International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048
Volume 9, Issue 5, pp 434-441, May-2025
https://doi.org/10.47001/IRJIET/2025.905048

A Review of Artificial Intelligence, Machine Learning, and Deep Learning in Advanced Robotics

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***Abstract* - Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL) have significantly transformed the field of advanced robotics, making robots more intelligent, efficient, and adaptable to complex tasks and environments. These technologies enable key capabilities such as autonomous navigation, object recognition and manipulation, natural language processing, and predictive maintenance. AI, ML, and DL are also instrumental in developing collaborative robots (cobots) that can work alongside humans and adjust to dynamic environments and tasks.**

Beyond robotics, these technologies play a vital role in enhancing transportation systems by improving safety, efficiency, and passenger convenience. In manufacturing, they enable assembly robots to operate with greater precision, safety, and intelligence. Additionally, AI-driven advancements in aviation management help optimize operations, reduce costs, and enhance customer satisfaction. In the taxi industry, these technologies contribute to safer, more efficient, and customer-friendly services.

This research provides an overview of the current developments and diverse applications of AI, ML, and DL in advanced robotics, highlighting their impact across multiple sectors. It also identifies areas for further study to bridge the gaps in existing research, aiming to improve robotic performance and drive productivity in the robotics industry.

Keywords: Artificial intelligence, Machine learning, Deep learning, Advanced robotics.

I. INTRODUCTION

Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL) are foundational technologies in the field of robotics. AI refers to a machine's ability to perform tasks that typically require human intelligence, such as speech recognition, natural language understanding, and decision-making. Through AI, robots can perceive and interact with their environments, make informed decisions, and execute complex tasks. ML, a subset of AI, involves the use of algorithms that enable robots to learn from data and improve their performance over time. In robotics, ML facilitates various functions such as object recognition, grasping, and path planning. DL, a specialized branch of ML, leverages artificial neural networks to process and learn from large datasets. It has been especially effective in tasks like image and speech recognition, natural language processing, and object detection. Together, these technologies have empowered robots to perform a wide array of functions—from basic pick-and-place operations to advanced manipulation and autonomous navigation in unstructured environments. The integration of AI, ML, and DL in robotics holds transformative potential, fostering the development of more intelligent, autonomous, and capable robotic systems. As robotics continues to evolve rapidly, these technologies are expected to remain central to shaping its future.

1. **Object Detection and Recognition:** In robotics, object detection and recognition are vital tasks made feasible through deep learning. By training neural networks on large volumes of labeled data, robots can accurately identify and classify objects in their surroundings.
2. **Predictive Maintenance:** Predictive maintenance leverages AI and machine learning to anticipate mechanical issues before they occur. By analyzing data from sensors and other sources, these algorithms can forecast component failures, enabling timely repairs or replacements.
3. **Gesture and Speech Recognition:** AI and ML also play a key role in gesture and speech recognition. Robots like Pepper can understand and respond to human gestures and speech, making them valuable in fields such as customer service and healthcare [9].
4. **Robotic Surgery:** AI and ML are transforming robotic surgery by enhancing precision and safety during complex procedures. Advanced algorithms assist surgeons by improving accuracy and reducing complications. These systems use AI, ML, and deep learning to optimize surgical performance.
5. **Medical Applications:** Deep learning is especially effective in medical image analysis, capable of detecting subtle patterns and features beyond human perception. This helps clinicians identify early signs of disease. Additionally, machine learning models such as ensemble methods, decision trees, random forests, instance-based

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https://doi.org/10.47001/IRJIET/2025.905048

algorithms, and artificial neural networks are applied to improve drug delivery in the treatment of infectious diseases (Fig. 1).

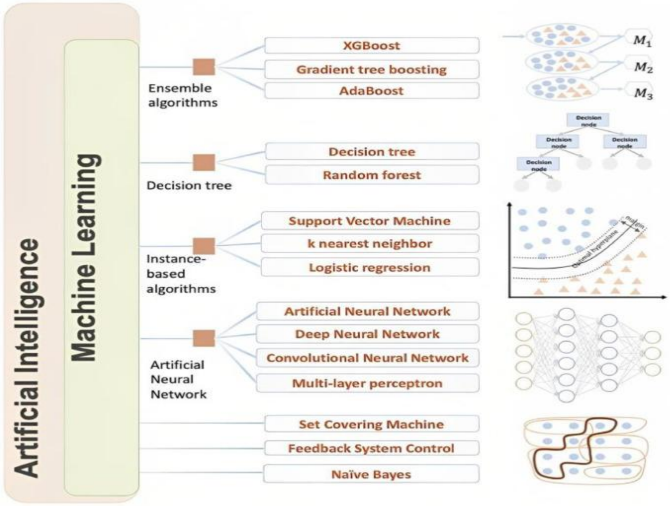

Figure 1: Application of machine learning algorithms in drug delivery for the treatment of infectious diseases

