AUTONOMOUS SURFACE VEHICLE (ASV)

An Internship Report
Submitted By

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BATCH: 2022-2026

BACHELOR OF TECHNOLOGY IN ELECTRONICS AND COMMUNICATION ENGINEERING

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TAMIL NADU

JUNE 2025

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NATIONAL INSTITUTE OF OCEAN TECHNOLOGY
पृथ्वी विज्ञान मंत्रालय, भारत सरकार
MINISTRY OF EARTH SCIENCES,
GOVERNMENT OF INDIA

सूचना का अधिकार
RIGHT TO INFORMATION

CERTIFICATE

This is to certify that the internship work titled **"AUTONOMOUS SURFACE VEHICLE (ASV): SENSOR FUSION AND OBSTACLE AVOIDANCE USING GPS-IMU AND ARTIFICIAL POTENTIAL FIELD (APF)"** is a record of research work carried out by **Mr. Aditya Kumar Jha, Mr. Guhapriyan K K, Mr. G Gokul, and Mr. Bhanu Pratap Singh** (BATCH: 2022-2026) of **B.Tech in Electronics and Communication Engineering** at **Vellore Institute of Technology, Chennai**, submitted in partial fulfilment of the requirements of the internship project for the award of **Bachelor of Technology (B.Tech.)** degree.

The internship was conducted during the period **from 16th May 2025 to 16th June 2025** at the **Ocean Electronics Division, National Institute of Ocean Technology (NIOT), Ministry of Earth Sciences, Chennai**, under my guidance. This is an original work of the candidates and has not been submitted for the award of any other degree or diploma at this institute or any other University.

RESEARCH GUIDE

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DECLARATION

We, **Aditya Kumar Jha, Guhapriyan K K, G Gokul, and Bhanu Pratap Singh**, do hereby declare that the internship report titled **"AUTONOMOUS SURFACE VEHICLE (ASV): SENSOR FUSION AND OBSTACLE AVOIDANCE USING GPS-IMU AND ARTIFICIAL POTENTIAL FIELD (APF)"** is an original work carried out by us during our internship program from **16th May 2025 to 16th June 2025** at the **Ocean Electronics Division, National Institute of Ocean Technology (NIOT), Ministry of Earth Sciences, Chennai**, under the guidance of **Mrs. Sarojani Maurya, Scientist 'E'**.
This report has been prepared by us and has not been submitted for the award of any degree, diploma, or other qualification at any other university or institute.

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Finally, we extend our warm thanks to our parents, friends, classmates, and everyone who directly or indirectly supported us and contributed towards the successful completion of this internship project.

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ABSTRACT

This project focuses on developing an Autonomous Surface Vehicle (ASV) navigation system using sensor fusion of GPS (L89-S90) and IMU (BNO055), enhanced with Artificial Potential Field (APF) algorithms for obstacle avoidance. The system is designed in two distinct phases: Part 1 focuses on an open-loop position estimation system where position is tracked without an active navigation target, while Part 2 implements a closed-loop navigation system where the ASV autonomously moves towards a goal using APF for obstacle avoidance. The system ensures accurate position tracking even under GPS outages using Kalman filtering and IMU-based dead reckoning. Field tests at the NIOT campus validate system performance, with visualization using Python libraries like Folium and Matplotlib. The integration of sensor fusion with APF demonstrates robust and reliable navigation capabilities for ASV applications, even in GPS-denied environments.

Contents

1. Introduction

Autonomous Surface Vehicles (ASVs) play a crucial role in marine research, environmental monitoring, and oceanographic studies. One of the primary challenges in ASV deployment is achieving accurate and reliable navigation in real-world conditions, where GPS signals may become unreliable due to environmental obstructions, and obstacle avoidance is necessary. This internship project aims to develop a reliable autonomous navigation system integrating GPS, IMU, and ultrasonic sensors with sensor fusion and path planning algorithms. The project has been divided into two distinct phases to demonstrate both position estimation and active navigation capabilities.

2. Project Breakdown

Part 1: Open Loop (Position Estimation System)

- Focuses on GPS-IMU fusion using Kalman Filter.
- No specific navigation goal; purely evaluates positional tracking and accuracy.
- Demonstrates the ability to maintain accurate positioning during GPS signal loss.

Part 2: Closed Loop (Navigation and Obstacle Avoidance System)

- Implements goal-directed movement using Artificial Potential Field (APF).
- Actively navigates towards a predefined goal while avoiding obstacles.
- Uses ultrasonic sensor input for real-time obstacle detection.

3. Objectives

The objective of this project is to design and implement an Autonomous Surface Vehicle (ASV) capable of navigating autonomously between predefined GPS coordinates with high positional accuracy and real-time obstacle avoidance. The system integrates:

- A GPS module (L89-S90) for absolute positioning,
- An Inertial Measurement Unit (BNO055) for orientation and acceleration,
- An ultrasonic sensor (HC-SR04) for obstacle detection,
- And an ESP32 microcontroller for sensor fusion and motor control.

