarily. The points that do not satisfy this condition are marked as outliers. The metric used for computation is the euclidean distance between the points. The complexity of this algorithm is $O(n \log (n))$, where n is number of points. Worst case complexity is given by $O(n^2)$.

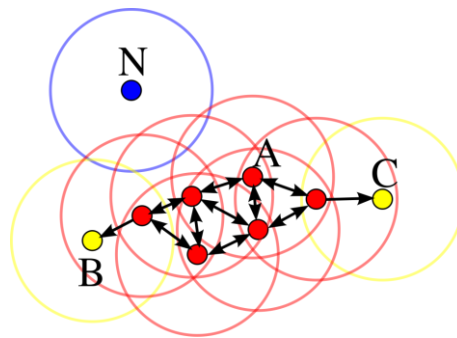


Fig. 17 Illustration of working of DBSCAN algorithm

5.1.3 BINARY MASK EXTRACTION

After clustering the laser point clouds, the filtered objects are projected on image plane using the calibration matrix between laser and camera. The next task is to extract the region of interest in the image plane, which represent the potential targets on the road that AV has to identify in order to avoid the collision and accurate path planning. In order to extract the ROI in image plane a binary mask is created which search for projected laser points. A NXN scanning window is run across the image plane, which collects and marks the potential targets. A novel algorithm is proposed to do this task. The algorithm is depicted below which shows the following steps taken.

The Algorithm

```
BinMask=False
For i = 1 : N : end of X coordinate
  For j = 1: N : end of Y coordinate
    For k = 1: Size(Projected laser Points)
      If (in the Image Plane)
        Extract Projected Points
      End
    End
    If Size(Extract Projected Points) > Threshold
      BinMask = True
    End
  End
End
```

5.2 MULTI TARGET TRACKING (MTT)

This section explains the steps taken for the process of multi target tracking which involves association of multiple detections over the time and updating the believe of where the objects in space are based on the predictions made on where the objects are going to move in future frames. The block diagram given below in figure 18 explains the methodology followed in order to design this system. It is important to note that the overall system design may vary as there is no uniform practice followed in the literature.

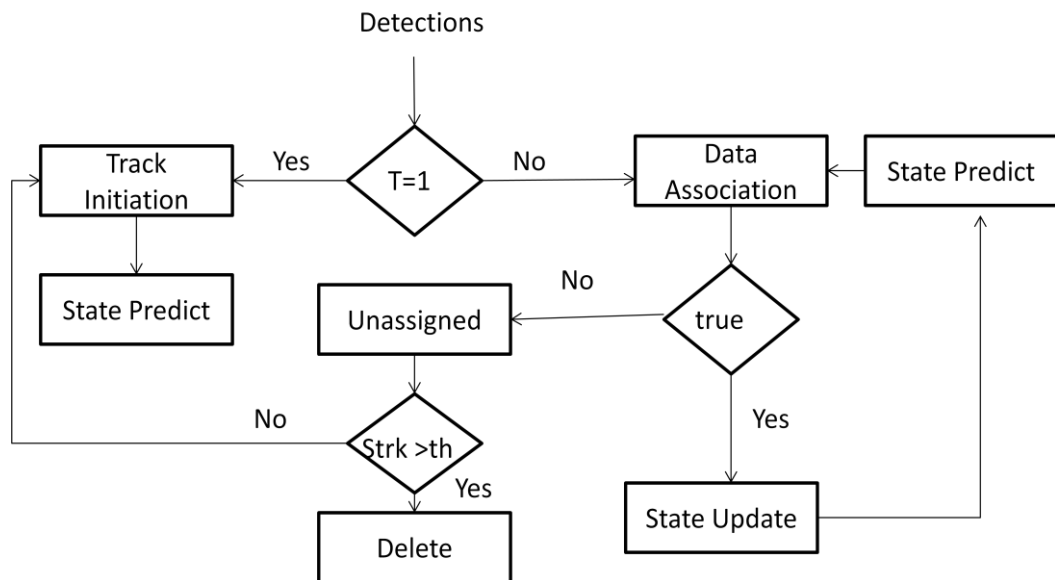


Fig. 18 Block diagram of Multi target tracker

5.2.1 DATA ASSOCIATION

In the case of MTT while maintaining the states of multiple occurrences of targets, what's important is to assign the measurements coming from particular targets to corresponding predicted states at every instance of time step. The relevant

information required to do this task is the detected features of the targets and the predicted states that come from the filtering step. Figure 19 below illustrates the association of three predicted states to the five measurements which clearly depicts the linkage between previous to the current time step.

In literature, there are many techniques to achieve this task, some of the commonly used methods for applications in the automotive field are Global Nearest Neighbors (GNN) [34], Multiple Hypothesis Tracker (MHT) [35] and Joint Probabilistic Data Association (JPDA) [36]. In this study GNN algorithm has been used to do the associations which take the distance between predicted states and measured data and globally optimizes the solutions to find the match between the last iteration in order to update the states in filtering step. The steps taken in order to make the correct associations are explained below