6. **Military Robotics:** Robotics is extensively used in military applications for tasks such as reconnaissance, surveillance, and bomb disposal. AI and machine learning (ML) algorithms support these operations by analyzing sensor data and enabling autonomous or semi-autonomous decision-making based on real-time information.
7. **Agriculture:** AI and ML are transforming agriculture by enabling the development of autonomous robots for tasks like planting, harvesting, and spraying. These technologies optimize farming operations by predicting weather patterns, managing water usage, and monitoring crop health, ultimately increasing efficiency and reducing labor costs.
8. **Service Robotics:** Service robots are designed to assist humans in various domains such as cleaning, food delivery, and customer support. AI and ML empower these robots to interact effectively with users, understand human preferences, and personalize services accordingly.
9. **Autonomous Driving:** Self-driving vehicles rely on AI and ML to navigate roads and make real-time driving decisions. Computer vision systems detect and recognize objects such as pedestrians and traffic signs, while ML models analyze data from sensors, cameras, and GPS to predict traffic patterns and adapt to changing conditions.
10. **Robotics in Manufacturing:** In manufacturing, robotics is used to automate repetitive tasks such as assembly, painting, and welding. AI and ML algorithms improve these operations by enhancing the precision, speed, and adaptability of robotic systems, contributing to increased productivity and reduced operational costs.

II. APPLICATIONS OF AI, ML, AND DL IN ADVANCED ROBOTICS

Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL) are revolutionizing the capabilities of advanced robotics, enabling intelligent decision-making, precision, and adaptability. Below are several key applications and associated performance insights:

1. **Object Recognition:** A foundational task in robotics, object recognition supports autonomous navigation and manipulation. Deep learning models, particularly Convolutional Neural Networks (CNNs), have shown remarkable accuracy in this domain.
2. **Motion Planning:** Motion planning ensures robots move efficiently without collisions. Reinforcement Learning (RL) techniques, such as the Deep Deterministic Policy Gradient (DDPG), have been effective in generating smooth, collision-free trajectories for robotic manipulators.
3. **Control:** Control involves regulating robot movement. Deep Reinforcement Learning (DRL), including algorithms like Proximal Policy Optimization (PPO), has demonstrated significant success in training robots for tasks such as object grasping and transport.
4. **Localization:** Localization determines a robot's position in its environment. ML techniques like Support Vector Machines (SVM) and Random Forests have achieved high accuracy, with some models reporting up to 98.8% success in localization tasks.
5. **Object Detection:** Object detection involves identifying and localizing items in images. DL models such as Faster R-CNN and YOLO have set new benchmarks in detection performance and speed.

AI enables robots to perceive, interpret, and act in real-time environments. ML allows them to learn from experience and adapt to dynamic conditions, while DL empowers them to perform tasks traditionally deemed too complex for rule-based systems.

Programming languages such as Python, C++, MATLAB, and frameworks like ROS (Robot Operating System) support integration of AI, ML, and DL in robotics. Libraries such as TensorFlow and PyTorch are widely used for developing and deploying deep learning models.

Tesla, for instance, applies AI and ML in its Autopilot system for semi-autonomous driving and in its manufacturing lines for enhancing production efficiency and quality control.

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Role of CNC Machining in Robotics

CNC (Computer Numerical Control) machining is vital for the precision manufacturing and maintenance of robotic components. It enables the production of highly accurate and complex parts critical for reliable robotic performance. CNC technology is also indispensable in fabricating replacement parts during maintenance, reducing downtime.

