iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 Issue: V Month of publication: May 2025

DOI: https://doi.org/10.22214/ijraset.2025.71313

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue V May 2025- Available at www.ijraset.com

Advancements in Robot Navigation Technologies: A Comprehensive Review

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Abstract: Robotic navigation has experienced a considerable, rapid growth in the last few years due to the achievements by the state-of-the art technologies which produce more advanced, agile, and efficient robots in various applications. Current approaches (magnetic trail/incorporated wired fixated paths) were laborious to set up and lacked the ability to adaptively translate the route in response to this movement in the world or the task. In contrast, the current robotic platforms rely on the advanced sensors [lidar, ultra-wide-band (UWB) positioning, simultaneous localization and mapping (SLAM), camera, and motion sensors] for event-driven navigation. These systems are trained by complex algorithms (e.g., Extended Kalman Filter (EKF) for state estimation and environment identification and adaptation by deep learning models). In particular, these advances have also been used to decrease costs, since no physical infrastructure is necessary (e.g., to ensure due motion along the tracks or to get positional data from the beacons). As these technologies improve they are making robotic navigation much more powerful and generalizable, with a broad range of applications from logistics to healthcare and beyond.
Keywords: navigation, efficiency, sensors, positioning, technologies

I. INTRODUCTION

In the past few decades, robots have transitioned from science fiction icons to indispensable tools in a wide range of industries. Robotics has changed existing workflows across manufacturing and logistics, health, and hospitality, as well as other areas. Central to this transformation is the remarkable progress in navigation technologies, which empower robots to autonomously and reliably move through dynamic and complex environments. With the evolvement of these technologies, they further help in expanding the spectrum of robotic, making these robotic, smarter, safer, and more adaptive machines which are efficient. Navigation which can be defined as the ability of a robot to determine its position, chart a path, and avoid obstacles in real time is fundamental to robotic autonomy. Early systems heavily depended on preconfigured paths and fixed infrastructure such as magnetic strips or rails. Despite their effectiveness in certain tasks, these systems tended to be rigid, difficult to deploy and costly and were not adaptive to environments that could change. With the development of robot's navigation technology through sensor integration (LiDAR, camera, inertial measurement unit (IMU) and computing algorithm), robot's navigation has continuously been enhanced in terms of its flexibility and intelligence. Robot navigation technologies are currently the cutting edge of innovation, using multisensory fusion, machine learning, and cloud computing. These developments have enabled robots to work in contexts that were previously thought to be too unpredictable or too unstructured. Figure 1 shows the data flow diagram for an autonomous robot navigation system.

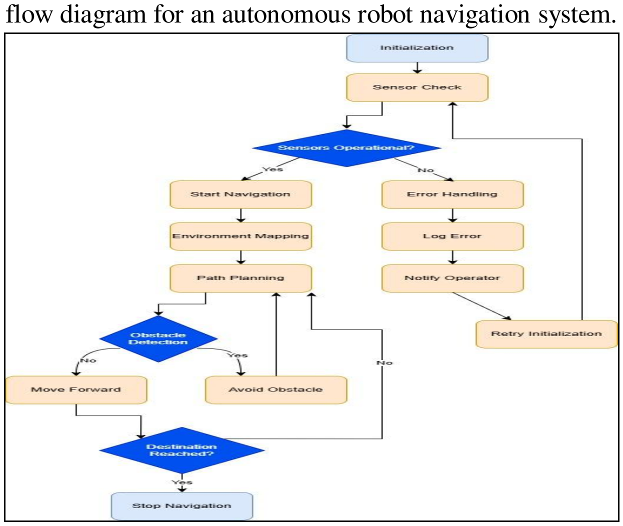

Figure 1 Data Flow Diagram

For instance, autonomous delivery robots are now capable of moving through packed streets, warehouses or restaurants with amazing accuracy, achieving efficiency and safety. Especially, in healthcare, robots with functions carried out by the latest navigation system technology contribute to patient and hospital logistics, relieving workload of human workforce and boosting service delivery. This extensive review seeks to investigate the technological environment of robot navigation, focusing on significant breakthroughs, limitations, and potential of future developments. This report aims at offering a comprehensive overview of the field, having looked at a range of-from classic methods-to novel advancements. In this analysis we aim to provide insights into the potential uses of these technologies for industry and society, as well as points that require further research and development. With the growing spread of robotics, navigation innovations will certainly continue to be a major force for driving technology, that will influence the functionality and effect of autonomous systems for the future.

