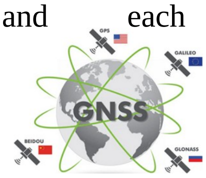
GNSS Localization Techniques and Improvement Methods

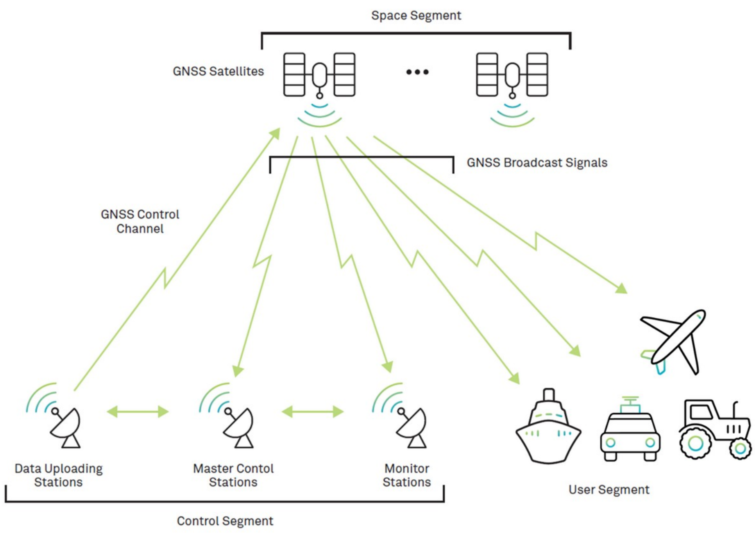
What is GNSS Localisation?

GNSS (**Global Navigation Satellite System**) localization refers to the process of determining the precise location of an object (such as a vehicle, smartphone, or other device) on Earth by using signals from satellites. GNSS includes systems like GPS (Global Positioning System), GLONASS (Russia), Galileo (Europe), and BeiDou (China) as well as two regional systems QZSS and IRNSS – and each are managed by a different country.



Global navigation satellite systems (GNSS) are invisible pieces of technology that people rely on everyday without thinking about it. From communications systems to mobile navigation applications like Google Maps, GNSS affects what we do every day. GNSS are more than the satellites orbiting Earth. The multiple groups of satellites, known as constellations, broadcast signals to master control stations and users of GNSS across the planet. These three segments – space, control and user – are all considered part of GNSS. But most frequently, GNSS is used to describe the satellites in space.

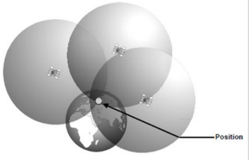
The control segment is a network of master control, data uploading and monitoring stations located around the world. These stations receive a satellite's signal and compare where the satellite says it is with orbit models showing where it should be. Operators at these stations can control the satellites position to correct or alter their orbital paths, for example if a satellite has drifted, or needs to be moved to avoid debris collision. This process, as well as monitoring a satellite's health, ensures a baseline of accuracy in GNSS positioning.



The user segment includes the equipment that receives satellite signals and outputs a position based on the time and orbital location of at least four satellites. This segment includes the user's antennas to identify and receive good-quality signals as well as high-precision receivers and positioning engines that process the signals and resolve potential timing errors.

How GNSS Localization Works:

1. Satellites: A GNSS receiver on Earth receives signals from multiple satellites. At least four satellites are required to determine a three-dimensional position (latitude, longitude, and altitude).
2. Signal Timing: Each satellite transmits a signal containing the time it was sent and the satellite's position at that time. The receiver calculates the time it took for the signal to reach it.
3. Distance Calculation: By knowing the speed of light, the receiver calculates the distance to each satellite based on the time delay of the signals.
4. Triangulation: The receiver uses the distance from multiple satellites to determine its exact position on Earth. This process is known as triangulation or trilateration.



5. Correction: To improve accuracy, GNSS systems often use techniques like differential correction, which involves using additional data from fixed ground stations to correct any errors in the satellite signals.

Applications:

1. Location – determining your position in the world
2. Navigation – identifying the best route from one location to another
3. Tracking – monitoring an object’s movement in the world
4. Mapping – creating maps of a specific area
5. Timing – computing precise timing within billionths of a second

GNSS localization is integral to many modern technologies, enabling everything from smartphone navigation to autonomous vehicles.

How GNSS Localization Works in Autonomous Vehicles:

1. Positioning: Autonomous vehicles use GNSS to determine their precise location (latitude, longitude, and altitude) on Earth. The GNSS receiver on the vehicle communicates with multiple satellites to calculate its position through trilateration.

2. High-Definition Maps: The GNSS data is often used in conjunction with high-definition (HD) maps that contain detailed information about the road, including lane markings, curbs, traffic signs, and other features. The vehicle's software compares its current GNSS position with the HD map to understand its surroundings accurately.

3. Sensor Fusion: GNSS data is combined with data from other sensors, such as LiDAR, cameras, radar, and inertial measurement units (IMUs), to create a more accurate and reliable understanding of the vehicle's position and environment. This process is known as sensor fusion.

4. Correction Services: To enhance the accuracy of GNSS localization, autonomous vehicles often rely on Real-Time Kinematic (RTK) correction or Differential GNSS (DGNSS) services. These techniques use ground-based reference stations to provide corrections to the GNSS signals, reducing errors and improving positioning accuracy to within a few centimeters.

