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Review Paper: Key Points on Robot Navigation and Its Practical Uses in the Field of Manufacturing

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Abstract: Key aspects are covered in this review article, along with a brief explanation of mobile robot navigation and its uses in the industrial sector. This study emphasizes the significance of robot navigation in enhancing productivity, efficiency, and safety in manufacturing processes by compiling important ideas from the body of research and literature. This study investigates several robot navigation algorithms and strategies, from simple algorithms to sophisticated ones like SLAM (Simultaneous Localization and Mapping). This study also examines particular issues and concerns about the application of robot navigation systems in industrial settings, such as path planning, obstacle avoidance, and worker cooperation. This paper presents some noted applications of robot navigation, such as material handling, assembly, quality control, and logistics, using case studies and examples. The conversation also touches on new developments and prospective paths for robot navigation technology, highlighting the possibility for more innovation and connection with Industry 4.0 projects. All things considered, this review article is an invaluable tool for scholars, practitioners, and business experts who want to comprehend the function of robot navigation in contemporary manufacturing processes and how it will affect industrial automation in the future.

Keywords: Mobile Robot Navigation, Navigation Technology, Robot Applications.

Introduction

One of the key areas of the robotics business is mobile robots, which are used extensively in a variety of applications, including unmanned aerial vehicles, intelligent inspection robots, and robots for logistics and warehousing (Shneier & Bostelman, 2015). Their ability to navigate autonomously in complicated surroundings, their mastery of difficult tasks, and their basic yet

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dependable structures are making them a focus point in both present and future robotics research and development. Robot intelligence and autonomy are made possible by navigation technology, which forms the basis of mobile robot technology. For mobile robots, there are numerous navigation techniques available, each with special qualities appropriate for the application setting. Numerous scientific fields are combined and applied in the study of mobile robots (Rubio et al., 2019). New directions for robot navigation research are always being explored as the field of applications for mobile robots grows. Robot navigation is a topic that this continuing research is positioned to expand and advance, creating more prospects for mobile robot applications.

Navigation Method

In order for robots to travel and function in a variety of contexts, navigation is a crucial component of mobile robotics. Robots can already navigate effectively and autonomously thanks to a variety of navigation techniques that have been developed (Kümmerle et al., 2015; Rigelsford, 2004; Rubio et al., 2019). Mobile robots frequently use GPS, Lidar, optical, inertial, and deep learning navigation techniques. Since each of these approaches has unique benefits and drawbacks, users can apply them in a way that best suits their needs and the operational environment of the robot. Using sensors like accelerometers and gyroscopes, inertial navigation determines the position and orientation of the robot by analysing variations in its rotational movement and speed. This technique is particularly helpful in locations where GPS signals are spotty or nonexistent, as indoors or spaces with a blocked view of satellites. But over time, accumulated mistakes in inertial navigation can cause inaccurate position estimation, particularly in long-term operations. Lidar navigation enables precise localization and obstacle avoidance for robots by using laser-based sensors to construct detailed maps of their surroundings. The Lidar technology is appropriate for both indoor and outdoor settings since it can precisely measure distance and detect objects in a range of lighting conditions. However, sensor resolution, range, and susceptibility to outside disturbances like rain, fog, or dust can all pose challenges to Lidar navigation. In order for a robot to comprehend visual data from its surroundings and travel appropriately, visual navigation depends on cameras and image processing algorithms. Robots can identify landmarks, navigate intricate surroundings, and carry out tasks like item identification and recognition thanks to this technique. Despite its versatility, changes in camera perspective, occlusion, and lighting can all have an impact on visual navigation. Robot position, speed, and time are all determined using GPS navigation using data from the worldwide navigation satellite system. GPS technology is frequently utilized in outdoor navigation, mapping, and surveying applications because it offers accurate localization across huge outdoor areas. However, in indoor or urban locations with tall buildings or extensive foliage, GPS signals may be lost or degraded, which limits their applicability in specific situations. In deep learning navigation, a neural network is trained with sensor data and historical experience to learn navigation policies. Deep learning navigation can attain a high degree of autonomy and adaptability in a variety of contexts by utilizing big data sets and sophisticated machine learning techniques. However, these navigations might be prone to overfitting or generalization mistakes in practical applications, and their training demands a substantial amount of computer power. In actual use, mobile robots frequently blend many navigation techniques to maximise each strategy's advantages and minimize its drawbacks. Robots, for instance, can utilize GPS for global localization and route planning, but in complicated situations, they must rely on optical navigation or Lidar for obstacle avoidance and detailed localization. A number of variables, including the robot's operational needs, the surrounding environment, budgetary restrictions, and the state of sensor technology, influence the navigation technique selection. All in all, mobile robots possess an array of navigation techniques, each with distinct advantages and disadvantages. When creating and implementing robot navigation systems in real-world applications, robot designers and engineers can make well-informed judgements by comprehending the advantages and disadvantages of various navigation strategies. Robot navigation will continue to evolve as technology develops, creating increasingly complex and intelligent robotic systems that are capable of autonomous navigation in a range of situations.

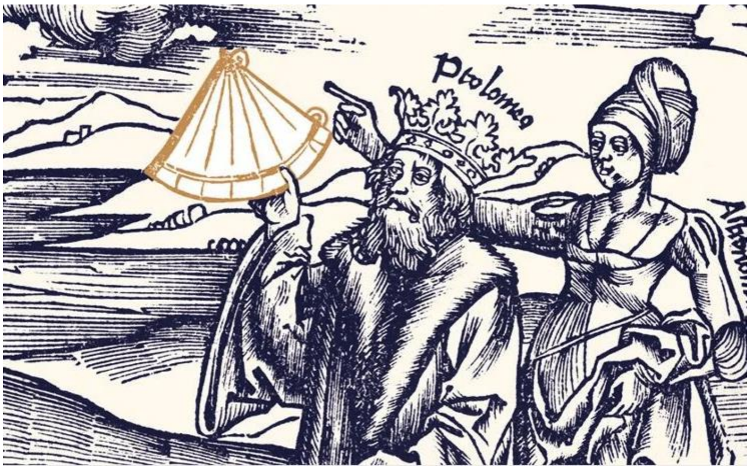

Figure 1 The Illustration for Navigations (https://www.historyhit.com/app/uploads/2022/03/Using_an_Horary_Quadrant-e1646301200501.jpg?x15493)

