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Sensor Fusion Techniques for Autonomous Robotic Navigation in Electrical Plants

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Abstract: In this paper, the researcher examine how autonomous robotic navigation in electrical plants can be made possible by sensor fusion techniques; GPS-denied conditions, electromagnetic interference, complex layout make this a difficult task. The main objective is to gauge the benefits of incorporating the various sensing modalities LiDAR, vision systems, inertial measurement units (IMUs), and wheel odometry to enhance the localization precision, obstacle detection and reliable functioning. The methodology of the research is that of secondary data, using peer-reviewed articles, IEEE conference proceeding papers, and industrial case reports in order to examine established models and proven metrics. Current results show that a multi-sensor fusion can enable centimeter-level localization accuracy, 92% obstacle recognition rates and greater than 95% successful task completion in a complex environment. Both probabilistic algorithms and deep learning fusion models are effective in terms of robustness but combining the two approaches produces the most adaptive solutions. All in all, the field study has proved the effectiveness and validity of sensor fusion in ensuring safe, accurate, and reliable in autonomous robotic activities in the electrical plants setting.

Keywords: Sensor fusion, Autonomous robots, Navigation, Electrical plants, Localization, LiDAR, IMU (Inertial Measurement Unit), Obstacle detection, GPS-denied environments, Probabilistic / Deep learning algorithms

Introduction

Autonomous robotic navigation in electrical plants is fully dependent on the use of sensor fusion techniques to provide safe and accurate navigation in electrical plants which are very complex and hazardous. The challenges that electrical plants have of high voltage equipment, confined spaces, metallic structures, and electromagnetic interferences test the reliability of the use of single sensor. Robots combine sensor information across systems, including LiDAR, stereo vision, and ultrasonic sensors, infrared camera, inertial measurement unit (IMU), and GPS denied localization. The fusion of sensors can improve spatial recognition regarding barriers and obstacles and make real-time decisions supported by complementary sensor capabilities and reducing uncertainty in probabilistic models and deep learning. With this multi-modal perception, robots can accurately, robustly and safely perform inspection, fault-detection and maintenance tasks without exposing humans to dangerous plant conditions.

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Objectives

- To develop a robust sensor fusion framework integrating LiDAR, vision, and IMU data for accurate robot localization in GPS-denied electrical plant environments.
- To enhance obstacle detection and path planning using multi-sensor perception under high-voltage and electromagnetic interference conditions.
- To evaluate probabilistic and deep learning-based fusion algorithms for improving navigation accuracy and operational safety.
- To design and validate autonomous robotic systems capable of performing inspection and maintenance tasks with minimal human intervention in electrical plants.

Literature review

Fan et al. (2024) discussed multi-sensor tropism package of the precise positioning and autonomous navigation in the substation inspection robot. Their work focused on combination of LiDAR, vision sensors, and IMUs to work in GPS denied environment, with an accuracy that is within centimeters. They have cited such challenges as electromagnetic interference and structural occlusions in substations that impede the use of conventional navigation systems. The probabilistic filtering and error corrections employments enabled the robot to be autonomously stable in the process of localization without collisions. The study proved that multi-sensor integration is not only used to improve the reliability of the positioning result but also helps to make an autonomous decision. This renders it very applicable in the navigation processes of electrical plant with complicated and potentially dangerous architecture.

The potential of a regression-based sensor data fusion approach to optimally navigate a robot in IoT-enabled systems is proposed by Aroulanandam et al. (2022). The researchers have integrated ultrasonic sensors, infrared sensing, and IMU and regression analysis to increase the efficiency of path planning. Their scheme decreased the localization errors and energy use together with providing smooth navigation in a dynamic environment. One of the major contributions was the incorporation of the IoT communication protocols: the data on state of robot navigation could be monitored in real-time remotely. This solution made a case of the use of lightweight statistical methods of fusion to deep learning, especially in systems with constraints, as may be the case with the electrical plant inspection robot which may need low latency decisions.

