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Enhancing Robotic Localization with IMUs: A Fundamental Technology for Precise Navigation

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Abstract

This article highlights the significance of the inertial measurement unit (IMU) sensor for localization in robotics and outlines its key benefits. IMUs have become an essential and integral part of precise robot positioning by providing crucial motion data. They integrate accelerometers, gyroscopes, and magnetometers, enabling robots to accurately determine their orientation, position, and movement by offering real-time responsiveness, thus allowing them to navigate a dynamically changing environment. Sensor fusion techniques combine IMU data with other sensors, such as cameras or LIDAR, to enhance localization accuracy by incorporating multiple data sources. IMUs are widely used in mobile robotics, humanoid robotics, unmanned aerial vehicles (UAVs), and virtual/augmented reality. Their role in achieving precise localization empowers robots to perform complex tasks autonomously and interact effectively with their surroundings. The article explores the use cases of IMUs in challenging environments where AMRs operate and how IMUs play a critical role in achieving precise localization.

Introduction

Autonomous mobile robots (AMRs) are essential for the smart factories and warehousing of the future, playing a pivotal role in shaping automated, sustainable, and cleaner factories of the future. AMRs enhance efficiency, reduce waste, and optimize utilization in industrial settings. While factories of the future may perhaps be purpose built and optimized for AMRs to operate in, adapting these robots to existing warehouses and factories presents challenges. The primary hurdle for AMRs involves two critical components: efficient path planning (determining the optimal path) and precise localization (continuously updating its position within its environment).[1]

This article focuses on indoor navigation within a GPS denied closed environments. AMRs utilize an array of sensors and algorithms for localization and navigation. These include visual sensors like cameras, LIDAR, and radar, as well as odometry sensors such as wheel encoders and IMUs. Each sensor modality has its own unique advantages in terms of range, accuracy, and sensory information. The combination of these sensors ensures comprehensive data for effective robot localization in dynamic environments. While an array of sensors is a must for full autonomy, this article highlights the use cases and challenging environment in which AMRs operate and how IMUs aid in precise localization, which is crucial for navigation and autonomy.

What Is an IMU?

IMUs are miniature devices made of microelectromechanical systems (MEMS) devices. They usually consist of the following elements:

- Triaxial accelerometer: Accelerometers measure acceleration with respect to the Earth's gravitational field. In an IMU, triaxial accelerometers are used to measure the x, y, and z axes (see Figure 1).

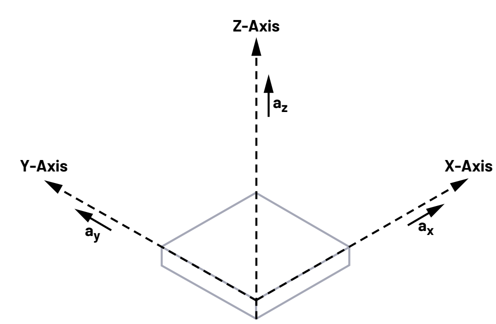

Figure 1. Acceleration measurements on the x, y, and z axes.

- Triaxial gyroscope: Gyroscopes measure the rate of rotation providing angular velocity in each of the three axes. Triaxial gyroscope enables measurement of the robot's angular velocity (ωx, ωy, ωz) along the x, y, and z axes (see Figure 2).

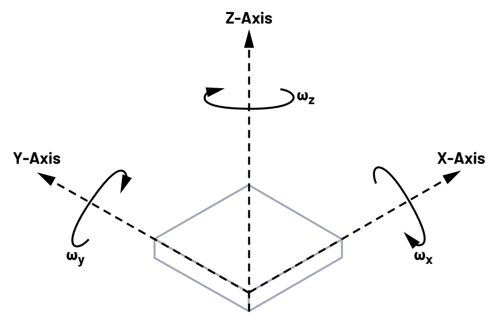

Figure 2. Gyroscope measurements on the x, y, and z axes.

- High performance magnetometer: It provides magnetic field measurements, essential for accurate orientation estimation in challenging environments. Although not popular, a magnetometer is available in some of the legacy IMUs.
- Other: A temperature sensor to compensate for temperature variations and a barometer to measure pressure.

Functional Block Diagram of IMU

- A typical IMU not only includes gyroscopes, accelerometers, and a temperature sensor, but also analog-to-digital conversion to extract the measurements and temperature compensation (see Figure 3).
- An IMU features onboard preliminary filtering algorithms such as FIR (finite impulse response) onboard.
- Calibration and compensation correct any misalignment or sensor biases.
- The user has the option to rotate (dϴ) from the IMU module internal axis to match the robot's frame of reference before transmitting the final data.