Inertial Navigation

As one of the most advanced areas of inertial technology research, inertial navigation has been identified as a navigation system with great future development potential. Its autonomy and concealment qualities make it indispensable for both military and civilian use in a range of industries, including aerospace, land, and marine applications (Alatise & Hancke, 2020; Chen & Pan, 2024; Elsanhoury et al., 2022; Laoudias et al., 2018; Tang et al., 2022). Integrating fields including control theory, mathematics, computer science, mechanics, and mechanical engineering, inertial navigation is a cutting-edge technology that is highly dependable and has a wide range of applications. As such, it is a crucial part of contemporary navigation systems. Fundamentally, inertial navigation systems utilize the property of objects that resist changes in motion in order to function based on the principle of inertia. Inertial navigation systems are immune to electromagnetic interference and do not require external input or output, in contrast to other navigation systems that rely on external signals (Albrektsen et al., 2018; Barbour, 2010; Grewal et al., 2007; Karimi & Karimi, 2011; RESEARCH & NEUILLY-SUR-SEINE, 2008). They can navigate on their own and give continuous, real-time position and orientation data in a range of environmental conditions and global locations. Inertial navigation has an advantage over other conventional navigation techniques like radio, satellite, and astronomical navigation because of its autonomy and concealment. The capacity to fully record object motion data, including variables like position, speed, acceleration, and attitude, is the primary benefit of inertial navigation systems. When there is potential for unreliability or unavailability of external signals, such as when there is no GPS or when there is electromagnetic interference, this function is especially helpful (Alkendi et al., 2021; Bachmann & Zyda, 2000; Gabaglio, 2003; Martins Costa, 2013; Roberts et al., 2005). Furthermore, inertial navigation systems' autonomous nature allows for seamless operation in a range of weather and media situations, offering dependable navigation and positioning capabilities independent of outside variables (Finn & Scheding, 2010; Frattasi & Della Rosa, 2017; Gast, 2008; Grejner-Brzezinska et al., 2016; Roberts et al., 2005; Thakur & Mishra, 2024) .

In real-world scenarios, inertial navigation systems are extensively employed in a variety of industries, including space exploration, aviation, marine navigation, and land vehicle guidance. Inertial navigation systems, for instance, are used extensively in aerospace applications to provide precise position and attitude data to aircraft, spacecraft, and unmanned aerial vehicles (UAVs) while they are in flight. Similarly, inertial navigation systems allow highly precise navigation and control of ships, submarines, and underwater vehicles in maritime operations—even in difficult underwater conditions where GPS signals might not always be dependable. Improvements in sensor technology, signal processing algorithms, and integration strategies are what are driving the development of inertial navigation technology. Inertial navigation systems have become widely used in a range of consumer electronics devices, such as smartphones, tablets, and wearables, thanks to the recent miniaturization and cost reduction of inertial sensors like accelerometers and gyroscopes. Along with standard outdoor navigation, this small and reasonably priced inertial sensor also provides additional navigation features including indoor positioning and augmented reality applications.

Inertial navigation offers numerous benefits, but it also has drawbacks. One of the primary drawbacks is the inertial measurement unit (IMU) drift, a gradual accumulation of errors that can result in inaccurate position estimates, particularly on extended missions. Inertial navigation systems frequently include extra sensors or sensor fusion methods, like Kalman filtering or extended Kalman filtering, to increase accuracy and dependability and decrease IMU drift. Maintaining accuracy and dependability requires routine alignment and calibration, which presents another difficulty. While alignment necessitates figuring out the inertial sensor's starting orientation with respect to the vehicle's reference frame, calibration entails changing the sensor's bias, scale factor, and misalignment. The development of complementing technologies like optical navigation, machine learning-based sensor fusion algorithms, and global navigation satellite systems (GNSS) propels advancements in inertial navigation technology. By integrating with GNSS, inertial navigation systems can use the benefits of both technologies, resulting in a navigation solution that is resistant to jamming and signal blackouts. Especially in situations without GPS, optical navigation methods like feature tracking and simultaneous localization and mapping (SLAM) enhance inertial navigation by adding more contextual awareness and localization capabilities. Sensor fusion methods based on machine learning present a viable way to raise the precision and dependability of inertial navigation systems. These algorithms can learn to model and compensate for sensor faults, drift, and environmental disturbances by utilizing massive data sets and cutting-edge machine learning techniques. This improves the overall performance of inertial navigation systems. Furthermore, in order to further increase navigation accuracy and durability, machine learning algorithms can adaptively optimize sensor fusion settings based on real-time sensor data and environmental variables.

Looking ahead, there is a lot of room for advancement and innovation in inertial navigation technology. The goal of ongoing research and development is to integrate cutting-edge sensors, algorithms, and calibration techniques into inertial navigation systems to increase their accuracy, robustness, and reliability. Novel technologies, like MEMS (microelectromechanical systems) sensors, fibre optic gyroscopes, and quantum sensors, present prospects for enhancing the efficiency of inertial navigation systems concerning dimensions, mass, energy usage, and expense. Future inertial navigation research is anticipated to concentrate on the creation of new algorithms and techniques for error correction, sensor fusion, and autonomous navigation in addition to hardware advancements. Specifically, machine learning approaches show promise in allowing inertial navigation systems to learn and optimize their performance in real-time, adaptively, based on sensor measurements and environmental variables. Inertial navigation systems can attain previously unheard-of levels of accuracy, dependability, and autonomy across a broad range of applications by utilising machine learning.

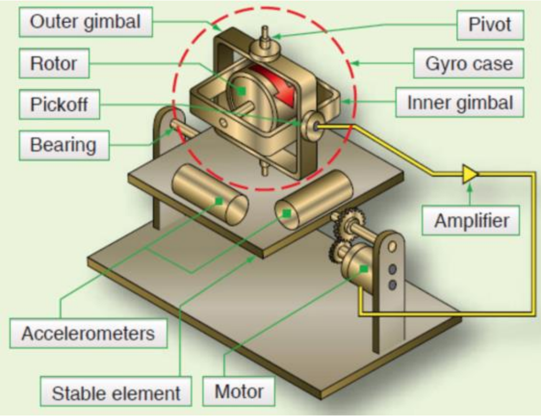

Figure 2 The Working Principle of Inertial Navigation System (https://wiki.ivao.aero/training/stable_platform.png)

Lidar Navigation

The basic idea behind lidar technology is that a laser beam is sent into its environment by a lidar sensor, and when the beam bounces back off an item, the sensor detects the reflection (Farzadpour, 2018; Gast, 2008; Weerasinghe, 2023; Zhang et al., 2022) . The precise distance between the robot and the object can be determined by timing how long it takes the laser beam to travel to it and back to the sensor. These distance data are used to establish safe navigation paths, create precise maps of the surroundings, and determine the position of the robot. The capacity of lidar sensors to gather precise geometric data about the surroundings is one of their primary benefits. This covers specifics like the form of the wall, where obstacles are, and how the furniture is arranged. Lidar navigation is useful both indoors and outdoors because, unlike other sensing techniques, it is unaffected by variations in lighting. Lidar sensors can create extremely detailed maps of the surroundings by merging data from several laser scans; these maps are an invaluable resource for robot navigation systems. With the aid of these maps, robots can effectively and precisely carry out activities like route planning and obstacle avoidance in intricate and dynamic situations.