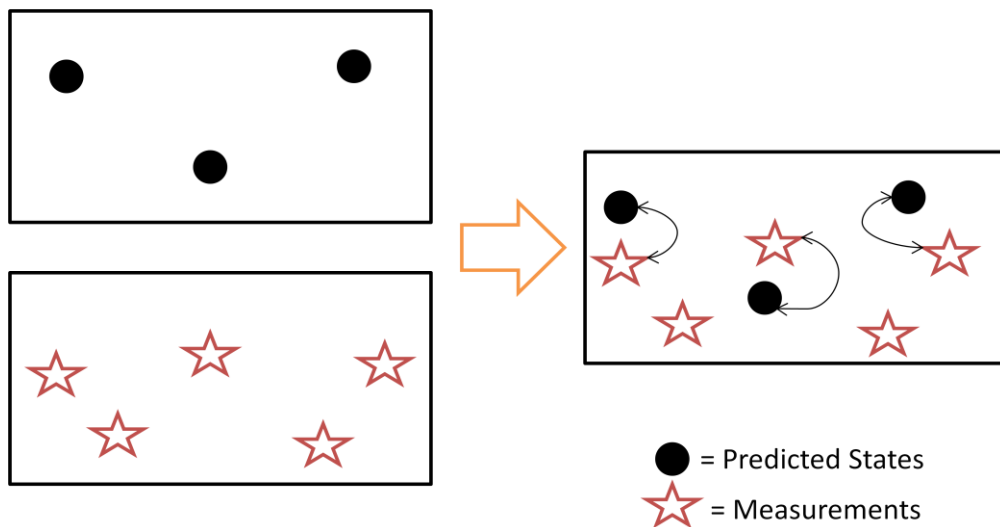


Fig. 19 Illustration of Data Association Process

Consider the two sets of data that's required for the association. Let Z be the measurement vector where, $z_i = 0, 1, 2, \dots, m-1$ with m being the number of

measurements. Let X be the predicted target states where $x_j = 0, 1, 2, \dots, n-1$ with n being the number of tracks. Now, the problem of data association can be formulated to find the Assignment matrix \bar{M} that minimizes the cost function given in equation 5.1 and 5.2 which evaluates the cost of assigning each predicted state j to their respective measurement i , with the distance $d = (i, j)$. In order to solve this linear assignment problem Hungarian algorithm is used.

$$f(\bar{M}) = \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} \bar{m}_{ij} d(i, j) \quad (5.1)$$

Where, (5.2)

$$\bar{m}_{ij} = \begin{cases} 1 & \text{if } z_i \text{ assigned to } x_j \\ 0 & \text{else} \end{cases}$$

The above equations hold true subjected to the following constraints given in equation 5.3 and 5.4 which follow the general rule of data association to ensure that every measurement gets assigned to exactly one predicted track and every predicted state gets assigned to at most, one measurement respectively.

$$\sum_{i=0}^{m-1} \bar{m}_{ij} \leq 1, \quad \forall j, 0, 1, \dots, n-1 \quad (5.3)$$

And

$$\sum_{j=0}^{n-1} \bar{m}_{ij} = 1, \quad \forall i, 0, 1, \dots, m-1 \quad (5.4)$$

5.2.2 STATE ESTIMATION

While maintaining the states of targets based on sensor measurements, due to the irregularities and noise subjected to sensors and clutter it becomes difficult to deduce the true nature of the environment. In order to overcome this a proper, timely correlation of knowledge about the world has to be maintained as tracks by eliminating the noise making sure the estimates are close to the real entities. The target states of interest include the position and velocity of the objects at every time step. The process includes two iterative steps: state update /correction and state prediction. The figure 20 below shows one of the example scenarios depicting the workflow of these kind of filters.

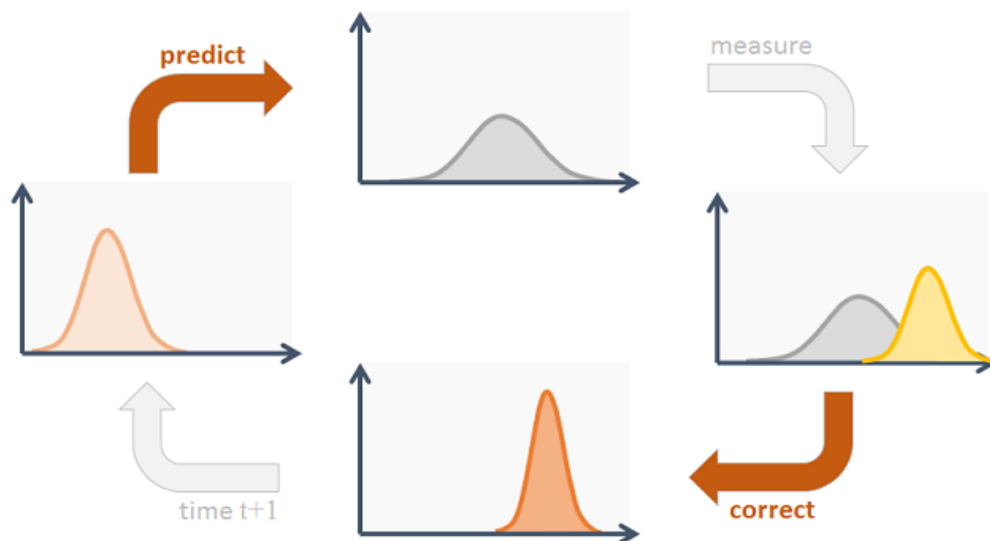


Fig. 20 Illustration of Kalman Filtering Process

In literature, most common methods adopted to achieve this task include Kalman filtering, extended Kalman filtering and particle filters [37]. Application of any of these filters may depend on the design chosen for a task based on certain

assumptions, such as the if the motion model is linear then Kalman filter is used and for non linear noise, particle filter and extended Kalman filters and its variants are used. Each has its own advantages and disadvantages in terms of a tradeoff between memory requirements and accuracy of the performance. For this proposed architecture, Kalman filter is used for accurate state estimation.

The design of Kalman filter includes the three steps: Initialization, State prediction and state update / correction. In the initialization step all the required filter parameters such as state estimate \hat{x}_k and covariance matrix P_k are set to initial values. The equations used for calculation of prediction and correction are depicted in figure 21 below.

