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Sensor Fusion Module Using IMU and GPS Sensors For Autonomous Car

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***Abstract*—Autonomous vehicle employ multiple sensors and algorithms to analyze data streams from the sensors to accurately interpret the surroundings. The aim of the research presented in this paper is to design a sensor fusion algorithm that predicts the next state of the position and orientation of Autonomous vehicle based on data fusion of IMU and GPS. This is essential to achieve the highest safety and security standards through enhanced performance that enable consistency, accuracy and reliability. Traditionally, for vehicle navigation, GPS standalone solutions have been utilized which lack to scan the surrounding environment. Therefore, the data from an Inertial Measurement unit (IMU) is fused and correlated with GPS measurements to overcome the limitations of GPS based navigation system.**

***Index Terms*—sensor fusion module, IMU, GPS, Extended Kalman filter, Navigation system, Autonomous vehicle**

I. INTRODUCTION

Multiple sensors are employed in the autonomous vehicle to get a better understanding of the system surroundings and to accurately view the environment around it. Sensor Fusion module combines input from various sensors to complement each other to achieve enhanced performance by attaining more reliability and accuracy [1]. Sensors like LIDAR, RADAR, Vision sensor, GPS are used by the autonomous vehicles for obstacle detection, lane detection, navigation et cetera [2].

Position is an important state for navigation. For Advanced Driver Assistance Systems (ADAS) like lane keeping or for vehicle safety systems like crash avoidance, position plays a key role. Using only GPS for providing a navigation solution to a car can have certain problems under some conditions. For instance, if a car passes through a newly-constructed tunnel or in an area with tall buildings or due to multipath errors a GPS signal may get blocked or faded [3].The precision and update rate of a GPS signal is less when compared to an Inertial Measurement Unit. The most possible accurate information about the states of a vehicle is required for most of the safety systems. Complementary positioning solutions are necessary to achieve redundancy. Therefore, a navigation system based on both GPS and IMU is a robust solution to overcome the limitations accompanied with GPS [4]. Merging measurements of IMU with GPS measurements using a fusion algorithm provides a reliable, compact and high-precision navigation system for the autonomous car [5,6].

II. BACKGROUND

Over the past decade, extensive research has been done in order to effectively combine the information from different sources for defense and surveillance applications. Some of the initial work has changed the techniques to be used by the automobiles industry such as the development of algorithms for advanced tracking, optimal filtering techniques and techniques for fusion of multi-sensor data. Many automobile industries have developed and implemented ADAS technologies in their cars. ADAS frameworks dependent on different advancements help drivers in keeping away from on-street impacts by creating cautions on potential dangers while driving and permitting the drivers to assume opportune responsibility for the vehicle [7]. The integration of automotive ADAS technology into cars has made partially automated driving possible. Now, ADAS is serving as a bridge between non autonomous vehicles and autonomous vehicles [8]. So, more research is going on in the field of multiple sensors data fusion to further develop these ADAS systems so that fully autonomous cars could come to reality.

Vehicle automation was at first proposed in the year 1918 and the idea of self-driving vehicle by General Motors in 1939. From the year 1964 to the year 2003, many countries have started their Research and Development in the field of automation in automobiles investing billions [9,10]. Research and Innovative works continued at a fast pace in both universities and industries. And many managed to test their autonomous vehicles on roads through DARPA (Defense Propelled Research Projects Agency's Grand challenges program) [11].

III. SENSOR FUSION MODULE

Autonomous car requires precise values of its position and orientation for safe maneuvering in the surroundings. To achieve this, a sensor fusion module is developed using IMU and GPS sensors.

A. Inertial Measurement Unit (IMU)

Inertial Measurement Unit is a combination of Inertial Sensors (Accelerometer, Gyroscope and Magnetometer) [12].An accelerometer measures its own linear acceleration and a Gyroscope measures angular rate relative to an inertial reference frame. Magnetometers measure the local magnetic field relative to the earth's magnetic field. IMU is a crucial dynamic sensor to steer the vehicle progressively, keeping up better exactness for brief periods of time.