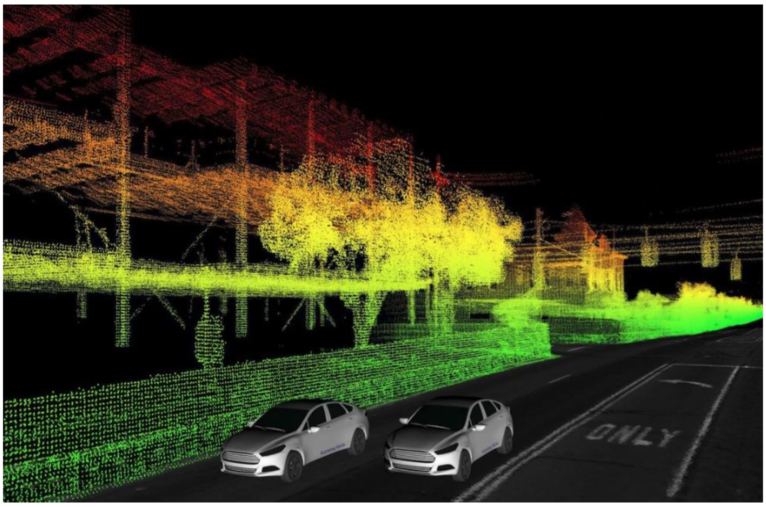

Figure 3 Lidar in Action (https://smartcdn.gprod.postmedia.digital/driving/wp-content/uploads/2021/06/AV-Data-3-scaled-1.jpg?quality=90&strip=all&w=1200&h=675&type=webp&sig=agQKxpK6m6eVRc6lFBbsHA)

Robotics relies heavily on lidar navigation to pinpoint its exact location in its surroundings. This is typically accomplished by applying sophisticated algorithms like "self-localization" or "SLAM" (Simultaneous Localization and Mapping), which make use of Lidar data to compare the robot's perceived environment to an already-created map in order to achieve precise localization. Numerous sectors and businesses, including as automated manufacturing, logistics, agriculture, autonomous vehicles (AV), medical devices, and more, use lidar navigation. Lidar navigation offers navigation solutions with excellent precision, dependability, and adaptability in each of these areas. Lidar navigation makes it possible for robots to navigate precisely across automated production environments, effectively completing activities like material handling, assembly, and quality inspection. Robot efficiency and throughput can be increased by having robots navigate complex production lines with minimal human intervention thanks to Lidar-based localization and mapping algorithms. Lidar navigation is crucial to order fulfilment and inventory management in logistics. Robots with Lidar sensors are able to navigate warehouse aisles, find inventory, and move objects with efficiency and accuracy. This lowers mistakes, streamlines logistics processes, and boosts productivity all around. Lidar navigation is a technology used in service robotics that allows robots to function independently inside buildings like malls, hospitals, and offices. These robots require little human assistance to complete a range of jobs, such as deliveries, cleaning, and customer support. By utilizing Lidar-based localization and mapping skills, service robots can enhance their usability and effectiveness in daily life by adjusting to changing settings and interacting with people in a safe manner. Lidar navigation systems are used in agriculture to enhance precision farming techniques like yield estimation, crop monitoring, and autonomous tractor navigation. Lidar-equipped agricultural robots are able to improve crop yields and resource efficiency by precisely mapping terrain and determining agricultural conditions. Furthermore, robots can function precisely and dependably in difficult outside conditions thanks to Lidar navigation (Goodin et al., 2021; Michaud, 2016; Morales et al., 2009; Urmson et al., 2006). Lidar navigation technology is essential to the unmanned vehicle (AV) industry for attaining effective and safe autonomous navigation. When maneuvering through intricate urban areas, autonomous vehicles (AVs) can make well-informed decisions thanks to the precise 3D depiction of the surrounding environment provided by lidar sensors. Lidar navigation systems are utilised in the medical device industry to enhance procedure accuracy and safety through patient monitoring, medical imaging, and surgical navigation. All things considered, Lidar navigation technology holds enormous promise for revolutionizing localization and navigation across industries, paving the way for future advancements in automation, efficiency, and creativity. The development of algorithms and ongoing advancements in sensor technology will make Lidar navigation systems more advanced, dependable, and adaptable in the future. This will create new avenues for the use of autonomous systems and robotics in many facets of our daily life.

Visual Navigation

One essential navigational approach based on computer vision is visual navigation. The goal of visual navigation, a significant navigational strategy based on computer vision technology, is to provide robots, self-driving cars, and other autonomous systems the ability to comprehend their surroundings via visual sensors (Lebrun, 2019; Tang et al., 2022; Yang, 2021). This enables them to independently ascertain their position, devise the best routes, and dodge obstacles. Essentially, visual navigation makes use of photos or video streams of the surrounding area, which are then analyzed by computer vision algorithms to identify significant elements like objects, landmarks, and reference points. Accurate autonomous navigation in both indoor and outdoor areas is made possible by these navigation systems by comparing this data with maps or stored visual data. The advancement of visual navigation has been fueled by developments in deep learning, computer vision, and sensor technologies, which have created enormous prospects in the automation, robotics, and autonomous vehicle domains. Numerous industries, including autonomous vehicles, unmanned aerial vehicles (UAVs), logistics, medical robotics, industrial automation, and automated agriculture, have adopted visual navigation. For instance, cameras and vision sensors in driverless automobiles enable the vehicle to gather real-time road data, make deft driving decisions, and accomplish autonomous navigation. Visual navigation aids in order fulfilment and warehouse management optimization in logistics. In the meantime, autonomous farming equipment is guided by visual navigation in automated farming, resulting in higher crop yields and more resource efficiency.

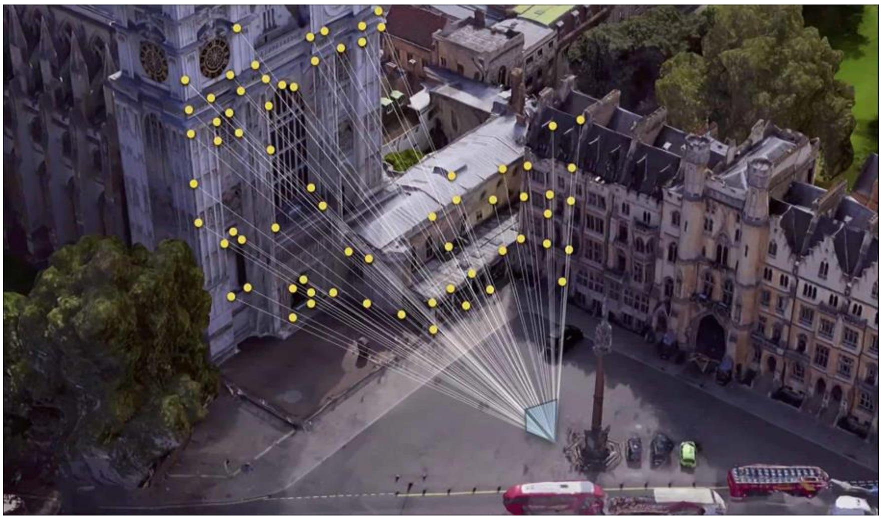

Figure 4 Visual Navigation System (https://www.geospatialworld.net/wp-content/uploads/2023/01/vps-camera-Google-IO-2018.jpg)

Additionally, visual navigation is essential for search and rescue missions because it enables unmanned systems to discover victims, navigate challenging terrain, and provide effective assistance (Naidoo et al., 2011). However, there are a number of obstacles this technology must overcome, such as complicated settings, changing lighting conditions, and the requirement for reliable real-time data processing. Nonetheless, visual navigation systems are growing more potent as deep learning methods and computer vision research continue to progress. With further development, visual navigation will be ready to take on new problems, spurring innovation and offering significant advantages for intelligent manufacturing, smart cities, and autonomous systems. Visual navigation will be crucial in determining the automation and robotics environment of the future through ongoing research and development, bringing in an era of previously unheard-of technical advancement and creativity.

