INDO-GLOBAL SUMMER INTERNSHIP 2021

INTEGRATION OF SENSOR FUSION FOR ENHANSING GPS NAVIGATION

Presented By: -

Gautham Gopan
SRM University

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INTRODUCTION

THE PROJECT

In bullet points, are the problems this project aims to solve or the opportunity it aims to develop.

- The main objective of this project is to present a more secured and computationally efficient procedure of Incorporating sensor fusion to enhance and improve the tracking and navigations abilities of GPS systems.

- To achieve more reliable and expanded data by infusing together multiple sensors that will be able read a variety of different measurable vector quantities and convert them into a singular output that will have extremely low amount of discrepancy.

- Even though the pivotal focus is given to building a system that uses sensor fusion properties to provide more reliable data, efforts were also made during the research to study about the possibilities of making an completely virtual geographical mappings of various important landmarks using advance satellite imagery and Artificial intelligence enabled systems.

THE HISTORY

In bullet points below are the well-used methods used prior to the development of GPS Based Navigation.

- **Pilotage: -** This was a system That was majorly used when commercial flying was only limited to daytime flying. Pilotage was a system of literally using points of reference on the ground, like mountains or lakes, to determine their position and their desired course.

- **Celestial Navigation: -** This System started taking shape after pilots around the world started venturing out during the night and night time flying gradually started gaining popularity. Celestial navigation uses the stars to guide pilots at night or in places where there were no visible landmarks.
- **Dead reckoning: -** This is fancy system of estimating your location based on your wind speed and heading. During the 1920's where the turbo prop aircrafts were being used for mail delivery many Ground beacons were constructed on the ground to help the pilots keep a track of their course and trajectory and correct their heading if needed.
- **ADOCK Range stations: -** These systems divided the area under their range into quadrants and each quadrant had their on individual signal tones thereby helping the pilot to determine which quadrant he was in.
- **LORAN (LONG RANGE NAVIGATION): -** These systems were the initial high-tech tools used in navigation. In this system a receiver on an aircraft or ship picks up radio signals broadcast by one or more pairs of radio stations spaced hundreds of miles apart and the system works by measuring the time delays between signals from the two stations. By tuning in different pairs, the navigator could plot lines of position in the form of hyperbolas (arcs) that intersect to give a precise location.
- **VOR & TCAN: -** These systems are still being widely used in commercial aviation, they have similarities to the LORAN system the only difference being that LORAN emits a study signal and VOR emits a modulated signal which consists of two sine waves which are out of phase. The phase difference allowed the pilots to determine their bearing or the direction the plane was pointed. This was the first technology that could give an aircrafts position and direction form one measurement and that too using just one VOR Station. The TCAN systems prove to use the same methodology but increases the signals used thereby making them more efficient.
- **The NAVSTAR GPS (1980) : -** This is the system that is mostly used now.

THE LIMITATIONS

Listed below are the factors that lead to the downfall of the above-mentioned systems and more importantly paved way to more advanced GPS Navigations System.

- The systems like pilotage, Celestial Navigation and dead reckoning were all highly susceptible to changes in weather conditions and would never be able to ensure safe and fast travel using air transport.

- The ADOCK range stations were not able to provide the pilots with adequate information to the pilots regarding their bearings and their positions as the signals emitted were extremely weak and vague.

- The LORAN systems were actually considered as a huge technological advancement at that point of time but were not able to provide reliable information's to the pilots as the signals emitted by them were highly susceptible to storms and other weather changes. Hence, they extremely unreliable during the circumstances were the pilot actually needed them.

- The VOR and TCAN even though its being still widely used in the air navigation industry they are still in need of constant upgrades and are simply not able to cope up with the tremendous needs of the modern air navigation industry.

- That's why there is a exponential amount of researches and developments taking place in the field of modern GPS navigations systems and that's where This project is trying to be resourceful.

- Through this project an effort is made to understand and study how the use of multiple sensors can prove to be helpful in creating a more precise and reliable data regarding the position, bearing, and attitude of an aircraft.

THE ABSTRACT

The GPS Navigation system plays a major role in all the major industries out there and has a major role to play in the aircraft industry. Today's modern passenger aircrafts comes equipped with state-of-the-art sensors and equipment's that ensures that the pilots are constantly fed with reliable and trustworthy data for the safe keeping of their aircraft. The same also applies for the sensors that are involved with providing data for the GPS navigations systems. One of the main concerns regarding these sensors are that they are extremely costly and requires intensive maintenance on a regular basis. That's were this project would like to present an more cost effective and a more simpler alternative by integrating sensor fusion to the entire process of GPS navigation. By using this technique, we will be able to provide a continuous stream of reliable data which will not only improve the precision and reduce the errors in the current navigation system but also bring down the entire cost of the whole operation.

THE PROBLEM STATEMENT

With respect to the existing methods used in collecting and processing data from sensors for GPS Navigation, there are a lot of discrepancies and errors that lead to huge deviations from the ground accurate measurements. These issues when being related to real life scenarios where such discrepancies can have catastrophic impact on both human life and monetary resources. That's were this project tries to removes these errors and discrepancies in the data by integrating the property of sensor fusion to the existing aircrafts doing so will enable an uninterrupted flow of precise and continuously evaluated data to the navigations systems which will thereby prove to be exponentially useful in providing more accurate and reliable instructions to the pilot and thereby increasing the overall efficiency of the whole operation.

THE STUDY ON SENSOR FUSION

Basic definition

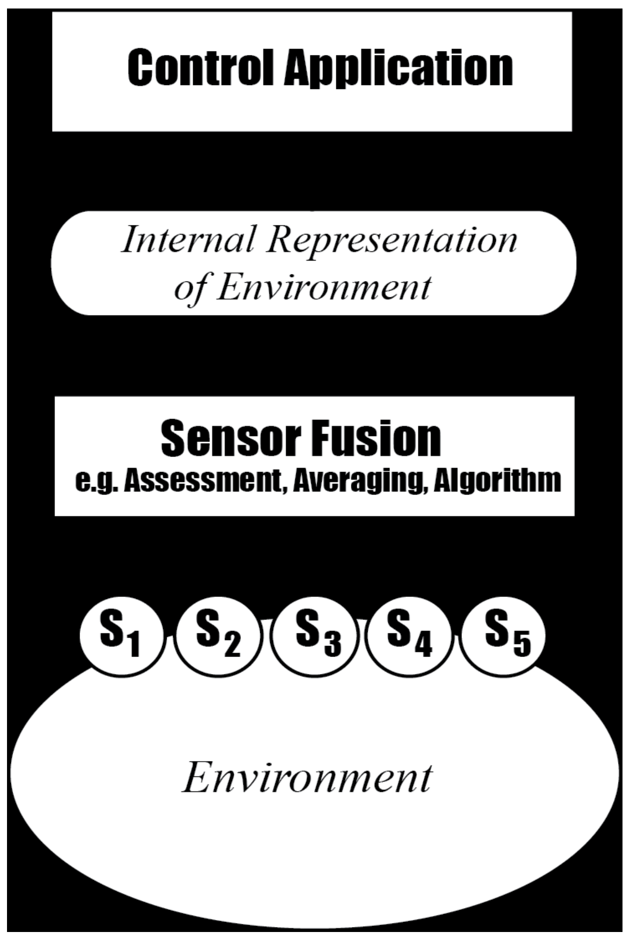
- **What is sensor fusion** :- This is the process of combining sensory data or data derived from disparate sources such that the resulting information has less uncertainty than would be possible when these sources were used individually