Hulbert et al. (2014) described an algorithm to allocate traffic across tasks in mobile robots built on the experience of more than 20 years of satellite traffic assignment. The paper developed EKF and Particle Filter methods of dealing with uncertainties in the sensor measurements needed to more confidently estimate the trajectory. Experimental findings reflected the improvement in the accuracy of the system in a cluttered environment which the individual sensors failed to perform. Their job highlights the multi-sensor fusion adaptability to a variety of industrial conditions. This paper lends excellent support to the argument that fusion-based navigation is more effective to enhance safety and efficiency of operations, which is exactly the confront the problem in autonomous robotic installations sent into electrical plants and substation inspections.

An anthropomorphic robot that readily performs inspection of substation by navigation assistant technique and multi-sensory integration was presented by Yang et al. (2025). By utilizing a combination of LiDAR, cameras, IMUs and an infrared sensor, they were able to build upon this and integrate into robust environmental perception under low-light and high-voltage situations. The research has contributed the hierarchical fusion strategy that integrated the low-level sensor and high-level semantic data and enhanced obstacle recognition and fault detection. Deployment within substation conditions proved higher navigation accuracy than when using a single sensor. It gives a critical perspective on the design of inspection robots in electrical plants, where hierarchical sensor fusion can greatly benefit in improving adaptability, risk-free operation, as well as influencing the operation decisions in a high-risk environment.

Binbin et al. (2021) provided a survey on the development of autonomous navigation technologies on agricultural robots, with regard to sensor fusion applications. The analysis of precision field navigation using GPS, machine vision, ultrasonic sensors and IMUs was done in the study. Though the research was carried out in an agricultural setting rather than at electrical plants, the study was able to demonstrate how to learn some lessons that can be easily transferred to addressing uneven terrain situations, the denial of GPS, and the presence of dynamic obstacles through multi-sensor fusion. They underlined how deep learning helps to improve visual perception and decision-making. Another limitation to a widespread deployment cited in the paper was cost and computing power. Such results guide the industrial navigation systems, and they indicate the significance of sensor fusion in various robots.

Methodology

In this research, the approach to the methodology is based on the secondary data analysis method to analyze the sensor fusion methods in the context of autonomous robotic navigations in electrical plants. The ability to use secondary data in peer-reviewed journals, IEEE conference proceedings, and industrial case studies has served as the solid ground to develop insight into current sensor fusion models, algorithmic characteristics, and performance measures specific to GPS-denied and high-voltage situations. The use of experimental results published previously in terms of accuracy of localization, rate of obstacles detection, and the efficiency of algorithms used enables highly significant comparison without the necessity to use new hardware as part of the experiment. Such approach allows covering a wide range of environments, e.g., in substations, agricultural robots, or industrial plants, and will, therefore, provide trustworthy cross-domain findings. Utilization of secondary data promotes effective synthesis of best-practices, algorithm comparison and verified metrics to ensure that scalable solutions to electrical plant navigation are created.

Result and Discussion

Enhanced Localization Accuracy through Multi-Sensor Fusion in GPS-Denied Electrical Plant Environments

Cheng et al. (2024) showed that mobile robots could be detected in GPS-limited spaces with far better precision by displaying a multi-modal array of LiDAR, IMUs, and wheel odometry fusion to advance localization by 38 percent over single sensors. Similarly, Yan et al. (2022) used bio-inspired fusion of visual-IMU-wheel odometry to locate agricultural robots with a positioning error of below 3 cm in changing conditions and which is regarded as high robustness to signal block scenarios.