B. Global Positioning System (GPS)

GPS modules provide information about position, velocity and time to navigate a car. The GPS technology can be divided into three segments [13,14]. The space segment comprises of thirty-one active satellites in the GPS constellation orbiting in the Medium Earth Orbit. The orbits have a 55 degrees inclination from the equator and the orbital period is 12 hours. At any given time, the constellation ensures that at least four satellites are visible from any place on the earth. The control segment is a universal network where ground facilities like Monitoring stations, Ground antennas and a Master control station are present whose purpose is to maintain and control the system. GPS signals are received by the user segment. The receivers receive the coded signals and estimate position, velocity and time.

IV. Extended Kalman Filter based Fusion Algorithm

Kalman filters are most widely used as fusion filters. The Kalman filter based on a mathematical model, predicts the next state of the system from the knowledge of the previous state [15].Rudolph Kalman developed Kalman filter (KF) algorithm which is a linear recursive filter. KF is efficient in the estimation of linear systems, but it cannot be applied to non-linear systems. To overcome this limitation, the improved version of Kalman Filter i.e. Extended Kalman Filter (EKF)has been proposed. EKF is a non-linear Kalman filter algorithm which linearizes non-linear system models using Taylor series and multivariate Jacobian matrices [16]. Since most of the practical systems are non-linear, to develop a navigation system for the autonomous car, EKF is used as the fusion algorithm in the sensor fusion module [17].

In the block diagram,

- t = 0 denotes initial time instant
- T denotes present time instant
- T+1 represents next time step
- e = difference between true measurements and predicted values at time instant 'T'

$$K = \frac{PredictionError}{PredictionError + ErrorinTrueMeasurement} \quad (1)$$

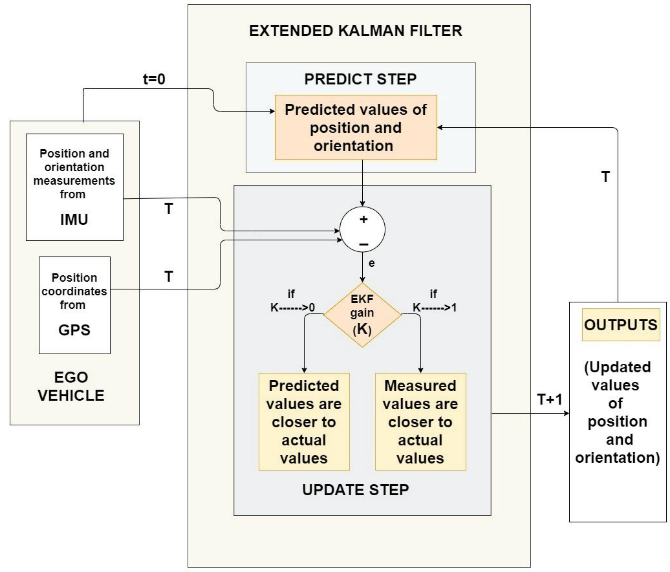

Fig. 1. Functional Block Diagram

To get the outputs at first time instant,

1) At t=0, Predict step predicts the values based on measurements of the sensors after eliminating noises present in them.
2) Based on the difference between true measurements and predicted values, EKF gain (K) is calculated using equation (1).
3) If the error in true measurements is large, then K decreases and tends to 0. In this case, Updated values in the next state will be predicted values in the present state.
4) In contrast, if error in predicted values are high, then K tends to 1. Here, the updated values in the next timestep will be measured values in the present state.

To get the outputs for the next time instants,

1) step predicts measurements in the next state based on the updated values in the present time instant.
2) K is calculated using the true measurements and predicted values, based on which the algorithm produces outputs.

Thus, at every time instant, position and orientation values get updated by the algorithm. Autonomous car navigates in its' path using these values of position and orientation.

V. Implementation of Sensor Fusion Module

EKF algorithm for the Sensor Fusion module is developed and tested using "Sensor Fusion and Tracking Toolbox" in MATLAB.

The true data from the sensors is obtained by employing them onthe test-vehicle. Alternatively, the sensor data file has been generated with the help of Automated Driving toolbox in MATLAB. This data is fed tothe fusion algorithm.

IMU sensor data contains measurements from accelerometer, gyroscope, magnetometer and orientation in the form of quaternion angle. It represents three-dimensional rotation between two different coordinate frames. Position coordinates from IMU data are obtained by dual integration of linear acceleration readings and by integrating angular velocity from accelerometer and a gyro respectively. GPS sensor data contains longitude, latitude and altitude information. These values are converted into Cartesian coordinates i.e. position coordinates in X, Y and Z axes.

