PROJECT

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* [Notion](https://www.notion.so/Submarine-Navigation-in-GPS-Denied-Pipelines-1561c000343c802caef9f1a08e559518)
* [GitHub](https://github.com/yoavbarak81/EE-CS-Project)

# **Problem Definition**

Mapping the trajectory of a closed pipeline using data from a small submarine, focusing on smoothing its motion to avoid zigzagging or irrelevant movements.Organizations performing maintenance inspections in underground or underwater pipelines, such as water, oil, and gas companies.

**Why is it important to solve?**Accurate pipeline mapping enables the identification of underground infrastructure and facilitates targeted maintenance. This eliminates the need to expose entire pipeline sections and ensures precise intervention where needed.

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**Background** Mapping the trajectory of a small submarine within a closed pipeline presents unique challenges. Traditional navigation systems, such as GPS, are ineffective in such environments due to the absence of electromagnetic signal reception. This necessitates alternative navigation methods, including Inertial Navigation Systems (INS), optical tracking through video data, and real-time data analysis. Pipelines often feature standard segment lengths, bends, and varying terrains, all of which must be accounted for to achieve precise navigation.

**Related Work** Several approaches have been explored to address similar challenges:

1. **Inertial Navigation Systems (INS):** INS utilize accelerometers and gyroscopes to compute position, orientation, and velocity. They are commonly employed in GPS-denied environments. However, they are prone to drift errors that accumulate over time without external correction.
2. **Optical Navigation and Visual Odometry:** These techniques involve analyzing video data to track movement by identifying visual features in the environment. Methods such as Simultaneous Localization and Mapping (SLAM) have been applied to map trajectories. Integrating visual data can help mitigate INS drift by providing additional reference points.
3. **Pipeline Inspection Robots:** Companies like Eddyfi Technologies have developed inspection crawlers, such as the VersaTrax series, designed for confined spaces and long-distance inspections. These robots focus primarily on defect detection using cameras and ultrasonic sensors but often lack real-time trajectory mapping capabilities. https://www.eddyfi.com/en/product/versatrax-inspection-crawlers?utm\_source=chatgpt.com
4. **Academic Research:** Studies have investigated the integration of INS with visual odometry to enhance navigation accuracy. For example, research published in the *International Journal of Intelligent Robotics and Applications* discusses a robust IMU/vision/geomagnetic integrated navigation system for unmanned ground vehicles in GPS-denied environments. https://link.springer.com/article/10.1007/s41315-023-00277-z?utm\_source=chatgpt.com

These existing solutions provide a foundation for our project, which aims to combine INS and video data for accurate trajectory mapping, addressing the limitations of standalone systems.

### **Proposed Solution**

**Overview**

To address the challenge of mapping a submarine's trajectory in GPS-denied environments, we propose two alternative solutions:

**1. Magnetic Field Mapping System** This approach utilizes magnetometers to measure variations in the Earth's magnetic field or detect artificial magnetic markers placed along the pipeline. By correlating the magnetic data with a pre-mapped field or using fixed markers, the submarine can determine its position. This method does not rely on visual data, making it robust in conditions where optical systems fail, such as darkness or obstructions. However, it requires pre-mapping or installing markers, which can be impractical in existing pipelines. Sensitivity to electromagnetic interference may also limit its accuracy.

**2. Hybrid System Combining INS and Optical Navigation** This approach integrates an Inertial Navigation System (INS) with visual data from a camera. The INS measures motion and orientation through accelerometers and gyroscopes, while the camera identifies features like welds or markers inside the pipeline. These features provide visual reference points to correct drift errors inherent in INS systems. By synchronizing visual and inertial data, the hybrid system delivers accurate trajectory mapping. However, it requires clear visual conditions and significant computational resources.

**Solution Proposal**

The hybrid INS and optical navigation system is our chosen solution. It balances the strengths of both methods, offering precise trajectory mapping through the integration of inertial and visual data. The presence of predictable visual features within pipelines, such as welds, ensures consistent corrections to INS errors. Unlike the magnetic field approach, this solution avoids logistical challenges like pre-mapping or marker installation.