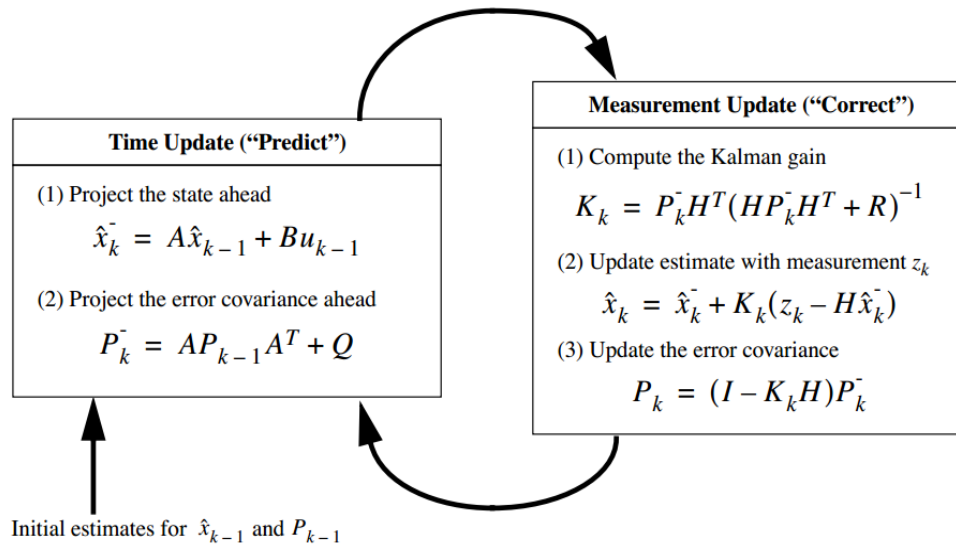


Fig. 21 Steps involved in Kalman Filtering with equations

5.2.3 TRACK MANAGEMENT

The above mentioned techniques of data association and state estimation cannot perform individually, without the assistance of the robust track management module. The main functionality of this module is to check for the newly entered objects in the sensor field of view and also to delete the objects that have already left the scene. This

also helps to identify the lost tracks for a couple of frames in the case of short missing instances of sensor data. The performance of the overall tracker depends on the decisions made here as the unwanted tracks may lead to exhaustive memory drain in the processor while failure to assign new tracks may lead to loss of information.

There are many ways one can design this system which may vary over the chosen algorithms for data association and the type of state estimation done. Just to mention a few examples, some methods take decisions based on track survival probability such as in [35], while another type includes checking the entropy or the information content as shown by [38]. In this thesis the decision module is built by choosing the heuristic approach to check for unassigned tracks after association so as to fit the randomness of the chosen data set. The unassigned tracks which do not get assigned to any of the measurements are given the strike rate, which keeps in count the number of frames, a particular track is idle. If the strike rate exceeds the selected threshold, then the track is deleted. Also, this module checks if any new targets have entered by scanning the past consecutive frames in order to initialize new tracks.

5.3 SIMULATION MODEL

Usually while designing the MSDF system, it gets difficult to evaluate the algorithms due to the plethora of architectures and sensor systems available. It is not feasible to test all the combinations of sensory systems in all the environment. In order to fill this gap a simulation analysis model is presented which gives the flexibility to the user to evaluate the architectures with different fusion paradigms.

The simulation model designed incorporates the different sensor models with varying detection probabilities. The model can be extended to fit the purpose of evaluation of different fusion architectures that could be designed for tracking and

data association techniques which are the core of any fusion paradigms. The aim here is to generate the random trajectories of the targets. This could be sensed by the sensors employed and the data is fused with different fusion paradigms. The figure 22 below shows the core of the simulation engine proposed for this thesis.

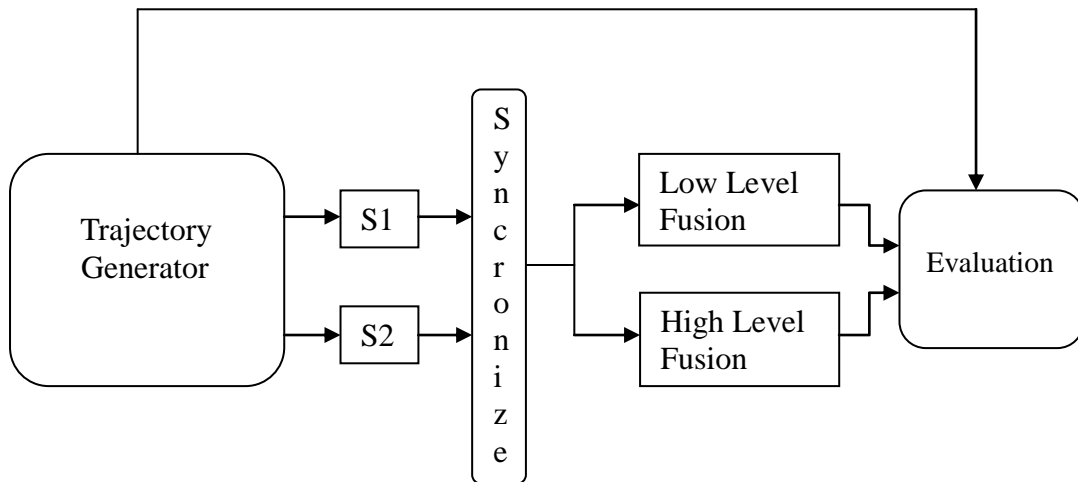
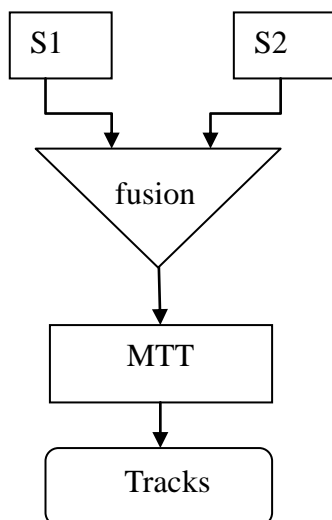