GPS Navigation

One technical innovation that is revolutionizing global navigation and position tracking is the Global Positioning System (GPS) (Aporta & Higgs, 2005; Kumar & Moore, 2002). GPS was first created by the US Department of Defence and is now well known for its unparalleled precision and dependability. A constellation of satellites orbiting the Earth and transmitting signals to pinpoint exact location coordinates is the fundamental idea behind GPS navigation. Due to these benefits, GPS navigation is now a necessary component of many different industries and sectors' navigation systems. GPS is extensively utilized in the transportation industry, since ground vehicles, aircraft, and ships are outfitted with this technology to facilitate navigation. For real-time route assistance, traffic congestion avoidance, and trip optimization, drivers rely on GPS units installed in their vehicles or GPS applications downloaded to their smartphones. GPS aids in safe navigation and accurate landings in aviation. GPS has a significant impact on military operations, missile guidance, and people positioning. Furthermore, GPS enhances safety, efficiency, and precision in a range of civil operations, including mapping, precision agriculture, outdoor adventure, and drone navigation. Nevertheless, in populated or metropolitan regions, multipath signal interference poses a difficulty to GPS. Research is still being done to increase the precision and dependability of GPS systems in order to combat this. GPS navigation is expected to continue evolving and play a bigger and bigger part in satisfying the needs of contemporary navigation systems in the future. The efficiency and efficacy of navigation will increase significantly with the integration of GPS with sectors like smart cities and intelligent transportation systems. As GPS technology develops, we can anticipate increases in precision, dependability, and immunity to interference, which will elevate GPS navigation and revolutionise how we place ourselves in the world.

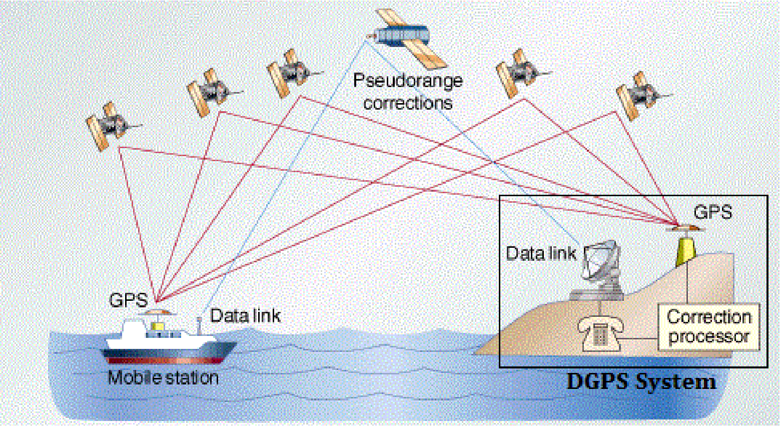

Figure 5 GPS Working Principle (https://marinegyaan.com/wp-content/uploads/2016/06/dgps-1.gif)

Research Method

Deep Learning Navigation

At the nexus of artificial intelligence and deep learning, Deep Learning Navigation is a state-of-the-art technology that seeks to enhance the perceptual and navigational capacities of machines and autonomous systems (Kaur & Gill, 2019; Nasrallah et al., 2024; Olugbade et al., 2022; Sharma et al., 2023). This technology, which makes use of neural networks and deep learning algorithms, revolutionises applications in fields like autonomous cars, drones, robots, and virtual reality by enabling machines to navigate complex situations with a high degree of intelligence and precision. In essence, Deep Learning Navigation processes sensory data, including pictures, LIDAR scans, and other sensor data, using neural networks to provide a thorough understanding of the surrounding environment. Deep learning models automatically extract features and patterns from sensory input by learning from large amounts of data. This allows machines to recognise their location, identify impediments, and determine the best course of action. These models also facilitate automated decision making, which enables robots to move autonomously with previously unheard-of efficiency and safety and to react in real-time to changes in their surroundings. Applications for deep learning navigation can be found in many domains, including autonomous cars. In the realm of autonomous vehicles, this technology allows cars to comprehend the state of the road, identify traffic signals, identify other cars and pedestrians, and make the right driving judgements to guarantee a safe and effective navigation experience. The same is true for drones, which navigate complicated situations by using this technology to maintain exact locations and avoid obstructions. Mobile robots employ Deep Learning Navigation both indoors and outdoors to automate various duties such as deliveries, patrols, and warehousing operations, ultimately leading to increased production and operational efficiency. A new era of intelligent navigation and environmental perception could be ushered in by the creative method of Deep Learning Navigation, which has the potential to greatly enhance the capabilities of autonomous systems and machines. Deep learning algorithms and sensory data processing are used in this technology to allow machines to navigate independently with previously unheard-of accuracy and adaptability, opening the door for revolutionary advancements in automation and machine intelligence. In general, Deep Learning Navigation is a cutting-edge technology that affects a wide range of sectors and businesses, creating new avenues for machine learning and automation innovation.

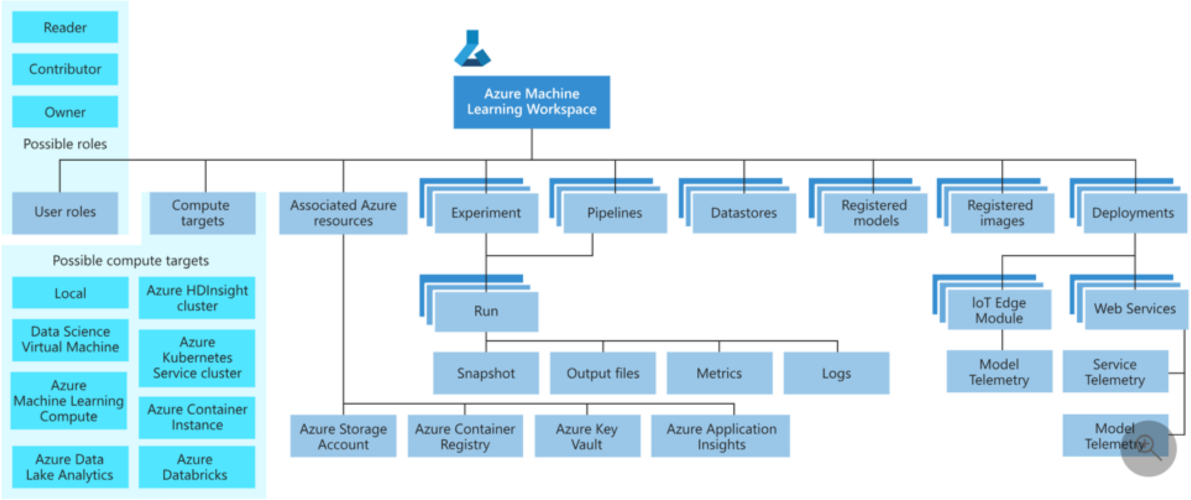

Figure 6 Deep Learning Architecture (https://learn.microsoft.com/en-us/previous-versions/azure/batch-ai/media/overview-what-happened-batch-ai/azure-machine-learning-service-heirarchy.png)