Why Are IMUs Beneficial for AMRs?

- Real-time localization with high update rates: Autonomy and real-time navigation are crucial elements in a robot's operational environment. Perception sensors, however, typically operate with a restricted update rate, ranging from approximately 10 Hz to 30 Hz. In contrast, IMUs boast the capability to deliver high fidelity positional output, reaching up to 200 Hz. This higher update rate significantly enhances the system's reliability in swiftly adapting to rapid changes in orientation within a dynamic environment, facilitating prompt responses. The accelerated update rate also empowers AMRs to provide an estimated pose during the brief intervals between other measurements. As a result, IMUs play a pivotal role in achieving real-time localization, surpassing perception sensors with update rates that are 10× faster.
- Dead reckoning: IMUs serve as the backbone for dead reckoning, a navigation technique to estimate the current position based on a previously known position. Constantly providing data on position, orientation, and speed over elapsed time, IMUs enable precise estimation, contributing to reliable navigation for AMRs.
- Compact size and weight: The compact size and lightweight design of IMUs make them ideal for integration into various mobile robot configurations. For instance, the Analog Devices ADIS16500, with a footprint of only 33.25 mm × 30.75 mm, ensures efficient placement without compromising the robot's maneuverability.
- Robustness in diverse environments: IMUs are relatively resistant to electromagnetic interference and can operate in a variety of environments, including outdoor and indoor settings. This makes them suitable for a wide range of applications.
- Enhanced reliability through accelerated update rates: With perception sensors typically limited to update rates of ~10 Hz to 30 Hz, IMUs stand out by providing a high fidelity positional output of up to 4 kHz raw data. This increased update rate enhances reliability, especially in dynamic environments, enabling AMRs to respond quickly and help estimate the pose in the short time between these other measurements.

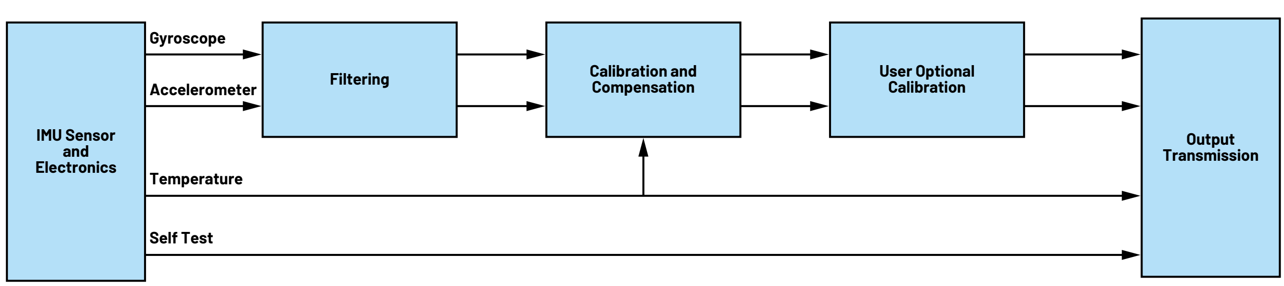

Figure 3. Typical functional block of an IMU.

Why IMUs Are Essential for AMRs Despite the Availability of Vision Sensors

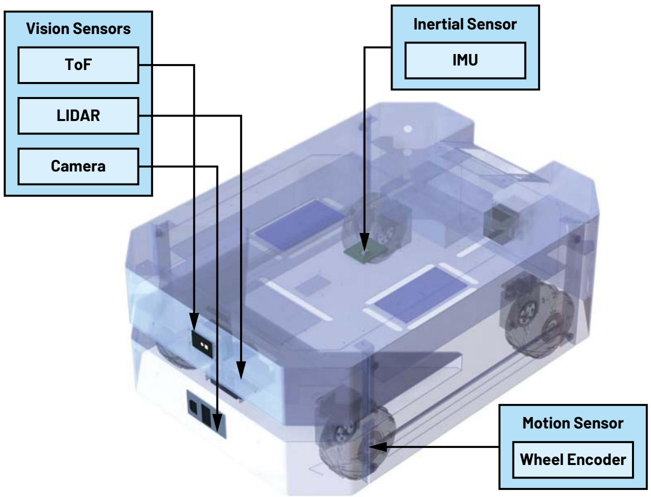

Figure 4. Sensor stack of an AMR.