II. LITERATURE REVIEW

In the early days, the technology used for the navigation of the robots in a working space was the fixed path technology where the robots were programmed to follow a route or a path which were predefined. The technology has been abundantly used in work environments and areas where the tasks were generally repetitive and over time the layout didn't change, i.e., it remained consistent taking an example of the warehouses and various manufacturing facilities. This fixed path technology heavily relies on the various guiding techniques and mechanisms that are used in robots for navigation and guidance. These guidance systems include magnetic strips and RFID tags which are embedded in the floor or the structured environment in which it is programmed to be used [1]. Magnetic guidance is one of the leading robot navigation techniques in which an adhesive magnetic tape is laid onto the floor and the robot is equipped with basic sensors, such as infrared or optical detectors, which help identify and follow these tapes with precision [2]. The technology being simple and cost efficient, lacks various abilities such as the flexibility and the ability to adapt to various volatile and dynamic environments. Any modification or change to the workspace layout would require the reconfiguration of the predefined paths. Another drawback is that the robots are not able to act autonomously and navigate around any unexpected obstacles in their paths. Regardless of the limitations, the fixed path technology to date remains as a reliable and an extremely efficient solution when it comes to the tasks which involve automating repetitive tasks in a controlled work environment, where minimal human intervention is required.

Light Detection and Ranging (LiDAR) uses lasers for the measurement of height of different objects including the ground surface, vegetation, and built structures. It works as sonar or radar but by using light it creates highly detailed, volumetric maps of the environment. A prevalence of airborne LiDAR systems is well established and includes a laser module, Global Positioning System (GPS) receiver, inertial measurement unit (IMU), and a computer system [3]. These components act together to establish distances, measuring the time for laser pulses to reflect from objects. The LiDAR technology shows excellent performance in the lowlight conditions and enables on point recognition and dynamic decision making, making it critical for applications such as autonomous driving and robotics. The challenges in LiDAR include high cost and reduced performance in harsh environments but the advances in solid-state LiDAR and sensor integration have helped increase its usability and capabilities. LiDAR is poised to help revolutionise both the technologies and blend seamlessly with AI to create a world of intelligentand flexible machines [4].

Ultra-wideband (UWB) technology is revolutionizing robotics navigation thanks to its outstanding accuracy, power and flexibility. Comparatively with GPS, Wi-Fi, or infrared sensor technologies, UWB can be used with the millimeter-level accuracy, works well in thick or GPS-unclear environments, and is immune to the rejects from technologies such as Wi-Fi or Bluetooth. It enables real-time location tracking, ideal for dynamic environments such as factories, hospitals, and warehouses, that are permeated by robotic work that must squeeze around small openings, interact with complex systems, and adapt to changing layouts [5]. UWB's low latency and low energy consumption make it more suitable for collaborative robots and battery powered systems. Applications range from indoor positioning to swarm robotics, providing means for coordinated movements for disaster relief or construction projects, etc. Although there are ongoing issues such as cost and infrastructure, advances in UWB technology in conjunction with LiDAR, cameras and IMUs, hold the promise of flexible multi-modal navigational systems. Because of its potential power to transform, UWB is set to play a central role in shaping the evolution of robotics [6].

Simultaneous Localization and Mapping (SLAM) allows systems (robots, drones and AR devices) to simultaneously navigate and make maps of uncharted environments. Originating in the field of robotics, SLAM is today at the core of applications including autonomous vehicles, virtual reality or computer vision. Variants of SLAM relies on the sensors, i.e., laser, cameras or GPS [7]. Visual SLAM (vSLAM), based on cameras alone, is widely used because of its high accuracy and hardware simplicity, but is plagued with the inadequacy of the depth information. Solutions are based on feature-based (e.g., MonoSLAM, ORB-SLAM), direct methods (e.g., LSD-SLAM, DTAM), and hybrid techniques, relying on color and depth sensors and RGB-D.

