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Artificial Intelligence in transforming maintenance and repair of armored vehicles

Mohammad Saidur Rahman *

Bangladesh Army, Ghatail Cantonment,1980, Bangladesh.

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Abstract

This analysis examines how artificial intelligence (AI) revolutionises armoured vehicle repair and Maintenance (M&R). It discusses emerging technologies, the current status of artificial intelligence (AI), and how these could enhance defence capabilities. The paper provides a comprehensive plan for potential integration and examines implementation issues. This paper aims to show AI's significant benefits in the defence sector by resolving these issues. With the correct funding, research, and collaborations, artificial intelligence (AI) can change M&R practices, enhancing operational readiness, effectiveness, and safety.

Keywords: Artificial Intelligence (AI); Armored Vehicles; Maintenance and Repair (M&R); Predictive Maintenance; Augmented Reality (AR); Virtual Reality (VR).

1. Introduction

Armoured vehicles are crucial for human safety and mission success in defence operations [1]. These vehicles constantly wear and tear due to the severe circumstances in which we operate [2-4]. Conventional maintenance and repair (M&R) systems often cannot meet these expectations, leading to inefficiencies, delays, and costly costs [5–9]. More clever and useful solutions have been needed [10–11]. Artificial intelligence (AI) offers a new way forward with automated prediction capabilities [12–16]. This study looks at the current state of affairs, recent advancements, and possible futures for M&R for AI-related armoured vehicles. Figure 1 shows how AI affects armoured vehicle M&R.

* Corresponding author: Mohammad Saidur Rahman

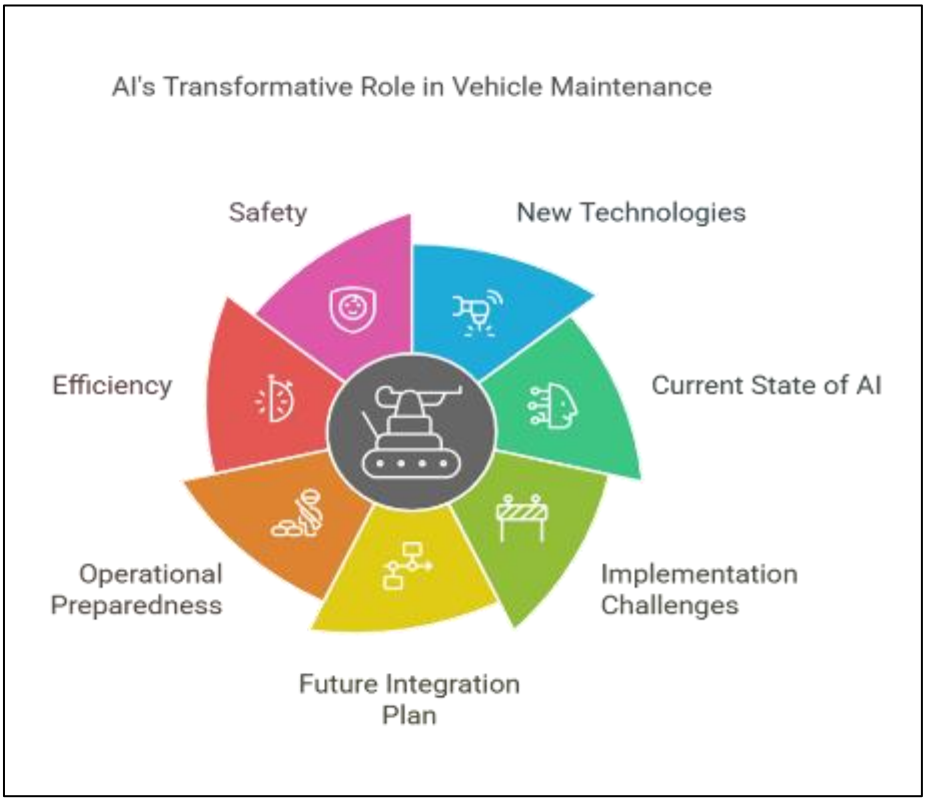

Figure 1 Illustrates AI's Impact on Armored Vehicle M&R.