**Key Components**

The hybrid system comprises:

1. **Inertial Sensors (IMU):** To measure linear and angular accelerations.
2. **Camera System:** To capture visual data and identify reference points.
3. **Data Synchronization Module:** Aligns inertial measurements with video frames.
4. **Computational Unit:** Handles real-time processing using platforms like NVIDIA Jetson.
5. **Software Framework:** Integrates all data and provides drift correction.

**Solution Feasibility**

This solution is feasible as it leverages proven technologies. INS and visual odometry are widely used in robotics for GPS-denied navigation. Pipelines provide structural consistency, making them ideal for feature detection. Advances in computational hardware support the real-time fusion of visual and inertial data, ensuring robust trajectory estimation.

**Technologies**

* **Hardware:** IMU sensors, high-definition cameras, and embedded processors (e.g., NVIDIA Jetson).
* **Software:** Python for data integration, OpenCV for image processing, and MATLAB for algorithm simulation.
* **Skill Set Required:** Knowledge of INS and computer vision, Python programming, and experience with data fusion techniques.

**Challenges and Uncertainties**

The primary challenges include poor visual data quality in certain conditions and the computational demands of real-time processing. These can be mitigated by adding onboard lighting, optimizing algorithms, and enabling offline processing if necessary. Algorithm complexity for fusing visual and inertial data is another challenge, but existing research provides a strong foundation.

**Required Knowledge**

Key knowledge areas include INS principles, computer vision, and data fusion techniques. Relevant courses include "Introduction to Robotics" and "Computer Vision Specialization" on Coursera. Academic papers on INS-visual integration will further support the project's development.

By adopting this hybrid system, we aim to create a practical and reliable solution for submarine navigation, combining accuracy, feasibility, and adaptability to pipeline environments.

### **Evaluation and Verification Scheme**

Our solution will be evaluated using a combination of real-world tests and simulations to ensure accuracy and reliability in mapping the submarine’s trajectory.

**Real-World Testing** The submarine will be deployed in a pipeline environment with weld markers at regular intervals (e.g., 12 meters), which act as known reference points. Entry and exit locations will provide a baseline for trajectory verification. The calculated positions will be compared against these markers under varying conditions, including dry and wet pipelines, to measure accuracy and robustness. The expected accuracy is a deviation of no more than 10 centimeters per 100 meters in real-world conditions.

**Simulations** Simulations will replicate pipeline conditions such as bends, inclines, and potential obstructions. These controlled tests will validate the integration of inertial and visual data, identify potential errors, and allow for algorithm refinement. Simulation results will be compared against predefined ground truth data to quantify performance.

**Stakeholders and Use Cases**We have established a collaboration with Hagihon, a leading water management company in Israel (hagihon.co.il). While we may not have access to their full pipeline layout, the company has provided a laboratory for controlled testing. We also aim to collect results from additional sites during the project. This partnership enables us to validate the solution under operational conditions and ensure it meets the accuracy and performance needs of a critical industry stakeholder.

This combined approach ensures practical, reliable, and accurate validation tailored to real-world applications.

### **Annual Work Plan**

**First Steps** In the first 1-2 months, we will focus on integrating the submarine's inertial sensors (IMU) and camera into a system for synchronized data collection. This phase will include calibrating the IMU sensors, establishing a shared time base, and developing basic algorithms for trajectory calculations. Controlled lab tests will validate the system’s ability to detect pipeline features, such as welds, and analyze data offline to ensure proper functionality.

**Minimum Viable Product (MVP)** By January 2025, our MVP will be a functional offline trajectory mapping prototype. The system will process IMU and camera data to generate a visualized trajectory between predefined entry and exit points. Initial real-world testing will take place in collaboration with Hagihon ([hagihon.co.il](https://www.hagihon.co.il/)), using their pipeline infrastructure to validate the solution’s performance in practical conditions.

**Future Steps** After the MVP, we will enhance offline processing and refine the algorithms for improved accuracy. The "bike" phase will include more advanced data fusion and the ability to handle complex pipeline scenarios. In the "car" phase, we aim to achieve real-time trajectory mapping with live error correction and processing. While we are confident in our approach, achieving real-time functionality depends on overcoming technical and computational challenges and is not guaranteed.

This step-by-step plan ensures systematic progress while addressing uncertainties with realistic milestones.