

Enhancing Ballistic Missile Defence

Comparing AI-Integrated Systems with Traditional Approaches

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The Ballistic Missile Defence (BMD) systems play a significant role in national security, and are designed to detect, track and intercept incoming missiles. Beginning in the 1950s, they have undergone rapid evolution in consonance with the advancement in technology. Artificial Intelligence (AI), in particular, has proven to be a transformative force in bolstering the capabilities of BMD systems.

Against this backdrop, this article analyses the efficiency and effectiveness of AI-integrated missile defence systems compared to traditional non-AI systems under different operational conditions and scenarios. Leveraging machine learning algorithms, neural networks and real-time data processing, AI increases detection accuracy, reduces false positives and improves interception success rates.

The article relies on quantitative analysis based on t-tests, statistical performance analysis and simulations under diverse conditions. The findings indicate that AI-integrated systems significantly outperform traditional systems in detection latency, false positive rates and interception success. Furthermore, the article analyses the potentially vulnerable sites, challenges and ethical considerations related to AI integration in missile defence, stressing the need for human oversight in the decision-making process. This research underscores the strategic

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advantages and limitations of AI-enhancing defence capabilities against advanced missile threats.

Keywords: *Ballistic Missile Defence (BMD); Artificial Intelligence; Missile Interception; Detection Accuracy; Defence System Comparison*

INTRODUCTION

Ballistic Missile Defence (BMD) is a top-notch defence system designed to defend against incoming missiles by detecting, tracking and intercepting them before they hit the potential targets.¹ These systems are vital for national defence. However, they face numerous challenges in distinguishing real missile threats from countermeasures, while precisely predicting missile trajectories and rapidly responding in a timely manner.

The BMD processes involve different stages. The first task for the BMD is to detect the incoming missile threat. After detecting the missile threat, the system distinguishes the threat (missile) from other objects such as debris, decoys, or other countermeasures launched to confuse and mislead the defence system. Once the incoming missile has been identified as a genuine threat, the BMD system starts to calculate the target's future location and trajectory. Calculating this information, the BMD defence system considers the optimal time and the trajectory for launching an interceptor missile to intercept the incoming missile threat. The last stage is to finally hit the incoming missile and destroy it in the atmosphere.²

The BMD system comes in various forms and each is characterised by different operational environments and requirements, such as the Ground-Based Missile Defence Systems (Ground-based Midcourse Defence [GMD] system), Sea-Based Missile Defence Systems (Aegis Ballistic Missile Defence System), Airborne Missile Defence Systems and Space-Based Missile Defence Systems.

The challenges pertaining to BMD mentioned earlier require advancement in technology, especially in the real-time data processing and nature of adaptive system. Artificial Intelligence (AI) helps in overcoming these shortcomings to improve the efficacy of the BMD system. AI-driven systems mark a paradigm shift as against the traditional automated systems, because of their capability in simultaneous learning and enhancement in their models.³ Comparing the static automated systems that work based on predefined algorithms and constant coefficients, AI-enabled systems adjust over time by processing new data and updating their primary models. These

adaptive characteristics give AI-integrated systems a better edge in responding rapidly to evolving threats, which is a critical feature for the modern missile defence systems.

AI-models used in the BMD systems leverage real-time data from missile tests, operational feedback and inputs from sensors.⁴ These systems use the machine learning algorithms to help make the prediction more accurate, minimise the false positives and improve the interception success rate. Over time, the self-learning process ensures that the systems become more adept at detecting patterns, anomalies and novel threats, the kind of capabilities clearly absent in the static systems.

The traditional non-AI integrated model automated systems work based on static coefficients, which is determined during the initial programming.⁵ These coefficients are not changed over time unless manually updated by the operators, limiting these systems' ability to adapt to unconventional scenarios. On the other hand, AI-enabled systems simultaneously refine these parameters by learning from new inputs, creating robust dynamic coefficient framework that develops with the time. For example, the static coefficients in automated systems depend on the fixed thresholds for the detection of upcoming missiles and response, which may not add variations in missile trajectory or countermeasures. Such rigidity can potentially lead to missed detections or incorrect classifications. On the contrary, AI systems use the neural networks⁶ and reinforcement learning to adjust coefficients in real-time. As new characteristics of missiles or countermeasures arise, the AI-enabled systems integrate this information into improving future performance.⁷

Table 1 Compare the evolution between AI integrated missile defence and traditional automated missile defence system.