Kalman Filter is applied to combine GPS and IMU data, allowing accurate position estimation even during GPS signal loss. The Artificial Potential Field (APF) algorithm is implemented to handle obstacle avoidance during navigation toward the destination.

Specific objectives include:

- Convert GPS coordinates to UTM (Universal Transverse Mercator) for accurate 2D path planning.
- Implement the Artificial Potential Field (APF) algorithm for obstacle-aware navigation.
- Simulate IMU-only navigation during GPS signal loss with noise-augmented motion estimation.
- Generate visually interpretable contour plots for potential fields.
- Visualize the ASV's planned and estimated paths using Python Folium maps.
- Evaluate IMU-based recovery performance during GPS unavailability.
- Establish a reusable simulation and hardware platform for real-world ASV deployment.

4. System Design

4.1 Hardware Components

Component	Description
ESP32	Main processing unit
GPS Module	L89-S90 GPS module for absolute positioning
IMU Sensor	BNO055 IMU for orientation, acceleration, and heading
Ultrasonic Sensor	HC-SR04 for obstacle detection
Power Supply	12V Lithium Polymer Battery
ASV Platform	Custom prototype surface vehicle

4.2 Software Components

- Arduino IDE for ESP32 firmware development
- Kalman Filter algorithm for sensor fusion
- Artificial Potential Field (APF) for obstacle avoidance
- Python with Matplotlib and Folium for data analysis and visualization
- CSV logging for data recording

5. Methodology

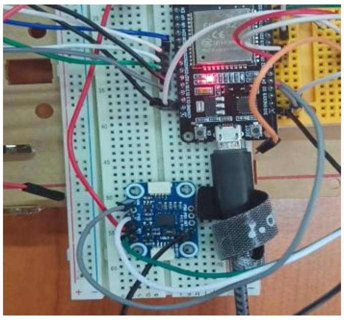
5.1 GPS Module

The L89-S90 is a high performance GNSS (Global Navigation Satellite System) module manufactured by Quectel. It supports multiple satellite constellations like GPS, GLONASS, Galileo and QZSS which allows for enhanced location accuracy. It has an update rate of 1Hz by default and can be configured up to 10Hz. In this project, the L89-S90 GPS module is interfaced with ESP32 via UART 1 port (GPIO16 and GPIO 17). It provides real time longitude, latitude and speed data which are parsed through TinyGPSPlus Arduino library. The GPS data serves two purposes:

1. Positioning: Determining the absolute position of the vehicle.
2. Sensor Fusion: The GPS readings are fused with IMU data via a Kalman Filter to estimate accurate vehicle position even in conditions where GPS signal may drop.

Quectel L89-S-90

IMU BNO055



5.2 IMU Module

The BNO055 is an intelligent Absolute Orientation Sensor developed by Bosch Sensortec. It integrates a 3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer, along with an onboard microcontroller that fuses these sensor readings to provide absolute orientation data in real-time. The sensor communicates with the ESP32 using the I2C interface. It gives acceleration vector, angular velocity, and Euler angles for the orientation/heading. It also has a built-in calibration engine to store calibration data and supports EEPROM-based calibration retention.

In this ASV project, the BNO055 is operated in NDOF mode, utilizing all three sensor units (accelerometer, gyroscope, and magnetometer) for complete orientation sensing. Its outputs are used in several critical functions:

1. Linear Acceleration: Used for Kalman Filter-based position estimation in the absence of GPS.
2. Quaternion Data: Used to rotate acceleration vectors into Earth's frame of reference.
3. Magnetometer Data: Provides compass-like heading for direction correction.
4. Calibration Status: Ensures that only accurate, stable data is used during sensor fusion.

5.3 Kalman Filter

The Kalman Filter is a recursive mathematical algorithm used to estimate the state of a dynamic system from noisy measurements. It is ideal for fusing noisy sensor data such as GPS (noisy but absolute) and IMU (precise but relative and drifts over time). In the Autonomous Surface Vehicle (ASV), the absolute position is received from the GPS, but at a low refresh rate with delay or noise. Also, the movement is estimated using IMU (acceleration), but it drifts over time. Kalman Filter blends these two sources - when GPS is accurate, it trusts it more; when GPS is missing or jumping, it relies on IMU and prediction.