Fig. 22 Block diagram of simulation model

The figure 23 explains the way low level and high level architectures are designed for this simulation analysis.

a) Low level Fusion



b) High level Fusion

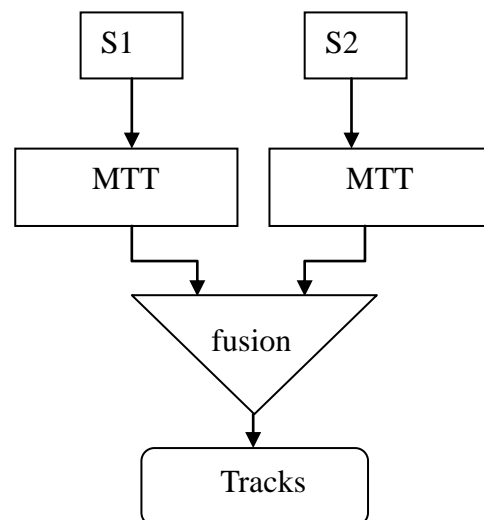


Fig. 23 Block diagram of fusion architectures

The sensor set's used for the simulation can be found in table 2 below. This includes Laser scanner (LS), long range radar(LRR), short range radar(SRR) and Lidar.

Sensors	Range	Azimuth	Variance in X	Variance in Y
LRR	120	10	0.45	0.15
SRR	40	60	0.5	0.2
LS	100	100	0.11	0.11
LIDAR	120	10	0.15	0.15

Table. 2 Types of Sensors used for simulation

The screenshot of one of the scenes, including the laser scanner and Long range radar can be seen in figure 24. The interface was built in python and as it can be seen in the figure, the red color box represents the ego-vehicle, while the blue and yellow color regions define the field of view of LS and LRR respectively. The blue boxes represent the targets in the scene while the black dots represent the error in detection with the circles on edge representing the detected positions (x, y) of the corresponding targets.

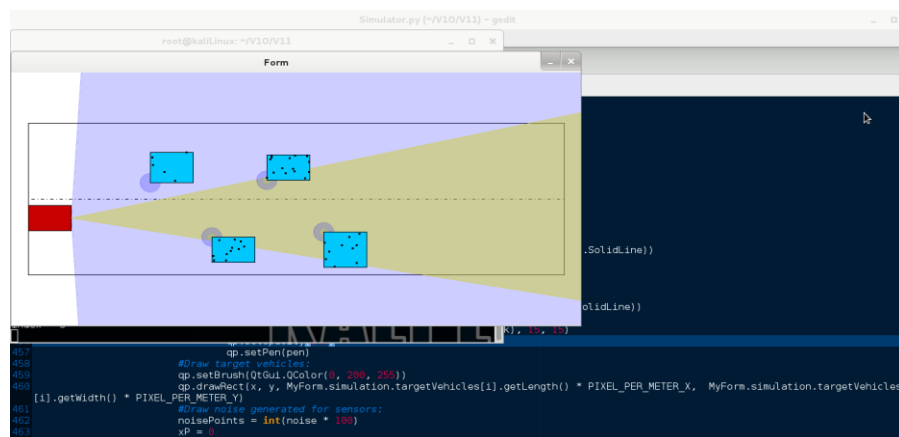


Fig. 24 Screenshot of the Simulator

CHAPTER 6

EXPERIMENTS AND RESULTS

This chapter provides the details of the evaluation made on the proposed architectures using real time and simulated sensor data. All the experiments were conducted on 2.4 GHz microprocessor running windows 7 Operating System using MATLAB and python for simulation interface. The assumptions made for the experiments and the metrics used is addressed in following sub-sections of this chapter. The purpose of the experiments was focused, keeping in mind answering three different research problems: detection, data association and Optimal Filtering. In the first part focus of study is to detect the potential road obstacles while the second part deals with predicting where the obstacles fall and updating the states based on detections obtained. The third problem, in fact the most important is the evaluation of how well the proposed multi target tracker performs with different fusion paradigms using discrete event simulation analysis.

6.1 COOPERATIVE FUSION RESULTS

For this experiment the registered sensor data from laser scanner and camera are considered. In order to do the clustering neighbors considered to be 5. If the nearest neighbors considered are larger, then the algorithm tends to misclassify the clusters which may be coming from the wall or pole. Also, for the proposed ROI extraction the window size chosen was 50X50. The values for neighbors and window size has been heuristically chosen and the performance of the algorithm can be seen in figure 25. The analysis shows the instances where the obstacles have been precisely defined in ROI of an image plane.

a) Frame 1



b) Frame 2



Fig. 25 a, b, c & d Results of cooperative Fusion of Laser and camera

c) Frame 3



d) Frame 4



Fig. 25 a, b, c & d Results of cooperative Fusion of Laser and camera (Cont...)

6.2 MULTI TARGET TRACKING

For Optimal filtering we considered the constant velocity model which assumes the linear Gaussian noise in nature. The evaluation metrics used and visual results are shown in the figures below.

