Technology levels in artificial intelligence robotics and industrial automation: impacts and implications

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ABSTRACT

Robotics technology has progressed rapidly since its debut in 1922, evolving from simple programmable automation to highly sophisticated systems. This study employs a hybrid methodology, combining qualitative analysis of key robotic components manipulators, controllers, end effectors, and geometric configurations with quantitative comparison of performance metrics to classify robots according to their technological level (low-tech versus high-tech). The findings show clear distinctions across these levels. Low-tech robots typically achieve positioning accuracy of about 0.025 mm and rely mainly on single electric motor actuation, making them suitable for simple, repetitive tasks. In contrast, high-tech robots can perform complex operations with positioning accuracy of up to 3 mm, integrating multiple actuation systems such as electric, pneumatic, and hydraulic mechanisms for enhanced flexibility and control. Moreover, high-tech robots exhibit greater manipulative capabilities and advanced control systems that enable multi-axis and adaptive operations not feasible for low-tech counterparts. These results demonstrate how the technological level directly shapes a robot's precision, actuation complexity, and functional range, providing a clear framework for selecting appropriate robotic solutions in both industrial and research settings.

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1. INTRODUCTION

Artificial intelligence (AI) robotics integrates AI into robots, enabling them to perform tasks autonomously, such as navigation, object manipulation, and interaction with their environment. AI-powered robots can learn, adapt, and make decisions based on sensor data and algorithms. Robotics has rapidly advanced over the past decades, focusing on the design, development, and application of robots for automated task execution. The term "robot" first appeared in 1922 in a New York theater production titled Rossum's Universal Robots (R.U.R.) by Karel Čapek, derived from the Czech word Robota, meaning "work." Since then, the concept of robots has evolved from science fiction into real-world technology, significantly impacting human life. The robotics industry took a commercial turn in 1956 with the establishment of UNIMATION, which became profitable by 1972, marking the industry's commercialization phase. Robots are defined as programmable machines designed to perform specific tasks. According to Rahman *et al.* [1], "A robot is something that can be programmed and reprogrammed, equipped with a mechanical manipulator designed to move objects, components, or specialized tools with flexible programming.” This definition highlights that robots are not merely human replicas but efficient tools for industrial and non-industrial applications [2].

Robotics is a multidisciplinary field encompassing AI, computer science, mechanical engineering, psychology, and anatomy. As technology progresses, robotics increasingly integrates with information technology, allowing robots to make smarter decisions and adapt to their environment. An AI model is often integrated into hierarchical control architectures, where low-level control ensures real-time safety and precision, while higher-level AI models handle planning, learning, and optimization, enabling smart robots to operate autonomously within fourth industrial revolution (Industry 4.0) production environments [3].

Understanding how robots function requires knowledge of their fundamental components: manipulator, controller, power supply, and end effector [4]. The manipulator enables movement and object manipulation, while the controller serves as the robot’s central processing unit, managing operational tasks. Energy sources for robots vary, including electricity, hydraulics, and pneumatics [5]. The end effector, attached to the manipulator, performs specific tasks. Robots are classified by technology level: low-tech, mid-tech, and high-tech. Low-tech robots are used for simple tasks, while high-tech robots handle complex operations with superior accuracy and speed [6]. Robot geometry refers to their physical configuration and movement capabilities, which are crucial in design. The complexity of a robot’s movement depends on its degrees of freedom (DOF), which can be linear, rotational, or twisting joints. Key specifications such as work volume, precision of movement, and weight-carrying capacity also influence robotic performance [7].

By understanding these aspects, engineers can design and develop robots that efficiently complete real-world tasks [8]. As a multidisciplinary field, robotics not only offers technological innovations but also has the potential to revolutionize how humans work and interact with machines [9]. Ongoing research in robotics promises further innovation and practical applications in the future [10]. This study holds significant importance in robotics technology, particularly in the development and application of robots in industrial settings [11]. The term “robot” gained mainstream recognition through movies like Star Wars, highlighting its integration into modern culture and technology [12]. The definition proposed by [13], describing robots as programmable mechanical systems with manipulators, expands the understanding of their functionality and lays the groundwork for further automation research [14].