- The main aim of sensor fusions is to overcome the limitations of individual sensors by gathering and fusing data from multiple sensors to produce more reliable information with less uncertainty. This more robust information can then be used to make decisions or take certain actions.

- There are many different kinds of algorithms used in sensor fusion software's that helps in the organization and analyzation of the large amount of data received from multiple sensors.

- As algorithms grow more and more complex, the costs of software and processing capabilities will increase.

- Sensor fusion helps the system to have a better understanding about the environment its is in constant relation with and thereby can also help the system in predicting or anticipating possible threats that can hinder the systems' final goal.



THE ADVANTAGES OF USING SENSOR FUSION

The four major ways in which sensor fusion can help in making more accurate data is by :-

1] It can increase the quality of the data: -

- This feature can be explained by a simple example consider an accelerometer placed on a table. Since the accelerometer is stationary the only reading it, records is the accelerations due to gravity. So if we take the readings out of this we should get a constant measurement of 9.8m/s but that's not the case as no sensor is at its optimal efficiency therefore the actual output that we will be receiving will be filler with **noises** or discrepancy's. The amount of noises present entirely depends on the quality of the sensor.

- However, we can reduce the noises present by using two accelerometers together and averaging out their results or in simple words fusing two sensors together will help in reducing the combined noise by a **factor of the square root of the number of sensors**.

- Noises can be reduced also by using sensors of different types together. This can be explained by the following example.

- Consider a person wants to know the direction he is facing towards using his/her phone ,we could use the phones magnetometer to measure the angle from magnetic north so that's pretty easy however just like with the accelerometer this sensor measurement will also be noisy and if we want to reduce that noise then we may be tempted to add a second magnetometer however at least some contribution of noises coming from the moving magnetic fields created by the electronics within the phone itself this means that every magnetometer will be affected by this correlated noise source and so averaging the sensors won't remove or reduce the noise .

- There are two ways to solve this problem, the first is to simply move the sensors away from the corrupting magnetic fields which is hard to do with a phone or we can just filter the measurement through some form of a low-pass filter which would add lag and make the measurement less responsive.

- The best thing to do in this scenario is fuse the magnetometer with an **angular rate sensor such as a gyro** the gyro will be noisy as well but by using two different sensor types, we're reducing the likelihood that that noise is correlated and so they can be used to calibrate each other the basic gist is that if the magnetometer measures a change in the magnetic field the gyro can be used to confirm if that rotation came from the phone physically moving or if it's just from noise.

2] <u>It can increase the reliability of the data</u>

- Consider a situation in which there are two identical sensors fused together like in the scenario with the averaged accelerometers then we have a backup in case one fails of course even though in this scenario we lose quality if one sensor fails but at least we don't lose the whole measurement we can also add a third sensor into the mix and the fusion algorithm could throw out the data of any single sensor that's producing a measurement that differs from the other two, This scenario can be explained by the example below

- The three pilot tubes are used in aircrafts to determine its air speed, in the unlikely scenario where one breaks or reads incorrectly then the air speed is still known using the other two so duplicating sensors is an effective way to increase reliability however we have to be careful of single failure modes that can affect all of the sensors at the same time.

- Imagine if the aircraft is going through a storm and all the three pilot tubes freezes at the same time this is where using sensors that read different quantities can turn out to be more efficient.

- For Example :- The aircraft can be set up to supplement the airspeed measurements from the pitot tubes with an **airspeed estimate using GPS**

and atmospheric wind models in this case airspeed can still be estimated when the primary sensor suite is unavailable again quality may be reduced but the airspeed can still be determined which is important for the safety of the aircraft.

3] <u>It can estimate unmeasured states</u>

- The initial thought to be understood is that unmeasured doesn't mean unmeasurable it just means that the system doesn't have a sensor that can directly measure the state we want to measure. This can be explained with an example.

- A visible camera can't measure the distance to an object in its field of view a large object far away can have the same number of pixels as a small but close object however we can add a second optical sensor and **through sensor fusion extract three-dimensional information** the fusion algorithm would compare the scene from the two different angles and measure the relative distances between the objects in the two images so in this way these two sensors can't measure distance individually but they can when combined.

4] <u>Sensor fusion can increase the coverage area</u>

- Consider an example of a short-range ultrasonic sensors on a car which are used for parking assist these are the sensors that are measuring the distance to nearby objects like other parked cars and the curb to let the driver know when the vehicle is close to impact each individual sensor may only have a range a few feet and a narrow field of view.
- Therefore if the car needs to have full coverage on all four sides additional sensors need to be added and the measurements fuse together to produce a larger total field of view now more than likely these measurements won't be averaged or combined mathematically in any way since it's usually helpful to know which sensor is registering an object so that you have an idea of where that object is relative to the car but the algorithm that pulls all of these sensors together into one coherent system is still a form of sensor fusion.

How Sensor Fusion can help with GPS Navigation

1] Using Sensor fusion to determine Linear Accelerations

- **What is Linear Acceleration:** - The rate of change of velocity without a change in direction

- The accurate measurement of linear acceleration plays a major role in GPS navigation as its extremely important in correcting time lags and prediction of possible locations of an object that is being tracked

- There are high possibilities of normal sensor providing corrupted values for linear accelerations and thereby leading to the complete failure of the GPS navigation system.

- We con combat this issue by using **two different approaches** one way to address this is by **predicting linear acceleration and removing it from the measurement** prior to using it and this might sound difficult to do but it is possible if the acceleration is the result of the system actuators you know rather than an unpredictable external disturbance what we can do is take the commands that are sent to the actuators and play it through a model of the system to estimate the expected linear acceleration and then subtract that value from the measurement this is something that is possible if say we are implementing it on a system such as a drone and we are flying it around by commanding the four propellers

- If we can't predict the linear acceleration or the external disturbances are too high another option is to ignore accelerometer readings that are outside of some threshold from a 1g measurement if the magnitude of the reading is not close to the magnitude of gravity then clearly the sensor is picking up on other movement and it can't be trusted this keeps corrupted measurements from getting into our fusion algorithm **but it's not a great solution because we stopped estimating orientation during these times and we lose track of the state of the system** again it's not really a problem if we're trying to estimate orientation for a static object this algorithm would work perfectly fine however often we want to know the orientation of something that is rotating and accelerating so we need something else here to help us out.