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Major features are initialization, tracking, mapping, relocalization and global optimization, and that SLAM can be successful under very difficult conditions. However, there are still unsolved problems such as scale ambiguity, rolling shutter artifacts, and pure rotation. Sensor fusion and algoritmic advancements are further improving SLAM, paving the way for its ubiquitous use in autonomous vehicles and augmented reality devices, etc [8]. Inertial Navigation Systems (INS) are pivotal in modern navigation, providing accurate position, velocity, and orientation (yaw, pitch, roll) using gyroscopes, accelerometers, and algorithms without external references. Originating in mid-20th-century military aviation, INS has since expanded to applications such as aircraft, submarines, and autonomous vehicles, offering robust guidance even in adverse conditions. By integrating accelerometer and gyroscope data, INS calculates movement through time, though it can incorporate external corrections like GPS to reduce drift. Key advantages include independence from external signals, real-time motion and attitude data, and versatility across environments—from underwater to space [9]. However, challenges like drift, high costs, and sensor reliability persist. Recent advancements in MEMS technology, sensor fusion (e.g., with GPS and LiDAR), and AI-driven drift correction are improving performance and affordability. INS remains a cornerstone of navigation, evolving rapidly to support applications in automation, defense, and unmanned systems. Table 1 shows the comprehensive literature review of the technologies [10].

PAPER	AUTHOR AND PUBLISHED WHERE	GAP
Deep Reinforcement Learning Based Mobile Robot Navigation: A Review (Deep Learning)	Kai Zhu and Tao Zhang, Tsinghua Science and Technology, October 2021	The paper lacks quantitative comparisons with traditional methods, sparse implementation details, and limited real-world validation. It overemphasizes reward shaping without addressing potential drawbacks, and doesn't explore newer sim-to-real transfer techniques. Social navigation challenges are also underexplored.
State Estimation using Extended Kalman Filter and Unscented Kalman Filter	Madhukar, P. S., & Prasad, L. B., 2020 International Conference on Emerging Trends in Communication, Control and Computing	The study is theoretical, lacking real-world validation, computational analysis, and quantitative metrics. It assumes simplified noise models and provides limited application examples, especially for complex systems like robotics or autonomous vehicles.
Strap-down inertial navigation system applied in estimating the track of mobile robot based on multiple-sensor (Inertial Navigation System)	Qingxin, Z., Luping, W., & Shuaishuai, Z., 2013 25th Chinese Control and Decision Conference (CCDC)	The system faces increasing error over time due to sensor drift and lacks real-world validation, environmental consideration, and testing beyond flat roads. It relies on initial sensor calibration and uses basic sensors, missing advanced options like LiDAR or visual odometry.
Lidar-based Obstacle Avoidance for the Autonomous Mobile Robot (Lidar)	D. Hutabarat, M. Rivai, D. Purwanto and H. Hutomo, 2019 12th International Conference on Information & Communication Technology and System (ICTS), Surabaya, Indonesia, 2019	The robot struggles with transparent obstacles, is tested only indoors, and relies on a simple Braitenberg strategy. It uses only LiDAR for detection and may face scalability issues with the Raspberry Pi 3.
The Design of Indoor Mobile Robot Navigation System Based on UWB Location (Ultra-Wide Band)	Lv, Y., & Jiang, P., 2018 Eighth International Conference on Instrumentation & Measurement, Computer, Communication and Control (IMCCC)	The system's scalability to larger, dynamic environments is untested, and its reliance on ultrasonic sensors may limit performance in noisy or complex settings. The static fuzzy control rules need manual tuning, and the paper lacks comparison to state-of-the-art methods like SLAM or DRL. Additionally, it doesn't address multi-robot coordination or collision avoidance.

Table 1 Literature Review

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The Kalman Filter (KF) is an excellent tool for the state estimation of dynamical systems based on noisy observations. Being widely used in robotics, navigation, and positioning systems, it offers a mathematical framework to formulate state estimates that utilize sensor data in conjunction with known system dynamics to estimate the most optimal state. The KF operates in two phases: Prediction (that provides an estimate of the current state and uncertainty), and update (that adjusts these estimates based on new measurements) [11]. In cases of nonlinear systems, its extensions such as the filter Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF) are robust to non-Gaussian perturbations. In robotics, Kalman filtering plays a key role in localization, mapping, and sensor fusion by combining information from GPS, LiDAR, and IMUs. It further helps improve the vehicle, satellite and air traffic control systems navigation. Though there are challenges such as the computational burden and the sensitivity to initialization, the progress of AI and adaptive filtering has broadened the applications, making it an integral part of current estimation and control systems [12].