Smart robotic technologies are a key enabler of the Industry 4.0 by embedding advanced automation, connectivity, and intelligence into manufacturing processes. Equipped with sensors, machine learning algorithms, and industrial internet of things (IIoT) connectivity, smart robots collect and exchange real-time production data, forming the backbone of cyber-physical systems. This real-time data sharing allows seamless integration with other digital technologies such as cloud computing, big data analytics, and digital twins so that production lines can self-monitor, self-optimize, and adapt quickly to changing market demands [15]. In practice, these technologies support mass customization, where factories can efficiently produce highly individualized products without sacrificing speed or cost. They also improve operational efficiency by enabling predictive maintenance and reducing unplanned downtime through AI-driven diagnostics. Collaborative robots (COBOTS) enhance human–machine interaction, allowing workers to focus on higher-value tasks while robots handle repetitive or hazardous operations, thereby boosting both productivity and workplace safety.

Moreover, smart robots generate a continuous feedback loop of operational data, providing decision-makers with actionable insights that strengthen supply chain agility and enable end-to-end digitalization. This convergence of automation, connectivity, and intelligent analytics represents the essence of Industry 4.0, driving a shift from traditional, linear manufacturing to flexible, data-driven smart factories that are more sustainable, responsive, and globally competitive. The classification of robots by technological level ranging from low-tech to high-tech reveals substantial differences in precision and cycle time. For instance, low-tech robots exhibit an accuracy of up to 0.025 mm, while high-tech robots can achieve 3 mm accuracy, as outlined in [16]. Understanding fundamental robot components such as manipulators, controllers, and power sources is crucial for grasping robot operations, as explained in [17]. Additionally, the discussion on robot geometry, including DOF and joint types such as linear, rotational, and twisting, provides deeper insights into robotic motion mechanics [3]. Other studies emphasize how DOF configurations impact movement flexibility and adaptability in industrial applications [18]. Overall, this research contributes significantly to the understanding of fundamental robotics principles and applications. By referencing international standards such as ISO 8373:2012, robotics continues to meet the demands of modern automation.

2. METHOD

This study employs a descriptive study design with a qualitative approach, aiming to explore and analyze the characteristics and fundamental components of robots, their technological levels, robotic geometry, and technical specifications that influence robotic performance.

2.1. Research procedures

The research process begins with a literature review, where information is gathered from books, journals, and articles related to robotics to develop a foundational understanding of key concepts and terminology. Next, field observations are conducted on various types of robots used in industrial settings, focusing on their operational methods and physical configurations across different environments. Data on robots with low, medium, and high technology levels are collected at this stage.

The next phase involves interviews with robotics experts and experienced technicians to gain insights into robotic performance and applications. A questionnaire is designed to obtain quantitative data on robotic characteristics and technical specifications from professionals in the field. Meanwhile, an interview guide is used to direct discussions with experts regarding the application and effectiveness of robots in industrial environments.

2.2. Data collection and analysis

Qualitative data: information obtained from interviews and observations is analyzed using content analysis to identify recurring themes and patterns related to robotic characteristics and performance. Quantitative data: data collected through questionnaires are processed using descriptive statistical analysis, illustrating the frequency, averages, and distribution of technological characteristics such as accuracy levels, cycle time, and load capacity.

To ensure data consistency and accuracy, triangulation of sources is applied by comparing data from multiple sources literature, interviews, and observations. The research follows a structured chronological process, starting from data collection through literature review, followed by field observations, expert interviews, data processing and analysis, and finally, the compilation of research findings.

2.3. Key considerations in robotics development

In managing and advancing robotics, it is crucial to understand classification criteria based on function and physical form, as well as the impact of artificial intelligence advancements on robotic classifications. Additionally, effective robotic maintenance, whether through preventive maintenance or condition-based maintenance, is crucial for sustaining optimal performance and addressing technical challenges during operation.

The primary advantages of this approach include flexibility, risk management, and operational efficiency, ensuring robots are effectively utilized across various industries. By following this methodology, the study aims to provide a comprehensive understanding of robotics technology, its characteristics, and applications in different industrial sectors.

3. RESULTS AND DISCUSSION

3.1. Basic components of robots

Robots are made up of several core components that work together to perform various tasks. The manipulator is the arm-like structure of the robot, composed of joints and links that allow the robot to move. It includes the appendage for movement and the base that provides stability. The manipulator is responsible for carrying out the robot's main functions, whether it's lifting, placing, or moving objects. The controller, often referred to as the robot's brain, regulates the robot's operations. It controls elements like the microprocessor, memory (random access memory (RAM), read only memory (ROM)), and sensors, ensuring that the robot's actions align with the intended purpose. The power supply provides the necessary energy for the robot to function, and this energy can come from electricity, hydraulics, or pneumatics, depending on the robot's design and application. Lastly, the end effector is the tool attached to the robot's manipulator that enables it to complete specific tasks. For example, it could be a gripper for picking up items, a welding tool for construction, or a cutting tool for precision work.