- This is where the **second method comes into play,** we can sole this issue by **introducing a Gyro into the mix to measure the angular rate of the system**

- The combination of **magnetometer, accelerometer and gyro are so popular** that they're often packaged together as an inertial measurement unit like. The Gyro can prove to be extremely useful because we can estimate orientation for a rotating object with just the gyro on its own no accelerometer and no magnetometer for this, we can multiply the angular rate measurement by the sample time to get the change in angle during that time.

- If the orientation of the entity at the previous sample time is known, we could just add this delta angle to it and have an updated estimate of the current orientation. Over time we're going to know the orientation of the phone over time this **process is called dead reckoning** and essentially, it's just integrating the gyro measurement.

- There are a **few downsides to both these methods** they are given below: -

1. **We still need to know the initial orientation of the entity**

2. **The sensors are not always perfect OR they have bias** and other high frequency noises that will corrupt our estimation now integration acts like a low-pass filter so that high frequency noise is smoothed out a little bit which is good but the result drifts away from the true position due to random walk as well as integrating any bias and the measurements so over time the orientation will smoothly drift away from the truth.

2] Using Sensor fusion to determine the attitude of the aircraft

We can do this by either using an accelerometer and an magnetometer or by just using a single Gyro. Both the methods have their own advantages and disadvantages as demonstrated below.

Accelerometer + Magnetometer	Gyro
ADVANTAGE • Produces absolute measurement	**ADVANTAGE** • Produces relative measurement
DISADVANTAGE • Corrupted by common disturbances	**DISADAVANTAGE** • Needs initial orientation • Drifts over time

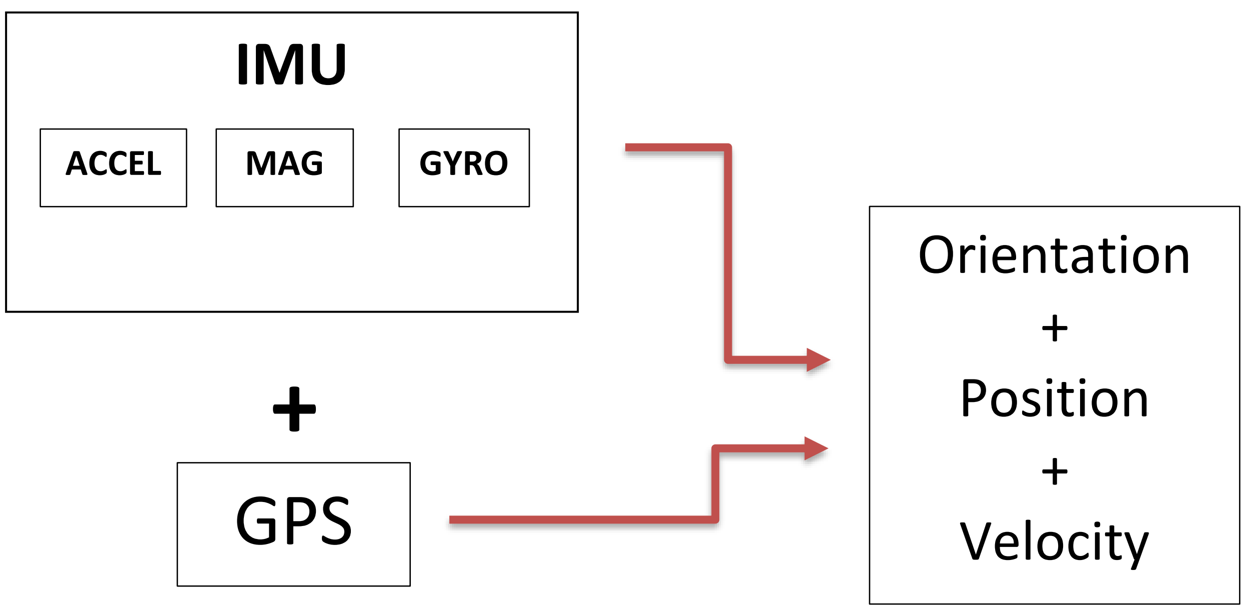
- Each has its own benefits and problems this is where sensor fusion comes into play, we can use it to combine these two estimates in a way **that emphasizes each of their strengths and minimizes their weaknesses**

- There are a number of sensor fusion algorithms that we can use like a **complementary filter or a Kalman filter or the more specialized but common magic or Mahony filters** but at their core every one of them does essentially the same thing they initialize the attitude either by setting manually or using the initial results of the Magon accelerometer and then over time they used the direction of the mag field and gravity to slowly correct for the drift in the gyro

FUSION OF GPS WITH IMU FOR NAVIGATION

Advantage of fusing them

The IMU (Inertial Measurement Unit) majorly consists of the following sensors Accelerometer, Magnetometer and the Gyro and can help in **determining the attitude of the aircraft**. To this set up we will be adding a **GPS sensor** which can measure the position and velocity and so in this way we can extend the fusion algorithm to estimate them as well, Thereby creating a system that will be able to completely provide all the required data for an navigation system to work.



- A GPS Navigation system enables you to know the position of an object relative to the surface of the earth by fixing an GPS sensor on to the object and it also gives us the data regarding **latitude. Longitude and altitude.**