5. Redundancy: Autonomous vehicles typically use GNSS as one part of a redundant system. If the GNSS signal is weak or unavailable (such as in tunnels or urban canyons), the vehicle can rely on its other sensors and onboard maps to continue operating safely.

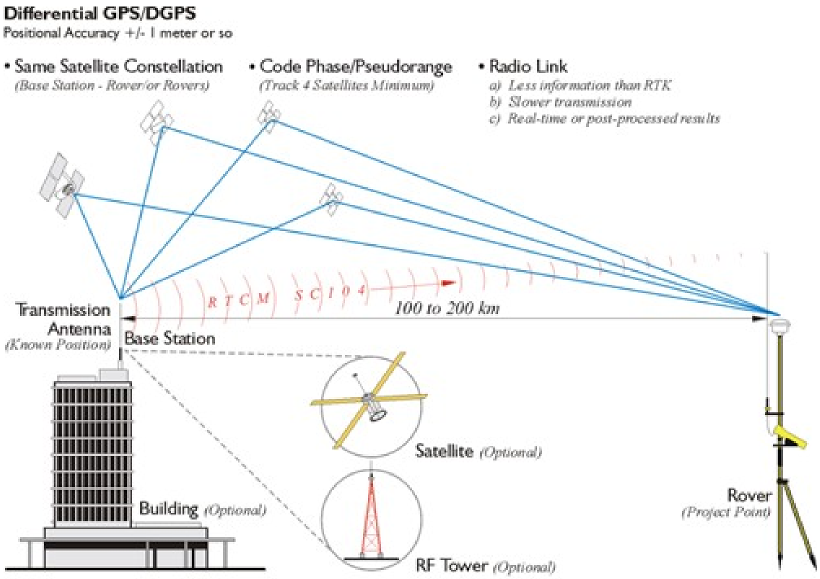
1. GNSS Localisation Techniques

GNSS localization techniques are methods used to enhance the accuracy, reliability, and performance of positioning systems in various applications, including autonomous vehicles, surveying, and mapping. Here's an overview of some of the key GNSS localization techniques:

- Standard Positioning Service (SPS) - This is the basic GNSS localization technique available to civilian users. It relies on signals from multiple satellites to provide positioning information.
- Precise Positioning Service (PPS) - A higher-accuracy service used primarily by military and authorized users. It involves the use of encrypted signals.
- Differential GNSS (DGNSS)/DGPS (Differential Global Positioning System) - DGNSS improves the accuracy of standard GNSS by using a network of ground-based reference stations. These stations compare their known positions to the positions calculated by GNSS signals, and the differences (errors) are transmitted to GNSS receivers to correct their position.
- Real-Time Kinematic (RTK) - RTK is a technique that enhances the precision of GNSS by using carrier-phase measurements from GNSS signals, along with real-time corrections from a nearby base station.
- Post-Processed Kinematic (PPK) - PPK is similar to RTK but involves post-processing the GNSS data rather than applying corrections in real-time. Data from both the rover (mobile receiver) and base station are collected and processed after the fact to achieve high precision.
- Satellite-Based Augmentation Systems (SBAS) - SBAS improves GNSS accuracy by using additional satellite signals and ground stations to provide corrections. Examples include WAAS (USA), EGNOS (Europe), and MSAS (Japan).
- Precise Point Positioning (PPP) - PPP is a technique that improves GNSS accuracy by using precise satellite orbit and clock data, without the need for a local base station. Corrections are applied globally using data from a network of ground stations.
- Inertial Navigation System (INS) Integration - INS uses accelerometers and gyroscopes to track a vehicle's movement and orientation. When integrated with GNSS, it helps maintain accurate positioning even when GNSS signals are weak or unavailable.
- Carrier-Phase Enhancement - This technique involves using the phase of the carrier signal (the underlying wave that carries the GNSS signal) to achieve higher accuracy than using the code (the data) alone. It's commonly used in RTK and PPP.
- Network RTK (NRTK) - NRTK uses a network of base stations rather than a single base station to provide corrections. The corrections are interpolated for the user's location, which extends the effective range of RTK and reduces errors.

- Assisted GPS (A-GPS) – It enhances traditional GPS by using data from network sources like cell towers to speed up the time it takes to get a location fix, especially in areas with weak GPS signals. This technology is commonly used in smartphones to provide faster and more reliable location services, particularly in urban areas or indoors.

a) Differential GPS (DGPS)



Differential Global Positioning Systems (DGPSs) supplement and enhance the positional data available from global navigation satellite systems (GNSSs). A DGPS for GPS can increase accuracy by about a thousandfold, from approximately 15 metres (49 ft) to 1–3 centimetres (1⁄2–1+1⁄4 in).Differential GPS (DGPS) is an important tool in modern navigation. This system uses satellites and reference stations to make GPS receivers more accurate. This technology helps military personnel and professional surveyors navigate accurately and reliably.

Working

1. Real-Time DGPS:

   Real-Time Differential GPS (DGPS) improves GPS accuracy by broadcasting correction signals from a base station to a roving receiver in real-time. The base station calculates corrections for each satellite signal it receives and sends these corrections to the rover, either through a land-based radio signal or a satellite. This process allows the rover to display and log differentially corrected positions with accuracy typically within one to two meters, depending on the service and receiver.