3.2. Robot technology levels

Robots are often categorized into three technology levels based on their complexity and functionality. Low-tech robots are typically used for simple tasks in manufacturing, such as material handling or assembly. These robots usually have only two to four DOF, meaning their movement is limited to a few axes. They operate at a slower cycle time (about 5-10 seconds) and are capable of handling lighter loads, ranging from 3 to 13.6 kg. These robots are typically driven by electric motors, as they are cost-effective and easy to control. Mid-tech robots are more advanced and can handle more complex tasks, such as part placement or assembly. These robots have five to six degrees of freedom and are capable of moving more precisely and at faster speeds. They can handle larger payloads, typically between 68 and 150 kg, and are equipped with both electric and hydraulic motors for increased performance. High-tech robots are the most sophisticated and are designed for tasks that require high precision, such as in the automotive or aerospace industries. These robots can have up to 10 degrees of freedom, and they are capable of handling very heavy payloads (up to 250 kg). They operate with high speed and precision, using a combination of electric, hydraulic, and pneumatic actuators. Technology level data in Indonesia is shown in Figure 1.

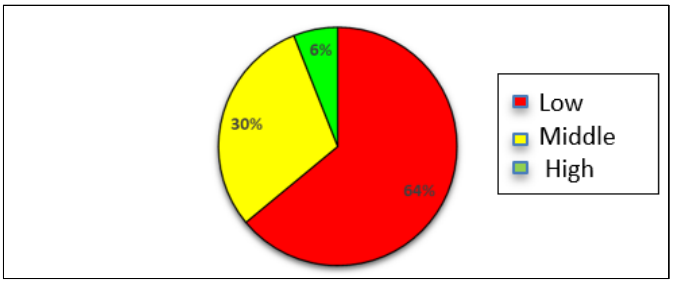


Figure 1. Technology level data in Indonesia

Based on the research from Sharma *et al.* [19] survey from 502 firm-level with the indicators company's characteristic (ownership, export, import), research and development activity (budget, activities), technological adoption (benefit and constraint, ICT adoption), industry 4.0 technology (awareness, utilization, impact), employment (structure, wages). The results from six sectors – food and beverages, garments, footwear, electronics, automotive, and rubber and plastics showed that the adoption of technology within the manufacturing sector varies significantly across different levels. Low-tech solutions dominate, with around 64% of manufacturing companies still relying on basic tools such as spreadsheets and email for daily operations. These technologies are often used for simple tasks, indicating that many companies are still in the early stages of digital transformation. A larger portion, approximately 30%, has moved to mid-tech solutions, adopting systems like systems, applications, and products (SAP) and Oracle. These technologies enable more efficient management of enterprise resources and supply chains, reflecting a move towards more structured and integrated operations. However, high-tech adoption remains limited, with only about 6% of companies implementing advanced technologies such as AI-driven automation or robotics in their manufacturing processes. This disparity highlights a significant opportunity for growth in the Indonesian manufacturing sector, as more companies explore advanced technologies to improve productivity and competitiveness in the era of Industry 4.0.

3.3. Robot geometry

The geometry of a robot is crucial for determining its movement and the tasks it can perform. This involves the DOF, which refer to the number of independent axes a robot can move along. For instance, a robot with six DOF can move along six axes, allowing for complex movements in three-dimensional space. These axes typically include rotation and flexing movements at various joints. The robot's joint types further affect its capabilities. Common joints include linear joints (for straight-line movement), rotational joints (for rotating parts), and twisting joints (for specific rotational movements). The links, or rigid parts connecting the joints, distribute the loads and enable the robot to reach various positions within its workspace. The combination of joint types and the arrangement of links play a vital role in the robot's flexibility, speed, and precision. The geometry robot is shown in Figure 2.

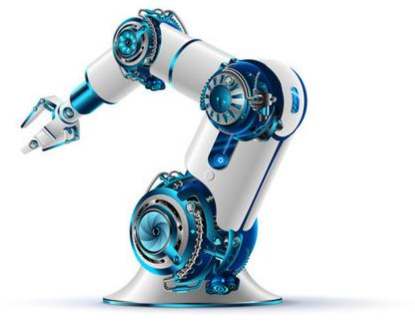
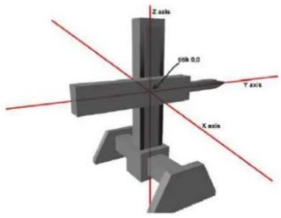
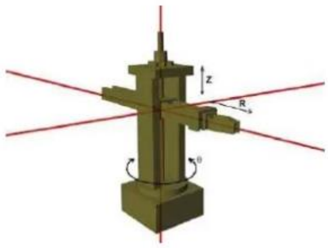
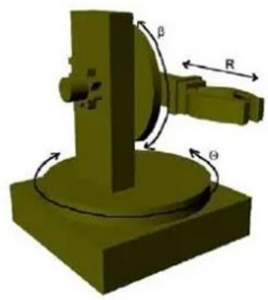
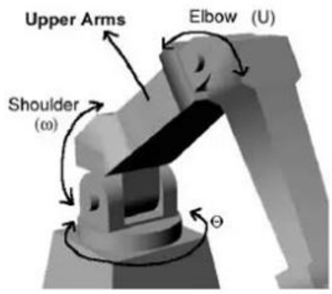