5.3.1 Working of Kalman Filter

State Representation vector

Define state vector *X* as:

$$X = \begin{bmatrix} x \\ y \\ v_x \\ v_y \end{bmatrix}$$

Where: x, y : positions in meters Vx, Vy : velocity in m/s

1. **Prediction (Dead Reckoning with Acceleration)**

The next state is predicted using the equations of motion

$$X_k^- = A \cdot X_{k-1} + B \cdot u_k$$

Where:
Xk : Predicted state
Xk-1 : Previous state
Uk : Control input (acceleration from IMU)
A: State transition matrix
B : Control matrix

Assuming time step dt:

$$A = \begin{bmatrix} 1 & 0 & dt & 0 \\ 0 & 1 & 0 & dt \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} B = \begin{bmatrix} \frac{1}{2}dt^2 & 0 \\ 0 & \frac{1}{2}dt^2 \\ dt & 0 \\ 0 & dt \end{bmatrix}$$

$$u_k = \begin{bmatrix} a_x \\ a_y \end{bmatrix}$$

So:

$$X_k^- = \begin{bmatrix} x + v_x dt + \frac{1}{2} a_x dt^2 \\ y + v_y dt + \frac{1}{2} a_y dt^2 \\ v_x + a_x dt \\ v_y + a_y dt \end{bmatrix}$$

2. **Prediction of Uncertainty**

$$P_k^- = A \cdot P_{k-1} \cdot A^T + Q$$

Where:
Pk : Predicted uncertainty
Q : Process noise covariance (IMU error)

Assuming equal uncertainty increase for all four state variables, each diagonal element is increased:

3. **Updation**

When a GPS position $z_k = [x_{gps}, y_{gps}]$ is received, the state estimate is updated.

Kalman Gain *K*

$$K = P_k^- H^T \left(H P_k^- H^T + R \right)^{-1}$$

Where:

H : Measurement matrix (maps state to measurement)
R : Measurement noise covariance (GPS uncertainty)
K : Kalman Gain

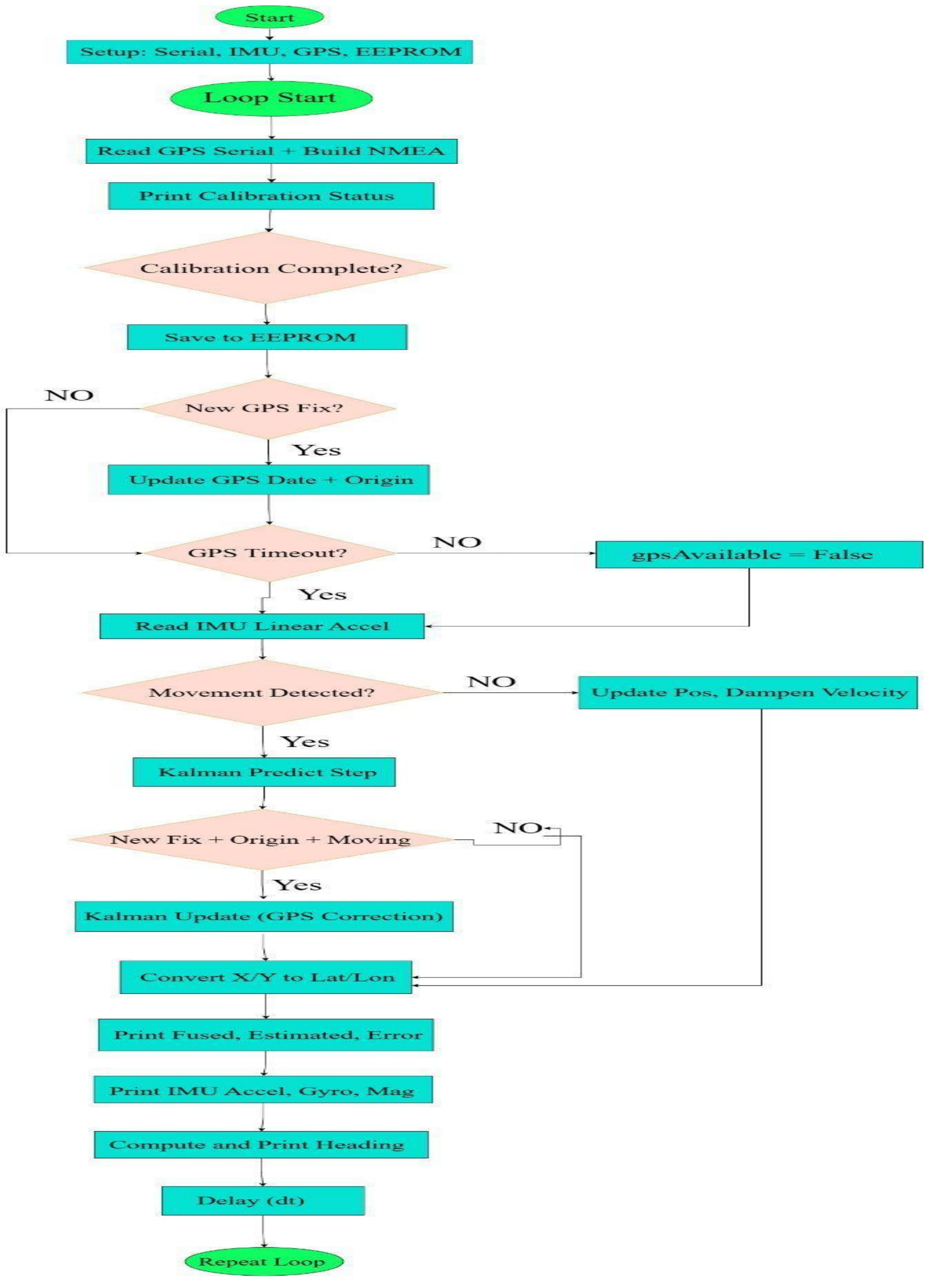
Updating the state vector:

$$X_k = X_k^- + K \cdot \left(z_k - H \cdot X_k^- \right)$$

Updating the Covarience:

$$P_k = (I - KH) \cdot P_k^-$$

6. LOGIC OVER-FLOW



6. Field Testing and Results

6.1 Field Testing and Data Logging at NIOT Campus

To evaluate the performance of the GPS-IMU fused navigation system, a field test was conducted within the NIOT (National Institute of Ocean Technology) campus. The goal was to verify how accurately the system could estimate position using a combination of GPS data and inertial measurements with a Kalman Filter.

6.1.1 Objective of the Test

- To validate the Kalman Filter's ability to track motion and estimate position.
- To compare pure GPS coordinates vs fused coordinates (GPS + IMU).
- To identify drift or deviation in estimated path when GPS is momentarily unavailable.
- To visualize the path for analysis on both 2D plots and geographical maps.

6.1.2 Testing Methodology

Hardware Setup:

The system was powered and deployed within the open grounds of NIOT for better GPS reception. The ESP32, L89-S90 GPS module, and BNO055 IMU were mounted on a movable test platform.

Data Capturing:

During the test, the system continuously computed:

- Raw GPS Latitude and Longitude.
- Fused Latitude and Longitude (using Kalman Filter).

  Each set of values was printed via Serial and logged in .csv format using a serial logger.

```
2025-06-10 16:27:40.830,-------------------------------
2025-06-10 16:27:41.027,"GPRMC: $GPRMC,105740.000,A,1256.76845,N,08012.72203,E,3.8,193.4,100625,,,A*6A"
2025-06-10 16:27:41.030,Calib: SYS=2 GYR=3 ACC=3 MAG=3
2025-06-10 16:27:41.033,"GPS Lat/Lon: 12.946141, 80.212034 (Valid? Yes)"
2025-06-10 16:27:41.037,GPS Speed (m/s): 1.955 (Valid? Yes)
2025-06-10 16:27:41.040,========== IMU DATA ==========
2025-06-10 16:27:41.043,"Linear Accel (m/s^2): -2.55, 1.16, 1.37"
2025-06-10 16:27:41.046,"Gyro (rad/s): 18.31, -7.31, -3.25"
2025-06-10 16:27:41.049,"Mag (uT): -83.25, 80.25, -27.69"
2025-06-10 16:27:41.051,--- Position ---
2025-06-10 16:27:41.054,"GPS only: 12.946256, 80.211976"
2025-06-10 16:27:41.057,"Estimated (IMU only): 12.94626899, 80.21193078"
2025-06-10 16:27:41.060,Position Error (m): 2.067
2025-06-10 16:27:41.062,--- Orientation ---
2025-06-10 16:27:41.063,Heading (deg): 136.05
2025-06-10 16:27:41.066,-------------------------------
```

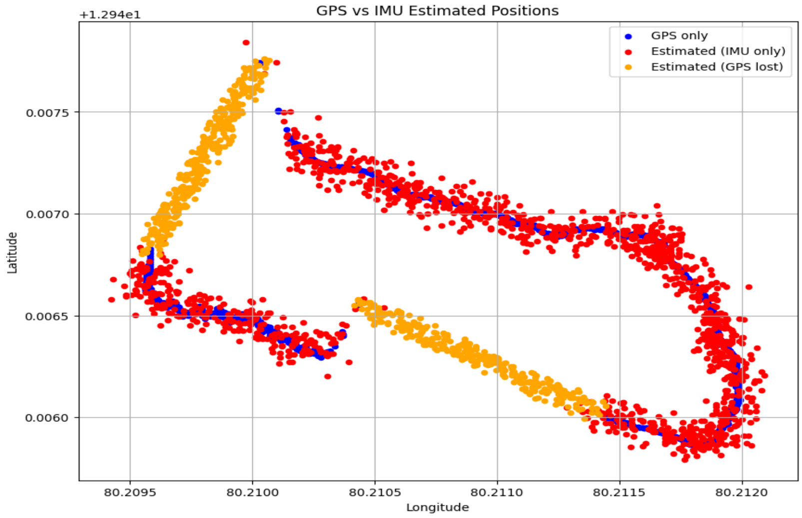
Python-Based Analysis:

A Python script was developed to read the .csv file and visualize the data using:

- matplotlib for 2D scatter plots.
- folium for interactive map rendering.