X axis represents direction which is in front to the car, Y axis represents the direction left of the car and Z axis represents the direction pointing upwards to the car.

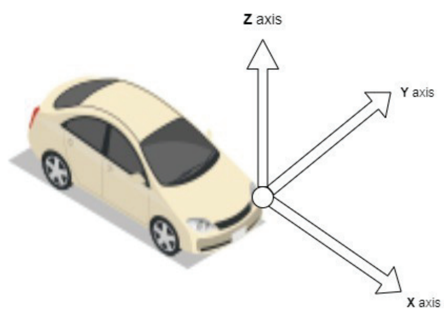

Fig. 2. Vehicle coordinate system

GPS sensor provides absolute position measurements where as IMU sensor provides relative position measurements. GPS sensor gets updated at a slow rate compared to that of an IMU which gets sampled at a higher rate. For example, GPS gets updated at a frequency of 5 Hz and IMU gets updated at a 100 Hz frequency. Position value from GPS remains constant for 200 milli seconds whereas position, orientation values from IMU change for every 10 milli seconds. The fusion algorithm is such that until GPS gets updated, EKF uses only IMU values and constant position value from GPS for prediction and updating. Whenever GPS is sampled, position coordinates from IMU and GPS are correlated and then fed to the EKF algorithm. Moreover,GPS receiver is accurate up to 5 meters and IMU has accuracy of around 0.15 meters. Since, IMU data is dependent on absolute values, it alone cannot deliver desired results though its' accuracy is high. So, an IMU fused with GPS provide better results with an accuracy up to 0.15 meters. Therefore, Sensor fusion module using GPS and IMU sensors for an autonomous car deliver results which are 95% more accurate than the results obtained without fusion. Different combinations of IMU data (Accelerometer, Gyroscope and Magnetometer data) and GPS data are fed to the sensor fusion module and the results are analyzed.

VI. Simulation Results

The algorithm estimated the next state of the autonomous car at every time step based on the measured sensor data and outputs of the present state. To analyze the dependence of input sensors, three different combinations of sensors are fused and the results are studied.

In the position plots, red line denotes the ground truth position of the autonomous vehicle with respect to time. Blue line denotes the variation of estimated position of the autonomous vehicle obtained from the EKF fusion algorithm. Similarly, in Orientation plots, the red and blue colored cubes represent ground truth orientation and estimated orientation respectively.

A. Fusion without GPS data

Fig. 3, 4 and 5 depict the deviation of estimated values of position and orientation from their ground truth values when GPS data is not fused in the fusion algorithm.

Here, the fusion algorithm depends only on IMU data to predict the next state of the car. Values obtained from IMU are relative to the previous position and orientation values.

Since, the absolute position coordinates are not available from the GPS, the estimate moves in the direction provided by position coordinates of IMU which are derived from accelerometer and gyroscope readings. From Fig.3 and Fig.5 we can see that as the ego vehicle is moving towards its' left (Y-axis), the deviation of the ground position estimate is more in Y axis compared to slight deviations in X and Z axes. As the time progressed, the quaternion distance between the estimated and true ground position increased. This shows that IMU data alone is not sufficient to calculate the accurate position of the autonomous vehicle.