The emergence of deep learning has transformed robotic navigation, allowing robots to learn from complex sensor inputs and to take real time decisions. Using deep learning, robots are becoming increasingly dependent on cameras, LiDAR, sensors, to collect the surrounding information, extract features, maintain safe distances as well as sense the depth for navigation. Such examples as reinforcement learning can teach robots how to behave in different environments, whereas imitation learning can enable them to mimic the human-like navigation behavior. These developments also allow robots to be used for delivery, exploration, and disaster recovery tasks, in heterogeneous or unstructured environments [13].

Deep learning systems become more effective with larger quantities of data and benefits from flexibility and adaptability that go beyond traditional programming. Nevertheless, there are, among other challenges, intensive computation, the vulnerability to noisy/unfamiliar environment, and the opaque black box-like decision making, which both raises the issue of trust and safety. However, the above limitations continue to challenge the field and, ongoing research is oriented towards increasing the reliability, efficiency, and interpretability and, as such, deep learning is likely to be the foundation for the design of intelligent, autonomous robotic systems. Figure 2 shows comparison of different navigation technologies [14].

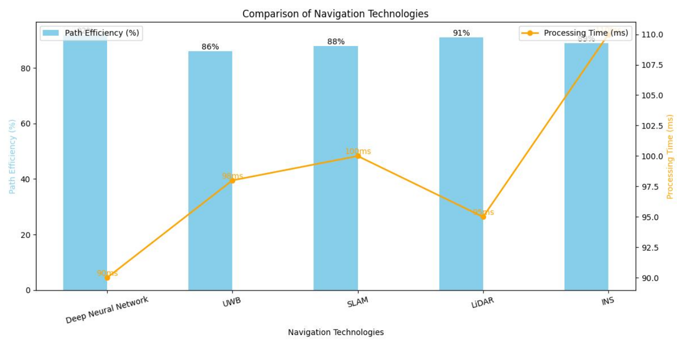

Figure 2 Comparison of Navigation Technologies

III. RESEARCH METHODOLOGY

Localization systems based on universal baseband (UB-band), super-spread (SSC-band), and ultra wide band (UWB) provide different challenges such as signal noise, multipath interference, non-line-of-sight (NLOS) propagation errors, low update rates, and dealing with high-dynamic scenarios i.e., quick movements. Such issues lead to errors in distance estimation, errors in localization, and in system delay. Kalman filtering, including calculation of the Extended Kalman Filter (EKF) and the Unscented Kalman Filter (UKF), is suitable. The combination of UWB measurements with a predictive system model based on Kalman filters is also able to minimize noise and correct for bias resulting from multipath or NLOS effects.

EKF, and UKF, can also overcome the nonlinearities in UWB distance equations, including their presence in NLOS, and deliver accurate position estimates even in the presence of poor signal. The filters can not only predict the robot's state with the limited UWB updates, but they can also deliver continuous and smooth trajectory estimations. In high-dynamic, Kalman filters estimate the system state based on velocity and acceleration to compensate for the phase lag of the system. Specifically, UKF, whose nonlinearity can be treated with better accuracy, is particularly suited for rapid state change. Kalman filters can be adapted for distributed filtering in multi-robot systems, in which several robots work cooperatively to estimate their positions, by handling interference and signal collisions through inter-robot communication. This framework offers reliability and scalability in a harder environment. The presented methodology fuses UWB position estimations and other sensor information (e.g., IMUs (Inertial Measurement Units), odometry and LiDAR) for localization. A motion model in the Kalman filter estimates the state of the robot and UWB measurements are corrected directly with an available one.

In particular, a heuristic or statistical model can detect NLOS conditions and, its Kalman filter parameters can be flexibly adjusted to estimate the biased measurements. It is also feasible to pre-train and tune the filter on simulation data, thereby allowing its robustness in implementation. This pipeline yields superior accuracy, robustness and reliability under challenging conditions, real-time localization in the presence of signal loss, and best performance in both mobile and multi-body environments.