6.2.1 EVALUATION METRICS

The metrics used to evaluate the proposed multi target tracker considering the ground truth values from the KITTI data set [39] are Recall, Precision, F-measure and False Positive rate.

Recall is also known as detection rate which gives the percentage of detected true positives as compared to the total number of true positives in the ground truth

$$\text{Recall} = \frac{tp}{(tp + fn)}$$

Where, tp is the number of true positives, fn is the total number of false negatives. Along with recall, the other metric used is Precision, which gives positive prediction. Which represents the percentage of detected true positives as compared to the total number of objects detected.

$$\text{Precision} = \frac{tp}{(tp + fp)}$$

Where, fp is false positive. The method is considered good if Recall is high without sacrificing Precision. The weighted harmonic mean of these two metrics is taken and called as F-measure or figure of merit. Given by,

$$F - \text{measure} = \frac{2 \cdot \text{Recall} \cdot \text{Precision}}{(\text{Recall} + \text{Precision})}$$

The last metric used is the percentage of false positive to the total number of

objects detected in the scene. This should usually be low as compared to all the above in order for the method to be considered as good.

$$\textit{Falsepositiverate} = \frac{tp}{(tp + fn + fp)}$$

For the evaluation two scene sequences are considered. The first sequence consists of the pedestrians and cyclists crossing the road with lots of occlusions and for the second sequence, the traffic junction scenario is considered which is challenging as the number of vehicles that occlude and pass by are huge.