   The Radio Technical Commission for Maritime Services (RTCM) defined the protocol for transmitting these corrections, known as RTCM SC-104 format. Real-time corrections are crucial for applications requiring immediate precision, such as navigation.

2. Satellite Differential Services:

   Satellite Differential Services use geostationary satellites to provide real-time DGPS corrections. Reference stations collect GPS data, relay it to a Network Control Center, and then to a geostationary satellite, which broadcasts the corrections to users. The Wide Area

Augmentation System (WAAS) is an example of such a service, designed for aviation but available to civilians. Commercial services like Thales Survey LandStar and OmniSTAR also provide satellite-based DGPS.

3. Post-Processing and Reprocessing:

   Post-processed DGPS involves correcting GPS data after it has been collected, using a known reference point. The rover and base station data are processed together in the office to improve accuracy, making it suitable for GIS and mapping applications. Reprocessing real-time data is another option, allowing for the correction of any errors encountered during data collection due to poor satellite signals.

   There are various sources for post-processing data, including government agencies, commercial services, and web-based platforms. Some users may choose to own their base stations for maximum control over data accuracy.

Summary

To achieve GPS accuracy within one to ten meters, differential correction is essential. The three main methods—real-time DGPS, reprocessing real-time data, and post-processing—each offer similar levels of accuracy, with the choice depending on project requirements and available resources.

Accuracy

The United States Federal Radionavigation Plan and the IALA Recommendation on the Performance and Monitoring of DGNSS Services in the Band 283.5–325 kHz cite the United States Department of Transportation's 1993 estimated error growth of 0.67 metres per 100 kilometres (3.5 ft/100 mi) from the broadcast site but measurements of accuracy across the Atlantic, in Portugal, suggest a degradation of just 0.22 m/100 km (1.2 ft/100 mi).

Advantages

- Increased Accuracy: By correcting GPS errors in real-time, DGPS can reduce positioning errors to within 1 to 3 meters.
- Reliability: DGPS provides consistent and reliable positioning data, which is crucial for applications requiring high precision.
- Wide Applicability: DGPS is useful in various fields, including surveying, construction, navigation, mapping, and engineering purposes.

Limitations

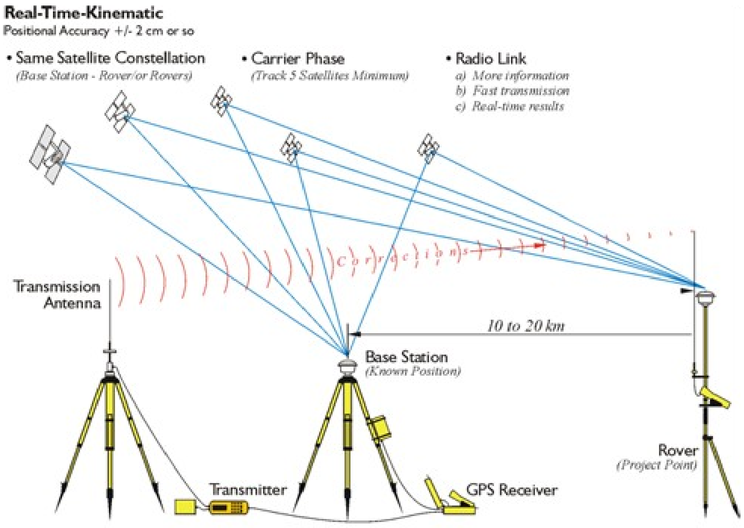
- Range Dependency: The accuracy of DGPS decreases as the distance from the reference station increases. Local DGPS systems are limited to relatively small areas.
- Infrastructure Requirements: DGPS requires a network of ground-based reference stations, which can be costly and complex to maintain.

- Signal Obstruction: Like standard GPS, DGPS signals can be affected by obstructions, such as buildings or trees, which may reduce its effectiveness in certain environments.

Applications

- Maritime Navigation: DGPS is widely used in marine environments to ensure precise navigation, especially in narrow channels or when approaching ports.
- Surveying and Mapping: In land surveying, DGPS provides the high accuracy needed for creating detailed maps and conducting geospatial analyses.
- Agriculture: Precision farming uses DGPS to guide machinery, ensuring accurate planting, fertilizing, and harvesting, which improves efficiency and crop yields.
- Aviation: DGPS is used in some aviation applications to improve the accuracy of approach and landing procedures.

b) Real Time Kinematic (RTK)



Working

1. Base Station and Rover:

   RTK involves a fixed base station at a known location and a mobile rover unit. The base station receives GPS signals and calculates the errors based on its known position.

2. Real-Time Corrections:

   The base station sends these correction data to the rover in real-time, typically via radio or cellular communication. The rover applies these corrections to its own GPS data to determine a highly accurate position.

3. Carrier-Phase Measurements:

Unlike standard GPS, which uses the coded signals for positioning, RTK uses the carrier phase of the signal, which has a much shorter wavelength, allowing for centimeter-level accuracy.

RTK v/s GPS

The key difference between RTK and traditional GPS positioning is that the base station and mobile receiver can communicate with each other in real time. This allows the mobile receiver to use the information from the base station to correct any errors in its own position calculations. The base station is typically connected to a reference station connected to a network of CORS (Continuously Operating Reference Station) that provides correction data to the base station.