Virtual Machining and Research Advancements

Several studies led by Soori and collaborators highlight significant advancements in virtual machining for robotic systems:

- **Virtual Machining Approaches:** Proposed to simulate and optimize CNC processes before physical implementation.
- **Friction Stir Welding:** Reviews recent developments in welding techniques for improved component manufacturing.
- **Turbine Blade Milling:** Explores virtual machining to reduce stress and deflection during five-axis operations.
- **Cutting Temperature Optimization:** Virtual machining applications help reduce tool temperature and enhance performance.
- **Surface Quality Enhancement:** Improved surface finish through optimized five-axis milling.
- **Parameter Optimization:** Analytical reviews for optimizing machining parameters.
- **RFID in Manufacturing:** Enhances efficiency and traceability across the supply chain.
- **AI in CNC Machines:** Machine learning and AI improve productivity and value in CNC-based production.
- **Residual Stress Reduction:** Reviews strategies to measure and minimize stress during machining.
- **Taguchi Methodology:** Optimizes grinding operations for materials like Inconel 718.
- **Tool Wear Prediction:** Examines techniques to prolong tool life.
- **Computer-Aided Process Planning:** Investigates digital solutions to streamline production workflows.
- **Web-Based Decision Systems:** Discusses decision-making tools for industrial data management.
- **Neural Networks:** Highlights AI uses in product performance, risk analysis, and control systems.
- **Virtual Drilling & AWJM:** Optimizes quality in drilling and water jet machining.
- **Environmental ICT:** Uses tech to reduce ecological impact.
- **Cyber security:** Reviews methods to enhance digital network security.
- **Image Processing:** Discusses AI-driven systems for visual data analysis.

Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL) are revolutionizing the field of advanced robotics by enabling the creation of intelligent systems capable of performing complex tasks with high precision and efficiency. This study presents a comprehensive review of recent developments in the application of AI, ML, and DL in advanced robotic systems. It explores various use cases where these technologies contribute to the enhancement and modification of robotic capabilities. Furthermore, existing gaps in the current body of research are identified and proposed as directions for future investigation. By examining these applications, the study provides insights into how the performance of advanced robots can be evaluated and optimized. Consequently, the integration of AI, ML, and DL into robotic systems can lead to significant improvements in both accuracy and productivity across a range of industrial and technological applications.

III. ADVANTAGES OF AI, ML, AND DL APPLICATIONS IN ADVANCED ROBOTICS

The integration of Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL) into robotics has brought transformative advancements, enabling intelligent automation and enhanced functionality across a range of applications. The following are key advantages of applying these technologies in advanced robotic systems:

1. **Automation of Repetitive Tasks:** AI, ML, and DL enable the automation of repetitive and labor-intensive tasks, allowing human workers to focus on more strategic and creative functions.
2. **Enhanced Accuracy and Precision:** These technologies significantly improve the accuracy and precision of robotic operations, thereby reducing errors and increasing overall system reliability.
3. **Adaptability and Versatility:** AI-powered robots can adapt dynamically to new environments and tasks, making them suitable for a broad spectrum of industries, including manufacturing, healthcare, agriculture, and defense.
4. **Predictive Maintenance:** ML algorithms can analyze sensor data to predict equipment failures before they occur. This proactive maintenance strategy helps minimize downtime and reduces repair costs.
5. **Data-Driven Decision Making:** AI and ML can process and analyze large volumes of data in real-time, enabling

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Volume 9, Issue 5, pp 434-441, May-2025

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robots to make informed decisions and execute optimal actions in dynamic scenarios.

6. **Operational Efficiency:** By optimizing workflows and minimizing waste, these technologies enhance the efficiency of robotic systems, leading to increased productivity and resource savings.
7. **Improved Safety:** The automation of hazardous tasks such as bomb disposal, heavy lifting, or operations in toxic environments reduces risks to human workers and enhances workplace safety.
8. **Cost Reduction:** The deployment of AI and ML in robotics contributes to long-term cost savings through labor reduction, minimized downtime, and optimized resource usage.
9. **Continuous Learning and Improvement:** DL models allow robots to continuously learn from their environments and past experiences, leading to performance improvements over time.
10. **Consistency in Performance:** Unlike humans, robots powered by AI and ML can maintain consistent performance over extended periods, ensuring high-quality outcomes with minimal variation.

Overall, the application of AI, ML, and DL in advanced robotics holds the potential to revolutionize the industry by enhancing performance, reducing operational costs, and opening new frontiers for innovation and safety.

IV. CHALLENGES OF AI, ML, AND DL IN ROBOTICS APPLICATIONS

While AI, ML, and DL have significantly advanced robotics, several critical challenges remain that must be addressed to fully leverage their potential:

1. Data Dependency and Quality:

- AI/ML models require vast amounts of high-quality, labeled data for training. In robotics, obtaining such data can be difficult, costly, and time-consuming.
- Data collected may also be noisy, biased, or inconsistent, negatively impacting model accuracy and generalization.