2. Current State of AI in Maintenance and Repair

2.1. Overview of AI Applications

By offering faster, more accurate, and less resource-intensive solutions, artificial intelligence has completely transformed M&R systems [17–20]. By using data to predict probable failures, predictive Maintenance allows for proactive measures to prevent malfunctions [21–23]. By precisely identifying faults, autonomous diagnostic systems lessen the need for human expertise [24–25]. Furthermore, supply chain optimisation powered by AI guarantees the availability of required spare parts, expediting maintenance procedures [26–29]. The effectiveness of M&R activities is increased by these applications taken together [30–31]. Around the world, military sectors are rapidly integrating these AI systems [32–33].

Table 1 An Overview of AI Applications in Maintenance and Repair.

Aspect	**Description**	**References**
Predictive Maintenance	Utilises data to forecast potential failures, enabling preemptive actions to avoid breakdowns.	[163-164]
Autonomous Diagnostics	Reduces reliance on human expertise by providing precise fault identification.	[165]
Supply Chain Optimisation	Ensures availability of necessary spare parts, streamlining repair processes.	[166-167]
Efficiency Improvement	Collectively improves M&R operations through faster and more accurate solutions.	[168]

2.2. Technologies Used

Machine learning techniques that evaluate real-time and historical data can be used to predict maintenance needs [45–46] correctly. Computer vision systems can use high-resolution photos to identify cracks and wear [47]. Through constant data collection on the vehicle's performance, Internet of Things (IoT) sensors offer a comprehensive view of operational health [48–49]. These technologies work together synergistically to create a strong system to track and repair [50-53]. Their use dramatically improves accuracy and decreases room for human mistakes during Maintenance [54-56].

Table 2 Technologies Used in AI-Driven M&R.

Technology	Function	References
Machine Learning	Analyses historical and real-time data for accurate maintenance predictions.	[169]
Computer Vision	Identifies visible damage (e.g., cracks, wear) from high-resolution images.	[170]
IoT-Enabled Sensors	Provides continuous data on vehicle performance for comprehensive operational health monitoring.	[171]

2.3. Case Studies/Examples

Incorporating AI into their M&R procedures is a growing trend across military organisations worldwide [57-59]. For example, the United States Army has used diagnostics powered by artificial intelligence, which has decreased vehicle downtime [60-61]. In Europe, NATO troops employ predictive Maintenance to boost the dependability of their armed vehicles [62-64]. Case studies indicate how AI-powered machines identify potential difficulties faster than conventional approaches [65]. These examples show the concrete benefits of incorporating AI into M&R processes. The efficacy of these programs underlines AI's potential to change military vehicle upkeep [66-68]. **Figure 2** provides a summary of Case Studies/Examples in M&R.