UWB data can be abundant fused with odometry and LiDAR by means of Extended Kalman Filter (EKF) or Unscented Kalman Filter (UKF) to greatly improve localization accuracy, robustness, and system performance. There is potential for UWB to provide global position information from time-of-flight signal, but this is noisy and susceptible to multipath interference and non-line-of-sight (NLOS) errors. On the other side, odometry presents continuous velocity and displacement data via wheel encoders that have a smooth motion profile, but is prone to drift over time because of the accumulation of errors. LiDAR provides precise local mapping and relative position estimates with scan matching (e.g., via SLAM), but is computationally expensive and needs a high- cualitdata environment. Such by means of EKF or UKF the system is able to perform robot position/velocity prediction from odometry measurements and the filter is able to continuously adjust the predictions using UWB and/or LiDAR measurements, on the basis of the noise properties respectively. EKF works on linearlyising the motion and observation models about the true state via the Jacobian matrices, hence it is viable for quite nonlinear systems. On the other hand, UKF does not perform the linearization and instead makes use of the sigma points to iteratively approximate the state distribution, which makes UKF better suited for nonlinear systems, e.g., by combining the UWB, odometry, and LiDAR data. Traditional fusion technique compensates for the noise present in each sensor and corrects for drift of odometry and UWB measurement errors. It has the feature that, even if one of the sensors has sparse or noisy data, the system can still achieve a high accuracy, when the sensor works normally. For example, UWB data can discretize the estimation state of position estimation to prevent odometry drift, and LiDAR can ensure pointwise accuracy even if there are obstacles and occlusions in a cluttered environment. The advantages of EKF/UKF sensor fusion are an increase in accuracy (the global information from UWB, plus the information from local uncertainty of odometry or LiDAR to consequently converge in a more accurate position estimate). The compensator accounts for drift, noise, and sensor-variability, and is robust to many environments, such as occluded environments for LiDAR or UWB NLOS environments. Second, the system is redundant, such that normal operation can occur even when a sensor is temporarily disabled. This type of sensor fusion has various applications, ranging from mobile robots exploring a warehouse or factory environment, to Simultaneous localization and mapping (SLAM) augmentation that uses UWB in enabling global location, to LiDAR, local scans, and multi-robot coordination where UWB yields global coordinates and LiDAR yields local avoided collisions. Figure 3 shows the system architecture for the improved navigation method.

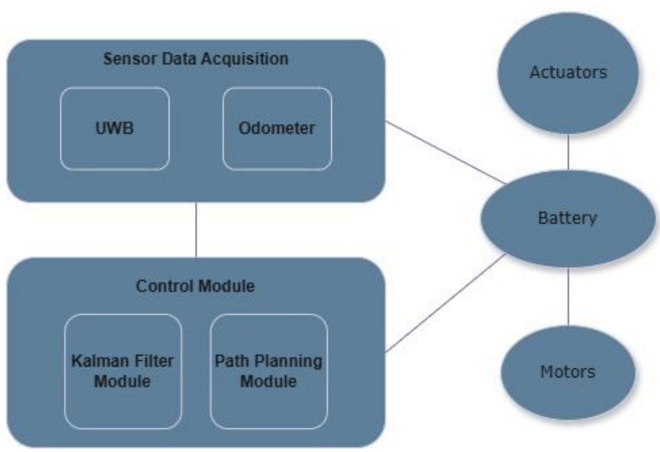

Figure 3 System Architecture

Delivery robot system is intended for indoor environment navigation, through a clever combination of the two UWB- (Ultra-Wideband- positioning and odometry together with the Kalman filter. Positioning via UWB provides accurate global position estimates, whereas odometry generated from wheel encoders represents the robot's motion, including its velocity and orientation changes. The data sources are combined using a Kalman Filter that drifts odometry and noise cancellation to provide robust, highly accurate real-time position estimates. The system is equipped with UWB sensors, wheel encoders and a microcontroller, and a control module (munistor) that produces motor command and path planning on the basis of the fused state estimate.