2. Real-Time Processing Requirements:

- Many robotic applications demand real-time data processing, which is computationally intensive.
- Meeting these requirements often necessitates specialized, high-performance hardware, increasing system complexity and cost.

3. Limited On-Board Computing Power:

- Robots are typically constrained by limited processing power and battery life. Running complex AI/ML/DL models in real-time can strain these resources, reducing performance.

4. Environmental Adaptability:

- Robots must operate in dynamic, unpredictable environments. AI models must therefore be capable of continual learning and adaptation—an ongoing research challenge.

5. Safety and Reliability:

- As robots increasingly interact with humans, ensuring safety becomes paramount. AI algorithms must be robust, able to detect hazards, and make safe decisions in uncertain environments.

6. Sensor and Hardware Integration:

- Accurate perception requires reliable sensor data. The integration of advanced sensors and real-time feedback mechanisms is critical for environment-aware decision-making.

7. Ethical and Societal Concerns:

- Automation raises concerns about job displacement, bias in AI algorithms, and the potential misuse of robots for harmful purposes, such as surveillance or military operations.
- Frameworks are needed to guide responsible AI deployment in robotics.

8. Algorithm Robustness and Transparency:

- Many deep learning models function as "black boxes," making it difficult to interpret or verify decisions—a significant concern in safety-critical applications.

Addressing these challenges requires interdisciplinary efforts combining algorithm development, hardware innovation, safety engineering, and ethical governance.

V. APPLICATIONS OF AI, ML, AND DL IN ADVANCED INDUSTRIAL ROBOTS

AI, ML, and DL have revolutionized industrial robotics, enhancing capabilities in automation, quality assurance, and intelligent decision-making. Key applications include:

1. Quality Control

- AI and DL systems can monitor manufacturing in real time, detecting defects or anomalies without human intervention.

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- Vision-based models (e.g., CNNs) ensure consistent product quality by identifying imperfections during production.

2. Predictive Maintenance

- ML models analyze machine usage data to predict potential failures, enabling preemptive maintenance and minimizing downtime.

3. Autonomous Robotics

- AI-driven robots can function autonomously in complex or hazardous environments where human intervention is limited.
- Such robots can make real-time decisions, navigate obstacles, and perform high-precision tasks.

4. Robotic Assembly

- AI and ML optimize assembly operations, allowing robots to adapt to changing product specifications and environmental conditions.
- Enhanced collaboration with human operators improves flexibility and safety in shared workspaces.

5. Process Optimization

- AI algorithms analyze manufacturing workflows to reduce waste and enhance overall process efficiency.

6. Supply Chain Management

- AI systems predict demand and optimize inventory and logistics operations, reducing cost and ensuring timely material availability.

7. Collaborative Robots (Cobots)

- Cobots use AI to safely share tasks with humans, handling repetitive or hazardous tasks while humans manage complex decision-making.

8. Object Detection and Recognition

- AI and ML enable robots and Automated Guided Vehicles (AGVs) to detect and identify objects within their operational environment, facilitating accurate interaction.

9. Real-Time Decision Making

- AI enables adaptive responses to dynamic changes on the factory floor by interpreting sensor data and making instant decisions.

10. Path Planning and Optimization

- AI algorithms calculate the most efficient routes for robots and AGVs, reducing travel time and boosting operational throughput.

The application of AI and DL in advanced manufacturing processes and robotics is illustrated in Fig. 2. This flowchart highlights a key concept from the perspective of system requirements, emphasizing the importance of evaluating AI technologies to ensure overall objectives are met and to prevent sub-optimization.

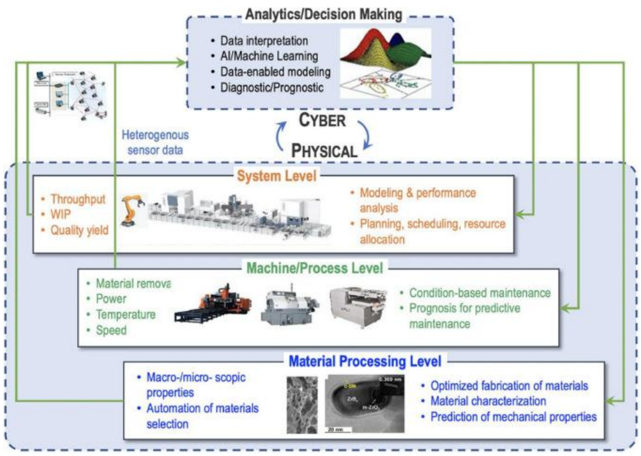

Figure 2: Application of AI and deep learning (DL) in advanced manufacturing processes and robotics

Overall, the use of AI, ML, and DL in advanced industrial robotics has the potential to revolutionize the manufacturing sector by increasing productivity, reducing costs, and enhancing product quality.