The correction data is sent to the mobile receiver via a radio or cellular link and is used to correct any errors in the mobile receiver's position calculations. This allows the mobile receiver to determine its position with an accuracy of a few centimeters rather than the several meters of accuracy typical of traditional GPS positioning.

RTK v/s DGPS

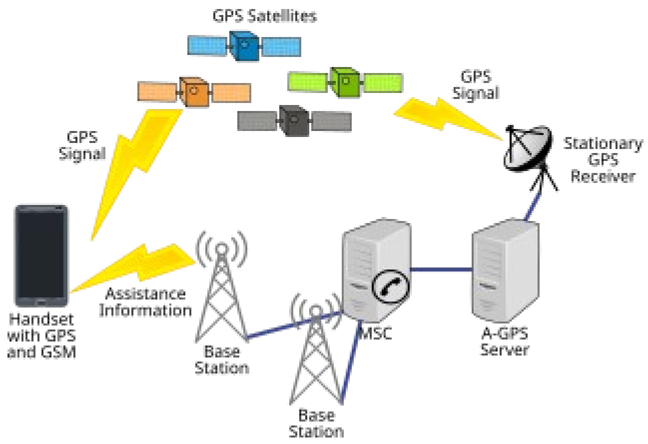
Aspect	DGPS	RTK
Accuracy	1–3 centimetres (1⁄2–1+1⁄4 in)	8mm + 1ppm (parts per million / 1mm per km) horizontal and 15mm + 1ppm vertical relative to the base station
Complexity	DGPS is less complex in terms of infrastructure, signal processing, and operational demands, making it more accessible for users and suitable for a wider range of applications that do not require extreme precision.	RTK is more complex, requiring precise infrastructure, advanced signal processing, and greater user expertise, but it provides much higher accuracy, which is essential for applications like precision surveying, autonomous vehicle navigation, and precision agriculture.
Typical Use Cases	• Maritime • Navigation • Surveying and Mapping • Agriculture • Aviation	• Surveying and mapping • Agriculture • Construction • Autonomous vehicles • Search and rescue

Disadvantages of RTK

- Unavailable in some areas, like marine areas, due to the difficulty of establishing a base station or reference station.

- Require to setup on a pre-surveyed base-station with known coordinates
- Requires accurate settings with a clear view of the rover at all times
- Requires stable and long-range radio-datalink
- Datalink dropouts and latency
- Limited to the radio range
- GPS outages can impact the system performance
- High cost
- Rovers are not very compact and therefore are not used in mobile devices

c) Assisted GPS(A-GPS)



Assisted GPS augments quality and precision of location data by supplementing it with external data sources. This is especially useful in geographic locations where a clear line of sight to satellites is inaccessible – whether due to natural geographic features like forests and mountains or human-made ones like skyscrapers overhead bridges.

There are two modes of Assisted GPS:

1. Mobile Station Assisted (MSA)

   GPS devices receive supplementary info (reference time, acquisition help, etc.) from a mobile service provider. An Assisted GPS server calculates and returns the position of the GPS device.

2. Mobile Station Based (MSB)

   GPS devices receive orbital data or almanac for the GPS satellites, allowing them to acquire satellites more quickly. Location calculation is performed locally on the GPS device.

Working

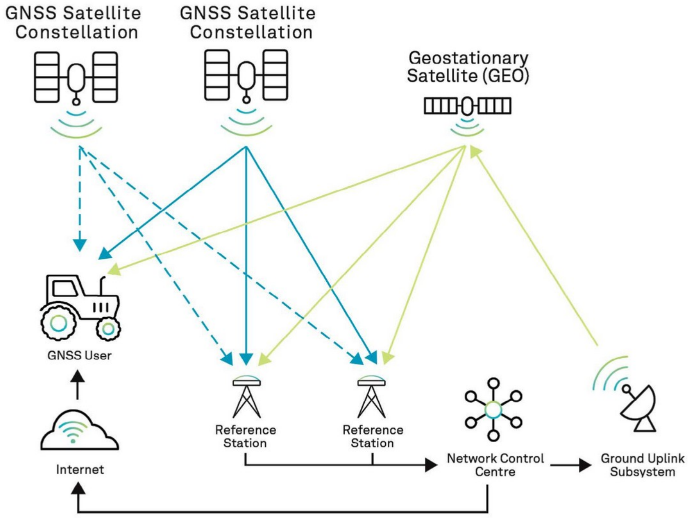
- Assistance Data: A-GPS supplements standard GPS by using data from network sources like cell towers and Wi-Fi networks. This data helps the GPS receiver in your device (like a smartphone) to quickly determine its location by providing information about nearby satellites, thereby reducing the time needed to acquire a position fix.

- Faster Time to First Fix (TTFF): One of the main benefits of A-GPS is its ability to significantly reduce the Time to First Fix (TTFF). Traditional GPS might take longer to lock onto satellites, especially when first activated or in difficult environments. A-GPS accelerates this process by providing relevant satellite data from a server over a cellular or Wi-Fi network.
- Enhanced Accuracy: A-GPS can improve location accuracy in areas with poor GPS signal reception by combining GPS data with network-based location data. This is particularly useful in urban canyons, inside buildings, or during poor weather conditions where GPS signals might be obstructed or weak.