6.2 Visualization and Interpretation

6.2.1 2D Scatter Plot



The GPS and estimated coordinates were plotted on an XY graph for visual comparison of raw vs. fused data trajectories. This helped to observe Kalman smoothing and reduced GPS noise.

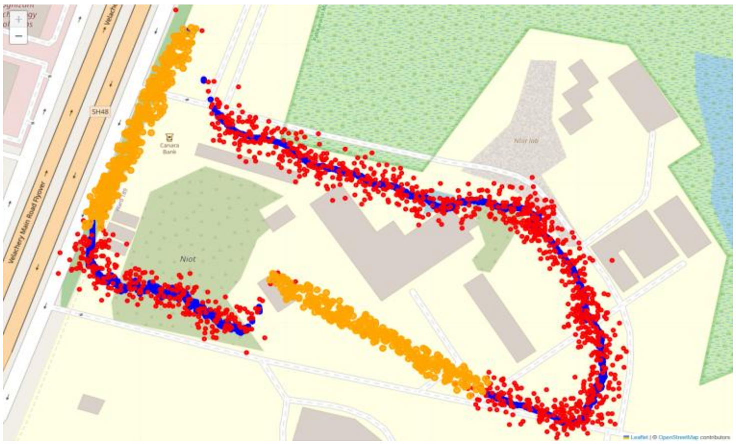
6.2.2 Map Plotting with Folium

The path was marked on a real-world map using folium. Each GPS and estimated coordinate was plotted as datapoints marked in distinct colors:

- Blue for raw GPS points.
- Red for IMU estimated positions.
- Yellow for Kalman-estimated positions (GPS lost).

6.3 Observations

- The fused data appeared smoother and more consistent, especially during stop-and-go scenarios.
- Short GPS losses were compensated by the IMU, reducing position jumps.
- The error margin between actual GPS and estimated points was minimal, validating the Kalman implementation.



7. Artificial Potential Field (APF) Path Planning

7.1 Overview

The APF algorithm was implemented for autonomous navigation with obstacle avoidance. It simulates a robot navigating from a start point to a goal while avoiding multiple obstacles. The forces from attractive and repulsive fields guide the ASV's movement.

7.2 Simulation Details

- Start: (12.946811, 80.211638)
- Goal: (12.946568, 80.209597)
- Coordinates were converted into UTM for accurate metric computation.

Obstacle Configuration:
Static obstacles were placed logically between the start and goal points.

Potential Field Formulation:
The total potential field U is the sum of:

- Attractive Potential (toward the goal)

$$U_{att}(x,y) = \frac{1}{2}k_{att} \cdot \left((x - x_g)^2 + (y - y_g)^2\right)$$

- Repulsive Potential (from obstacles within certain distance d0)

$$U_{rep}(x,y) = \begin{cases} \frac{1}{2}k_{rep}\left(\frac{1}{d(x,y)} - \frac{1}{d_0}\right)^2 & , if\, d(x,y) < d_0 \\ 0 & , otherwise \end{cases}$$