VI. APPLICATIONS OF ARTIFICIAL INTELLIGENCE, MACHINE LEARNING, AND DEEP LEARNING IN ADVANCED TRANSPORTATION SYSTEMS

Artificial intelligence (AI), machine learning (ML), and deep learning (DL) are increasingly being integrated into advanced transportation systems to enhance safety, efficiency, and convenience [79]. These technologies are playing a transformative role in a wide range of applications, including:

- **Intelligent Transportation Systems (ITS):** AI-powered ITS solutions contribute to improved traffic flow, reduced congestion, and enhanced road safety. ML algorithms can analyze real-time traffic data and optimize signal timings at intersections, while DL algorithms are capable of detecting potential hazards and providing real-time alerts to drivers.
- **Traffic Management:** AI, ML, and DL are employed to monitor and analyze traffic patterns for more effective

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International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 9, Issue 5, pp 434-441, May-2025

https://doi.org/10.47001/IRJIET/2025.905048

traffic control and reduced congestion .Figure 3 illustrates the application of AI in intelligent traffic management. Smart cameras and AI-controlled traffic lights continuously monitor and assess traffic conditions, thereby improving the overall performance of traffic management systems.

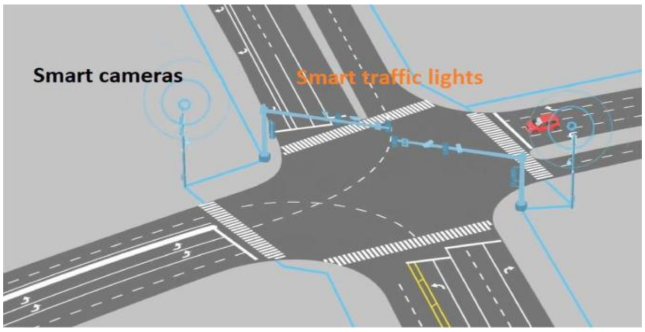

Figure 3: Applications of artificial intelligence (AI) in intelligent traffic management systems

- **Autonomous Vehicles:** AI, ML, and DL are foundational technologies in the development of autonomous vehicles. These systems enable self-driving cars to perceive and interpret their environment, make data-driven decisions, and safely navigate roads without human intervention.
- **Advanced ITS Infrastructure:** Beyond traffic control, AI, ML, and DL contribute to the broader development of ITS technologies, such as smart traffic signals, electronic toll collection, and intelligent parking systems, all aimed at optimizing transportation infrastructure.
- **Predictive Maintenance:** ML algorithms analyze data from onboard sensors to predict mechanical issues before they occur. This allows for proactive maintenance, reducing vehicle downtime especially valuable in large vehicle fleets, such as those in public transit systems.
- **Smart Parking:** AI-based parking solutions help drivers locate available parking spots, thereby reducing congestion. ML models optimize the use of parking spaces, while DL technologies support functions like license plate recognition and enforcement of parking regulations.
- **Route Optimization:** ML algorithms are used to identify the most efficient delivery routes, reducing travel time and fuel consumption. This application supports logistics optimization, leading to significant cost savings and a smaller environmental footprint.
- **Road Safety Enhancement:** AI, ML, and DL can analyze traffic data to identify accident-prone zones and predict potential risks. These systems help prevent accidents by alerting drivers to hazards and recommending safer travel routes.
- **Intelligent Public Transportation:** AI and ML are applied to optimize public transportation schedules and routes, enhancing service reliability and user convenience. DL can also be used to monitor passenger behavior and detect potential safety concerns.

VII. INTEGRATION OF AI, ML, AND DL IN ROBOTICS

Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL) are increasingly being integrated into robotics, providing machines with the ability to **learn, adapt, and improve their performance** over time. The rapid convergence of robotics and AI has significantly advanced the development of intelligent robotic systems. ML and DL, in particular, play a pivotal role in enabling robots to handle tasks once considered too complex or hazardous for humans.