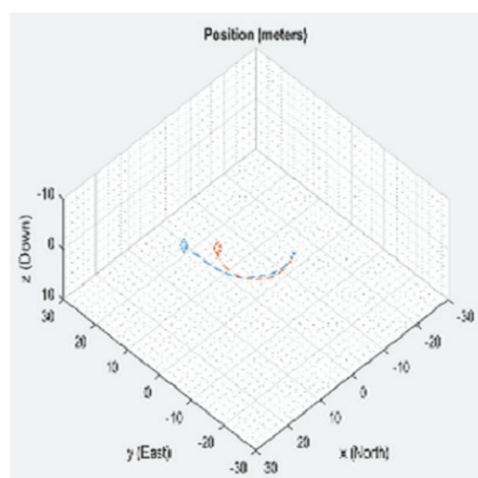

Fig. 3. Estimated position compared to ground truth-position

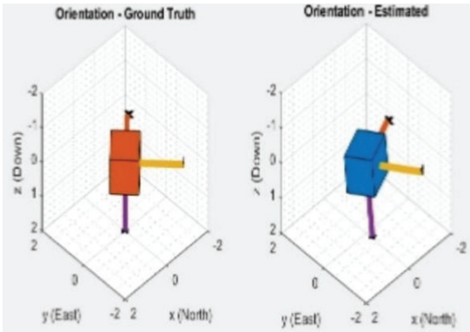

Fig. 4. Estimated orientation compared to ground truth- orientation

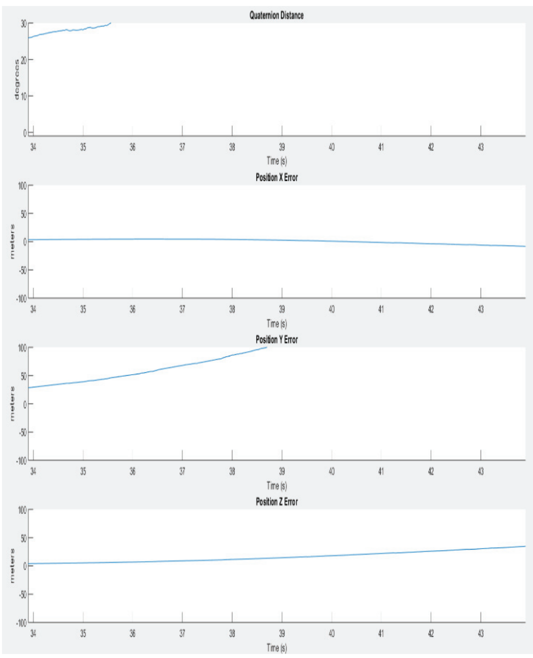

Fig. 5. Quaternion distance and errors in x, y, z axes of position estimations

B. Fusion without Gyroscope and Magnetometer data

Fig. 6, 7 and 8 depict the deviation of estimated values of position and orientation from their ground truth values when gyroscope and magnetometer data are not used in the fusion algorithm.

From an IMU, relative position coordinates can be derived by dual integration of accelerometer readings. But to determine orientation precisely, all the 3 sensors in an IMU must be present. Here, we observe that, though position estimates are close to their ground truth values, orientation estimate is rapidly changing. The Quaternion distance is unstable when Magnetometer and Gyroscope measurements are not combined in the fusion algorithm. This shows that gyroscope and magnetometer data is required for estimating the orientation and thereby providing stability to the orientation of the autonomous vehicle.