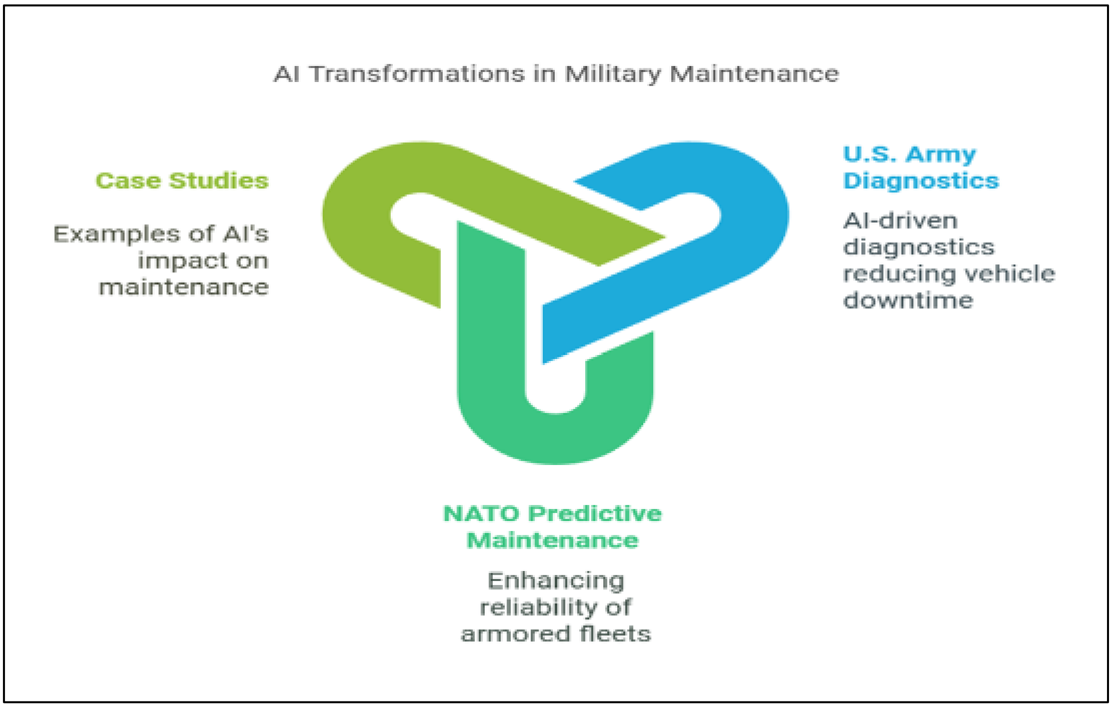

Figure 2 Illustrates Triadic Diagram of AI Transformations in Military Maintenance

3. Emerging AI Technologies

Figure 3 Demonstrates different aspects of emerging AI technology.

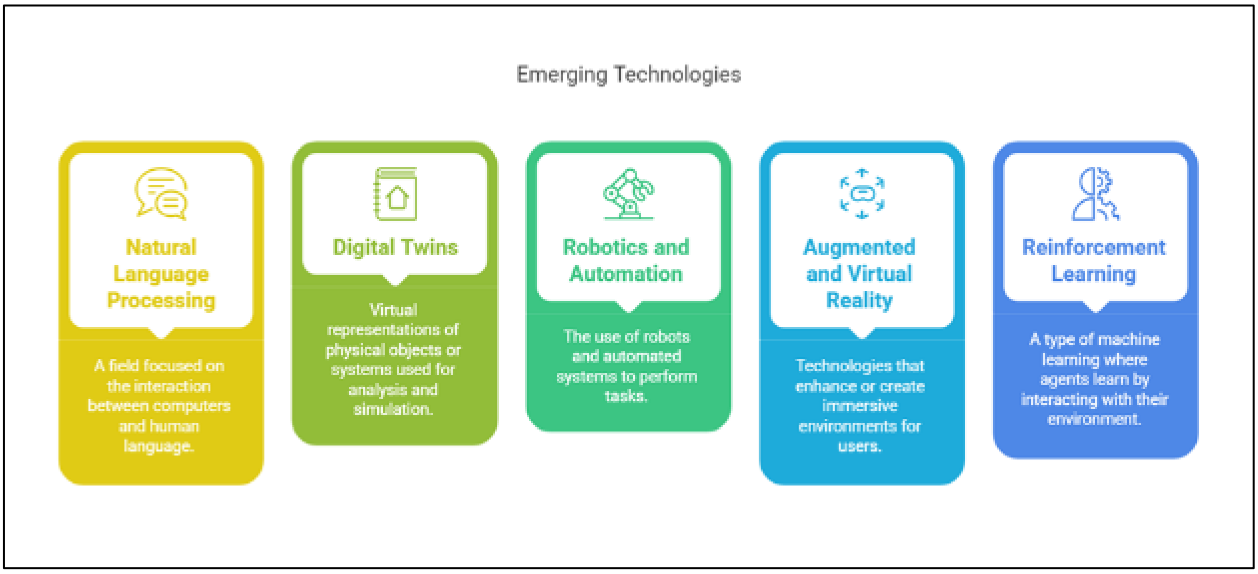

Figure 3 Overview of Emerging AI Technologies in Maintenance and Repair

Table 3 Emerging AI Technologies and Their Applications.

Technology	Application	References
Natural Language Processing (NLP)	AI-powered manuals and interactive assistants simplify repair tasks.	[172]
Digital Twins	Virtual replicas simulate performance and predict failures for optimised Maintenance.	[173]
Robotics and Automation	Robots perform intricate tasks; drones inspect vehicles and report real-time damage.	[174-175]
AR/VR	Enhances training and operational support with immersive solutions and step-by-step overlays.	[176-177]
Reinforcement Learning	Dynamically adapts repair strategies to evolving operational conditions.	[178]

3.1. Natural Language Processing (NLP)

NLP plays a pivotal role in streamlining M&R workflows [69]. AI-powered maintenance manuals provide technicians with instant, accurate repair instructions [70]. Interactive troubleshooting assistants leverage NLP to understand and respond to queries, simplifying complex repair tasks [71]. These systems ensure that even non-expert technicians can perform Maintenance efficiently [72]. By reducing reliance on extensive training, NLP enhances the overall adaptability of repair crews [73-74]. As NLP technologies evolve, their applications in military M&R will expand further [75-77]. **Figure 4** Shows Natural Language Processing (NLP) in M&R.