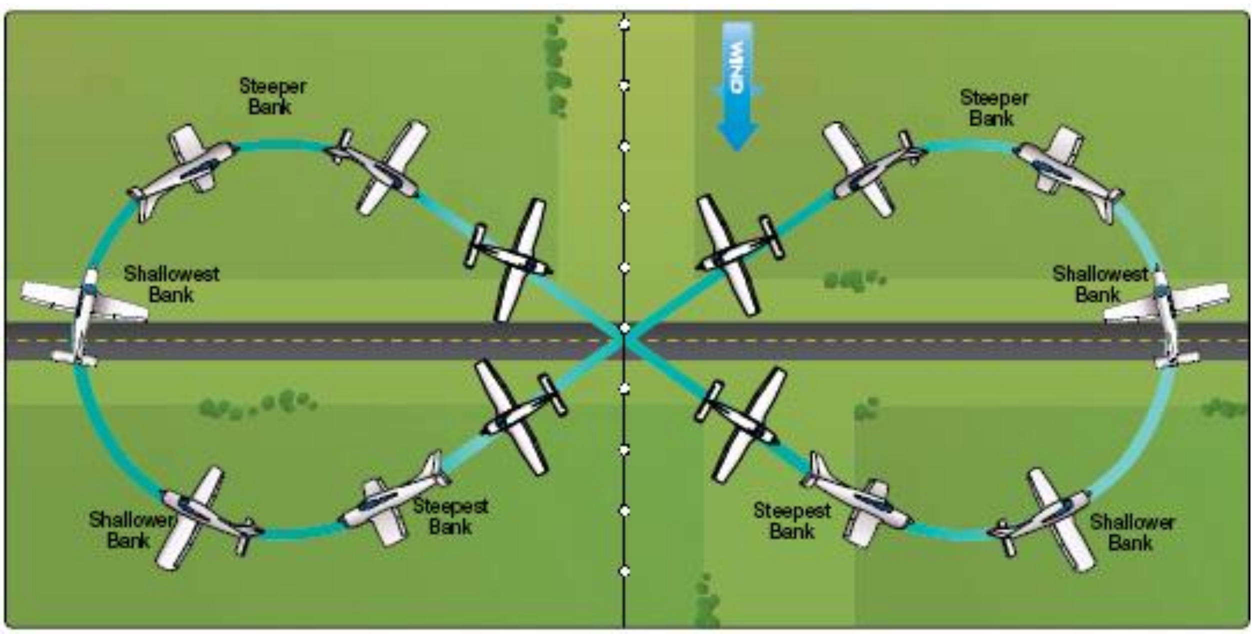
- The above-mentioned setup works fine in some situations like when the system is accelerating and changing directions relatively slowly and we only need position accuracy to be a few meters.

- This might be the case for a system that is **determining directions in a car** as the GPS navigation system only requires position information and accuracy to only a few feet or less.

In The case of aircrafts (Especially military of smaller aircrafts)

- On the other hand, when we are discussing about smaller, fast travelling and highly manurable aircrafts we are taking into consideration a system that requires position information to a few feet or less and it needs position updates **at hundreds of times per second** to keep up with the fast motion of the aircraft.

- Especially when the aircrafts are flying through terrains filled with obstacles and other enemy aircrafts in such scenarios a simple GPS sensor will prove to be of no use and can eventually lead to a catastrophic crash.

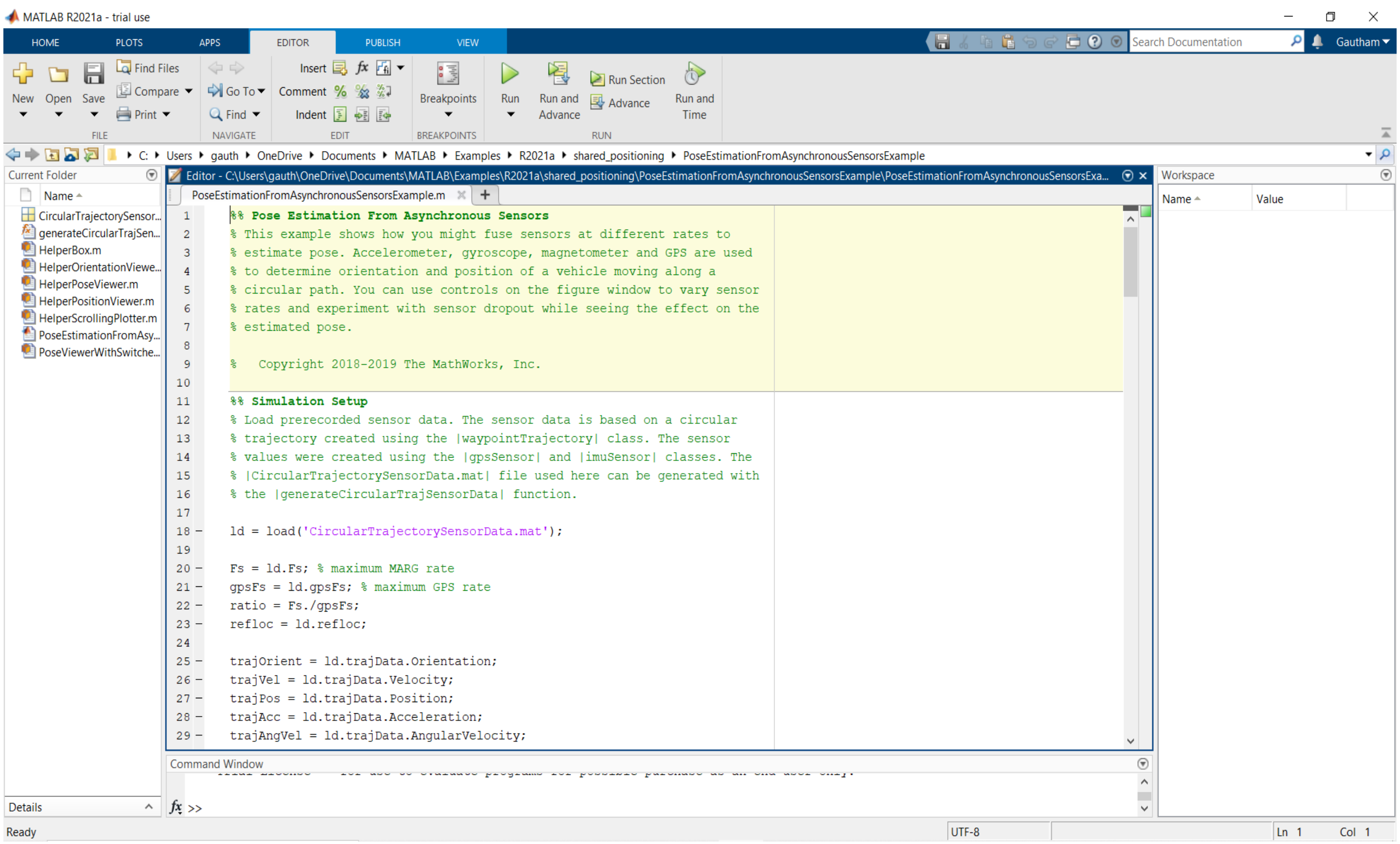


- These are the exact scenarios where Sensor fusion can be integrated and the GPS sensors might have to be paired with additional sensors like the IMU to get a more accurate flow of Data.