Navigation Algorithm Commonly Used for Robotic

In the discipline of robotics, navigation algorithms are essential to allowing robots to travel around their environment on their own, avoid obstacles, and efficiently accomplish missions. These algorithms form a crucial basis for robotic systems, providing precise and dependable guidance while the robot navigates a variety of situations. Robots that are equipped with navigation algorithms are able to perceive their environment, make the best use of their sensors, and navigate through a variety of activities. Algorithms for navigation are primarily concerned with enabling robots to precisely identify their own location within their surroundings in the discipline of robotics, navigation algorithms are essential to allowing robots to travel around their environment on their own, avoid obstacles, and efficiently accomplish missions. These algorithms form a crucial basis for robotic systems, providing precise and dependable guidance while the robot navigates a variety of situations. Robots that are equipped with navigation algorithms are able to perceive their environment, make the best use of their sensors, and navigate through a variety of activities. Algorithms for navigation are primarily concerned with enabling robots to precisely identify their own location within their surroundings. The robot can move precisely because localization methods enable it to determine its position in relation to a map or known coordinate system. Techniques like odometry, which records a robot's movement using wheels or inertial sensors, and sensor fusion, which integrates data from several sensors to more precisely estimate a robot's position, are frequently used in this procedure. Following localization, the optimal path from the robot's present location to the intended destination—while avoiding obstacles—is ascertained using a route planning algorithm. To determine a safe and effective path, the route planning algorithm takes into account variables including robot kinematics, ambient circumstances, and dynamic impediments. The techniques employed include sampling-based approaches (Bhattacharya, 2010; Cohen et al., 2010; Khalidi et al., 2020) like Rapidly-exploring Random Trees (RRT), optimization-based approaches (Li et al., 2012) like potential field methods and genetic algorithms, and search-based approaches like A* and D* algorithms. Furthermore, the navigation system integrates obstacle avoidance strategies to guarantee the robot's security while navigating its surroundings. With the help of this method, the robot is able to identify obstacles in its immediate environment and avoid collisions by evading them. Obstacle avoidance algorithms identify impediments and compute evasive actions in real-time using sensor data from devices like laser rangefinders, depth cameras, and ultrasonic sensors. Reactive techniques like potential fields and artificial potential fields, as well as model-based techniques like predictive control and dynamic programming, are frequently employed. Furthermore, mapping and map creation techniques are frequently integrated by navigation algorithms to create and update a representation of the robot's environment. A robot can map an unknown area and concurrently determine its position within it thanks to the Simultaneous Localization and Mapping (SLAM) technique. The SLAM system builds a map bit by bit and estimates the robot's position in relation to it using sensor input, including images from cameras and laser scans. Through constant map updating, the robot can adjust to changes in its surroundings and manoeuvre efficiently in a dynamic setting. Learning-based navigation algorithms have emerged as a consequence of advances in artificial intelligence and machine learning in recent years. These methods allow robots to learn navigation behaviour through experience using data-driven techniques like deep reinforcement learning and imitation learning. Learning-based navigation algorithms are able to learn complicated navigation abilities and adapt to various situations with minimum human intervention, thanks to training on massive sensor datasets and expert demonstrations. All things considered, navigation algorithms are a crucial part of robotic systems since they enable autonomous robot operation in a range of real-world situations. Robots can navigate well in a range of environments, including industrial and outdoor ones, thanks to navigation algorithms that include localization, route planning, obstacle avoidance, map development, and learning-based techniques. Navigation algorithms will play a bigger role as robotics develops, allowing robots to accomplish more complicated jobs and engage with their surroundings in a safe and intelligent manner.

Global and Local Path Planning Algorithm

The two primary components of navigation systems that allow robots to navigate effectively and securely in ever-changing surroundings are global and local path planning. Finding the optimal route for a robot to take in the environment from its starting point to its destination is known as global path planning (N Buniyamin et al., 2011; Jaillet et al., 2010). This procedure takes into account the whole environmental context and seeks to identify the best path, cutting down on travel time, distance, or energy use while also avoiding obstructions and adhering to preset guidelines. Usually done offline or in the initial phases of operation, global path planning enables the robot to choose a high-level route prior to completing its navigational tasks. Graph-based algorithms like Dijkstra or A*, which operate on a discretized representation of the environment like a grid or road map, are frequently used in global path planning techniques. In order to determine the best route from point A to point B, this algorithm looks for connections between adjacent cells or nodes and assesses the transition costs between them. Algorithms for global path planning take into account variables including user choices or constraints, dynamic impediments, terrain features, and stationary barriers. The robot is given a set of waypoints or trajectory segments that specify the intended course once the global path has been computed. After that, the robot follows this global path using local navigation algorithms, adjusting its motions in response to real-time sensor feedback and avoiding unforeseen obstructions or changes in the surrounding environment. Local path planning (Norlida Buniyamin et al., 2011), sometimes referred to as reactive or short-range planning, on the other hand, is in charge of creating collision-free trajectories in real time while concentrating on the robot's immediate surroundings. Local route planning uses a local map that is centred on the robot's current position, as opposed to global path planning, which takes the entire environment into account. To maintain robot safety and agility, local path planning algorithms need to be computationally economical and quick to react to changes in the surrounding environment. Usually, these algorithms identify surrounding objects and provide a path free of collisions by utilising sensor data from cameras, sonar, or laser scans. Reactive methods like Dynamic Window Approach (DWA) or Vector Field Histogram (VFH), which assess potential trajectories based on the robot's dynamics and the position of surrounding obstacles, are also commonly used. Potential field methods pull the robot to a goal position while being avoided by obstacles. In order to ensure that the robot can avoid obstacles and follow the planned course, local path planning is used in conjunction with global path planning, which provides a high-level route to the target.