AGPS v/s RTK v/s DGPS

Aspect	DGPS	RTK	AGPS
Accuracy	Provides meter-level accuracy, suitable for professional tasks like marine navigation and GIS.	Delivers centimeter-level accuracy, ideal for high-precision applications like surveying and autonomous vehicles.	Offers meter-level accuracy, sufficient for consumer applications, but less precise than DGPS and RTK.
Speed and Time to First Fix (TTFF)	Slower TTFF than A-GPS, but offers real-time corrected positions.	Quick and precise once operational, but initial setup can be slower compared to A-GPS.	Fast TTFF using network data, especially useful in urban or indoor settings.
Infrastructure and Complexity	Requires ground-based reference stations, more complex than A-GPS, but less demanding than RTK.	Highly complex, requiring a base station, rover, and reliable communication links for synchronization.	Minimal infrastructure, relying on existing cellular networks, but dependent on network availability.
Coverage and Usability	Good coverage near base stations but performance declines with distance.	Offers the highest precision within a limited range (10-20 km), with performance diminishing over distance.	Effective in urban and indoor environments but limited by network coverage.

d) Precise Point Positioning(PPP)



Working

1. Data Collection:

- GNSS Receivers: PPP starts with GNSS receivers collecting raw satellite signals from multiple GNSS constellations (such as GPS, GLONASS, Galileo, and BeiDou).
- Observations: The receivers measure the time it takes for signals to travel from satellites to the receiver, recording pseudorange and carrier phase data.

2. Correction Data:

- Global Correction Services: PPP uses precise satellite orbit and clock data from global correction services, such as the International GNSS Service (IGS) or commercial providers. These corrections account for satellite clock errors, orbital deviations, and other factors affecting signal accuracy.
- Data Integration: The correction data is integrated with the receiver's raw observations to account for errors and enhance the positioning accuracy.

3. Data Processing:

- Algorithm Application: Advanced algorithms process the GNSS observations and correction data to compute precise positions. This involves complex mathematical models to correct for various error sources, such as atmospheric delays and satellite clock errors.
- Convergence: PPP typically requires a period of data collection to converge to high accuracy. The system gradually improves positioning accuracy as more data is integrated and corrections are applied.

4. Position Calculation:

- Precise Positioning: After processing the data, PPP calculates the receiver's position with high precision, typically within a few centimeters. The positioning accuracy depends on the quality of the correction data and the duration of data collection.

PPP v/s RTK

Aspect	PPP	RTK
Real-time corrections required	No	Yes
Base station required	No	Yes
Internet during surveying required	No	Yes, but not necessary when radio is used
Logging required	Yes	No, but can be used as backup data
Possible accuracy	Cm	Cm
Corrections	Offsite	Onsite
Baseline	No	Up to 60 km

2. Methods to improve GNSS Localisation

a. Kalman Filter and EFKs

Kalman Filter in GNSS Localization

Overview:

The Kalman Filter is a powerful algorithm used to estimate the state of a dynamic system from noisy observations. In GNSS (Global Navigation Satellite System) localization, it helps to smooth and predict position data, enhancing accuracy and reliability.

How It Works:

1. Prediction Step:
   a) System Model: Uses a mathematical model of the system to predict the next state (position, velocity, etc.) based on the current state and known dynamics.
   b) Forecasting: Calculates the predicted state and its uncertainty.
2. Update Step:
   a) Measurement Update: When new GNSS measurements are received, the Kalman Filter updates the state estimate by incorporating these measurements.

b) Correction: Adjusts the predicted state based on the difference between the actual measurements and the predicted values, weighted by their uncertainties.

Benefits for GNSS Localization:

1. Noise Reduction:
   a) Filtering Noise: The Kalman Filter reduces measurement noise by blending predictions with observations. It smooths out erratic fluctuations caused by noisy GNSS signals, resulting in more stable position estimates.
2. Error Compensation:
   a) Mitigating Errors: Compensates for systematic errors and biases in GNSS data, such as clock errors and atmospheric delays, by using a prediction model that accounts for these factors.
   b) Kalman Gain: Adjusts the influence of new measurements based on their reliability, which helps to correct errors effectively.
3. Smoothing:
   a) Consistent Estimates: Provides a smoothed trajectory by continuously updating the state estimate as new data arrives, resulting in a more accurate representation of the actual position.

Applications:

- Navigation Systems: Enhances the accuracy of GNSS receivers in vehicles, aircraft, and maritime navigation by providing smoothed and reliable position estimates.
- Tracking: Improves the accuracy of tracking systems for objects or people using GNSS data.

Extended Kalman Filter (EKF) in GNSS Localization

Overview:

The Extended Kalman Filter is an extension of the Kalman Filter designed to handle nonlinear systems. It linearizes the nonlinear system around the current estimate to apply the Kalman Filter equations.

How It Works:

1. Prediction Step:
   a) Nonlinear System Model: Uses a nonlinear model to predict the next state. The model is linearized around the current estimate using Jacobian matrices.
   b) Forecasting: Predicts the state and its uncertainty, considering the nonlinear nature of the system.
2. Update Step:

a) Measurement Update: Incorporates new GNSS measurements by linearizing the measurement model with Jacobians and updating the state estimate accordingly.

b) Correction: Adjusts the state estimate based on the new measurements, with corrections accounting for the nonlinearities.