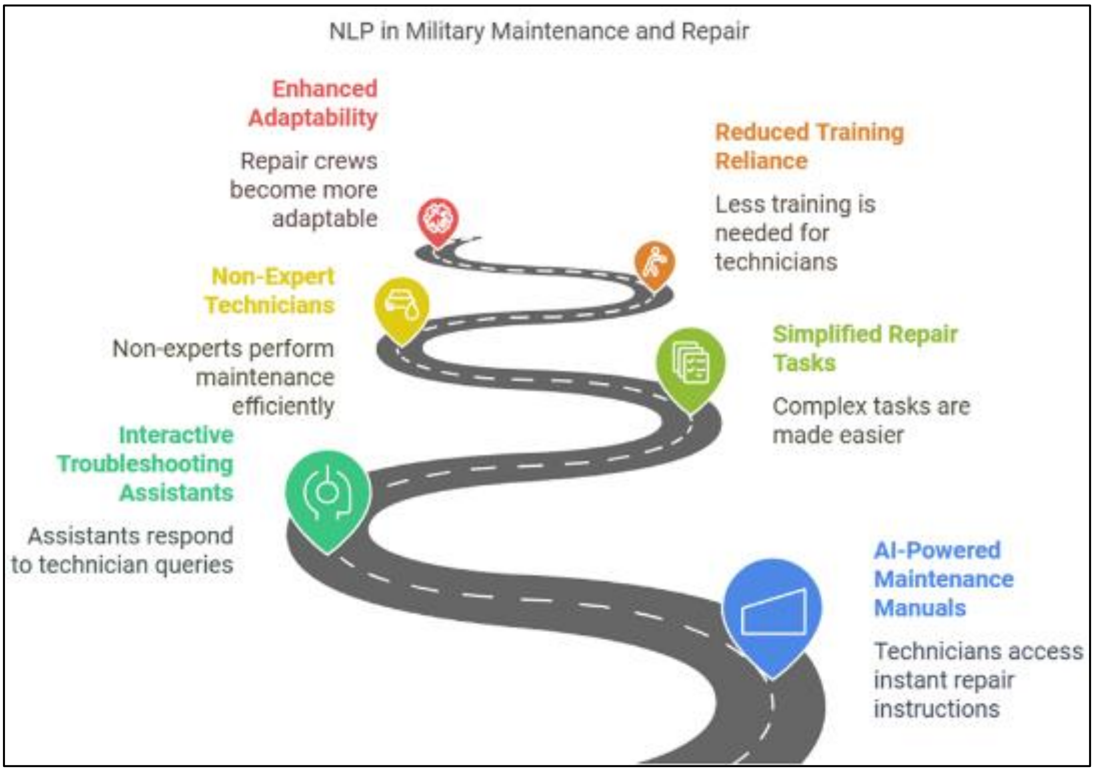

Figure 4 Roadmap of NLP in Military Maintenance and Repair

3.2. Digital Twins

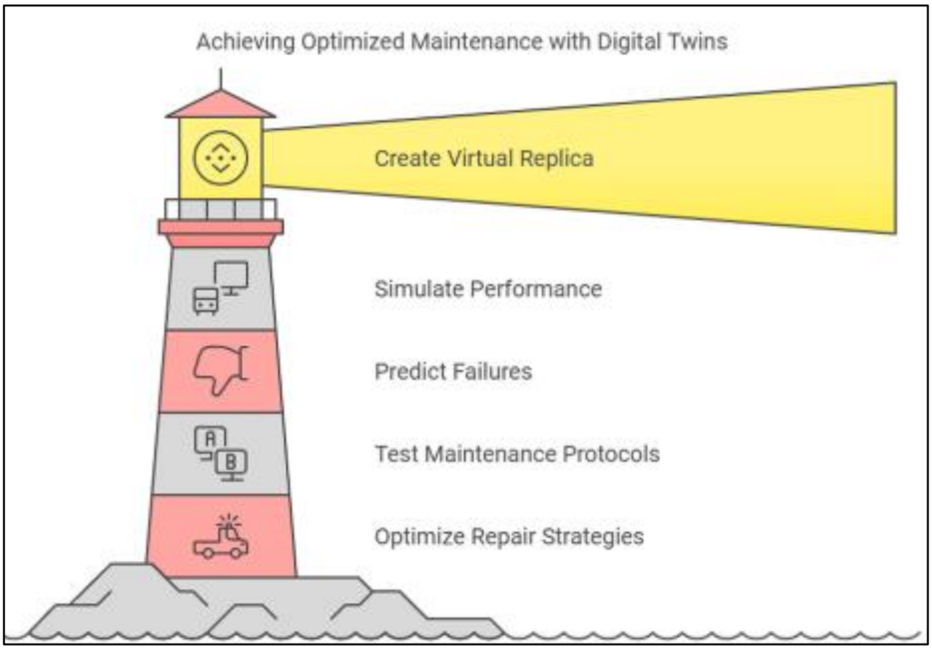

Figure 5 Lighthouse Diagram for Achieving Optimised Maintenance with Digital Twins

Digital twin technology creates virtual replicas of armoured vehicles, simulating their real-time performance [78-80]. These simulations enable the prediction of failures and allow for the virtual testing of maintenance protocols [81-82]. By identifying issues before they occur, digital twins reduce downtime and repair costs [83]. This technology optimises repair strategies through continuous data analysis [84-85]. Integrating digital twins into M&R systems represents a significant leap forward in predictive and preventive Maintenance [86]. Figure 5 Shows digital twins in AI-driven M&R.

3.3. Robotics and Automation

Robotics and automation are redefining the repair landscape [87-88]. AI-driven robots perform intricate repair tasks with unparalleled precision, reducing human involvement in hazardous conditions [89-92]. Drones equipped with AI inspect vehicle exteriors for damage, providing detailed reports in real-time [93-96]. These innovations significantly enhance the efficiency of the repair process [97]. By automating repetitive and dangerous tasks, robotics ensure higher safety standards for technicians [98]. This technology is rapidly gaining traction in military applications worldwide [99-100]. **Figure 6** Shows Robotics and Automation in AI-driven M&R.