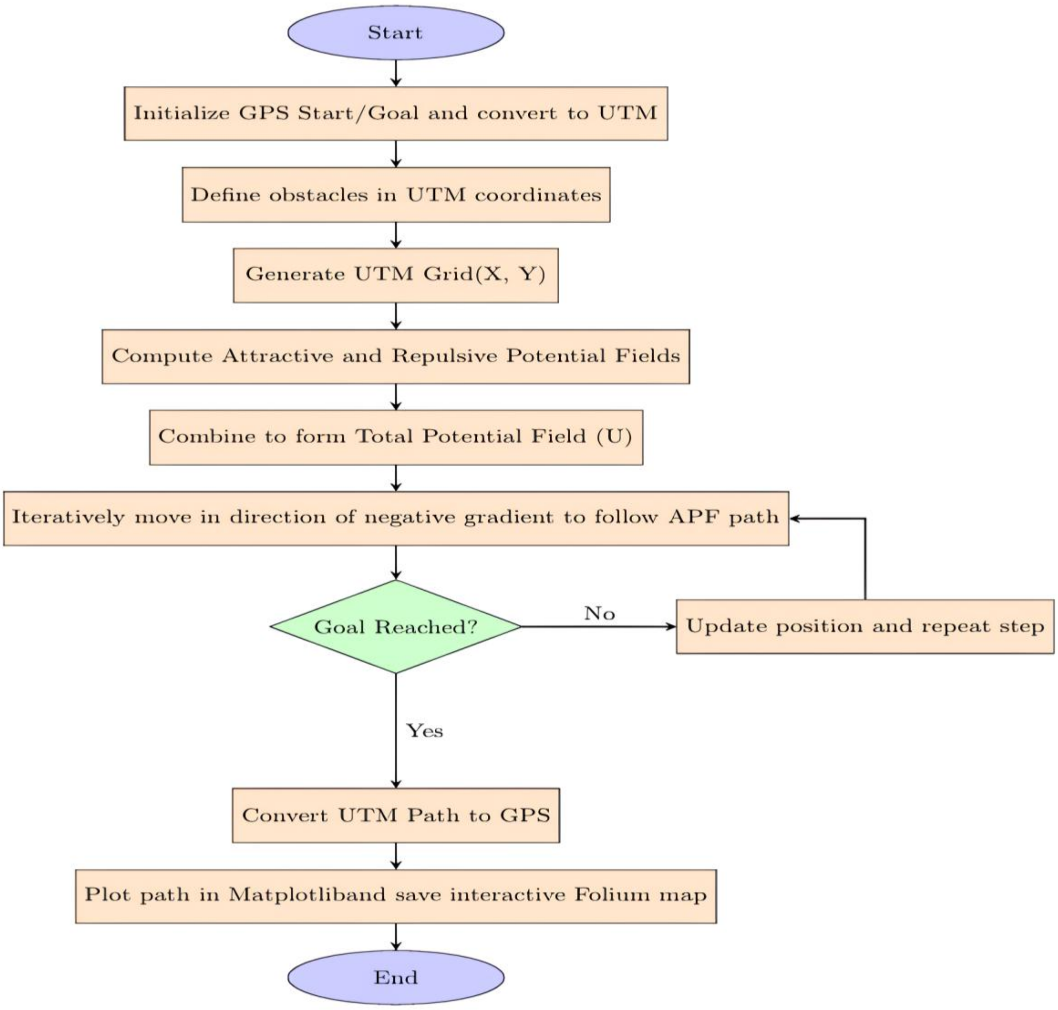
Path Generation:
An iterative gradient descent approach was used to trace the path by following the negative gradient of the total potential field.