VISULISATION OF THE EFFECTS OF THE FUSION USING MATLAB

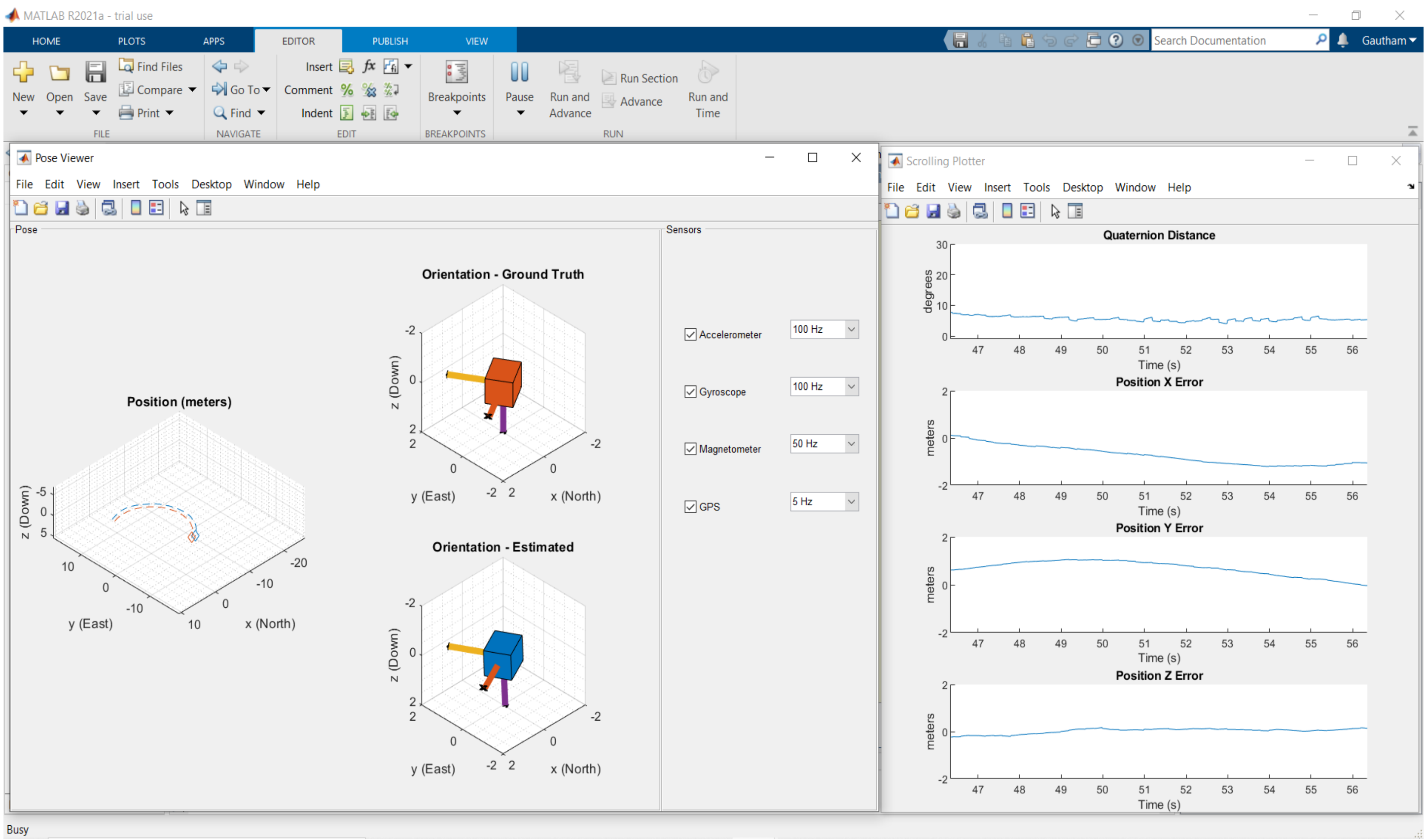
- All the discussed points above, other effects and correlations between the various sensors of the IMU and the GPS sensor can all be visually represented using MATLAB and SIMULINK.

- In This project we are using an Example from MATLAB Sensor Fusion and tracking tool box called **Pose Estimation from Asynchronous Sensors.** This example uses a GPS excel gyro and magnetometer to estimate **Pose** which is both orientation and position as well as a few other states.



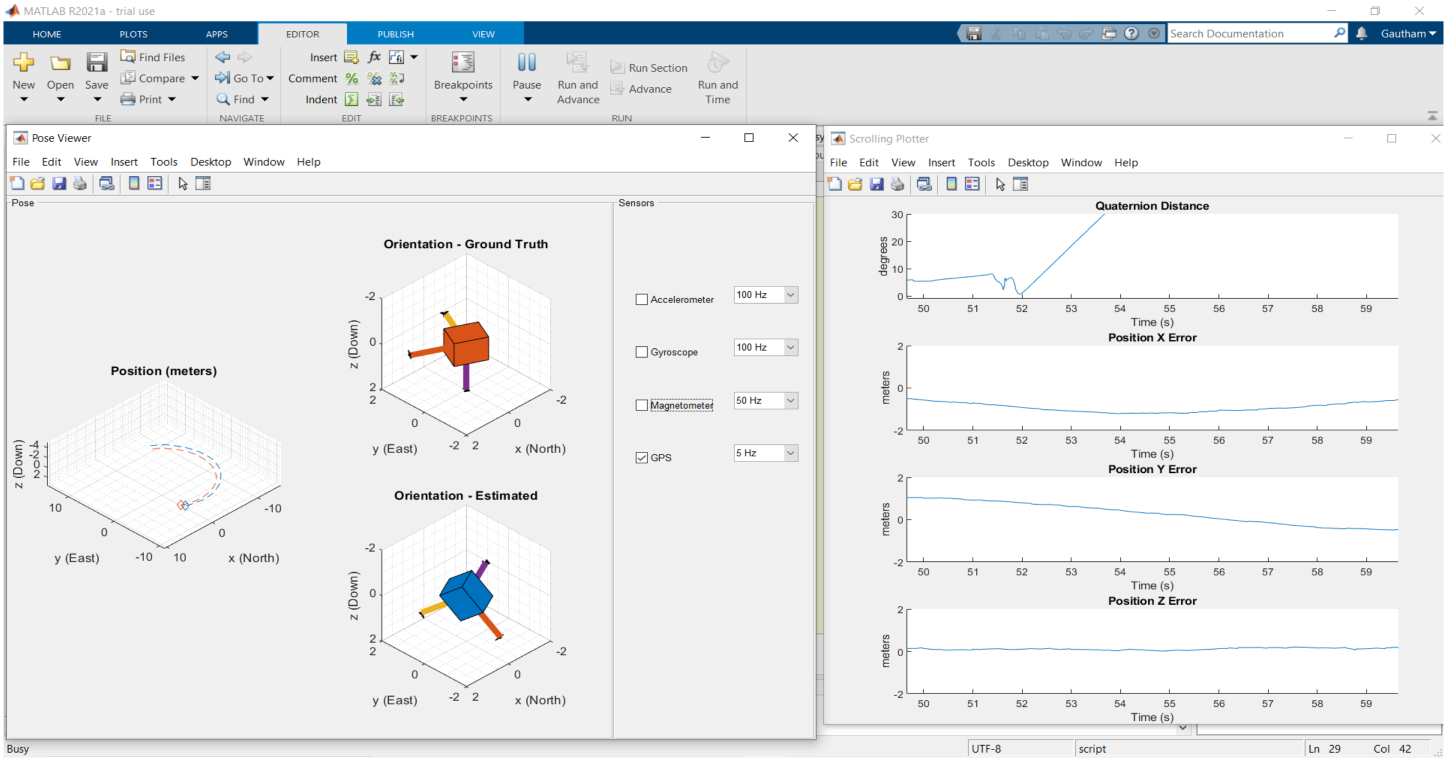
- The script generates a true path and orientation profile that the system Follows and we can see the visual differences in them as the values are fluctuated