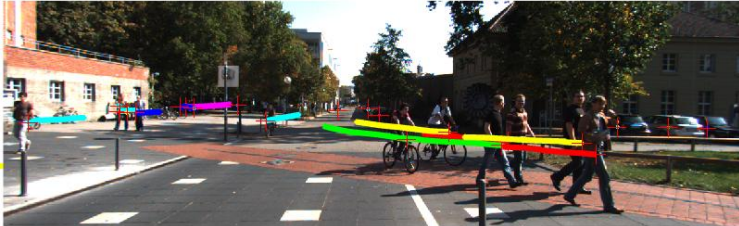
6.2.2 VISUAL RESULTS

a) For sequence 1

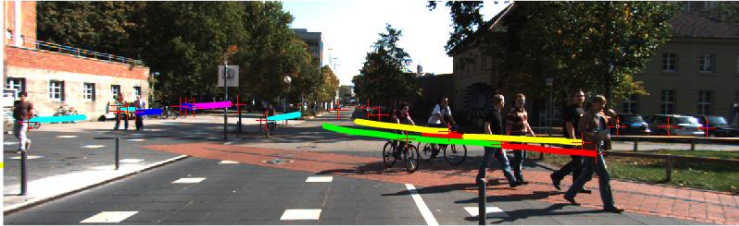
a) Frame 153



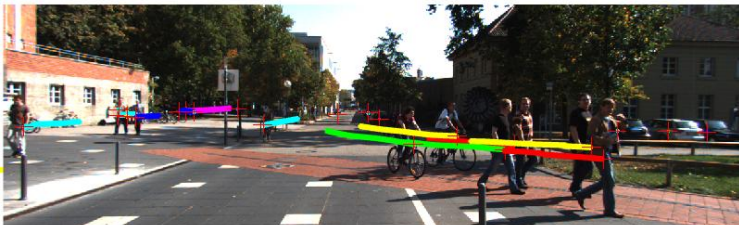
b) Frame 154



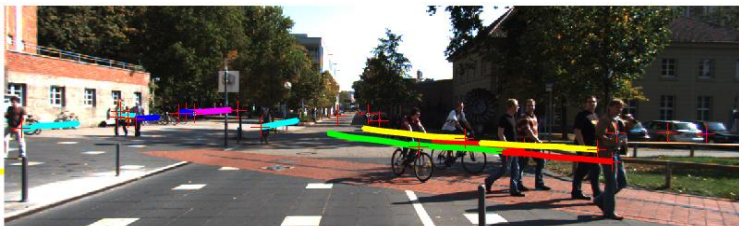
c) Frame 155



d) Frame 156



e) Frame 157



f) Frame 158

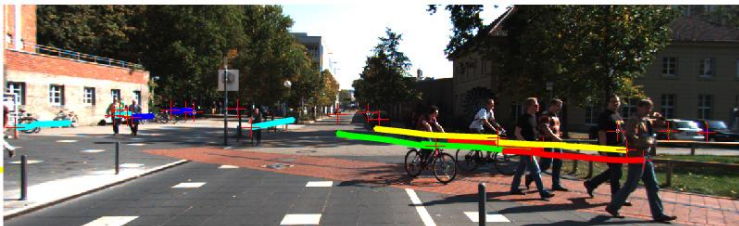


Fig. 26 Visual Results of Multi target tracking for sequence 1

b) For Sequence 2

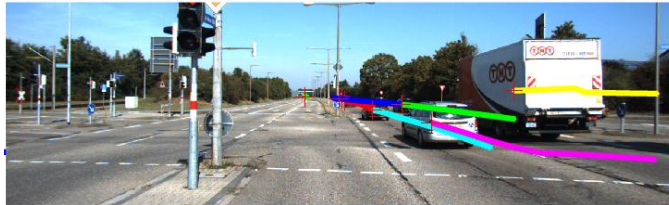
a) Frame 52



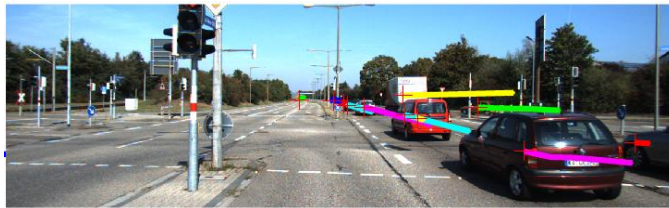
b) Frame 65



c) Frame 84



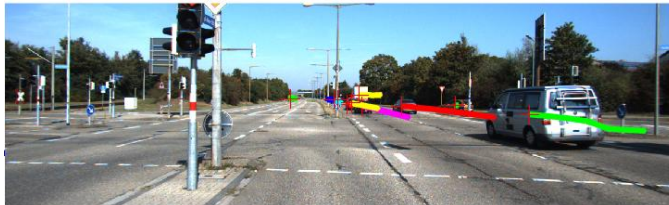
d) Frame 103



e) Frame 112



f) Frame 132



g) Frame 139

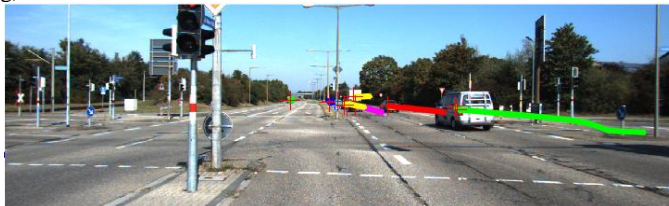
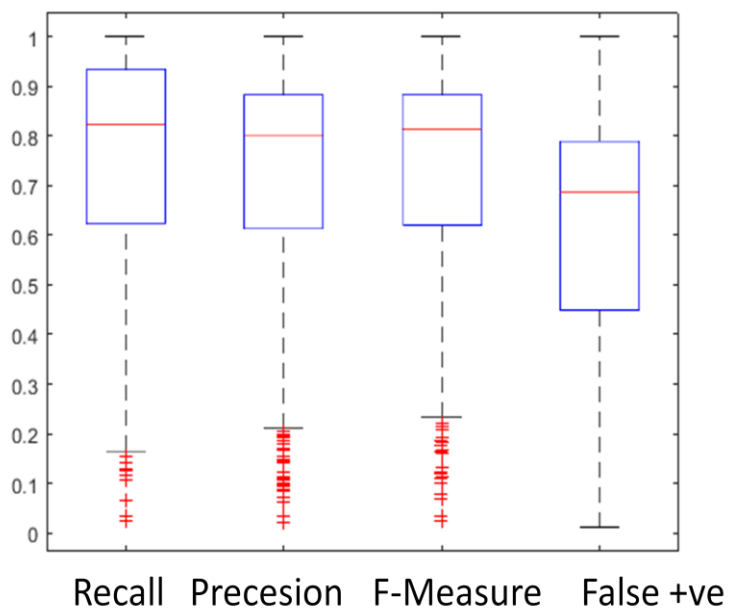


Fig. 27 Visual Results of Multi target tracking for sequence 2

6.2.3 QUANTITATIVE RESULTS

a) For Sequence 1



b) For Sequence 2

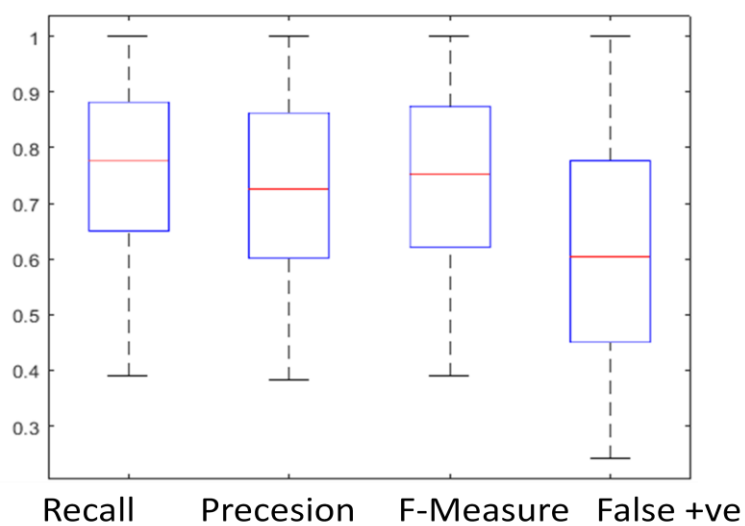
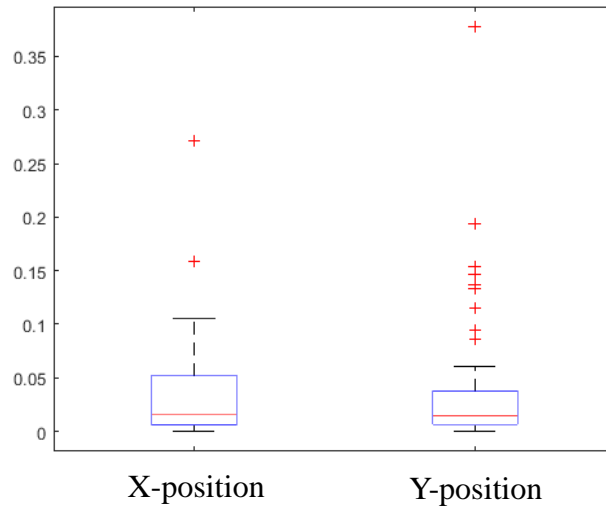