Metric	AI-integrated Missile Defence System	Traditional Automated Missile Defence system
Co-efficient adaptability over time	Dynamic: Self-learning process	Static: Manually updated by operator
Response to unconventional threats	Adaptive	Limited
Prediction accuracy	Develops accuracy over time	Fixed
Success rate of interception	Constantly increasing	Fixed

This article analyses the potential impact of AI on developing the efficacy of BMD systems, investigating how AI-driven enhancements could successfully address current technical limitations and overcome the BMD capabilities. The article also explores the role of AI in threat detection, interception accuracy and overall system efficiency improvement.

HISTORICAL EVOLUTION OF THE BMD SYSTEM

Missile defence systems can be traced back to the late 1940s and 1950s with the rapid development of the radar systems and interceptors intended to protect the US against Soviet bombers and later intercontinental ballistic missiles (ICBMs). The first operational missile defence systems were developed in the 1950s, whose main task was to intercept ICBMs mid-course. However, they were ineffective due to technological limitations and the changing nature of missile threats.⁸

In 1983, President Ronald Reagan initiated the development of a comprehensive missile defence system using ground-based and space-based systems to protect against nuclear missile attacks, under the framework of the Strategic Defense Initiative (SDI). However, it faced significant technical and political challenges due to concerns over its feasibility and potential to upset the strategic balance between the US and the Soviet Union.⁹ Detecting and differentiating real threats from decoys, space-based directed energy and kinetic energy weapon development, resilience of space-based systems against Anti-satellite weapon (ASAT) were the main technical challenges for SDI.¹⁰

After the collapse of the Soviet Union, the focus shifted towards regional threats and the proliferation of ballistic missile technology to 'rogue' states. The Theater Missile Defense (TMD) systems were thus developed, which included systems like the Patriot that gained prominence during the Gulf War in 1991 for intercepting Scud missiles.¹¹

The US began deploying a National Missile Defense (NMD) system in 1999, which was designed to protect against limited long-range missile attacks. This culminated in the development of the Ground-based Midcourse Defense (GMD) system, which became operational in the early 2000s. The GMD was aimed at detecting and intercepting ICBMs in their midcourse phase using ground-based interceptors.¹²

After the 2000s, the development of advanced radar systems such as AN/TPY-2 and Aegis Ballistic Missile Defense increased the capabilities. Moreover, the integration of space-based sensors with improved command and control (C2) systems enhanced situational awareness and coordination.¹³

CHALLENGES AND VULNERABILITY OF THE BMD SYSTEM

BMD is not an absolute system without errors. Primary challenges and vulnerabilities of such systems arise from several factors which affect their effectiveness and reliability. As the boost phase of a missile flight is short, it requires rapid detection and response. As satellite can be very fast when it comes to detecting the launch, the real challenge relates to the integration of long-range interceptors with the detection systems to guide the interceptors accurately over long distances. This coordination is vital for the successful interception. Sensors must quickly identify a launch and relay precise information. This poses a significant technical barrier. Positioning the sensors strategically and quick response capabilities are the challenges for early detection and interception of incoming missiles.¹⁴ The proliferation of advanced missiles and decoys can hinder the effectiveness and success rate of the BMD systems.¹⁵

Furthermore, advancements in conventional countermeasures capabilities to attack BMD critical infrastructure raise significant concerns regarding the efficacy of BMD systems.¹⁶ The conventional countermeasures such as decoy missiles or electronic jamming still keep posing serious challenges to the efficacy of BMD systems despite the integration of AI into the BMD, as countermeasures are expected to evolve alongside the improvement in defence technologies.

AI INTEGRATION IN BMD SYSTEM

Considering these challenges, AI brings new opportunities in the military domain, especially in areas such as logistics, navigation command and control (C2), prediction on the battlefield, etc. AI has huge potential to significantly increase the capabilities of the BMD system by improving detection accuracy, minimising the false positives and optimising the interception strategies. However, before reaching that, for AI to overcome traditional existing vulnerabilities, it is important to explore how these developments are achieved and shortcomings are minimised with regard to AI integration in BMD operations.

AI offers a unique approach to quickening response times by analysing data rapidly. This supports potential autonomy and faster reaction times. Currently, some of the existing BMD systems such as THAAD (Terminal High Altitude Area Defense) and Patriot can autonomously detect, monitor and track enemy missiles without any human intervention.¹⁷ It is pertinent to

mention that AI and autonomy are interconnected and autonomous systems increase the effectiveness of the AI-integrated BMD system.