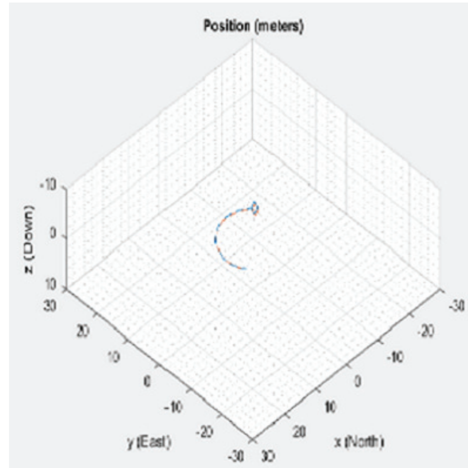

Fig. 6. Estimated position compared to ground truth-position

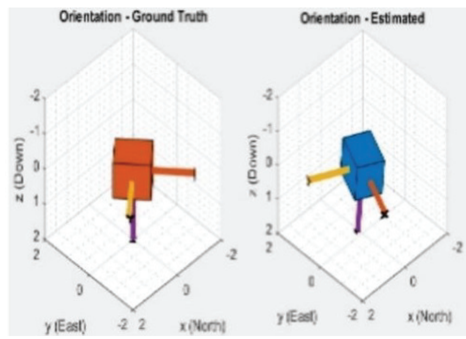

Fig. 7. Estimated orientation compared to ground truth- orientation

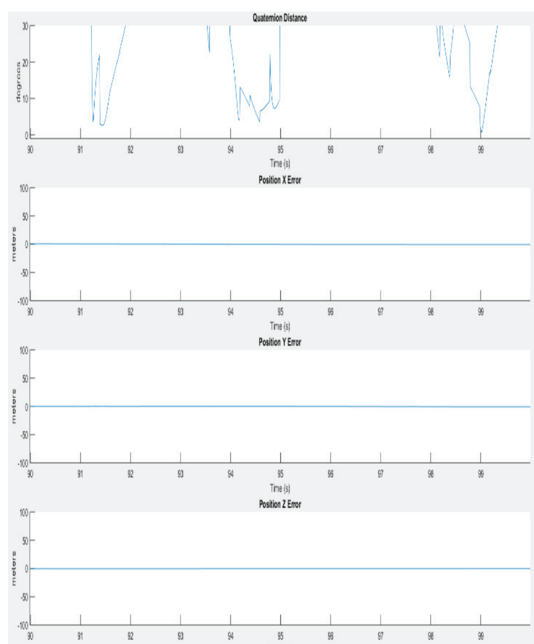

Fig. 8. Quaternion distance and errors in x, y, z axes of position estimations

C. Fusion of IMU data (Accelerometer, Magnetometer and Gyroscope data) and GPS data

Fig. 9, 10 and 11 depict the deviation of estimated values from their ground truth values when all the sensors are fused in the fusion algorithm.

We can see that the position and orientation estimates are able to track their ground-truth values with negligible errors when all the sensor data i.e. accelerometer, gyroscope, magnetometer data of IMU and GPS data are fused together.

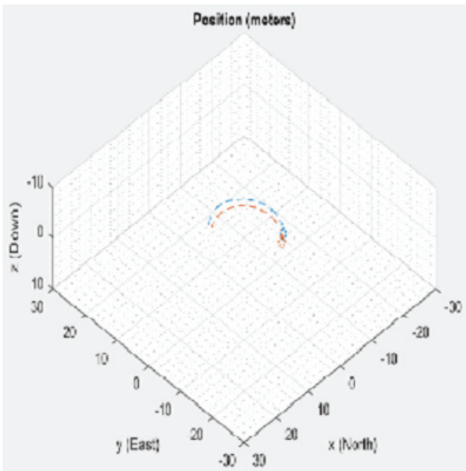

Fig. 9. Estimated position compared to ground truth-position

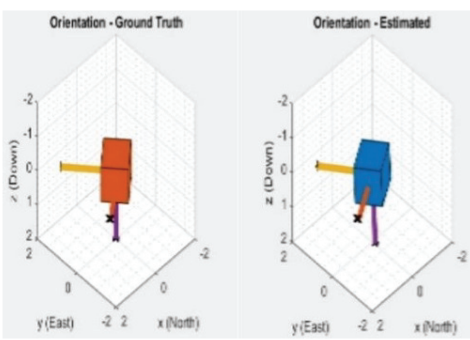

Fig. 10. Estimated orientation compared to ground truth- orientation

VII. Conclusion and Future Scope

In this paper, the design and simulation results of IMU and GPS sensor fusion algorithm in MATLAB is presented. The fusion algorithm incorporates data from Accelerometer, Gyroscope, Magnetometer and GPS sensor in the module and estimates the ground-truth values of position and orientation of the autonomous car. The proposed system, i.e. Sensor fusion module using IMU and GPS sensors resolves these limitations by greatly improving the autonomous car's accuracy in estimating the position and orientation values at every time step.The future work of this research would be to integrate the results of position and orientation estimations

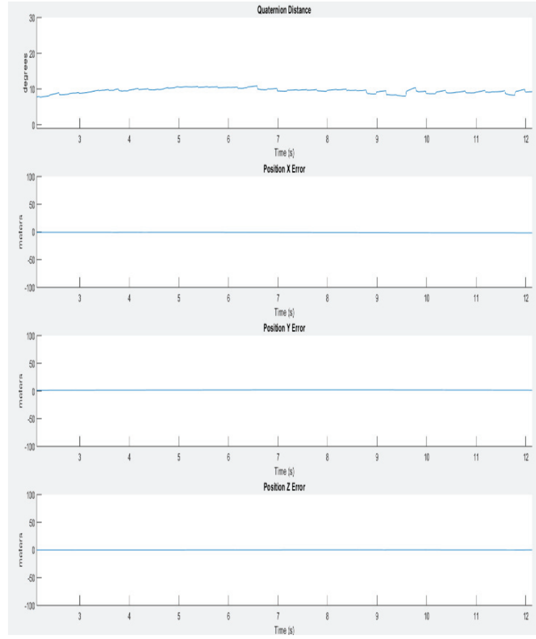

Fig. 11. Quaternion distance and errors in x, y, z axes of position estimations

obtained from the sensor fusion module with the absolute measurements obtained from cameras, RADARs/LIDARs and the map-information. This will help attain highest safety and security standards.

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