Reference	Sensor Fusion Method	Environment	Localization Error / Drift	Improvement (%)
Cheng et al. (2024)	LiDAR + IMU + Wheel Odometry	Greenhouse (GPS-denied)	±3.2 cm	38% vs. single-sensor
Yan et al. (2022)	Visual–IMU–Wheel Odometry	Agricultural (dynamic)	<3 cm	42% vs. GPS-only

Rakun et al. (2022)	LiDAR + Odometry Fusion	Vineyard robot	±5 cm	67% vs. GPS-only (±15 cm)
Nahavandi et al. (2025)	Extended Kalman Filter	Industrial robots	Drift reduced by 45%	–

Table 1: Enhanced Localization Accuracy through Multi-Sensor Fusion

Rakun et al. (2022) deployed a vineyard robot with a fusion-based localization system and recorded controlled accuracy of 5 cm, the GPS-only approach was less accurate with a fluctuation up to 15 cm when being obstructed. Nahavandi et al. (2025) pointed out that by making use of probabilistic filters, specifically the Extended Kalman Filter (EKF), drift error was minimized by 45 percent in long-range navigation. These results indicate that fusion-based localization in electrical plants robots can be used to achieve centimeter-level accuracy even in a GPS-denied environment with electromagnetic interference, allowing path tracking reliability under indoor substation occlusion problems. Looking at the evidence of several studies together, the scalability of the techniques employed to agriculture and industrial plants is validated, and by extension, these methods can be used in electrical settings by inspection robots.

Improved Obstacle Detection and Path Planning under High-Voltage and Electromagnetic Interference Conditions

Nagy and L(advantages of the computer vision technology were previously reported by Nagy and L(fused with LiDAR recognition accuracy was 92%, that is, high as compared to those of vision alone at 71%. The multi-sensor fusion used by Yan et al. (2022) enabled the real-time recognition of dynamic obstacles at low latency with an average of 120 ms that support quick adaptation of robots in complex environments. Cheng et al. (2024) demonstrated that LiDAR-equipped greenhouse robots with fusion, whose navigation depended on processing LiDAR-based and wheel-based information, allowed keeping the deviations of their path within a range of +/- 4 cm, despite exposure to reflective surfaces that significantly worsened the performance of LiDAR-only robots.

Reference	Fusion Method	Recognition Accuracy	Path Deviation	Response Latency	Success Rate
Nagy & Lăzăroiu (2022)	Vision + LiDAR	92% vs. 71% (vision only)	±6 cm	210 ms	–
Yan et al. (2022)	Visual + IMU + LiDAR	89%	±5 cm	120 ms	–
Cheng et al. (2024)	LiDAR + IMU	90%	±4 cm	140 ms	–
Rakun et al. (2022)	LiDAR + Vision	–	±4.5 cm	–	

Table 2: Improved Obstacle Detection and Path Planning

Nahavandi et al. (2025) stated that fusing IMU with cameras helps alleviate the distortion caused by the electromagnetic noise by 34%, making it less likely to detect false obstacles. In a narrow row environment, Rakun et al. (2022) reported successful path completion of 95% with LiDAR-vision fusion as compared to 76% using single-shot filters as inputs. These results are substantiated to show that sensor fusion outperforms individual sensors when it comes to obstacle detection and path planning robustness in high-voltage electrical facilities where reflective metallic structures and EMI impair the reliability of individual sensors. Their robots with such systems can safely move around transformers, switchgear and cabling without violation of supply inspection operations.

Performance Evaluation of Probabilistic and Deep Learning-Based Fusion Algorithms for Robust Navigation

Nahavandi et al. (2025) surveyed more than 150 fusion algorithms and uncovered that probabilistic-based models, such as the EKF and Particle filters, improved localisation drifts by 40-55 per cent in all the industrial robots. Xue et al. (2024) used sensor fusion, including the regression algorithm and probabilistic methods, on automated guided vehicles (AGVs), and managed to obtain the navigation reliability of 97%, and decreased the risk of collisions by 43% compared to baseline systems. Hpmwgems 2021, Cheng et al. (2024) indicated that EKF-based multi-sensor fusion reduced the odometry drift by 2.1 cm over 100 m, and thus it maintained a consistent performance level of the EKF in GPS-deprived environments.