KEY CHALLENGES AND IMPLICATIONS

One of the key issues regarding AI integration into BMD is the computational complexity involved in optimising missile allocation, which can lead to the 'heuristic approaches'.¹⁸ Moreover, data processing can have an impact on the accuracy of missile movement, especially in response to changes in target position and motion.¹⁹ Further, the development of BMD integrating AI can inadvertently blur the boundaries between theatre and strategic defences, which potentially raises concerns about arms control and international stability in the absence of binding treaties.²⁰ There is always a risk that the integration of AI into one country's BMD system can be interpreted as a threat to other countries' nuclear deterrence capability.

One major concern regarding AI integration into BMD is 'trust' due to the complexity. The complexity of incorporation of AI algorithms and their potential to work in a way that is not always predictable or transparent make human operators hesitate in completely relying on them when it comes to critical defence scenarios. A complete understanding of why and how AI models make certain decisions, and how these models evolve as they consume and process more data is crucial for developing confidence in AI-driven applications.²¹

The 'Three Mile Island' accident is an example of the importance of proper evaluation for calibrating trust in automation. Research shows that the faith of human operators in the system changes based on the performance—while successes increase their faith, failures decrease their faith.²² These dynamics underscore the challenge of keeping operator confidence in AI systems, which may result in unpredictable behaviour due to the complexities involved.

The question this article seeks to answer is how do AI-integrated missile defence systems fare *vis-à-vis* non-AI integrated systems in detecting and intercepting missiles under different environmental conditions and scenarios.

In answering this question, this article employs the mixed method by integrating quantitative and qualitative analyses to evaluate AI-integrated missile defences with the non-AI integrated missile defence systems. The article uses the t-test to statistically assess differences in performance metrics (detection latency, false positive rates and interception success rate)

between the two systems. The qualitative analysis complements this by exploring the human factors and decision-making process, analysing the role of human oversight in the AI systems, and analysing the impact of AI on operational strategies and trust. This combined approach gives a robust assessment of the effectiveness and reliability of AI-integrated missile defence systems.

EFFICIENCY OF BMD: AI-INTEGRATED VERSUS NON-AI INTEGRATED MISSILE DEFENCE SYSTEMS

AI-integrated missile defence system implies that the system uses AI to enhance the capabilities of detecting, tracking and intercepting incoming missiles, while leveraging machine learning algorithms, neural networks and real-time data processing to rapidly analyse sensor data. It thereafter predicts missile trajectories which help in making autonomous decisions regarding threat identification and interception.

On the other hand, a non-AI integrated missile defence system relies on traditional technologies and methodologies for detecting, tracking and intercepting incoming missiles. This system uses predefined algorithms, human-operated controls and conventional data processing techniques. Detection and interception decisions are typically based on fixed parameters and require significant human intervention.

One of the critical elements of missile defence is the early warning system, which helps in detecting incoming missiles to launch an interceptor. AI integration into the sensor-weapon-target cooperative task for the ground-to-air defence systems can make efficient early warning and classification of incoming threats.²³

AI-integrated systems can also recognise the abnormal behaviours in sensor data that may indicate the presence of an upcoming missile threat, which includes sudden changes in trajectory, intense hotness signatures or unexpected seismic activity. By considering these anomalies for further investigation, AI helps prioritise threat assessment and response efforts, reducing the likelihood of false missile detections.²⁴ AI systems are efficient at combining information from several sensors to produce a complete picture of the battlefield. AI can improve overall detection accuracy by filtering out false positives and cross-validating information by combining data from radar, infrared and other sensors.

AI can, for example, learn the data that helps in differentiating missile threats from other objects or environmental phenomena by simultaneously

analysing and adapting to new data, such as comparing radar tracks with infrared signals. Over time, the self-learning capability develops the system's accuracy and reduces the false positive. Unlike the traditional systems which heavily rely on special programming for every possible scenario, AI systems use machine learning algorithms to analyse data and accordingly change their behaviour. They can identify patterns, trends and anomalies in data, allowing them to improve their performance over time, without the need for extra manual programming. In contrast, traditional automated processes typically follow pre-programmed rules and cannot learn or adapt to new information.

From the satellite image, analysing the preparation of a missile launch, for example, the missile transporter-erector-launcher (TEL), can help to recognise the possibility of a missile launch. Currently, the US expects to use this technology to detect adversaries' mobile missiles and trucks.²⁵ AI is capable of generating models for specific enemy country or the region and the intention to hit critical targets by evaluating the previous historical data. This can offer recommendations for better defence measures, help with pre-emptive strikes and mobilise the resources.