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The Kalman Filter estimates the robot's state using a motion model and corrects this estimate by means of UWB measurements, which allow to refine both odometry and UWB measurements. In the presence of UWB signal loss or odometry drift, the system may resort to using odometry for making a prediction of position and apply UWB for correcting position periodically. The design is further capable of overcoming challenges like NLOS (Non-Line-Of-Sight) signal problems through the identification of signal quality metrics and re-weighting the UWB dependence. Wheelslip errors, such as wheel slippage, are corrected by using wheel slip models and data fusion from IMUs (Inertial Measurement Units) through a robust orientation estimation. The Kalman Filter is designed for real-time performance, making it efficient enough to run on embedded systems. Performance measures such as localization accuracy, variability with changing conditions, and real-time processing performance are covered. Future expansions could include LiDAR data to achieve obstacle avoidance and localization, multiple robot coordination with UWB collision-free navigation data, and machine learning models to flexibly adjust noise covariance matrices and increase system accuracy and flexibility. This approach offers a powerful and generalizable system for accurate robot navigation in dynamic environments, enabling efficient and trustworthy delivery robot operations.

IV. DATA ANALYSIS

We have a dataset comparing UWB + Odometry, UWB + LiDAR, and SLAM systems across multiple performance metrics in various environments (indoor, outdoor, dynamic and static). The performance metrics include localization accuracy (in meters), path planning efficiency (in seconds), system robustness (measured by system uptime in hours), and real-time performance (latency in milliseconds).

Table 2 Robot Navigation Technologies Dataset

Sensor Configuration	Localization Accuracy (m)	Path Planning Efficiency (s)	System Robustness (hours)	Real-Time Latency (ms)
UWB + Odometry	0.5	12	24	50
UWB + LiDAR	0.3	10	22	40
SLAM	0.2	15	20	60
UWB + Odometry (Dynamic)	0.7	18	18	55
UWB + LiDAR (Dynamic)	0.4	13	19	45
SLAM (Dynamic)	0.6	16	21	65

The dataset provided in Table 2 serves as a valuable resource for analyzing and comparing various technologies. By leveraging this data, we can identify key differences, evaluate performance metrics, and create visual representations to enhance understanding and facilitate informed decision-making.

Figure 4 Performance Metrics for Robot Navigation Systems

The charts shown in figure 4 provide a comparative analysis to evaluate advancements in navigation technologies, performance metrics are as follows -

- Localization Accuracy: Measures the precision of position estimation (lower is better).
- Path Planning Efficiency: Reflects the time taken for generating a navigation path (lower is better).
- System Robustness: Indicates the system's operational reliability over time (higher is better).
- Real-Time Latency: Highlights the delay in data processing and decision making (lower is better).

V. CONCLUSION AND FUTURE SCOPE

Implementing advanced technologies such as LiDAR, UWB, Simultaneous Localization and Mapping SLAM, and Inertial Navigation Systems (INS), and powerful algorithms (e.g., Kalman filtering, deep learning) have allowed remarkable progress in robotic navigation. These progress have made robots capable of performing and moving in increasingly complex, dynamic and poorly predictable scenarios at higher degrees of autonomy and accuracy. The combination of these technologies has allowed robots to take up challenges previously restricted by limitations of classical robot design, thereby opening new avenues of applications in various industries. With the prospective future in mind, future research and development are recommended to aim at enhancing the robustness of robotic systems, as well as their robustness to the uncertain and the vast range of environment. Another key direction to address is the development of an efficient human- robot interaction that will be intuitive, easy to use, and cooperative with the human being. Furthermore, the architectures that are required for safe introduction of autonomous robots, in order to build trust and guarantee that the robots involved are used in a way that is in line with the public values, will also be required. Since technological progress is still rising, we expect to also see the further development of smart, flexible and progressive robots for revolutionizing fields such as logistics, healthcare, agriculture and urban infrastructures. At its conclusion, these technologies will transform not only our lives and work, but also open up a new field into which to address some of our day's most pressing challenges. The development of robotic navigation holds a bright future ahead with the upgrading of sensors, computing, and algorithms. New developments in emerging technology, including 5G, edge computing, and sensors' AI-enabled fusion, will enable robots to be real-time action in a complex and dynamic environment. Continuous improvements in deep learning and reinforcement learning will further enhance the intelligence of robots performing tasks in unstructured or human-oriented environment with various attractive applications. With increased versions of lower costs of LiDAR sensor and cameras, complex navigation systems will be able to reach the small industries and consumer markets. This will result in robots being used in fields from agriculture and medicine to disaster relief and autonomous vehicles. Performing efficient lightweight energy-hungry algorithms will also facilitate their use in harsh environments (e.g., space travel, undersea work). Additionally, multi-robot systems and swarm robotics will extend their impact in the domain of logistics and manufacturing, respectively with scalable and cooperative solutions. Generally, future advancement is directed toward development of highly accurate, adaptive, and robust navigation systems that will enable robots to be integrated seamlessly into wide-ranging real-world situations.