Advanced robotics applications that harness these technologies **include autonomous vehicles, drone navigation, industrial robots, healthcare robots, and search and rescue robots**. These systems leverage large volumes of sensory data such as images, audio, and environmental cues—to perceive, interpret, and act upon their surroundings in a manner similar to human cognition. DL is especially valuable in robotics due to its capacity to develop sophisticated algorithms that process and learn from high-dimensional sensory inputs, enabling more nuanced decision-making and autonomy.

A notable example is Tesla's Autopilot system, which utilizes a fusion of AI, ML, and DL to enable advanced self-driving capabilities. Tesla vehicles are equipped with cameras, radar, and ultrasonic sensors that collect real-time data about the environment. ML algorithms process this data to make informed driving decisions, such as adjusting speed and steering to avoid obstacles. Meanwhile, DL enhances object detection and recognition, enabling the system to accurately identify pedestrians, cyclists, and other vehicles. As Tesla continues to evolve its autonomous driving technology, these AI-driven components are expected to play an even more critical role in ensuring safe and efficient operation.

VIII. EMERGING RESEARCH DIRECTIONS IN AI, ML, AND DL FOR ROBOTICS

The integration of AI, ML, and DL into robotics is a dynamic and fast-growing field with numerous promising avenues for future research. Below are several key areas where these technologies are making a significant impact:

1. **Autonomous Robots:** Research is focused on developing robots capable of independent navigation and

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International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 9, Issue 5, pp 434-441, May-2025

https://doi.org/10.47001/IRJIET/2025.905048

interaction. ML algorithms enable recognition of objects, path planning, and obstacle avoidance.

2. **Reinforcement Learning (RL):** RL allows robots to learn optimal behaviors through trial-and-error, guided by reward mechanisms. This is particularly useful for complex tasks such as robotic manipulation and navigation.
3. **Learning from Demonstration:** Robots can learn tasks by observing human demonstrations, reducing the need for extensive programming. This approach allows for rapid adaptation to new environments and tasks.
4. **Natural Language Processing (NLP):** NLP enables robots to interpret and respond to human language, facilitating natural interaction. Future work aims to improve accuracy and speed, expanding use cases for language-enabled robots.
5. **Computer Vision:** Vision is essential for robots to interact with their environment. Research in this area focuses on improving object recognition, scene understanding, and robust tracking through DL-based models.
6. **Neural Networks:** Neural networks allow robots to learn from past experiences and refine their behavior over time. This adaptability enhances efficiency and performance in dynamic settings.
7. **Vision-Based Navigation:** Robots equipped with cameras and visual sensors use ML/DL to interpret surroundings for navigation in complex environments.
8. **Collaborative Robotics (Cobots):** Cobots work safely alongside humans, combining human intuition with robotic precision. Research focuses on improving collaboration through adaptive control and intent recognition.
9. **Human-Robot Interaction:** Understanding human behavior and preferences is critical. ML models can tailor robotic responses to individual users, making interactions more intuitive and effective.
10. **Robotic Vision:** DL excels in image and video analysis, allowing robots to identify people, objects, and activities in real time, critical for surveillance, search and rescue, and caregiving tasks.
11. **Object Recognition and Manipulation:** Enhanced computer vision enables precise object handling. Future developments aim to improve the naturalness and dexterity of robotic interactions.
12. **Robotics in Healthcare:** Robots assist in surgery, medication delivery, and patient monitoring. AI-driven analysis of medical data helps personalize care and improve outcomes.
13. **Swarm Robotics:** This field studies large groups of simple robots that work collectively. ML helps these robots coordinate, communicate, and adapt to environmental changes.
14. **Robot Control:** Adaptive control algorithms powered by ML/DL allow robots to respond to environmental changes and perform tasks with greater precision and autonomy.

IX. CONCLUSION

The combination of AI, ML, and DL in robotics is enabling the development of intelligent, versatile, and highly capable robotic systems. These technologies empower robots to learn from experience, perform complex tasks autonomously, and interact more naturally with human users. From self-driving cars to collaborative industrial robots and healthcare assistants, the future of robotics is being reshaped by continuous advancements in intelligent algorithms. As research progresses, this field will likely yield transformative innovations with widespread societal benefits.

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Citation of this Article:

Manoj Kumar K M. (2025). A Review of Artificial Intelligence, Machine Learning, and Deep Learning in Advanced Robotics. *International Research Journal of Innovations in Engineering and Technology - IRJIET*, 9(5), 434-441. Article DOI https://doi.org/10.47001/IRJIET/2025.905048

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