Sensor fusion with Deep Learning

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***Abstract*—Over the years the advancement in transistors technology made it possible to build computers with greater processing power.This also helped to solve more complex issues related to artificial intelligence.AI can be divided in two subsections which are machine learning and deep learning.The decision to use either of this two algorithm or to combine both in a project depend on the type of problem we are trying to solve.Different DL algorithms are getting develop and refine for safety critical applications such as pedestrian detection in vehicles.In this case the DL model has to process and fuse the data from the different sensors like camera,lidar,radar to make the appropriate decision related to the type of object it sees.**

That is the reason why in this paper we will focus on deep learning with its application in the field of sensor fusion.We will define what sensor fusion is,explore the architecture of a multi-modal sensor fusion network.We will also use a practical example for illustration purpose and give advantages of DL in sensor fusion.We will also highlight the impact of DL in the field of sensor fusion.

I. Motivation

Traditional sensor fusion method use mathematical models to be able to fuse data coming from sensors.The common ones are the Kalman Filter.It relies on the linearity of the system,but in reality the system can also behave in a non linear way.Particle Filter method compensate for the limitations of the Kalman filter but it still cannot deal with a measurement noise being non Gaussian [12].Although the aforementioned techniques are more than suitable for certain use cases,the fact that we live in a world where the amount of data to be process increases drastically requires that we refer to more advance solutions.Hence the need to use DL for more complex and extensive applications.

II. Foundation

Deep learning extract patterns from data using neural networks with the aim to teach a computer how to learn a task using raw data. The application of DL can be found in image recognition,speech recognition,big data and natural language processing.DL tend to perform better than other machine learning algorithm when we dealing with large amount of data.Autonomous vehicles use sensor fusion with a DL algorithm to be able to identify objects in their surroundings.Sensor fusion consist of combining data coming from multiple sensors.The aim is to get the highest possible accuracy of the parameters being measured or the environment that we are trying to monitor. The main criteria in choosing a sensor for fusion application are:how the sensors are compatible when it comes to working in the same environment and how much the data coming from those sensors can complement each other.In case we would like to have redundancy to improve the reliability of the system,we can build a fusion setup in which sensors simply duplicate information.In an application where we want relevant fusion information from our fusion network it is important to make sure sensors complement each other when it comes to parameters such as:data rates,field of view, range and sensitivity [4]

III. sensor Fusion

A sensor is a device that detects and responds to some type of input from the physical environment.As output, it generate an analog or digital signal(voltage ,current output) that can further be process by circuitry and computer systems.sensors can measure some parameters such as temperature, pressure,vibration,acceleration [1]. A sensor is consider passive when it measures the energy coming from the environment and active when it emits it own energy and measure the reaction.Before starting with the fusion, sensors need to be calibrated and synchronized properly.

A. Benefits of Sensor Fusion [9]

- Reliability:
  Having more than one sensor helps to cater for a potential partial sensor failure and improve redundancy and reliability
- Extended spatial coverage:
  We can have each sensor covering a separate area.When we put together all the different areas covered by those sensors,we get a better coverage of surrounding environment.
- Extended temporal coverage:
  With each sensor updating at different time intervals,we can interpolate those updates put them together to improve the temporal coverage
- Increased Confidence:
  Combining sensor data will provide increased confidence by providing measurements resilient to the uncertainties in any particular sensor based on the combined coverage and error mitigation of all sensors.
- Reduced Uncertainty:
  Given the resilience of multiple sensors to the specific uncertainty of any one, the overall uncertainty of the perception system can be drastically reduced using sensor fusion.
- Robustness against noise:
  With different sensor sources,we can detect when any single sensor has come across noise.This helps to attenuate the effect of that noise in the system.

- Increased Resolution:
When we combine the data from the sensor network,we improve the resolution of measurements

The different types of sensor fusion that exist are [3]:

- Data Fusion(Data in-Data out):
Here the fusion is done at the raw or pre-processed data level collected from sensors with the aim to improve accuracy and precision by directly combining information coming from different sources.It is also known as Early fusion.

- Feature Fusion(Data in-Feature out):
Here we extract from each sensor the features from the raw data before combining it.This makes it possible to get a better representation of the environment.

- Decision Fusion(Feature in -Decision Out):
After the raw data get collected and features are extracted,decisions made at each individual sensor level finally get combined.By doing so, we can improve the final decision making process.It is also known as late fusion.Decision fusion gives better performance than others because errors from multiple models are dealt with independently.

- Multi-modal sensor Fusion:
Here we combine sensor data from different physical parameters. As example we can mention the estimation of a cellphone orientation using accelerometer,gyroscope and magnetometer

- Hierarchical sensor Fusion:
Here the fusion of information is all done at sensor,feature and decision level at the same time.