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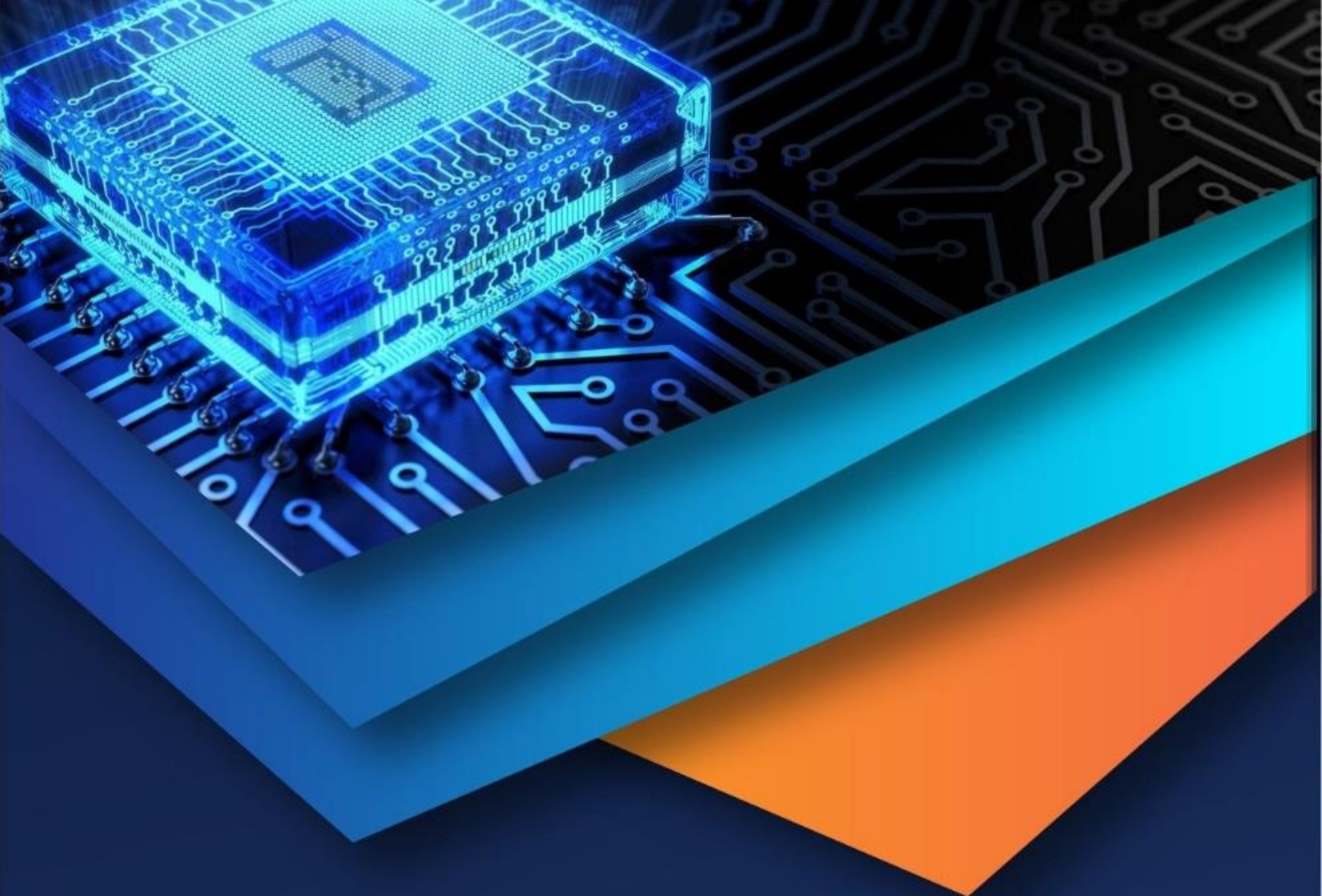

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