- The **true orientation is the red cube** and the **true position is the red diamond** now the pose algorithm is using the available sensors to estimate orientation and position and it shows **the results of that as the blue cube** and the **blue diamond respectively** so that's what we want to watch how closely do the blue objects follow the red objects and the graph on the right plots the error if you just want to see a more quantitative result

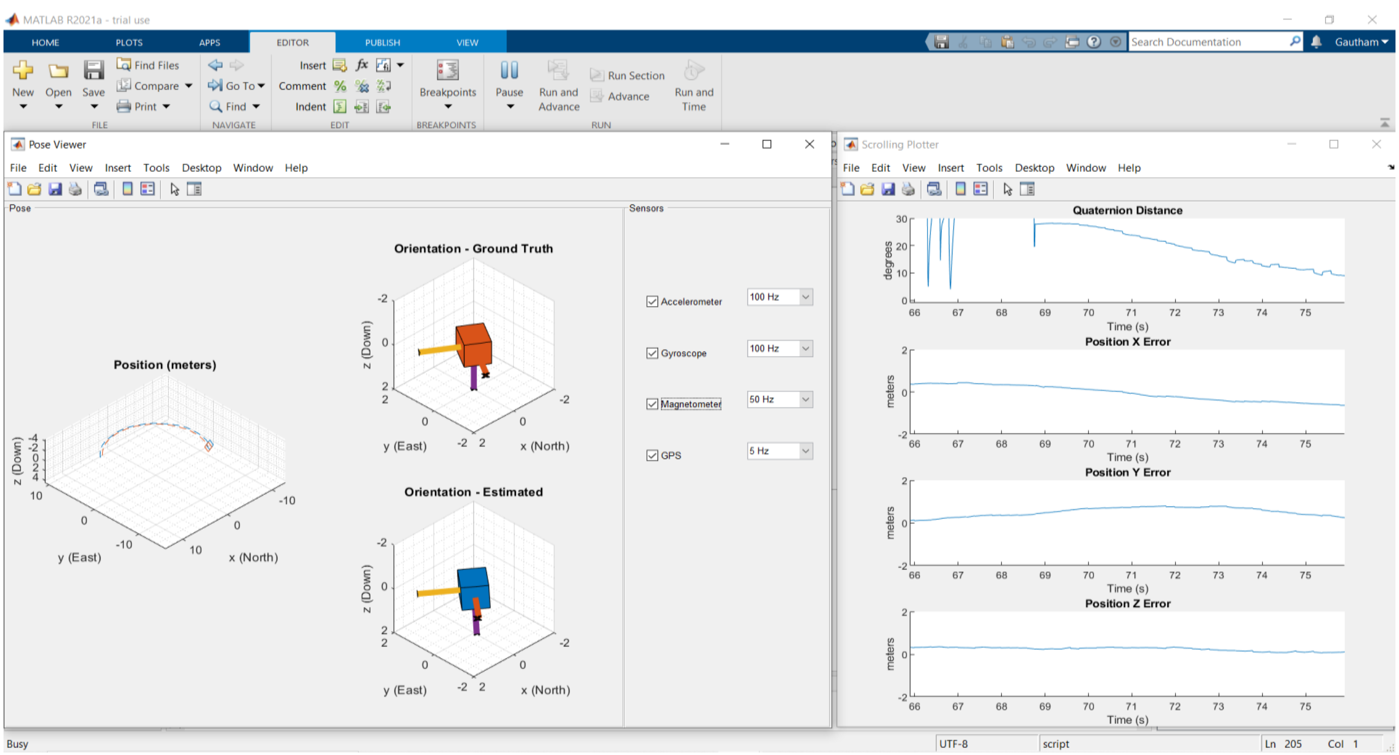


- One of the pivotal advantages of this simulation is that while the script is running the interface allows us to change the sample rates of each of the sensors or remove them from the solution altogether so that we can see how it impacts the estimation so let's start by removing all of the sensors except for the GPS and we'll read the GPS five times a second the default trajectory in the script is to follow a circle with a radius of about 15 meters.

- After removing the IMU sensors (i.e., The accelerometer, The magnetometer and the Gyro) we can see the diamond shapes are still moving around this circle pretty slowly, But the point to be noticed is that now **the orientation estimate is way off** as you'd expect since we don't have any orientation sensors active but the **position estimate isn't too bad** after the algorithm settles and removes that initial bias, we see position errors of around plus and minus 2 meters in each axis.