Figure 2. Geometry robot

3.4. Robot configurations

Robots can be designed in various configurations, each tailored to perform specific tasks efficiently. Common robot configurations include cartesian, cylindrical, spherical, articulated, selective compliance assembly robot arm (SCARA), and parallel robots, which differ in structure, range of motion, and degrees of freedom. The choice of configuration affects a robot's precision, flexibility, speed, and load capacity, making certain designs more suitable for applications such as assembly, welding, material handling, medical procedures, or inspection. By selecting an appropriate configuration, engineers can optimize robot performance to meet the technical and operational requirements of a particular task. Robot configurations are specifically shown in Table 1.

Table 1. Robot configurations specific

Type	Description	Picture
Cartesian coordinate	The Cartesian coordinate configuration is one of the simplest, using three linear axes (x, y, and z) for movement, which is ideal for tasks requiring straight-line precision.	
Cylindrical coordinate	Cylindrical robots have a configuration that combines rotational and linear movements. These robots are good for tasks that require vertical movement, along with radial motion.	
Polar coordinate	Polar robots, on the other hand, utilize angular and radial movements, typically suited for circular workspaces.	
Articulated coordinate	Articulated robots are more flexible, resembling the movement of a human arm with multiple joints that provide high versatility.	
SCARA	The SCARA configuration is similar to articulated robots but focuses more on horizontal movement, making it ideal for assembly line tasks requiring high precision.	

3.5. Technical specifications

When assessing a robot's performance, several technical specifications come into play. The work volume refers to the physical area within which the robot can operate. This is influenced by the robot's configuration, reach, and the relationship between its joints. The precision of movement is also crucial and is typically categorized into three areas: spatial resolution (the smallest movement the robot can make), accuracy (how closely the robot can reach a designated point), and repeatability (how consistently the robot can return to the same point). The robot's weight-carrying capacity is another important factor, as it determines the robot's ability to handle heavy loads, which is essential for tasks involving large or heavy objects. Finally, the drive system (whether hydraulic, pneumatic, or electric) is selected based on the task's requirements. Hydraulic systems are used for high power and force, pneumatic systems for flexibility, and electric systems for precision and control.

3.6. Discussion

The end effector plays a crucial role in robot operations as it is the tool attached to the end of the manipulator to perform specific tasks, such as lifting, gripping, or assembling objects. The design of the end effector is tailored to the task requirements, programming control, and the size of the workspace. For instance, a mechanical gripper is used for gripping objects, a vacuum gripper is effective for handling smooth or delicate surfaces, and a magnetic gripper is used for metallic surfaces. On the other hand, tooling can include devices for applications like drilling, painting, welding, and surface finishing. The robot's control systems also vary depending on the complexity of the tasks [20] . Limited sequence robots are inexpensive and typically use pneumatic drivers, while point-to-point control enables movement between fixed points, and continuous path control allows for smoother motion paths. The choice of control system is essential for optimizing robot movement, ensuring both efficiency and effectiveness in industrial operations [21], [22].

The study provides a comprehensive view of robot performance and applications in the industry by analyzing the basic components, technology levels, geometry, technical specifications, end effector, and control systems. The primary robot components, including the manipulator, controller, power supply, and end effector, function together seamlessly. The manipulator moves different parts of the robot, while the controller acts as the brain, regulating sensors and actuators. The power supply provides the energy required for operation, and the end effector performs the task-specific functions, such as gripping or cutting objects [23]. In terms of robot technology, the study classifies robots into three categories: low-tech, mid-tech, and high-tech, based on operational capabilities and task complexity. Low-tech robots are typically used for simple tasks, such as machine placement, while high-tech robots are designed for complex tasks requiring precision and higher power. High-tech robots utilize various actuators, such as electric, hydraulic, and pneumatic motors, depending on performance needs, as noted in earlier research [24].