Benefits for GNSS Localization:

1. Handling Nonlinearity:

    a) Nonlinear Dynamics: Can handle the nonlinear characteristics of GNSS positioning systems, such as satellite orbits and signal propagation effects, by linearizing them around the current estimate.

2. Improved Accuracy:

    a) Refined Estimates: Provides more accurate position estimates in scenarios where GNSS data and system dynamics are nonlinear, such as in complex environments with varying signal conditions.

    b) Better Compensation: More effective at dealing with non-linear errors and biases, leading to improved position accuracy compared to the standard Kalman Filter.

3. Smoothing and Prediction:

    a) Enhanced Smoothing: Like the Kalman Filter, the EKF smooths the GNSS data and provides consistent estimates, but it does so more accurately in nonlinear scenarios.

    b) Accurate Prediction: Predicts future states with higher fidelity when the system dynamics are nonlinear.

Applications:

- Autonomous Vehicles: Enhances GNSS accuracy for navigation and control systems where vehicle dynamics and GNSS signal interactions are nonlinear.
- Robotics: Improves positioning and mapping in robotic systems operating in complex or dynamic environments.

b. Particle Filter

Overview:

The Particle Filter (PF), also known as Sequential Monte Carlo (SMC) methods, is a non-parametric filtering technique used to estimate the state of a system. It is particularly well-suited for handling non-linear and non-Gaussian systems.

How It Works:

1. Initialization:

    a) Particles: The filter initializes a set of particles, each representing a possible state of the system. The particles are sampled from an initial distribution.

2. Prediction:

a) State Propagation: Each particle is propagated according to the system's dynamic model, which may be nonlinear. This step generates predicted states for each particle.

3. Update:

   a) Weight Assignment: Each particle’s weight is updated based on how well it matches the observed measurements. Weights reflect the likelihood of each particle’s state given the new data.

4. Resampling:

   a) Particle Resampling: Particles with higher weights are more likely to be retained, while those with lower weights may be discarded. This step helps to focus computational resources on the more probable states.

5. Estimation:

   a) State Estimate: The final state estimate is typically obtained by computing the weighted average of the particle states.

Suitability for GNSS Applications:

- Non-Linear Systems:

  The Particle Filter excels in environments where the system dynamics and measurement models are nonlinear. It does not require linearization, making it versatile for complex GNSS scenarios.

- Non-Gaussian Noise:

  It handles non-Gaussian noise distributions effectively, providing robust estimates even in the presence of highly irregular measurement noise.

Comparison with Kalman Filter

Aspect	Kalman Filter	Particle Filter
System Suitability	Linear systems with Gaussian noise	Non-linear and non-Gaussian systems
Computational Complexity	Generally low; efficient for real-time applications with linear dynamics	High; computational cost increases with the number of particles and system dimensions
Accuracy	Optimal for linear systems with Gaussian noise	High accuracy for non-linear and non-Gaussian systems; approximates posterior distribution
Robustness	Less robust to non-linearities and non-Gaussian noise	Highly robust to non-linearities and non-Gaussian noise
State Estimation	Uses closed-form equations; assumes linearity and Gaussian noise	Uses particle sampling and resampling; handles complex distributions

Aspect	Kalman Filter	Particle Filter
Data Handling	Efficient with lower dimensional systems; updates state estimates and covariance in closed form	Handles high-dimensional systems but requires substantial computational resources
Application	Effective in GNSS systems with linear models and Gaussian noise; e.g., simple navigation	Suitable for GNSS applications with complex dynamics and irregular noise; e.g., advanced tracking and localization

c. Sensor Fusion

Overview: Sensor fusion integrates data from various sensors to improve the accuracy and reliability of GNSS localization. By combining GNSS data with inputs from other sensors such as IMUs, LiDAR, and cameras, sensor fusion provides a more comprehensive understanding of position and movement, especially in challenging environments.

Working of Sensor Fusion

1. Data Collection:
   a) GNSS: Receives signals from satellites to determine the receiver's position and velocity. The data includes latitude, longitude, altitude, and time information.
   b) IMU: Measures accelerations and angular velocities to estimate changes in position and orientation. Provides data on how the object is moving in space.
   c) LiDAR: Emits laser pulses to measure distances to objects and create a detailed 3D map of the surroundings. Provides spatial data about the environment.
2. Data Integration:
   a) Preprocessing: Raw data from each sensor is cleaned and preprocessed to remove noise and errors. This step ensures that the data is suitable for fusion.
   b) Alignment: Sensor data is aligned in a common coordinate system. This step is crucial for accurately combining measurements from different sensors.
3. Fusion Algorithms:
   a) Kalman Filter: A common algorithm used for sensor fusion. It combines the GNSS data with IMU measurements by predicting the state of the system (position and velocity) and updating it with new measurements. The Kalman Filter maintains a state estimate and its uncertainty, improving accuracy by weighing predictions and measurements.
      - Prediction Step: Uses the system's dynamics (e.g., motion model) to predict the next state and its uncertainty.
      - Update Step: Incorporates new GNSS measurements and adjusts the state estimate based on their reliability and the predicted state.

b) Particle Filter: Used in scenarios where the system is highly nonlinear or non-Gaussian. It involves:

- Sampling: Generating a set of particles, each representing a possible state.
- Prediction: Propagating each particle according to the system model.
- Update: Updating particle weights based on how well they match new sensor measurements.
- Resampling: Adjusting the particle set by focusing on particles with higher weights.