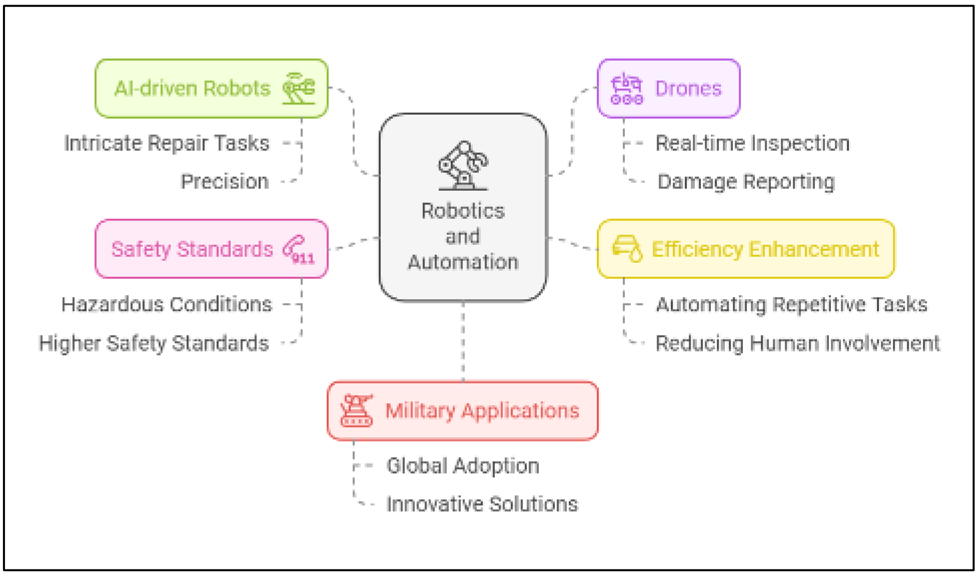

Figure 6 Mind Map of Robotics and Automation Applications

3.4. Augmented and Virtual Reality (AR/VR)

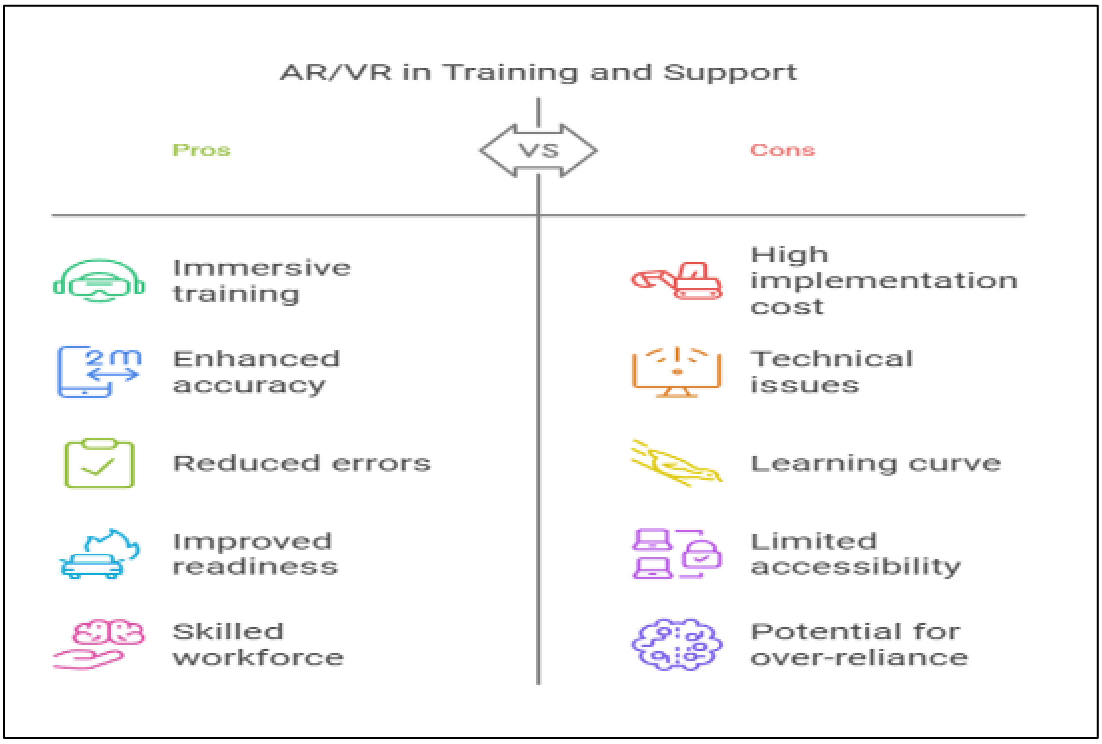

Figure 7 A graphical abstract of the Pros and Cons Table of AR/VR in Training and Support

AR/VR technologies provide immersive solutions for training and operational support [101]. AI-powered AR overlays guide technicians through repair procedures step by step, enhancing accuracy and reducing errors [102-103]. VR-based training programs prepare repair crews for real-world scenarios, improving their readiness and efficiency [104-105]. These technologies bridge the gap between theoretical knowledge and practical application [106-107]. Incorporating AR/VR into M&R systems fosters a more skilled and capable workforce [108-109]. Their role in enhancing operational efficiency is undeniable [110-111]. **Figure 7** shows Augmented and Virtual Reality (AR/VR) in AI-based M&R.

3.5. Reinforcement Learning

Reinforcement learning enables AI systems to adapt and optimise repair strategies [112-113]. These systems learn from past experiences to develop more effective approaches to maintenance [114]. Reinforcement learning ensures that repair protocols evolve alongside changing operational conditions [115-116]. By continuously improving their performance, these AI systems enhance the reliability and efficiency of M&R processes [117-118]. Their application in military contexts is expected to grow significantly in the coming years [119-120]. **Figure 8** shows Reinforcement Learning in M&R.