The geometry of robots, which includes the DOF and joint types, plays a critical role in determining the robot's performance and flexibility. The configuration of the robot, including the number of DOF and the type of joints, affects its ability to adapt to various industrial applications. Studies have shown that optimal geometric arrangements can enhance robot efficiency, precision, and adaptability in dynamic environments. This flexibility is especially important for industrial applications that require quick adaptation to changes in the working environment [25]. Technical specifications, such as work volume, precision of movement, weight-carrying capacity, and drive systems, also influence robot performance. These specifications must be aligned with the requirements of the task and industrial application to ensure optimal functioning. For instance, the choice of drive system whether hydraulic, pneumatic, or electric should be based on the speed, precision, and safety required for a particular task [26]. The end effector and the robot's control system are key to improving its performance in specific tasks. The choice of grippers and tooling affects the robot's effectiveness in lifting, gripping, or manipulating objects. For example, using the appropriate gripper ensures that the robot can handle delicate or heavy objects according to the task's needs. Control systems like point-to-point and continuous path control ensure that the robot moves efficiently and accurately, depending on the complexity of the task [27], [28].

The adoption of smart robots in factory operations brings clear productivity gains but also introduces notable technical and security challenges. On the technical side, system failures caused by hardware malfunctions, sensor errors, or software bugs can disrupt production, while the complexity of integrating robots with legacy systems may create data bottlenecks or unpredictable behavior [18]. These advanced machines also require regular calibration and software updates; neglecting maintenance can lead to reduced accuracy or even safety hazards. Because many smart robots rely on real-time connectivity, network outages or latency can further impair performance [21]. From a cybersecurity perspective, network-connected robots are potential entry points for hackers, exposing factories to risks such as unauthorized access, data breaches, theft of intellectual property, or ransomware attacks. Supply chain vulnerabilities in third-party software or firmware also heighten the threat [29]. Human factors compound these risks: insufficient cybersecurity training and skills gaps in managing robotic systems can result in weak authentication practices or misconfiguration. To mitigate these challenges, factories should implement a robust security architecture with network segmentation, multi-factor authentication, and end-to-end encryption; apply regular patches and continuous monitoring; build redundant systems and fail-safes to allow safe shutdowns; and adhere to recognized standards such as IEC 62443 or the National Institute of Standards and Technology (NIST) cybersecurity framework. Continuous staff training and regular security audits are equally essential to maintain both operational reliability and cyber resilience.

Overall, the findings of the study confirm that the design and performance of a robot depend heavily on the careful selection of components, technology levels, geometry, technical specifications, end effectors, and control systems that match the needs of the industry. A deep understanding of these factors is crucial for designing and deploying robots effectively in industrial settings, aiming to improve efficiency, productivity, and the quality of work [15].

4. CONCLUSION

This study highlights clear distinctions in robotics technology across low-tech and high-tech levels, particularly in terms of accuracy (from about 0.025 mm in low-tech robots to 3 mm in high-tech robots), actuation methods (simple electric motors versus multi-actuator systems), and operational complexity. These findings confirm that the technological level directly influences precision, flexibility, and potential applications in industrial automation. To capitalize on these insights, policymakers should establish national standards and certification frameworks for safe deployment and introduce incentives such as tax breaks or grants to accelerate adoption in manufacturing and service sectors. Industry stakeholders are advised to invest in workforce training to bridge skills gaps, preparing operators for high-tech robot integration while leveraging low-tech robots as cost-effective automation solutions for small and medium enterprises. Researchers should explore hybrid robotics systems that combine the affordability of low-tech designs with the precision of high-tech capabilities and conduct longitudinal studies on the economic and social impacts of robotics adoption. Coordinated action across these groups can foster innovation, enhance productivity, and support sustainable industrial growth.

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AUTHOR CONTRIBUTIONS STATEMENT

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Agnes Sondita Payani		✓				✓		✓	✓	✓	✓	✓		
Siti Rabiatul Adawiyah	✓		✓	✓			✓			✓	✓		✓	✓
Ogi Gumelar		✓				✓		✓		✓	✓			

C: **C**onceptualization
M: **M**ethodology
So: **So**ftware
Va : **Va**lidation
Fo: **Fo**rmal analysis
I: **I**nvestigation
R: **R**esources
D: **D**ata Curation
O: Writing - **O**riginal Draft
E: Writing - Review & **E**diting
Vi: **Vi**sualization
Su: **Su**pervision
P: **P**roject administration
Fu: **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

DATA AVAILABILITY

Data availability does not apply to this paper, as no new data were created or analyzed in this study.

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