4. State Estimation:

a) Combining Data: The fusion algorithm combines GNSS data with inputs from IMU, LiDAR, and other sensors to produce a more accurate estimate of the system's state.

b) Error Correction: Sensor fusion helps correct errors by comparing and reconciling discrepancies between different data sources. For example, if GNSS signals are unreliable due to obstructions, the IMU can provide position updates based on motion dynamics.

Role in Enhancing GNSS Localization:

1. Combining Strengths:

a) GNSS: Provides global positioning data but can be susceptible to errors and performance degradation in challenging environments.

b) IMU: Measures acceleration and angular velocity, helping to estimate changes in position and orientation. It complements GNSS by providing continuous data even when GNSS signals are weak or intermittent.

c) LiDAR: Offers detailed 3D spatial information about the environment, improving obstacle detection and mapping. LiDAR data helps to refine position estimates and can be used to correct GNSS errors based on known environmental features.

2. Data Integration:

a) Kalman Filter: Often used in sensor fusion to combine GNSS, IMU, and other sensor data. It provides a recursive method for estimating the state of the system by integrating measurements and predictions from multiple sources.

b) Particle Filter: Can also be used for sensor fusion, especially in non-linear systems, by combining data from various sensors to estimate the state with high accuracy.

3. Error Mitigation:

a) Error Reduction: Sensor fusion helps to mitigate errors by cross-referencing and validating GNSS data with other sensor measurements. For example, discrepancies between GNSS and IMU data can highlight potential errors, leading to corrections and improved accuracy.

b) Complementary Data: When GNSS signals are weak or blocked, IMU can provide position updates based on motion dynamics, and LiDAR can offer detailed environmental context to refine position estimates.

Improvement in Challenging Environments

1. Urban Canyons:

   a) Signal Blockage: GNSS signals can be obstructed by tall buildings and other structures in urban canyons, leading to reduced accuracy or loss of signal.

   b) Sensor Fusion Benefits: IMU data can help to maintain position estimates during periods of GNSS signal loss by providing inertial navigation. LiDAR can map surrounding structures, assisting in localization by identifying landmarks and improving position estimates based on the known environment.

2. Indoors:

   a) GNSS Limitations: GNSS signals are often weak or unavailable indoors, making it challenging to rely on GNSS alone for accurate localization

   b) Sensor Fusion Benefits: IMUs provide continuous motion data, while indoor mapping sensors like LiDAR or vision-based systems (cameras) can create detailed floor plans and track movement within buildings. Combining these data sources helps to maintain accurate localization even in the absence of GNSS signals.

3. Overall Enhancements:

   a) Robust Positioning: By integrating data from multiple sensors, sensor fusion improves positioning robustness and accuracy in challenging environments where GNSS alone might struggle.

   b) Enhanced Navigation: Provides a more reliable and continuous navigation solution by compensating for GNSS limitations with complementary data from other sensors.

3. Simulation And Implimentation

A. Simulation Setup

1. Simulation Environment

   For the simulation environment, we’ll use Python due to its rich ecosystem of libraries for scientific computing and data analysis.

   a) Libraries:

      - NumPy: For numerical operations and array manipulations.
      - Matplotlib: For plotting graphs and visualizing results.
      - SciPy: For additional scientific computations, if needed.

- PyKalman: A library specifically for Kalman Filter implementations, but for this case, we'll focus on the Particle Filter as requested.

b) Tools:

- Python: Ensure you have Python installed (Python 3.x recommended).
- IDE/Text Editor: Use any IDE or text editor like VSCode, PyCharm, or even Jupyter notebooks for writing and executing code.

c) Datasets:

- For GNSS data simulation, you can use synthetic data generated within the script. For real data, replace synthetic data with actual GNSS measurements.