An AMR, as depicted in Figure 4, commonly features a variety of visual sensors, such as time of flight (ToF), camera, LIDAR, etc. Despite the rich dataset provided by visual odometry, the necessity for IMU persists. The following scenarios explore some of the reasons why:

1. AMR navigating a feature-sparse corridor: Simultaneous localization and mapping (SLAM) algorithms essentially operate by matching observed sensor data, which is stored in the map to localize within the map. When an AMR travels through a long corridor (see Figure 5), it is bound to lose its position quickly. Due to a lack of distinctive features such as straight walls with uniform color, texture, or reflectivity, SLAM struggles to localize precisely. In this case, IMUs act as a valuable guidance system by providing a heading and orientation information.

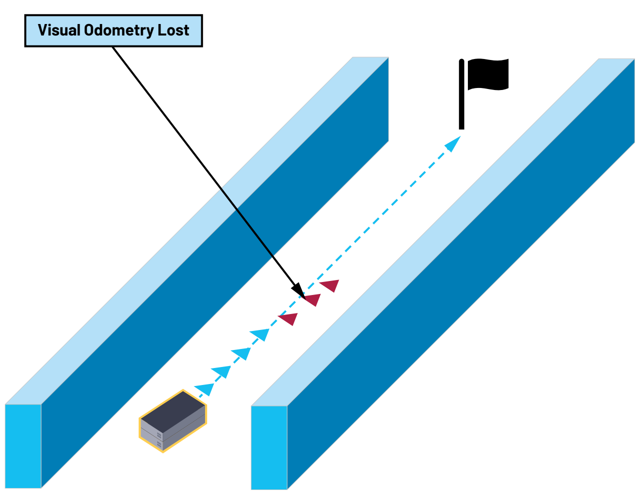

Figure 5. AMR losing visual odometry in a featureless corridor.

2. Navigating across vast open environments: Range limitations: When operating in a large open space such as a huge warehouse (say 50 m × 50 m), AMRs have difficulty localizing as unique features extend beyond the sensor range (maximum reach of lidars is typically around 10 m to 15 m). As shown in Figure 6, the AMR's odometry has already been lost due to the large space. Additionally, warehouses often exhibit uniform features, thus rendering it difficult for visual sensors. In such scenarios, IMUs and wheel encoders are the only reliable sources for precise local localization.

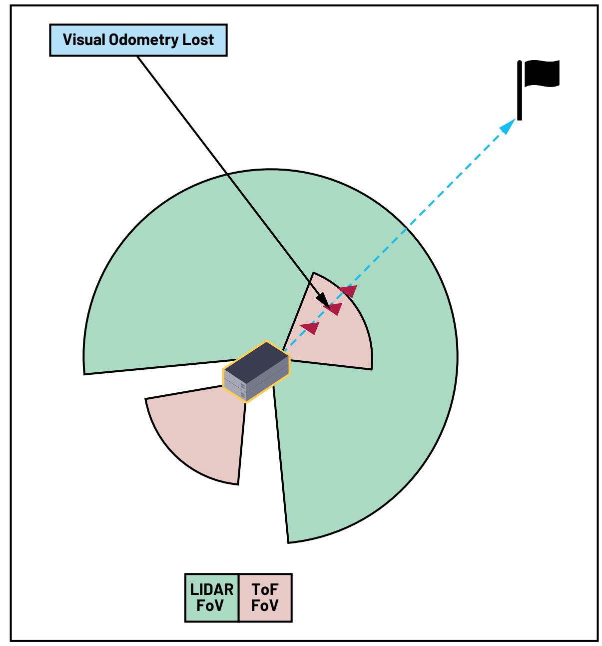

Figure 6. Limited field-of-view (FoV) of sensors, AMR unable to localize in a large open space.

3. Navigating on a slope: While maneuvering on a slope, the traditional SLAM algorithm encounters a challenge when relying on LIDAR, as the 2D point data does not show gradient information. Consequently, slopes are misconstrued as walls or obstacles, leading to higher cost maps. As a result, conventional SLAM approaches with 2D systems become ineffective on slopes. IMUs help to solve this challenge by extracting gradient information (Figure 7) to effectively negotiate navigating on a slope.