Fig. 28 Quantitative Results of Multi target tracking for sequence a) 1 & b) 2

6.3 SIMULATION RESULTS

6.3.1 FOR SENSOR SET 1- LRR & SRR

a) Low Level Fusion



b) High Level Fusion

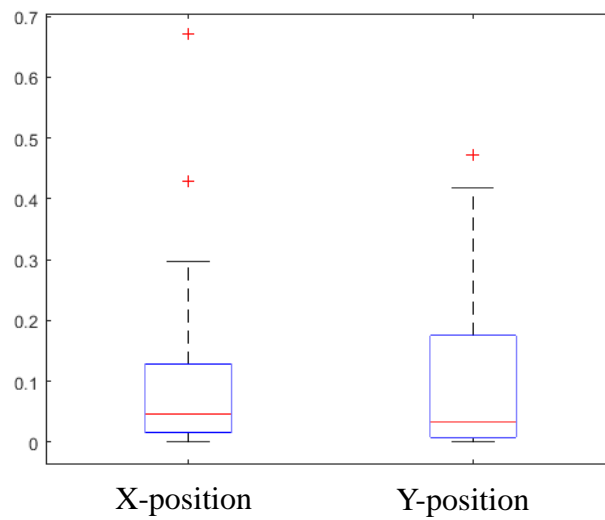
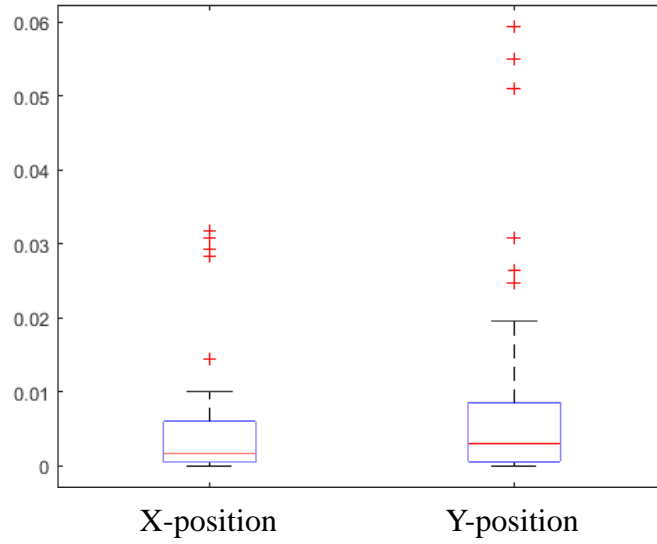


Fig. 29 Simulation Results for sensor set 1

6.3.2 FOR SENSOR SET 2- LS & LRR

a) Low Level Fusion



b) High Level Fusion

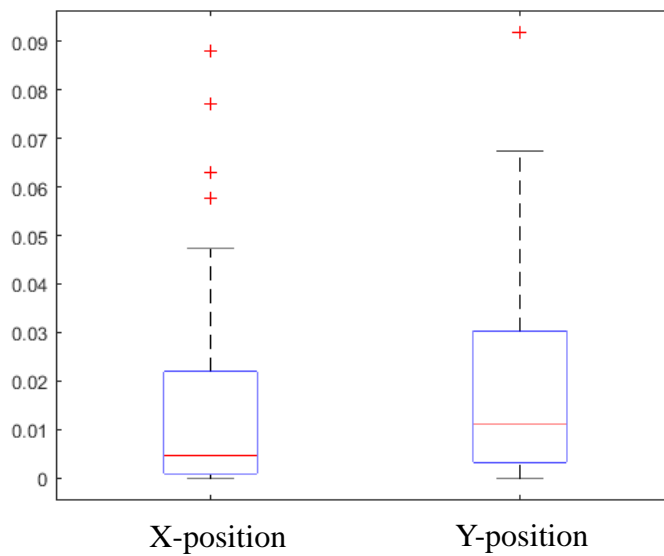
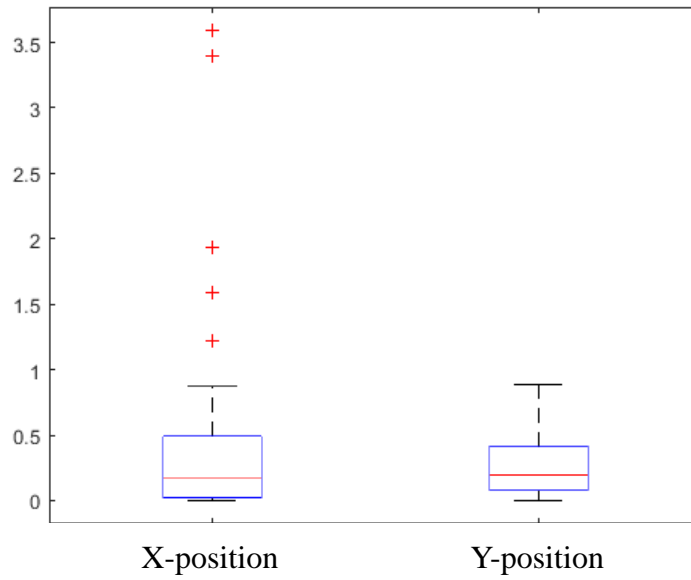