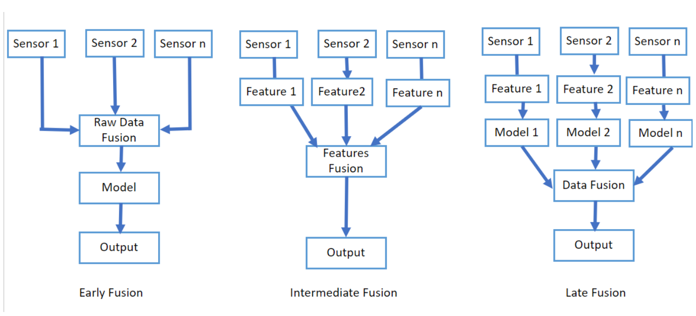

Fig. 1. Early ,Intermediate & Late fusion

Based on the way sensors in a network interact ,we can classify Sensor Fusion Algorithms as follow [4]:

- Complementary: Here the sensors work in an independent way , but it is still possible to combine their data to get a better understanding of the environment.
- Competitive: here all sensors measure the same parameter and each of them will give its own measurement.This way we can increase the reliability ,accuracy and robustness of the system.Due to redundancy in this type of setup,we have to pay attention not get inconsistent readings.
- Cooperative: In this setup independent sensors measurements are combined in a way that at the end we get an image of the environment that no single sensor alone will be able to provide. The picture bellow illustrate the working principle to different sensor network.

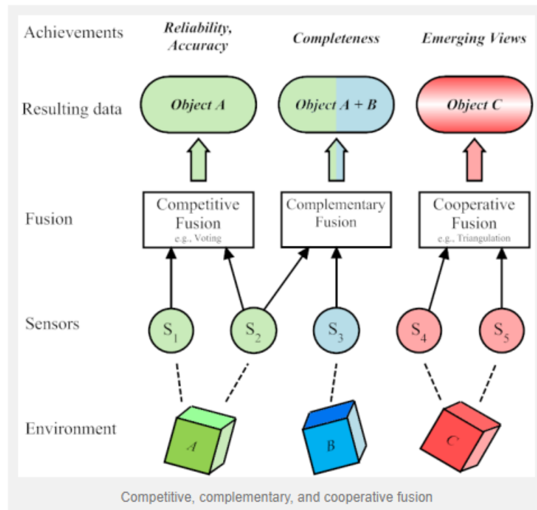

Fig. 2. Sensor Network Type [5]

IV. Deep Neural network

Neural network is the building block of DL.This network is made of multiple layers containing artificial neurons. To be able to predict and make some decision, the deep learning models process and analyse huge amount of data during the training process.Here we will dive into the architecture and working principle of a neural network.

A. Layers [11]

They represent the data processing module of the network.It can take as input one or many tensors and output also one or many tensors.Each layer has a weight and bias which are parameters that are important for the performance of a model during the training/learning process.The combination of layers form a neural network.

- Input layer:first layer that is responsible for collecting the data
- Hidden Layer:positioned between the input and output layer.As example we can mention fully connected, convolutional and fully connected layer
- Output Layer: as the last layer of the network,it is there to generate the final output.

The different types of layers that can be used are:

- Fully connected layers:
also known as dense layers, are the foundation of any feedforward neural network. They bind all the neurons from one layer to the next.

- Convolutional layers:
  These layers are essential for working with photo and video data. Using a set of convolved filters with the input image, they detect and extract the most critical features to create a detailed map of its features.
- Recurrent layers:
  Specialise for applications like text, speech, or time series. These layers maintain an updated internal state at each time step, helping the model to remember important information from the past and make more accurate predictions.

B. Input

This represent the data that is fed into our model.This could be for example a 4D array of images.

C. Weight

Represent the strength of the connection between two nodes.This value get updated during the learning process.So that the input get mapped accurately to the output.

D. Transfer function

The transfer function combines multiple inputs into one output value.

E. Activation Function

We use it to avoid the output being always be a linear combination of input values by controlling the activation of the neurons.

F. Bias

The bias shift the value produced by the activation function.