In order to understand the efficiency of the AI-integrated missile defence and the non-AI-integrated missile defence, the article uses the simulation.

Environment

Consider a region 500 km × 500 km, covering the potential missile launch sites and targets. The geographical area includes urban areas, mountains and open fields, which can affect the sensor performance.

There are multiple pre-determined missile launch sites located around the perimeter of the area to simulate various threats. For the missile launch, different missile types with varying speeds and trajectories are considered to test the test adaptability.

The radar sensors of the missile defence systems cover large areas for early detection of incoming missiles. Infrared sensors for detecting heat signatures are especially useful against stealth missiles. The satellite sensors provide wide-area surveillance and monitoring.

Missile Defence System

There are two different types of missile defence systems used. The first one is the AI-integrated defence system and the second one is the non-AI integrated system. The AI-integrated algorithms use real-time data processing and decision-making, while the traditional systems rely on set rules and manual processing for detection and interception.

Operational Conditions

Simulating different weather conditions, including clear, cloudy and rainy weather conditions, can affect the sensor's effectiveness. Different times of day and night can also impact sensor visibility and detection capabilities.

Simulation Scenarios

There are three types of simulation scenarios here, which include:

1. Single missile launches with a straight trajectory to access baseline detection and interception capabilities.
2. Multiple missiles launch with varying trajectories and speeds. For this specific scenario, missile trajectories are generated using a randomisation algorithm. This could involve varying angles of launch, altitudes and speeds within specified limits to simulate unpredictable paths. Each missile is assigned a unique speed and trajectory pattern to mimic realistic attack scenarios.
3. Stealth missile launches with low radar visibility. This scenario focuses on missiles designed to have low radar visibility. Assumptions might include reduced thermal signatures and altered trajectories to test the effectiveness of infrared and radar sensors.

Simulation Parameters

Missile speed: Assume the missile's speed is 2 km/s, which is considered the real-world scenario.

Missile Trajectory: Randomised for scenarios 2 & 3 to simulate unpredictability in missile paths.

Detection Range: Each system can monitor a 500 km radius. The missile launches sites and target areas distance vary between 100 km and 500 km. This range accounts for the travel time of the missiles and effective engagement area for the interceptors.

The simulation counts three phases of the missile flights that include: Boost Phase (0–100 km), Midcourse Phase (100–1000 km) and Terminal Phase (100 km).

Interception window: A critical time limit of 10 seconds from detection to interception. A missile travelling at the speed of 2 km/s shows 20 km interception zone; the key interception time is 10 seconds approximately. The interceptors are categorised as 'ex atmospheric' or 'end atmospheric' with the capabilities adjusted for the realistic operational scenarios.

Radar, satellite sensors and infrared sensors cover the detection range of 500 km radius to track and detect incoming missiles. It is also important

to take into consideration that different environmental conditions affect the sensor performance.

Randomisation Process for Missile Trajectories: For each missile in the multiple launch scenarios, random angles (0 to 360 degrees) and altitudes (surface to a maximum of 500 km) are generated using a uniform distribution. This helps in ensuring a wide range of potential paths.

While maintaining a base speed of 2 km/s, minor variations could be introduced to simulate different missile types ($\pm 10\%$ speed variation).

Metrics to Measure

Detection Latency: From the time the missile is launched to the time it is detected.

False Negative or False Positive: The rates of failure to identify.

Prediction Capability: Precisely estimating missile trajectories.

Interception Success Rate: Percentage of successfully intercepted missiles.

Operation Efficiency: Reduction in human operator workload.

AI-integrated missile defence uses advanced algorithms compared to traditional systems.

The AI systems work to maximise the sensitivity in detecting upcoming missile threats, meaning they err on the side of caution, which underscore that sensitivity often leads to higher rate of positives. On the other hand, traditional missile defence relies on the static, that is rule-based algorithms and manual verification, which are inherently more conservative in classifying the treats. This approach results in lowering the rate of false positives.

I assume,

AI-integrated missile defence false positive = 0.5

Non-AI integrated missile defence false positive = 0.15

False positive is defined when missile defence incorrectly identifies non-threat as a threat. As AI can develop certain detection, I assume it might be prone to higher sensitivity which might lead to many events as a threat. On the other hand, non-AI integrated missile defence has conservative detection capability, which may cause fewer false positives but also risk missing some real threats.