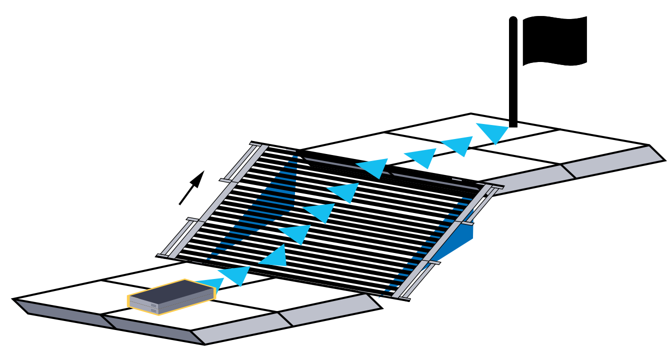

Figure 7. AMR moving on a slope.

Table 1. Estimation of Pose and Orientation for Various Sensor Modalities for Localization

Sensor Modality	Affected by Poor Lighting	Affected by Dynamic Movers	Affected by Reflective Surfaces	Reliant on Rich Scene Geometry
Standard RGB camera	Yes	Yes	No	No
Time of flight	No	Yes	Yes	Yes
LIDAR	No	Yes	Yes	Yes
Radar	No	Yes	Yes	Yes
Wheel odometry	No	No	No	No
IMU	No	No	No	No

4. Environmental factors while navigating: Sensitivity to environmental factors: LIDAR sensors can be sensitive to various environmental factors, such as ambient light, dust, fog, and rain. These factors can degrade the quality of the sensor data and, in turn, affect the performance of the SLAM algorithm. Similarly, other sensor modalities do get affected by reflective surfaces and dynamic moving objects (other AMRs or workers), thus further confusing SLAM. Table 1 summarizes how the environment affects different sensor modalities. IMUs can reliably operate in a variety of environments, making them a versatile choice for mobile robots.

However, No Sensor Is Perfect!

While IMUs have benefits, there are risks involved and they present challenges[2]:

1. Noise: IMU measurements are subject to noise, which can degrade the accuracy of the robot's navigation and control. To compensate for noise, IMUs often employ advanced filtering techniques such as Kalman filtering or FIR.

2. Bias: IMU sensors accumulate biases over time, which can lead to errors in orientation and motion estimation. To address this issue, bias estimation algorithms are used to continuously update the IMU sensor readings.

3. Nonlinearity: IMU sensors exhibit nonlinear behavior, which can further complicate data processing and interpretation. To compensate for nonlinearity, they need to be calibrated to characterize the sensor's behavior and apply appropriate corrections.

4. Random walk: IMUs are susceptible to external thermomechanical events causing errors in ARW—angle random walk (in gyro) and VRW—velocity random walk (in accelerometer).

How Do We Mitigate These Risks? The Answer Is Sensor Fusion!

- How does sensor fusion help?
  - Increase reliability.
  - Increase the quality of the data.
  - Estimate unmeasured states better.
  - Increase coverage thus ensuring safety.
- Sensor fusion algorithm significance:
  - State estimation techniques like extended Kalman filtering can correct noise, ARW, and bias instability errors during regular AMRs operation.
  - Pitch and roll gyroscope errors can be removed within an IMU by measuring acceleration due to Earth's gravity.
  - The algorithm tracks and corrects the bias drift and corrects the ARW error.
- Extended Kalman filter (EKF):
  - Supports estimation of past, present, and future states even when the precise nature of the modeled system is unknown. Figure 8 shows a simplified EKF algorithm.
  - Measurement is observed over time that contains Gaussian white noise or other inaccuracies and estimates the true values of measurements by
    - Synchronizing measurements between sensors
    - Predicting pose and error estimates
    - Estimating and updating the uncertainty of the predicted value