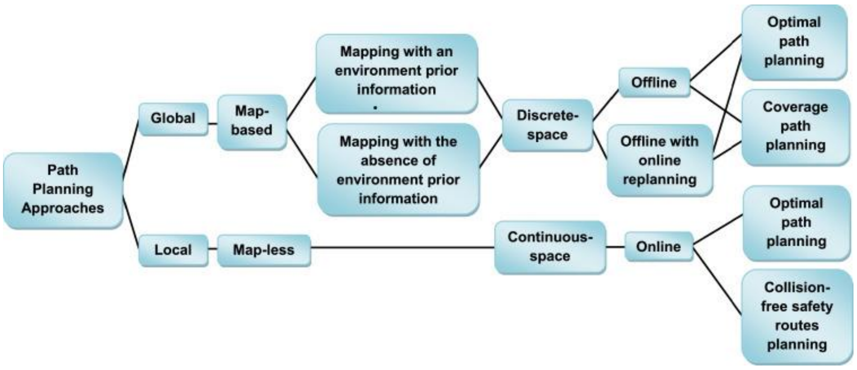

Figure 7 Global and Local Path Planning (Liu et al., 2023)

Behavior-Based Movement in Robotic Navigation

Robot navigation algorithms that use behavior-based movement describe an approach that lets a robot communicate with its surroundings by following a predetermined set of rules or behaviours. Behavioural locomotion centres on breaking down a robot's control system into discrete behaviours, each of which is in charge of carrying out a particular task or action. This is in contrast to traditional navigation systems, which rely on centralised planning to construct full trajectories. Robots can exhibit adaptive and robust navigation capabilities appropriate for dynamic and uncertain situations by integrating and coordinating these behaviours based on sensory input and environmental cues. The fundamental ideas of behavior-based movement are parallel execution, sensor action mapping, modularity, and hierarchical control. Additionally, typical robotic behaviour includes:

1. Obstacle Avoidance: A key behaviour in behavior-based navigation is obstacle avoidance, in which a robot uses sensors like sonar or laser rangefinders to identify obstructions in its path and then modifies its trajectory to avoid collisions.
2. Goal Seeking: This is an additional behaviour in which the robot moves in the direction of a predetermined objective. To lead the robot to its destination, methods like gradient descent or vector-based navigation may be used.
3. Wall Following: Wall following is the behaviour when a robot moves over a small area while keeping a constant distance from walls or other barriers. This facilitates the robot's effective navigation of hallways and other maze-like settings.
4. Exploration: To acquire data and make maps, the robot that exhibits exploratory behaviour is encouraged to investigate new or uncharted regions of its surroundings.

This could entail using methodical or haphazard exploring techniques to explore the entire terrain.

5. Collision Recovery: By turning or changing its path to avoid obstacles, collision recovery behaviour enables the robot to recover from unanticipated collisions or disturbances.

Result and Discussion

Path Tracking and Its Commonly Used Algorithms

Robot movement is primarily controlled by path tracking navigation; it is crucial to guide the robot along a predetermined path while maintaining accurate trajectory tracking in real-time. This procedure enables the robot to navigate through diverse settings on its own, adhering to predetermined routes, accomplishing predetermined goals, or dodging obstructions. Robotic systems depend on path tracking algorithms to keep their intended direction in the face of disruption, uncertainty, and shifting environmental variables. It consists of components including reference pathways that establish the intended trajectory, feedback control that modifies the robot's motion in response to sensors, and control laws that provide the necessary actions to accomplish the desired movement. Proportional-Derivative (PD) and Proportional-Integral-Derivative (PID) control techniques are two of the many control strategies included in general route tracking algorithms. route tracking navigation typically employs PD control, a direct method in which control inputs are computed based on the discrepancy between the robot's actual state and the desired state indicated by the reference route. In PD control, derivative factors help reduce oscillations and improve movement stability while proportional factors push the robot in the direction of the intended trajectory. In the meantime, PID control improves tracking precision and removes steady-state errors by expanding the idea of PD control with integral terms. PID control is widely used in robotics because to its adaptability, durability, and efficiency across a range of application scenarios.

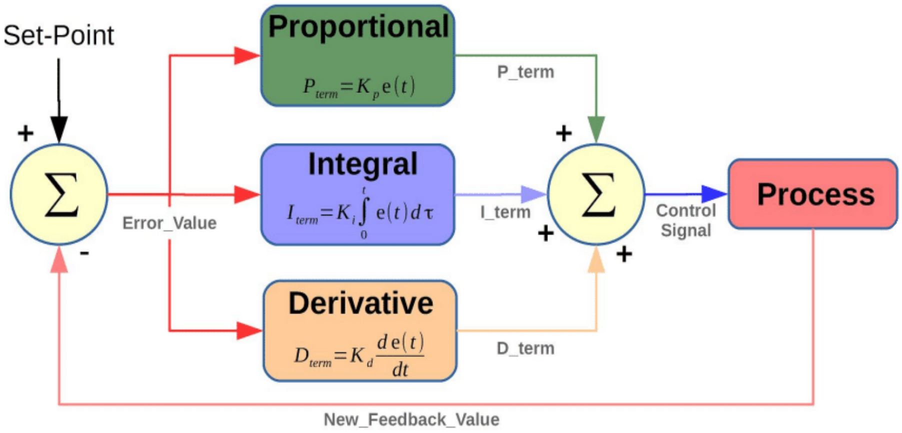

Figure 8 Working Principle of PID Controller

(https://www.researchgate.net/publication/345362064/figure/fig60/AS:954795997294593@1604652513067/3-b-illustrates-the-main-working-principle-of-the-PID-controller-which-substitutes-the.ppm)

Additionally, Proportional-Integral-Derivative (PID) Controllers can be substituted by Model Predictive Control (MPC). MPC is a more advanced control method that arranges control inputs within a preset time window by using predictive models of robot dynamics. The MPC method, which takes into consideration limits on control inputs and system dynamic features, predicts how robot settings will change in the future and optimizes control input adjustments to minimize tracking mistakes.

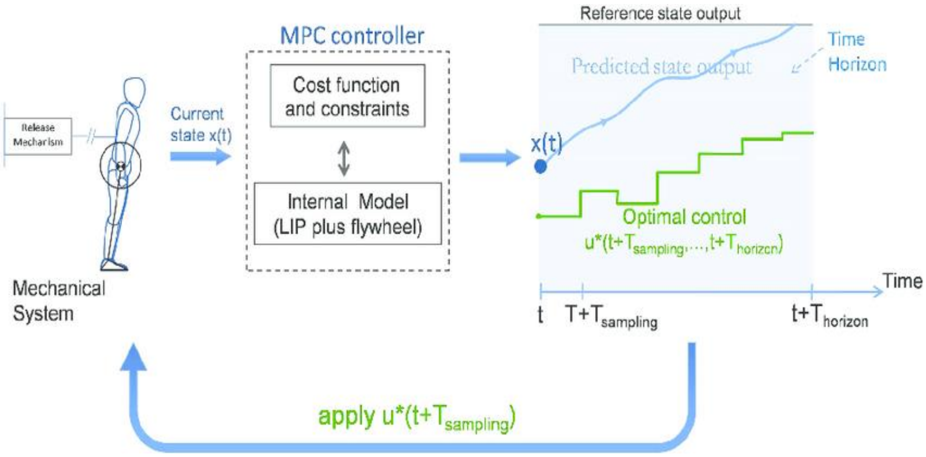

Figure 9 MPC Working Principle (Aftab et al., 2016)