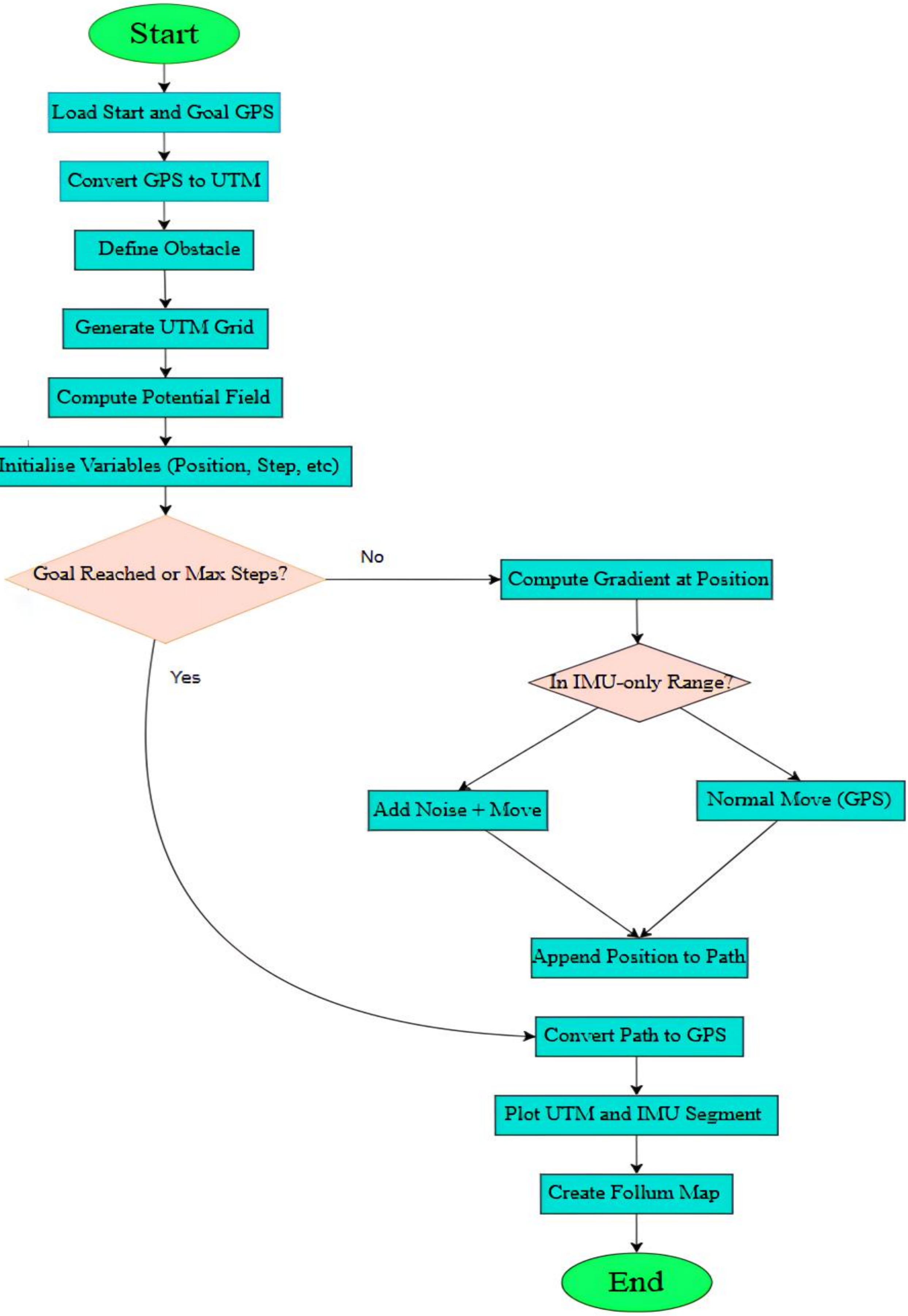
$$f = -\nabla U(x,y)$$

7.3 Visualization and Analysis

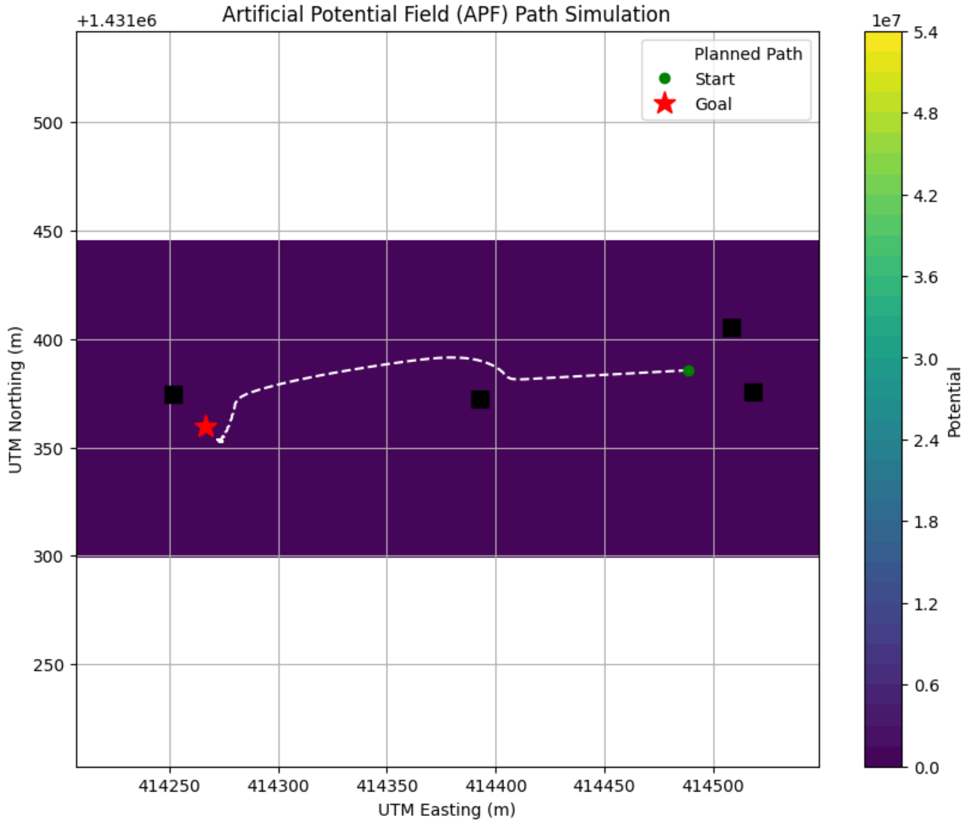
- Contour plots display the potential field (obstacles as black squares, start as green circle, goal as red star).
- Interactive folium maps plot GPS coordinates, obstacles, start/goal points, and path lines.