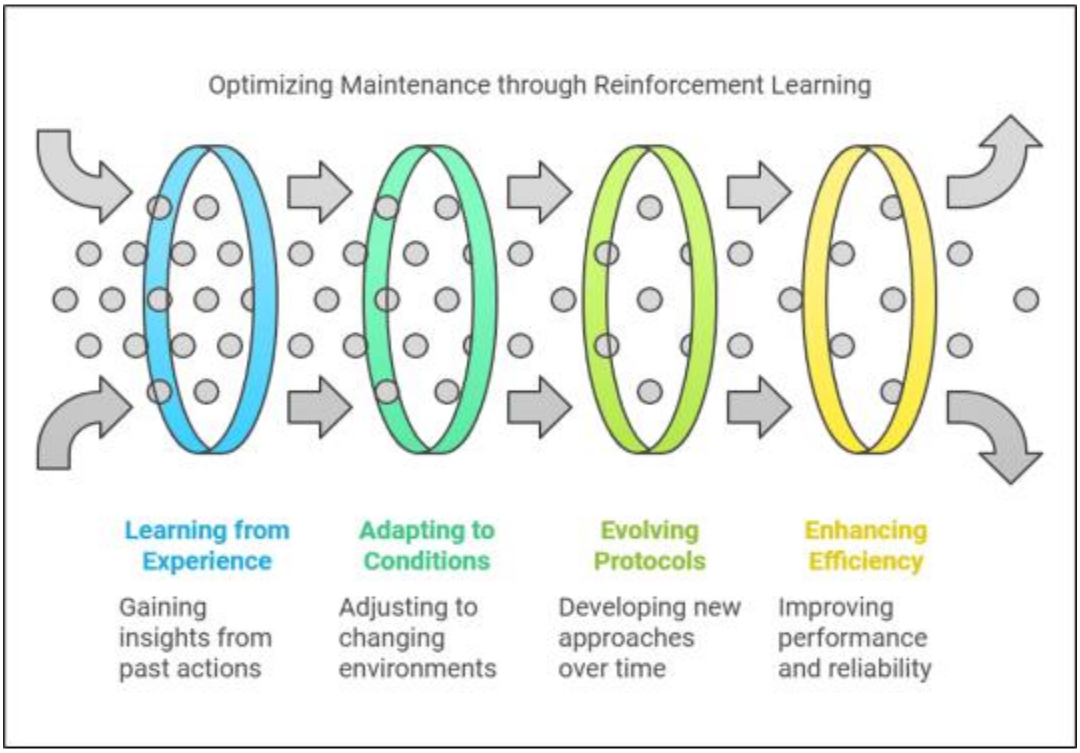

Figure 8 Process Flow Diagram for Optimising Maintenance with Reinforcement Learning

4. Impact on Defense Operations

The integration of AI in M&R systems has a profound impact on defence operations [121]. Enhanced operational readiness is one of the most significant benefits, ensuring vehicles are always mission-ready [122]. AI-driven maintenance schedules reduce downtime, allowing fleets to remain in service longer [123-124]. Cost savings are another crucial advantage, with optimised processes reducing unnecessary expenses [125]. Additionally, the improved reliability of vehicles enhances safety for personnel [126]. These benefits collectively strengthen the operational capabilities of defence forces. **Table 4** shows the benefits of AI Integration in Defense Operations.

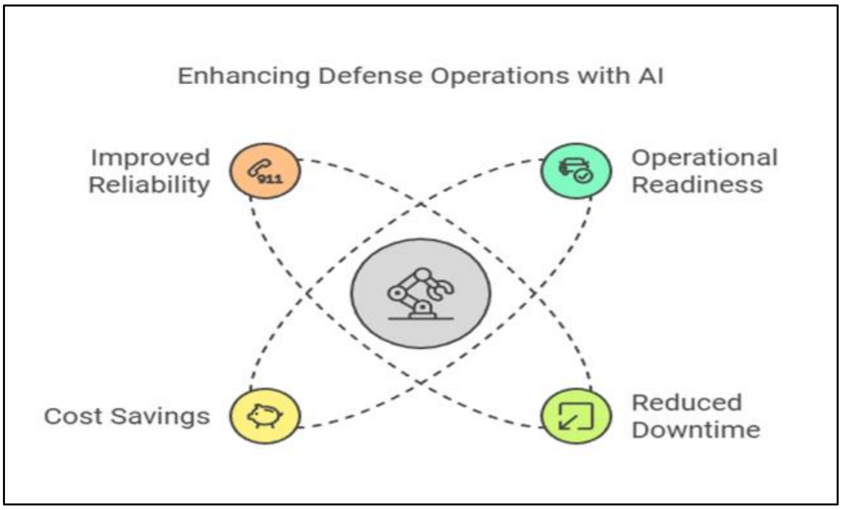

Figure 9 Enhancing Defence Operations with AI

Table 4 Benefits of AI Integration in Defense Operations.