One of the key pillars in the development of mobile robotics navigation systems is now the Pure Pursuit Algorithm. In this situation, having sufficient route followers is essential to guaranteeing precise and effective robot movement. In particular, this method uses a geometric approach that enables the robot to reliably and precisely follow a predetermined course. The idea of pursuit points, in which the robot is guided towards specific predefined spots along a reference path, is given priority in this approach. These markers are positioned strategically to guarantee that the best possible path is formed for robot navigation. Furthermore, this procedure is updated on a regular basis, enabling suitable modifications according to the robot's actual situation. Consequently, this algorithm generates dynamics that are adaptable and versatile, which is crucial for handling changes in the surrounding environment or in the state of the road. These algorithms frequently prove to be a solid basis for the creation of dependable and effective navigation systems. Different iterations of the Pure Pursuit algorithm have surfaced as technology progresses, with the Stanley Controller being one of the most notable. By using lateral error feedback, the Stanley controller innovates and enhances tracking performance, particularly in complicated environmental scenarios with changing road conditions or slippage. By utilising this input, the Stanley controller cleverly modifies the robot's steering angle, guaranteeing that it maintains a high level of accuracy while staying on course. The capacity of the Pure Pursuit algorithm and its variants to combine data from several sensors is a crucial feature. Many sensors that can offer information about position, direction, and the circumstances of the path are built into modern robots. Algorithms can use this data to make intelligent, flexible navigation decisions in real time. Furthermore, there are several uses for the Pure Pursuit algorithm across a range of industries. These algorithms can be utilized by industrial robots to navigate along production lines, improving factory operations' dependability and efficiency. Robots using the Pure Pursuit algorithm can perform a variety of jobs in the service industry, including security patrol and delivery of commodities. In actuality, this algorithm directs spacecraft motion along the mission path during space exploration. Therefore, research and development in the field of mobile robotics continue to be heavily focused on the Pure Pursuit algorithm and its modifications, such as the Stanley Controller. They are a widely sought-after option in many different applications because of their capacity to offer accurate and flexible navigation. It is intended that by keeping these algorithms improved and developed, they will continue to be a major factor in the future development of robotics technology.

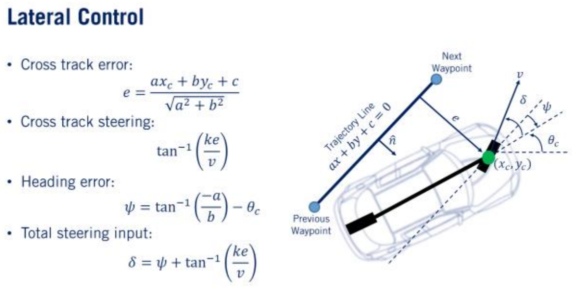

Figure 10 Stanley Controller Working Principle (https://i.stack.imgur.com/nixfE.png)

Robots cannot follow predetermined trajectories on their own; accurate, real-time trajectory tracking is dependent on path tracking navigation algorithms. These algorithms make sure that robots can reliably and precisely navigate across complex surroundings and accomplish desired navigation objectives by combining mathematical models, sensor data, and feedback control.

Localization and Simultaneous Localization and Mapping (SLAM) in Robotic

Fundamental ideas in robotics, localization and simultaneous localization and mapping (SLAM) are necessary for allowing robots to move around and interact with their surroundings on their own. While SLAM includes creating an environment map and localizing the robot inside it, localization is the act of figuring out a robot's location and orientation in relation to its surroundings. Robotic systems utilize diverse theoretical frameworks and algorithms to get precise and resilient localization and self-localization and mapping (SLAM) capabilities.

Localization:

Estimating a robot's posture, or position and orientation within its surroundings, is known as localization. Usually, sensor data from GPS, inertial measuring units (IMUs), odometry, and external landmarks are used. Key theoretical stances and localization algorithms include the following:

1. Bayesian Filters: In robotics, Bayesian filters are frequently utilised for localization. Examples of these filters are the Kalman Filter and the Extended Kalman Filter (EKF). By using motion models and sensor readings to update the belief about the robot's position over time, these filters preserve a probability distribution over its posture.
2. Particle Filters: Particle filters use a collection of particles, each of which represents a hypothesis regarding the robot's position, to represent the robot's pose. They are also referred to as Monte Carlo localization or the Particle Filter Localization (PFSLAM). Robust localization is made possible in nonlinear and multimodal environments by these particles, which propagate and update in response to sensor readings.
3. Graph-Based Techniques: Localization is formulated as a graph optimisation problem using graph-based techniques like Pose Graph Optimisation. They use a graph to depict the robot's journey, where nodes stand for the robot's poses and edges for constraints imposed by sensor readings. The robot's trajectory and posture estimates are estimated using optimisation techniques like nonlinear least squares.
4. Methods Based on Features: Keypoints in photos or landmarks in 3D point clouds are examples of distinguishing elements that feature-based localization techniques find and match in sensor data. Robot localization is made possible in surroundings with few and distinct landmarks by employing techniques such as Iterative Closest Point (ICP) and Feature Matching to estimate the robot's pose in relation to these features.

Simultaneous Localization and Mapping (SLAM):

Building a map of the surroundings and concurrently localizing the robot within it is known as simultaneous localization and mapping (SLAM) (Aftab et al., 2016). It solves the paradox of needing precise localization in order to generate a map, but also needing a map in order to localise accurately. SLAM techniques use sensor data to estimate the robot's pose while iteratively building and updating the map. The main theoretical models and SLAM algorithms are as follows:

1. The first is Extended Kalman Filter SLAM (EKF-SLAM), which extends the EKF to estimate the robot's pose and map features' locations at the same time. By updating the belief with sensor readings and motion models, it preserves a joint probability

distribution across the robot's stance and the map. Small to medium-sized locations with well-known landmarks are a good fit for EKF-SLAM.

2. FastSLAM: FastSLAM is a particle filter-based SLAM technique that maintains a local map of features and their corresponding likelihoods for each particle in the map. It splits the SLAM problem into two components: localization by particle filtering and mapping via local map updates. FastSLAM can withstand non-Gaussian sensor noise and is effective for large-scale mapping.
3. 3. Graph-Based SLAM: SLAM is formulated as a graph optimisation problem using graph-based SLAM techniques like GraphSLAM and Pose Graph Optimisation. They uphold a graph structure in which robot poses and landmark locations are represented, and edges denote spatial limitations obtained from sensor readings. To estimate the robot's trajectory and improve the map, optimisation techniques are applied.
4. 4. Visual SLAM: To create maps and locate the robot, visual SLAM techniques use visual sensor data, such as pictures or video clips. Feature-Based SLAM and Direct SLAM are two methods that use sensor data to extract visual features and estimate the camera posture in relation to those characteristics. Visual SLAM may give precise localization and mapping under a variety of circumstances, and it works well in situations with a wealth of visual input.