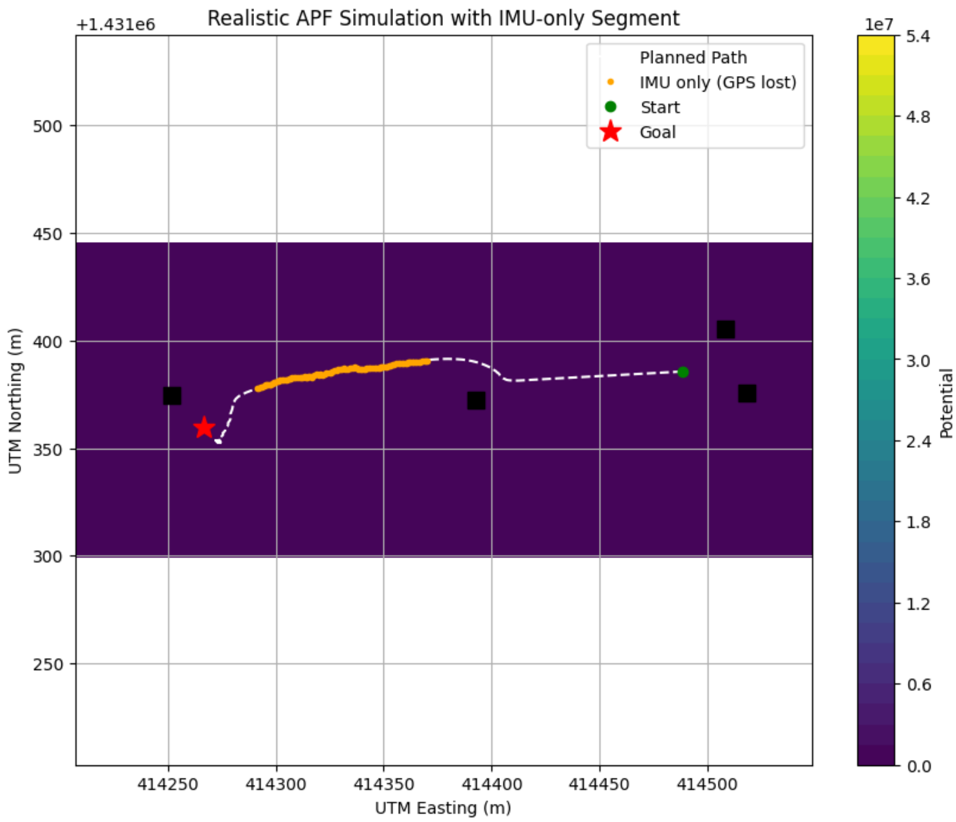
- The APF algorithm generated smooth, collision-free paths.
- In IMU-only segments, the vehicle-maintained direction despite GPS outages, simulating real-world sensor behavior.




Start
Load Start and Goal GPS
Convert GPS to UTM
Define Obstacle
Generate UTM Grid
Compute Potential Field
Initialise Variables (Position, Step, etc)
Goal Reached or Max Steps?
No
Compute Gradient at Position
Yes
In IMU-only Range?
Add Noise + Move
Normal Move (GPS)
Append Position to Path
Convert Path to GPS
Plot UTM and IMU Segment
Create Follum Map
End

Output


Artificial Potential Field (APF) Path Simulation
+1.431e6
Planned Path
Start
Goal
UTM Northing (m)
UTM Easting (m)
500
450
400
350
300
250
414250
414300
414350
414400
414450
414500
1e7
5.4
4.8
4.2
3.6
3.0
2.4
1.8
1.2
0.6
0.0
Potential


Realistic APF Simulation with IMU-only Segment
+1.431e6
Planned Path
IMU only (GPS lost)
Start
Goal
UTM Northing (m)
UTM Easting (m)
500
450
400
350
300
250
414250
414300
414350
414400
414450
414500
1e7
5.4
4.8
4.2
3.6
3.0
2.4
1.8
1.2
0.6
0.0
Potential

8. Challenges Faced

- Frequent calibration required for IMU stability.
- GPS signal fluctuations caused noise during high-rise or shielded zones.
- Tuning Kalman filter parameters for optimal performance was non-trivial.
- Sensor data synchronization on the ESP32 posed minor timing challenges.

9. Conclusion

The integration of GPS and IMU using Kalman Filter successfully enhanced the accuracy and reliability of ASV navigation. Field tests validated that the fused output was smoother and more stable compared to standalone GPS. The addition of APF allowed safe and efficient obstacle avoidance even in GPS-denied environments.

The system demonstrates a strong foundation for real-world ASV deployment using multi-sensor fusion and adaptive path planning algorithms.

10. Future Scope

- Integrate real-time dynamic obstacle detection using LiDAR or vision sensors.
- Implement advanced fusion algorithms such as Extended Kalman Filter (EKF) or Particle Filters.
- Combine APF with global path planning algorithms like Dijkstra.
- Extend testing to open-water field trials under various conditions.
- Optimize path planning for energy efficiency to extend mission duration.
- Enable cloud-based telemetry for live monitoring and remote control.
- Integrate marine charts and sonar for underwater hazard detection.

11. References

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4. S. Thrun, W. Burgard, and D. Fox, "Probabilistic Robotics", MIT Press, 2005.
5. Sebastian Thrun et al., “Robotic Mapping: A Survey,” CMU, 2002.