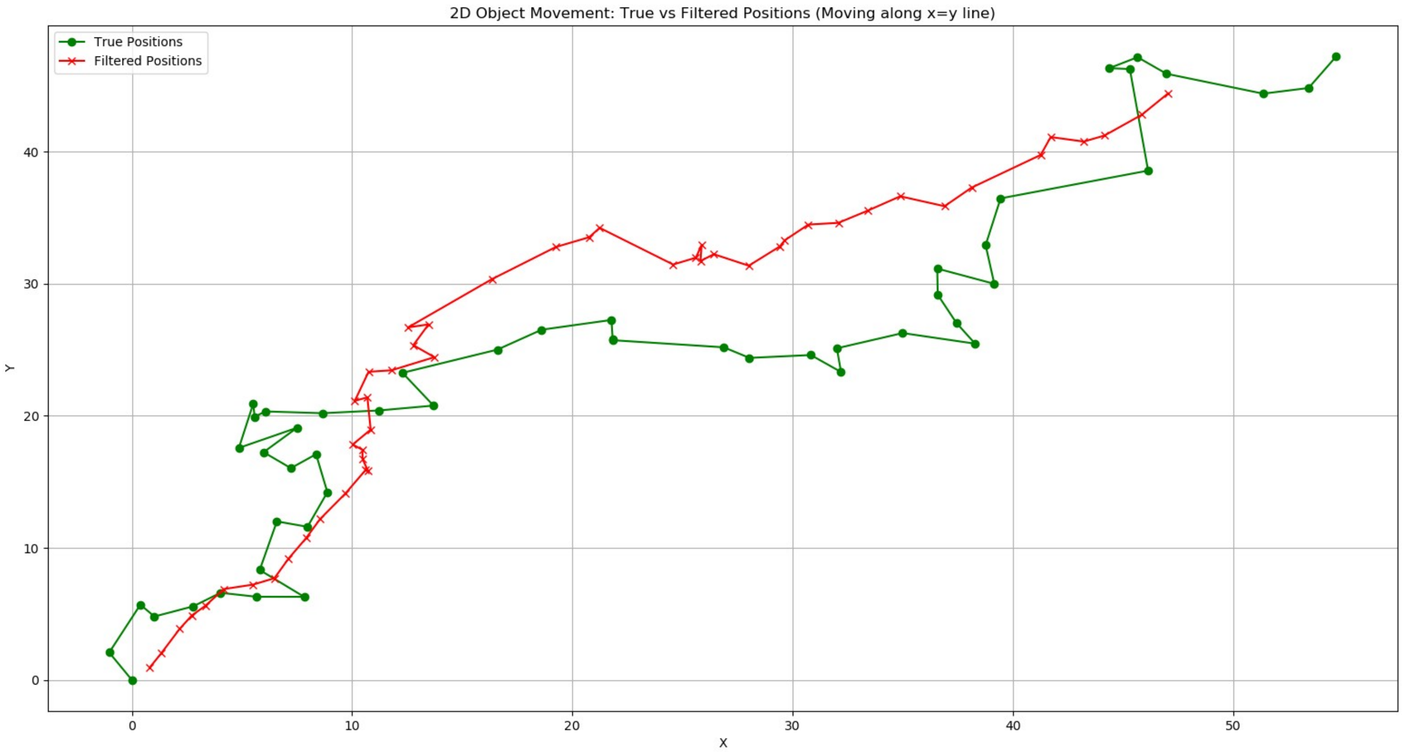
2. Installing Required Libraries

```
varun@varun:~$ pip install numpy matplotlib scipy
Requirement already satisfied: numpy in ./.local/lib/python3.8/site-packages (1.24.4)
Requirement already satisfied: matplotlib in /usr/lib/python3/dist-packages (3.1.2)
Collecting scipy
  Downloading scipy-1.10.1-cp38-cp38-manylinux_2_17_x86_64.manylinux2014_x86_64.whl (34.5 MB)
     |████████████████████████████████| 34.5 MB 1.9 MB/s
Installing collected packages: scipy
Successfully installed scipy-1.10.1
varun@varun:~$ pip install pykalman
Collecting pykalman
  Downloading pykalman-0.9.7-py2.py3-none-any.whl (251 kB)
     |████████████████████████████████| 251 kB 733 kB/s
Requirement already satisfied: scipy in ./.local/lib/python3.8/site-packages (from pykalman) (1.10.1)
Requirement already satisfied: numpy in ./.local/lib/python3.8/site-packages (from pykalman) (1.24.4)
Installing collected packages: pykalman
Successfully installed pykalman-0.9.7
varun@varun:~$
```

B. Implementation of Improvement Technique

Code implemented successfully in particle_filter.py.

C. Results and Analysis



1. Results

The output graph will show:

- True Positions: The actual path of the object, moving along the line x=y.
- Filtered Positions: The estimated positions from the particle filter.

2. Analysis

- Accuracy: Compare how closely the red line (filtered positions) follows the green line (true positions).
- Good Performance: The filtered positions closely match the true positions.
- Poor Performance: Significant deviation indicates the filter needs adjustments.

Challenges

1. Parameter Tuning:

   a) Noise Levels: Finding the right balance for motion and measurement noise is crucial. Too much noise can lead to inaccurate estimates, while too little noise might not account for real-world variability.

b) Number of Particles: Too few particles may not capture the state accurately, while too many can increase computation time.

2. Particle Deprivation:

    a) Weight Degeneracy: Over time, only a few particles may have significant weights, which can degrade the filter's performance.

3. Computational Complexity:

    a) Efficiency: More particles increase computation time. Finding a balance between accuracy and efficiency is essential.

4. State Space Coverage:

    a) Coverage: Ensuring particles represent the entire state space well can be challenging.

Improvements

1. Parameter Optimization:

    a) Tune Parameters: Adjust noise levels and the number of particles based on performance. Use trial and error or automated optimization techniques.

2. Advanced Resampling:

    a) Systematic Resampling: Use systematic resampling to distribute particles more evenly and reduce weight degeneracy.

3. Enhanced Techniques:

    a) Compare with Kalman Filter: For linear systems, the Kalman Filter might be more efficient. Compare its performance to decide the best filter for your needs.

4. Real-world Validation:

    a) Test with Actual Data: Validate the filter with real GNSS data to ensure it performs well in practical scenarios.