AI-integrated missile defence false negative = 0.2

Non-AI integrated missile defence false negative = 0.10

A false negative is when the missile defence fails to identify the real threat. I assume that AI-integrated missiles would act more aggressively, which lowers the rate of false negatives compared to non-AI-integrated missile defence. On the other hand, non-AI missile defence would be more cautious, leading to even lower false negatives.

AI-integrated missile defence prediction accuracy = 0.90

Non-AI integrated missile defence prediction accuracy = 0.70

Prediction accuracy considers how often the missile defence can accurately identify the threat or non-threat. I assume that despite the higher false positive rate, AI-integrated missile defence would identify more precisely the threat or non-threat, whereas the non-AI missile defence system, due to their conservative approach, may not be able to precisely identify the threat. Even though both AI-integrated and non-AI integrated missile defence systems depend on the same type of sensors (i.e., radar, satellite systems, infrared), the key difference pertains to how these systems process and analyse the sensor data.

AI-integrated missile defence systems use advanced algorithms to fuse data from multiple sensors, making it more precise in producing cohesive pictures of the battlefield. Moreover, AI systems are good at detecting the pattern and anomalies in data sensor. For example, the heat signatures and trajectory path potentially indicate real threat.²⁶ In contrast, a non-AI missile defence system uses rule-based algorithms that lack flexibility to adapt to unconventional scenarios or novel attack, which may lead to misclassification of threats. So, the non-AI integration of missile defence heavily depends on human operator for decision-making, which results in cognitive biases, errors or sometimes delays, specially under high-pressure situations.²⁷

AI-integrated missile defence interception Success Rate = 0.85

Non-AI integrated missile defence Interception Rate = 0.60

The interception success rate considers the success of a missile defence system in intercepting an upcoming missile. AI improves the decision-making process, leading to a more quick and accurate response considering the non-AI integrated conventional missile defence system which has limited decision-making capability, leading to a lower success rate.

AI-integrated missile defence workload reduction = 0.50

Non-AI integrated missile defence workload reduction = 1

Workload reduction refers to the level of human involvement required. Automatic threat detection and response reduce the workload to a larger extent, whereas non-AI integrated missile defence systems heavily depend on human operators.

Table 2 Summary Table of the Matrix

Metric	AI-integrated Missile Defence System	Non-AI integrated Missile Defence System
False Negative	0.5	0.15
False Positive	0.2	0.10
Prediction Accuracy	0.90	0.70
Interception Success Rate	0.85	0.60
Workload Reduction	0.50	1

To analyse and evaluate the performance metrics, such as detection latency, false positive and negative, prediction accuracy, interception success rate and operational efficiency, I use the t-tests to analyse the statistical significance of the differences between the two defence systems. For instance, the t-test helps in determining the robustness of AI algorithms in enhancing missile defence capabilities.

After doing the t-test, here are the results:

Detection Latency T-Test: T-statistic = -10.84005898600964, p-value = 8.549202322856378e-22

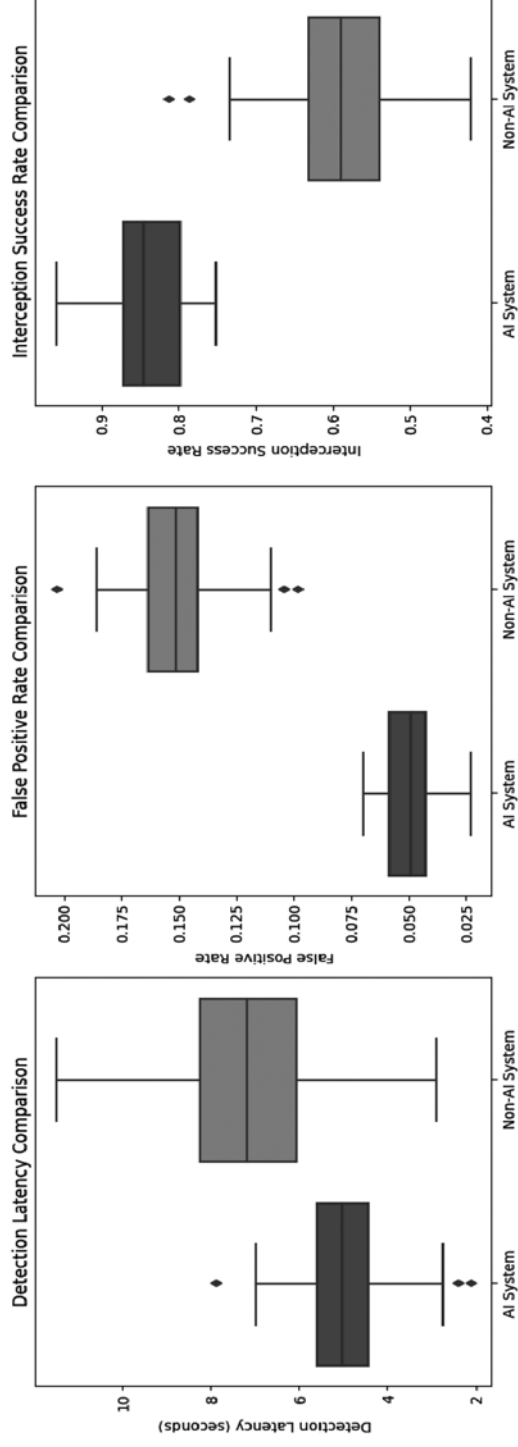
False Positive Rate T-Test: T-statistic = -46.66010875048045, p-value = 8.869898394431442e-109