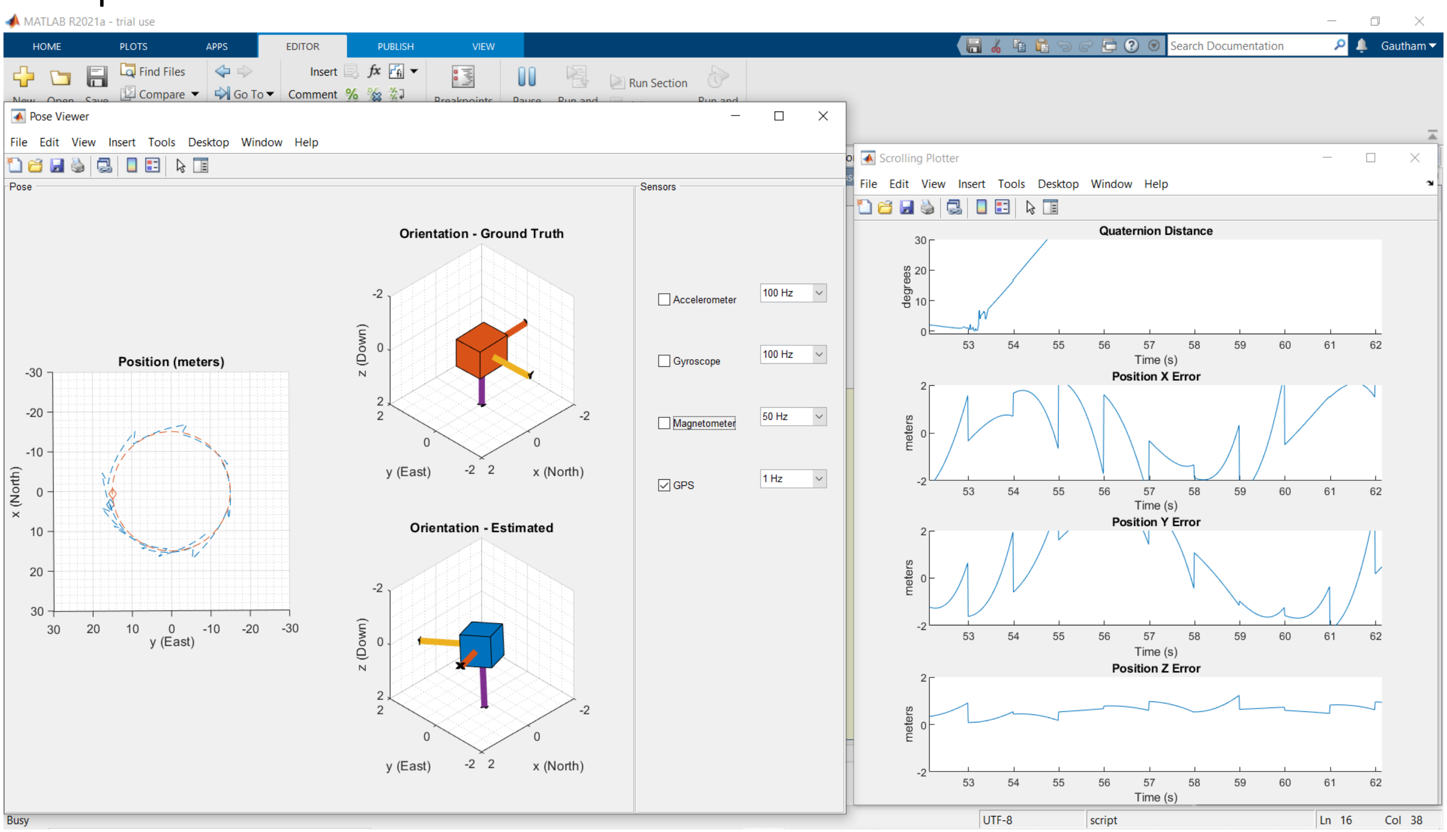


Now when we turn the IMU sensors back on we can see that our result is improved well it's taking several seconds for the orientation to converge but you can see that it's slowly correcting itself back to the true orientation also the position estimate is well it's about the same plus or minus two meters maybe a little less.



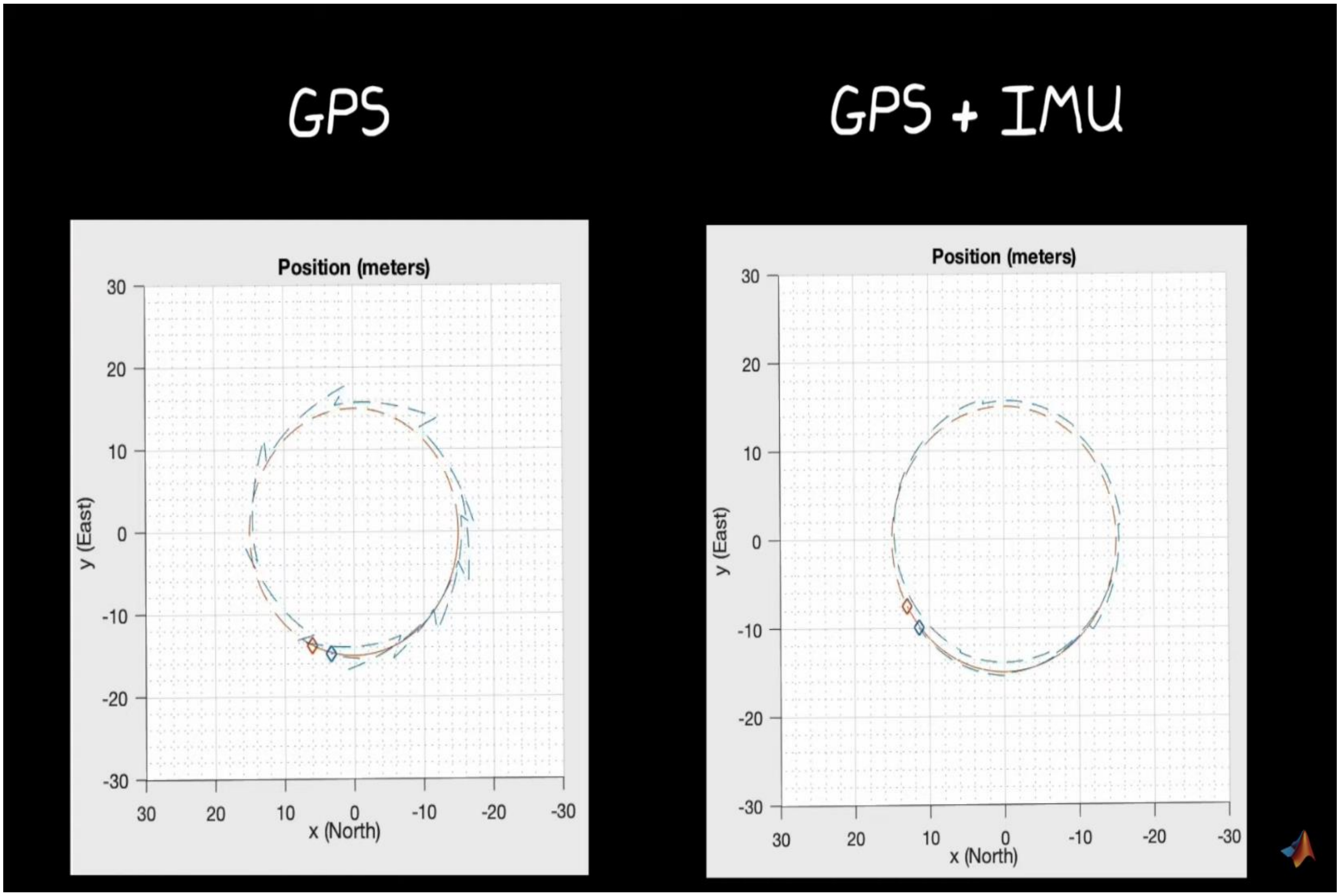
Now we shall run the same simulation on an object travelling at a much more higher velocity

Now let's create a trajectory that is much faster in order to do that slight changes have to made in the trajectory generation script by just speeding up the velocity of the object going around the circle from two point five to twelve point five meters per second this is going to create more angular acceleration in a shorter amount of time and to really emphasize the point we are trying to make here additional changes are also done to the code in order to slow the GPS sample time down to once per second and the results are shown below.