Benefit	Description	References
Operational Readiness	Ensures vehicles are mission-ready at all times by reducing downtime.	[127]
Cost Savings	Optimised maintenance processes lead to reduced expenses.	[128]
Improved Reliability	Enhances safety for personnel by ensuring higher reliability of vehicles.	[129]
Safety Enhancements	Reduces risk to technicians through automation of hazardous tasks.	[130]

5. Challenges and Limitations

The implementation of AI systems faces several technical challenges [131]]. Data quality and availability are critical concerns, as accurate predictions require comprehensive datasets [132]. Legacy systems often lack compatibility with modern AI technologies, complicating integration efforts [133]. Addressing these barriers requires substantial investment in infrastructure and training. Despite these challenges, ongoing advancements in AI are gradually overcoming technical limitations. However, further research and development are necessary to ensure seamless integration. AI in military applications raises significant ethical and security concerns [134]. Data privacy is a major issue, as sensitive information must be safeguarded against breaches [135]. Cybersecurity risks threaten the integrity of AI systems, potentially leading to catastrophic failures [136-137]. Additionally, accountability in autonomous systems remains an unresolved ethical dilemma. Addressing these concerns is crucial to the responsible adoption of AI in defence applications [138-139]. Robust policies and safeguards must accompany technological advancements [140-141]. High implementation and training costs present economic challenges for AI adoption in M&R systems [142]. Developing and maintaining AI-driven solutions requires substantial financial resources [143]. Many defence budgets are already constrained, limiting the scope of such investments [144]. However, the long-term cost savings offered by AI systems could offset these initial expenses. Strategic planning and resource allocation are essential to overcoming these economic barriers.

6. Future Roadmap

The immediate focus should be on pilot programs for AI in predictive maintenance [145]. These initiatives will demonstrate the feasibility and benefits of AI-driven solutions. Developing training modules for technicians to use AI systems effectively is another critical step [146]. These short-term goals lay the foundation for broader AI adoption in the defence sector. In the mid-term, scaling AI integration across vehicle fleets will become a priority [147]. Standardising protocols for AI-driven M&R systems ensures consistency and reliability [148]. These efforts will solidify AI's role in enhancing maintenance efficiency and operational readiness [149]. The long-term vision includes developing fully autonomous maintenance systems [150]. Self-repairing armoured vehicles represent the pinnacle of AI-driven innovation in M&R [151]. Achieving these goals will require sustained research, funding, and collaboration [152-153]. Partnerships between military organisations, AI firms, and academic institutions will drive innovation [154-156]. These collaborations ensure access to cutting-edge technologies and expertise [157]. By pooling resources and knowledge, stakeholders can accelerate the adoption of AI-driven solutions [158].

Highlights

- **Integration of Advanced AI Technologies:** This paper examines using several AI technologies, such as computer vision, machine learning, IoT sensors, and predictive Maintenance, in the defence sector to optimise maintenance and repair processes.
- **Emerging AI Solutions in M&R:** This paper investigates the potential of technologies such as natural language processing (NLP), digital twins, robotics, augmented reality (AR/VR), and reinforcement learning to transform maintenance and repair procedures.
- **Impact on Defense Operations:** The study highlights how artificial intelligence (AI) improves operational preparedness, lowers downtime, increases reliability, and helps armed personnel save money and stay safer.

Abbreviations

- AI: Artificial Intelligence
- M&R: Maintenance and Repair
- IoT: Internet of Things
- NLP: Natural Language Processing
- AR: Augmented Reality
- VR: Virtual Reality
- ML: Machine Learning
- NATO: North Atlantic Treaty Organization
- R&D: Research and Development
- COTS: Commercial Off-The-Shelf
- MRO: Maintenance, Repair, and Overhaul
- DoD: Department of Defense

7. Conclusion

There has been much discussed about the revolutionary impact of Artificial Intelligence on armoured vehicle maintenance and repair (M&R). Hence, a lot of research is done in order to resolve these limitations in the present era of technology. Regarding the revolutionary impact of AI assistance to armoured vehicle maintenance and repair (M&R) it is worth noting that:

- AI capable of transforming the M&R systems of armoured vehicle by providing unmatched efficiency and reliability
- There are various technical, financial, security and ethical challenges to utilize AI in M&R systems yet advantages of AI-based solutions are seen to be significantly larger than the disadvantages.
- The defence sector must address these technical, ethical, and economic barriers to unlock the transformative potential of AI.
- This will require ongoing research, investment, and partnerships to accomplish.
- Article provides insights into future course of AI in M&R, Idea for autonomous maintenance system, Scalable integration and implementation, and pilot programs.

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