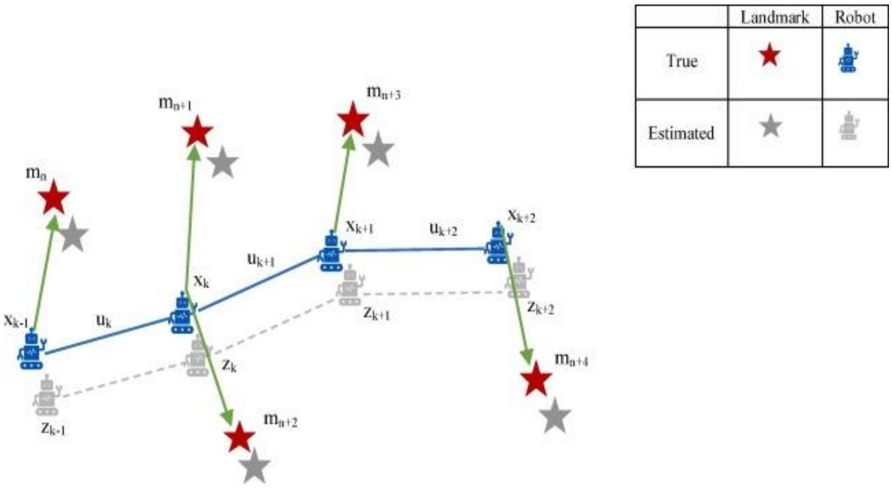

Figure 10 Solving SLAM Principle [59]

Application of Navigation Technology

In the manufacturing sector, navigation is essential for streamlining procedures, increasing productivity, and guaranteeing the seamless completion of several jobs. In manufacturing facilities, mobile robots with navigation systems are being used more frequently for a variety of tasks, such as assembly, quality control, inventory management, and material handling. The following are some significant uses of navigation in the industrial industry:

Material Handling and Transportation:

Mobile robots with navigation systems can move components, finished goods, and raw materials between workstations in manufacturing facilities on their own. In order to minimise bottlenecks and streamline material flow, these robots can either dynamically plot routes or follow established courses in order to avoid impediments and maximise travel durations.

Figure 11 Material Handling Robot (https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcR9WICuS7GRmSEFS-lL43NTx8XVkJZvpHbvpMA1uq_ywA&s)

Inventory Management:

Mobile robots with navigational capabilities can move around storage and warehouse spaces and carry out inventory management duties like finding products, restocking shelves, and counting inventories. These robots assist minimize stockouts, increase order fulfilment rates, and maximize storage space utilization by effectively controlling inventory levels and guaranteeing correct stock information.

Figure 12 Inventory Management Robot (https://assets-global.website files.com/64232ccc44af581c3ee445bd/659b9bd777b008b56bd46af1_Screenshot%202024-01-08%20at%2014.53.00.png)

Assembly and Production:

Robots with navigation capabilities are used on assembly lines to carry out jobs like product assembly, component installation, and part delivery. These robots are able to accurately go to the desired spot on the assembly line, which guarantees smooth component integration and productive production procedures. Manufacturers can increase output, lower errors, and improve product quality by automating repetitive assembly operations.

Figure 13 Assembly Robot (https://assets.robots.com/general/Assembly_Line_Robots.png)

Quality Inspection:

Mobile robots having sensing and navigational capabilities can move along manufacturing lines to verify manufactured parts and completed goods for quality. These robots are able to verify adherence to standards and specifications by checking dimensions, surface flaws, and other quality parameters. Manufacturers can enhance overall product quality, minimize rework, and identify flaws early by automating quality inspection operations.

Workstation Assistance:

Robots with navigation capabilities can support humans at different manufacturing plant workstations. Collaborative robots with navigation systems, for instance, can help with ergonomically difficult activities, support workers lifting large weights, and transfer tools, components, and materials to assembly stations. These robots improve workplace safety, ergonomics, and productivity when they operate alongside human operators.

Logistics and Material Flow Optimization:

In order to maximize logistics and material flow in industrial plants, navigation systems are essential. When given the ability to navigate, mobile robots can adjust their routes dynamically in response to changes in traffic, inventory levels, and production demands in real time. Lead times, production costs, and overall operational efficiency can all be decreased by manufacturers through the optimization of material flow and logistics processes.

As a result, navigation technology is essential to raising manufacturing sector productivity, flexibility, and efficiency. Mobile robots with navigation systems allow for the automation of a wide range of operations, increase quality control, simplify the flow of materials, and assist human operators in their work. Navigation technology will continue to be a vital component of industry innovation and competitiveness as production processes change.

Figure 14 Logistic Robots

(https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcSeKlmsjOC_HmbhRhzXEQy3z0TiutjniboiZqds3lKMrg&s)

Conclusions and Future Work

The field of mobile robot navigation and positioning technology is well-positioned for ongoing development and gradual improvement due to the rapid advancements in sensing, electronic, computer network, control, information processing, machining, and new materials technologies. Navigating mobile robots in an increasingly complex movement environment with expanding functions will likely lead to various important avenues for navigation technology development.

First, a concentrated effort will be made to improve conventional navigation algorithms. Given the current algorithms' shortcomings, further work must be done to improve and optimise them in order to increase the safety, accuracy, and responsiveness of robot navigation in real time. Researchers want to clear the path for more dependable and efficient navigation systems that can easily travel through complex surroundings by resolving the flaws in conventional algorithms.

Second, the use of multimodal perception in robot navigation is becoming more and more popular. This entails outfitting robots with a variety of sensors at once, such as lidar, cameras, and ultrasonic sensors, in order to acquire a thorough awareness of their environment. Robots can improve the robustness and reliability of their navigation systems by utilising a wide range of sensory inputs to improve their perception capabilities. Robots can navigate more skillfully in dynamic and unexpected settings where traditional sensor modalities might not be sufficient because to this multimodal approach to perception.

Furthermore, increases in the functionality of sensing devices like lidar, cameras, and ultrasonic sensors are anticipated as a result of advances in sensing technology. Higher resolution, greater coverage, and more accurate data collecting capabilities will be the outcomes of these improvements, giving robots the ability to gather more detailed information about their environment. Robots will be better able to travel across difficult terrain, avoid obstacles, and adjust to changing environmental circumstances with greater confidence and precision if they have access to superior sensory data.

Furthermore, mobile robot navigation is about to undergo a revolutionary change thanks to the widespread deployment of deep learning and machine learning technology. Robots can improve perception of their surroundings, target recognition, and path planning by utilising artificial intelligence. Robots can now analyse massive volumes of data, identify important patterns, and make defensible conclusions based on current inputs as well as historical data thanks to deep learning algorithms. Robots can now navigate autonomously in complex and dynamic situations where traditional rule-based methods might not be sufficient thanks to this adaptive and data-driven approach to navigation.

In summary, the subject of mobile robot navigation is going through a major transition that is being fueled by developments in computer power, artificial intelligence, and sensing technology. Through the use of these technical advancements, scientists are well-positioned to create more resilient, adaptable, and next-generation navigation systems. These developments could revolutionize industries and improve human-robot interaction by enabling robots to operate autonomously in a variety of settings, including outdoor and urban areas, warehouses, and manufacturing facilities.

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