After running the simulation we notice that when we get a GPS measurement we get both position and velocity so once a second we get a new position update that puts the estimate within a few meters of the truth but we also get the current velocity and so for one second the algorithm propagates that velocity forward to predict what the object is doing between measurements and this works really well if the velocity is near constant for that one second but poorly as you can see when the velocity is rapidly changing this is the type of situation that is similar to an aircraft that has to make rapid turns and avoid obstacles and **it's here where the addition of the IMU will help because we won't have to rely on propagating a static velocity for one second we can estimate velocity and rotation using the IMU sensors.**

COMPARISON BETWEEN THE RESULTS OBTAINED WITH AND WITHOUT FUSION



- In image given above we can see the results with GPS sensor alone in the left and the right is with the addition of the IMU we can see that at least visually how the GPS with the IMU is different than the GPS alone **it's able to follow the position of the object more closely and creates a circular result rather than a saw blade** so adding an IMU seems to help estimate position.

- What is happening here the IMU is allowing us to dead rec in the state of the system between GPS updates in the exact same way how we use the gyro to dead reckon between the mag and accel updates in the sensor made from the fusion of the magnetometer and the accelerometer and this is true except it's not as cut and dry as that it's a lot more intertwined.

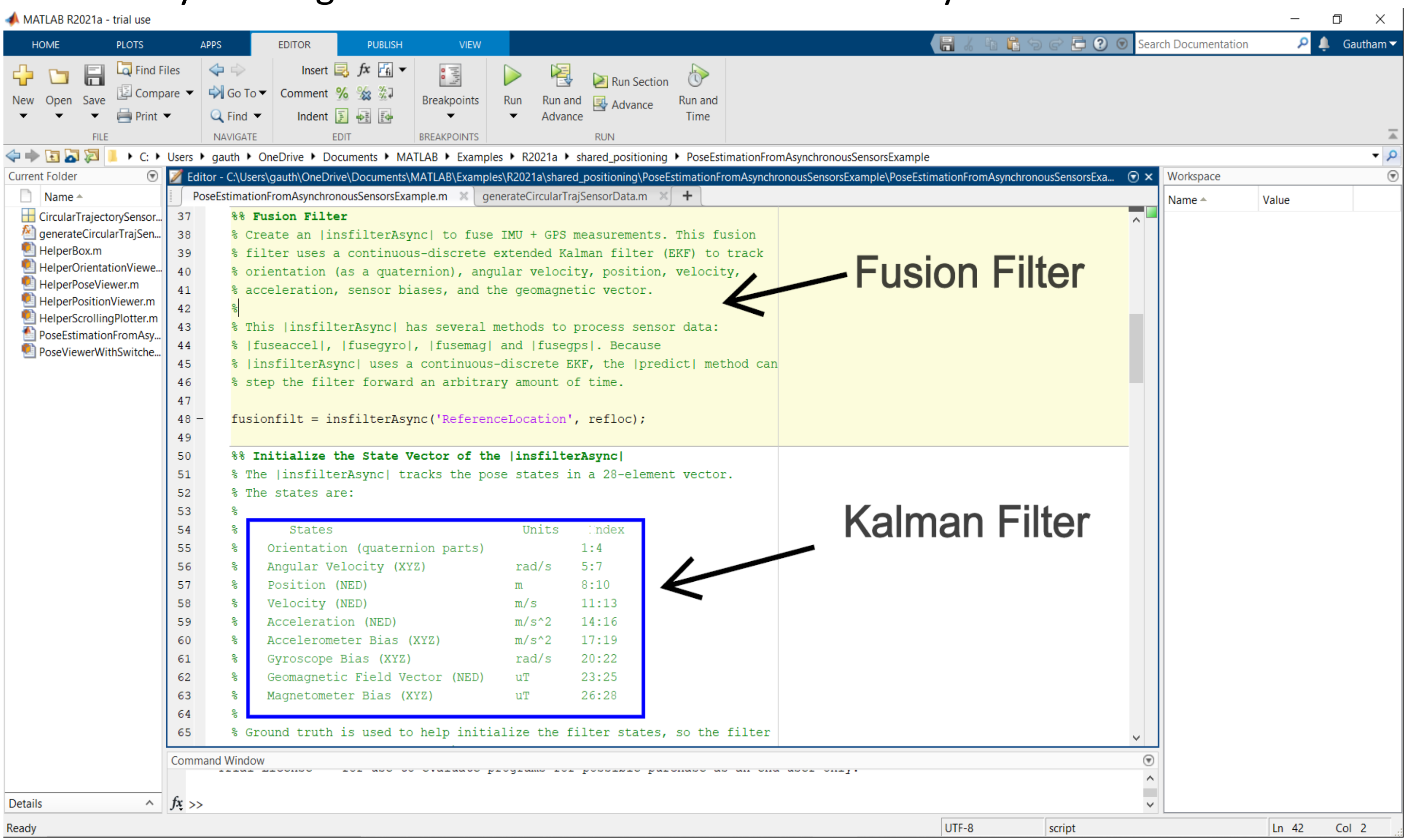
STUDY ON KALMAN FILTER

What is Kalman filter

- Kalman filtering is an algorithm that provides estimates of some unknown variables given the measurements observed over time.
- Kalman filters are used to estimate states based on linear dynamical systems in state space format.

Significance of Kalman filter in the simulation above

The fusion algorithm which we are using in the simulation above is a continuous **discrete extended Kalman filter** and this particular one is set up to accept the sensor measurements **asynchronously** which means that each of the sensors can be read at their own rate and this is beneficial if you want to run say your gyro at 100 Hertz your mag and accelerometer at 50 Hertz and your GPS at 1 Hertz.



This is a massive common filter the state vector has 28 elements in it that are being estimated simultaneously there's the obvious states like orientation angular velocity linear position velocity and acceleration but the filter is also estimating the sensor biases and the mag field vector.

CONCLUSION

- Through this Project **"INTEGRATION OF SENSOR FUSION FOR ENHANSING GPS NAVIGATION**" we have been able to study the adverse capabilities of the Sensor fusion methodology and how it can be integrated into an existing real-world system.

- The Project has also helped shed lights on how sensor fusion can be used to fuse together two different real-world sensors and using diverse fusing algorithms to provide a continuous flow of data that is extremely reliable and has very low amounts of Noise or discrepancies.

- The Project also provides a short insight regarding the development of navigation systems especially in the field of air transport going through various technological developments before the invention of modern GPS Navigation.

- The next anticipated modification of this Project will be to create an Artificial intelligence enabled system that will be able to create real world models of various geographical locations using advanced satellite imagery and engineering graphics.

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