Fig. 30 Simulation Results for sensor set 2

6.3.3 FOR SENSOR SET 3- LIDAR & SRR

a) Low Level Fusion



b) High Level Fusion

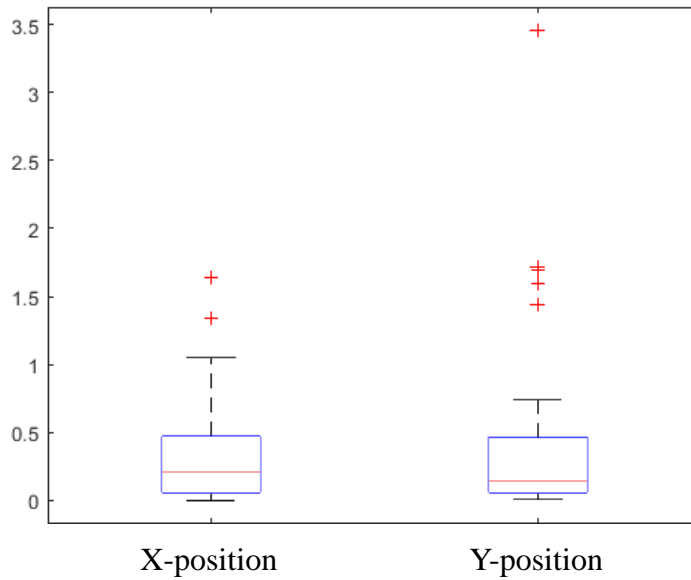
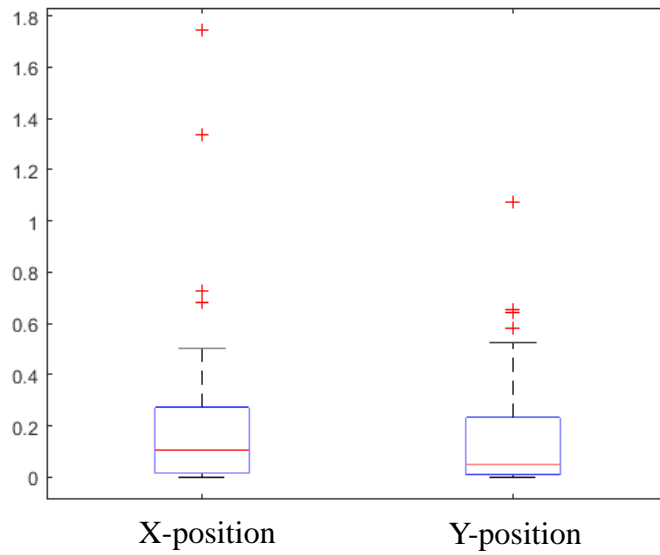


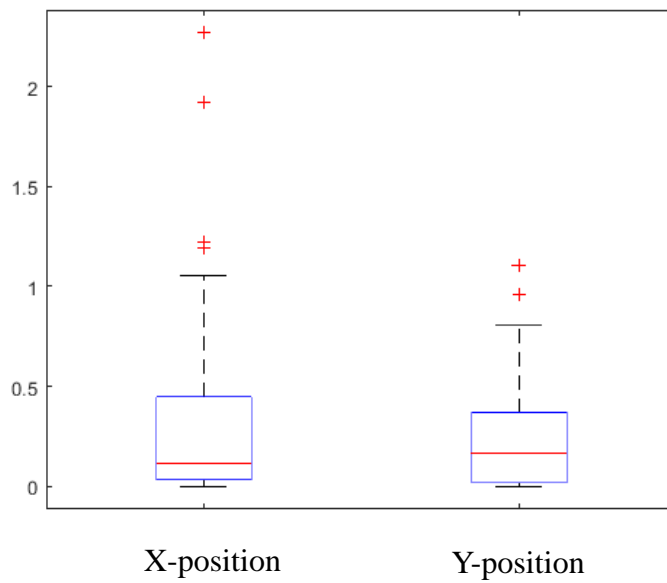
Fig. 31 Simulation Results for sensor set 3

6.3.4 FOR SENSOR SET 4- LS & SRR

a) **Low Level Fusion**



b) **High Level Fusion**



CHAPTER 7

CONCLUSION AND FUTURE WORK

In this thesis different architectures for designing of the multi sensor fusion system has been considered. In the first part a novel cooperative fusion of a laser scanner and camera is proposed to obtain the ROIs in an image plane. It can be seen from figure 25 that, the ROIs obtained are consistent enough to localize the potential road obstacles which should be avoided in order to design applications for safety and autonomous driving. Although, there is variation in the shapes detected, it is shown how it can be improvised further in this section. In the second part, multi target tracking was proposed with robust track management along with algorithms for data association and filtering. The visual results for tracking show the robustness of the proposed architecture. With the evaluation metrics mentioned, the method does fairly well for the challenging scene sequences with many occluding targets keeping the false alarms low compared to overall errors. Further, the aim considered for this study was to evaluate this proposed tracker for low level and high level fusion paradigms. For this purpose, a simulation model was proposed and with the help of discrete event simulation the results show that for varying combinations of sensor sets, the low level fusion paradigm performs better than high level fusion paradigm.

For the future work, the work considered for cooperative fusion can be extended by adding the confidence factor from the pixel intensities. The feature vector representing the obstacles on the road could be built by combining the histogram of pixel intensity values from the extracted ROIs which overlap on a corresponding image plane to improve the shapes perceived. Also, The model has

been kept flexible to account for further integration of knowledge about the targets by combining the additional sensor values in the high level architecture. In the second part, the robustness of multi target tracker could be increased by considering data association techniques like JPDA and filtering techniques like Particle filters. This in turn will help for more applications where the noise model is nonlinear unlike the one considered here as linear. Also, the new sets of trackers are available which do label free estimation like random finite sets that does not require any specific data association to be built explicitly. Complexity and feasibility of these methods need to be tested more on the public data sets as per the suggestion from prior work done in this field. Also, in order to do the statistical data analysis, the simulation model can be extended to consider more sensor values and technologies like V2V and V2X infrastructure. Since the fusion architecture that could be built are diverse, the analysis that is done so far is not enough to validate any of the methods. More research is required in simulation analysis to study the effect of combined sub-systems as in sensors, algorithms and the scenarios where these methods are tested. This also could answer some of the questions as in what fusion paradigms to choose while designing specific applications based on the types of sensors used.

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