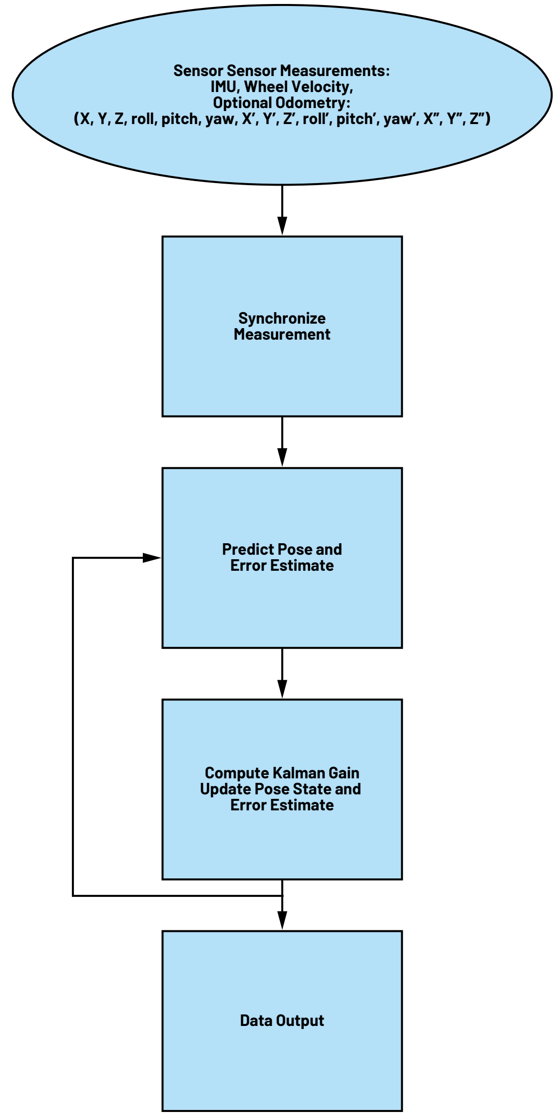

Figure 8. EKF algorithm (simplified).

- Sensor fusion:
  - In a typical robot operating system (ROS)-based system, vision sensors along with IMU and wheel odometry (Figure 9) are fused using a popular open-source ROS-based package called robot_localization,[3] which utilizes the EKF algorithm at its core. This package enables the fusion of an unrestricted number of sensors and various sensor inputs like IMU, wheel velocity, and odometry. The pose output given by robot_localization includes 3D estimates of the position and orientation of the robot as well as linear/angular velocities and acceleration, which is fed to the SLAM algorithm. The pose output is expressed in terms of:

Pose State = $(X, Y, Z, roll, pitch, yaw, \dot{X}, \dot{Y}, \dot{Z}, \dot{roll}, \dot{pitch}, \dot{yaw}, \ddot{X}, \ddot{Y}, \ddot{Z})$.

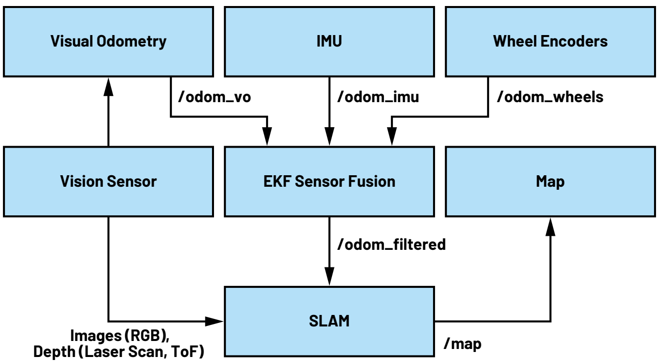

Figure 9. Typical sensor fusion system using ROS.

How Does Using an ADI IMU Help Solve Those Challenges?

Analog Devices provides several IMUs for various applications including mobile robots. The offered unique value proposition is listed as follows:

- Built-in calibration: ADI IMUs have a fully factory calibrated accelerometer and gyro addressing parameters such as sensitivity, bias, alignment, gyroscope bias for linear acceleration, and accelerometer. The built-in dynamic offset corrections compensate for variations in supply voltage, temperature, and magnetic interference along with noise reduction capabilities.[4] This enables a significant reduction in system integration time and cost of acquisition, streamlining the overall implementation of accurate sensor measurements in industrial applications across diverse conditions.
- Low noise, high bandwidth analog-to-digital converters (ADCs): Capture sensor data with high accuracy and high bandwidth, ensuring reliable and responsive operation.
- High precision: ADI IMUs provide accurate orientation, motion, and velocity measurements, enabling robots to make informed decisions and navigate their surroundings with precision.
- Low power consumption: Mobile robots typically operate on batteries, so low power consumption is essential to extend their operational range. ADI IMUs are highly efficient, minimizing power consumption and maximizing battery life.
- Compact size: To fit within the limited space constraints of mobile robots, ADI IMUs are designed with compact form factors. This allows for easy integration into various robot configurations without compromising on performance.
- Ease of integration: Easy integration with the robot's control system is essential for seamless operation. ADI's coupon boards for IMUs, combined with open-source ROS nodes, enable ease of integration for building AMRs.

Conclusion

IMUs are a must for localization in AMRs as they provide orientation estimates and motion tracking and offer real-time response with high update rates for allowing AMRs to navigate in dynamic environments. Sensor fusion techniques such as the Kalman filter allow the combination of other sensor modalities to compensate for each other's limitations. ADI's offers a wide range of IMUs to suit the specific requirements of various mobile robot applications.

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