The following figure illustrate a Neuron a layers of a neural network

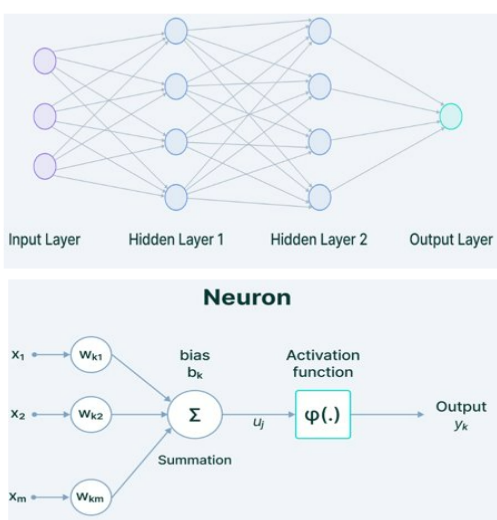

Fig. 3. Layers and Neuron [11]

G. Convolutional Neural network [8]

Convolutional Neural Networks (CNNs) are a type of neural network that can extract and learn features from images. that is why they deployed in cases where we need to do image classification, object detection, and image segmentation.CNNs can process images and videos to identify patterns and features, such as edges and shapes.With the found patterns,CNN can predict what the content of the image or video is. CNNs can also do transfer learning, which is a process where the knowledge learn from previously trained models to improve accuracy and reduce training time.(Explanation of CNNs and their suitability for image-based sensor data.)

The working steps of a CNN are as follow:

- Convolution:
  In This first step, a set of filters is applied to the input image to extract features. The filters are small matrices of weights that are learned during the training process. The convolution operation involves sliding the filters across the input image and computing a dot product between the filter weights and the corresponding pixels in the input image.
- Activation:
  In This first step,a non-linear activation function is applied to the output of the convolution operation. By introducing non-linearity it is made possible for the neural network to capture more complex patterns in the data.
- Pooling:
  In This first step where we do downsampling of the output of the convolution operation to reduce the spatial dimensionality of the feature maps. This can be done using various pooling operations, such as max pooling or average pooling.
- Flattening:
  In This first step we flattened the pooled feature maps into a single vector. This vector can then be fed into a fully connected neural network for further processing.
- Fully Connected Layers:
  This neural network layers takes the flattened feature vector as input and generate the final output. The output layer typically uses a softmax activation function to generate a probability distribution over the possible classes or labels.
- Training:
  Here the weights of the CNN is optimize to minimize a loss function. This is done using gradient descent and backpropagation, where the error in the output is propagated backwards through the network to update the weights.

H. Neural Network Evaluation

Here a loss function is used.In the evaluation process of a NN we have to look at the accuracy,that tells us how much many correct predictions were made.Confusion Matrix is also one important parameter to look at.Here we can see all the true,false negative and positive related to the predictions.

V. Applications of Sensor fusion using Deep learning

The 4th industrial revolution also called industry 4.0 relies heavily on Sensor fusion.The control algorithm have to make use of the fuse sensors data to successfully monitor and predict with a high level of accuracy when component is going to fail in a manufacturing plant.
In a smartwatch combining data from accelerometer, gyroscope, and heart rate sensor can be used to recognize and distinguish between physical activities like cycling,running or walking.
Modern cars come very often with advance driver assistance system(ADAS) or the ability to drive up to a certains level in an autonomous way.One of the option that belong to the (ADAS)is Adaptive Cruise Control (ACC).The ACC use the fused data from radar and lidar to constantly adjust the car speed and therefore keeps a safe following distance with other vehicle ahead.

A Deep learning model of a sensor fusion is illustrated by the picture bellow:

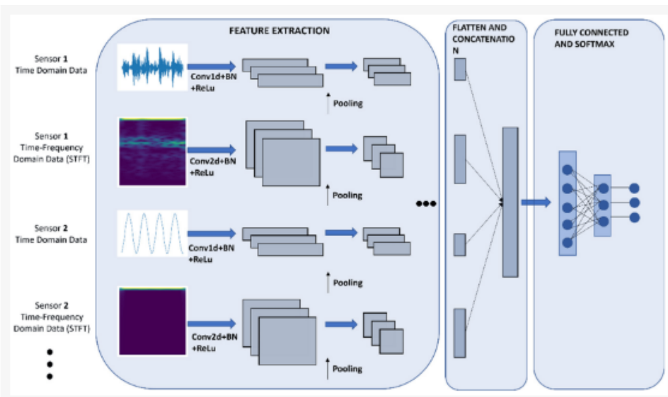

Fig. 4. Sensor Fusion model with DL [6]

VI. Benefits Of using DL in Sensor fusion [7]

- Be able to classify how each sensor is appropriate and fit for a specific task so that data coming from a less relevant sensor can be discarded.
- The fact that the DL model is continuously train helps to identify any potential changes in system behavior.
- The DL model can predict possible sources of failures, which helps with preventative maintenance.