Reference	Algorithm	Accuracy / Reliability	Drift Reduction	Resource Use
Nahavandi et al. (2025)	EKF, Particle Filters	90–95%	40–55%	Low
Xue et al. (2024)	Regression + Probabilistic Fusion	97% navigation reliability	–	Moderate
Cheng et al. (2024)	EKF Fusion	Drift reduced by 2.1 cm per 100 m	–	Low
Yan et al. (2022)	CNN-based Fusion	94% obstacle classification vs. 82% regression	–	GPU power ↑ 27%

Table 3: Performance of Probabilistic vs. Deep Learning Fusion Algorithms

Concerning the deeper learning, Yan et al. (2022) found that the models based on CNN had achieved obstacle classification accuracy of 94 and outperformed the results obtained by traditional regression approaches at 82. The deep learning systems were found to demand more computation resources, where power use by GPU grew by 27% in deep learning systems. Rakun et al. (2022) confirmed that integrating machine learning with EKF increased the location stability compared with the localisation only EKF or machine learning-based localization. These observations indicate that the probabilistic models are efficient and steady in terms of computations but as result of deep learning fusion the models are more adaptable when the environment is unstructured. Electrical plants can also capitalize on a hybrid solution, that offers a trade-off between efficient and sturdy solutions in areas of safety critical inspection.

Operational Reliability of Autonomous Robots in Inspection and Maintenance Tasks within Electrical Plants

Xue et al. (2024) showed that the 24-hours continuous working of the AGV had achieved 99 percent recharging success rate, thus demonstrating the long-term reliability of autonomous inspection systems. Nahavandi et al. (2025) underlined that industrial robots fitted with multi-sensor fusion completion tasks in complicated conditions with 95 percent, as opposed to 72 percent under unfused conditions, confirming their high levels of reliable operations. Cheng et al. (2024) said that the upgrade of greenhouse robot use with fusion navigation enabled it to perform inspection procedures with an accuracy range of +/ 3 cm, which helped to reduce maintenance errors by 41%. Yan et al. (2022) additionally demonstrated the stability of agricultural robots in monitor-free environments over half a working day, and the localization drift was contained below 2.5 cm, indicating the scalability of the approach into the industrial sector.

Reference	Application	Task Completion
Xue et al. (2024)	AGVs (multi-sensor)	99% recharging success
Nahavandi et al. (2025)	Industrial robots	95% task completion vs. 72% without fusion
Cheng et al. (2024)	Greenhouse robot	±3 cm accuracy

Yan et al. (2022)	Agricultural robot	Stable for 6 hours
Rakun et al. (2022)	Vineyard robot	93% efficiency vs. 68% GPS-only

Table 4: Operational Reliability of Autonomous Robots in Electrical Plant Context

Rakun et al. (2022) examined fusion-based vineyard robots, which attained the number of 93 percent in the area of navigation performance, and surpassed the outcomes of GPS-only robots that decreased to 68 percent in areas with canopy interference. These findings demonstrate that autonomous robots in electrical plants, which are powered with multi-sensor fusion, can safely perform the work on inspection, fault identification, and maintenance. They are resistant to electromagnetic disturbances and structural complexity to enhance plant safety, downtime and minimal intervention by humans within the hazardous high-voltage workplaces.

Conclusion

This study has proved that fusion of sensors is indeed plausible and can be very helpful towards autonomous navigation of robots in electrical plants. The paper synthesizes secondary data on various industrial/agricultural fields and explains how an ensemble of LiDAR, vision, IMUs, and probabilistic/deep learning algorithms have led to reliable centimeter-level localization performance, high success rates on obstacle detection, and high task completion rates in diverse challenging environments. The results support that, sensor fusion largely reduces electromagnetic interference, GPS-denial, and structure occlusions contributing to a robust navigation and operational reliability. The numeric uniformity of such different studies proves the scalability of such techniques. Hence, the study provides a strong foundation in the implementation of autonomous robots in electrical plants, where the safety, accuracy, and risk to human lives will decrease.

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