VII. Limitation Of using DL in Sensor fusion

Deep learning model need to be continuously train with new data for it to make correct prediction for a rare scenario it had never face. As example we can mention Tesla autopilot that has made wrong decision leading to accidents with casualties. this is because the DL algorithm was face with a situation it was never train with before.It is challenging to deploy a DL algorithm on an embedded system because of challenges related to heavy energy consumption and computation.This is the reason why modern smartphone or wearable devices need to have more powerful chips with Ai core but suffer sometimes from poor battery life

VIII. Practical case [10]

To illustrate how sensor fusion works, we use the Forward Vehicle Sensor Fusion example from Matlab.Here we have 3 vehicles driving in front of the ego vehicle and two other vehicles driving on the left lane coming down in the opposite direction.The ego vehicle is equipe with 2 sensors:camera and radar to be able to detect all other 5 vehicles in it surrounding.

The Model is made of the following 3 subsystems:Forward Vehicle Sensor Fusion and Evaluate Tracker Metrics

- Sensors and Environment
  Here we can do any configuration related to the type of scene, vehicles and sensors.

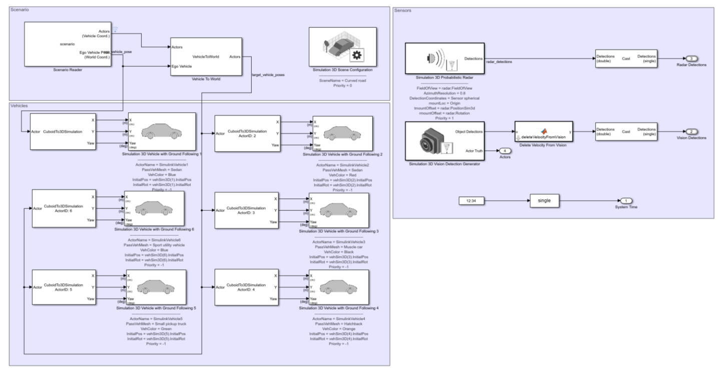

Fig. 5. Sensors and Environment Block

- Forward Vehicle Sensor Fusion
  This block is for the camera, radar fusion and decisi Gt on making related to the detection of objects(vehicles)

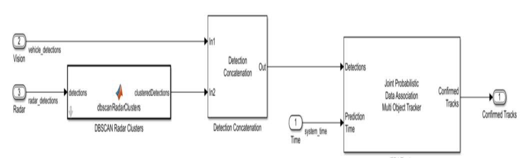

Fig. 6. Forward Vehicle Sensor Fusion Block

- Evaluate Tracker Metrics
  This block is to evaluate the performance of the sensor fusion algorithm.we check how good it was at detecting objects.

A. *Simulation and Object detection*

The blue dot shows vehicles detected by camera and the red one by the radar

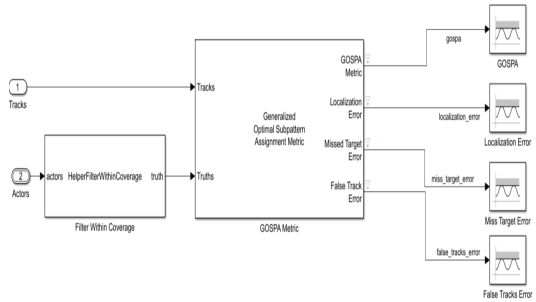

Fig. 7. Performance Metric Block

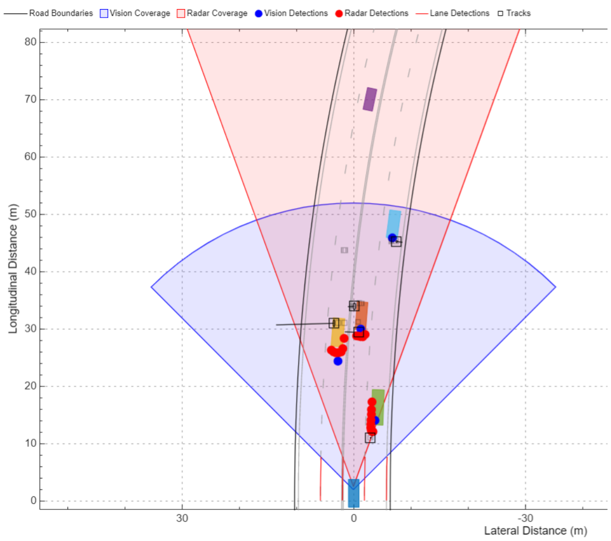

Fig. 8. Simulation

IX. Conclusion

Sensor fusion helps systems to be more consistent, accurate and dependable.For a better result the sensors need to be synchronised in time and space before sending any data to the neural network for training and predictions. Deep learning can achieve higher level of performance compare to traditional mathematical model when it comes to sensor fusion.The quality of the data also affect how well the DL model performs.

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