Interception Success Rate T-Test: T-statistic = 30.139448541990063, p-value = 6.583920666928047e-76

Detection Latency: T-Statistic: -10.84, P-Value: 8.55e-22

The AI-integrated missile defence detects missiles significantly faster than the non-AI traditional missile defence system. The negative number indicated that the AI-integrated missile system’s latency is lower. The p-value is extremely small, which is close to 0, meaning the difference is very unlikely to happen by chance. So, from this aspect, AI-integrated missile defence is better than traditional non-AI-integrated missile defence.

Figure 1 Comparing the missile defence performance: AI integrated missile defence system vs Non-AI integrated missile defence system



False Positive Rate: T-Statistic: -46.66, P-Value: 8.87e-109

The AI-integrated missile defence system has a much lower rate of incorrectly identifying threats compared to the non-AI-integrated missile defence system. The negative value shows the AI system is performing better. The p-value is also very small, which indicates a very strong statistical difference. This means the AI system is much more reliable in destringing real threats from false alarms.

Interception Success Rate: T-Statistic: 30.14, P-Value: 6.58e-76

AI systems are much more successful at intercepting the upcoming missiles than the traditional non-AI systems. The positive value indicates that the AI has a higher success rate. The p-value is very small, meaning that the difference is statistically significant and not used for random choices.

ENHANCING BMD AGAINST SATURATION ATTACKS: AI-DRIVEN DEFENCE STRATEGIES VERSUS THE TRADITIONAL MISSILE DEFENCE SYSTEM

A 'saturation attack' in the context of missile defence, is considered a tactic where large numbers of missiles, drones and other measures are launched simultaneously towards a target from different directions, overwhelming the target's missile defence systems.²⁸ The aim here is to maximise the likelihood of the success of penetrating the target's defence system by creating a challenging scenario for the defence system to handle.²⁹ The idea of a 'saturation attack' is similar to employing numerous defenders in a defensive guidance approach.³⁰

During the Cold War and after that, the conventional saturation missile strike against naval and land targets continues to be a highly feared possibility. Within a very short time, attacking missiles are fired from different directions and levels to hit the same target. This overwhelms the enemy's air defence system and makes it much more likely that the missiles will penetrate the defence network. Later, the 'anti-saturation attack' methods are created to defend against the 'saturation attack'. These methods evaluate the system's capabilities and find the best way to place interceptors, so that the cost of defending an asset's value is kept as low as possible.

To understand the efficiency, consider the two missile defence systems. The first one is the AI-integrated missile defence system (A), and the second one is the non-AI-integrated missile defence system (B).

First, the AI-integrated missile defence system uses advanced AI technology to help detect and intercept incoming missiles more effectively, whereas system B relies on traditional methods without AI assistance.

For the simulation, I used 100 missiles that launched simultaneously towards each system. This number allows us to simulate a significant and challenging scenario for both systems. This number is large enough to potentially overwhelm a defence system and test its capabilities realistically. Here in the simulation, use the random process to decide if the missile is intercepted or not, choose the random number between 0 and 1 which is a uniform distribution. Using randomness in the simulation reflects the real-world unpredictability and variability in missile trajectory, speed and other factors that can affect interception success. In the simulation, I consider if the random number is less than 0.8, the AI-integrated missile system will intercept the upcoming missile, and for the non-AI integrated missile defence system if the number is 0.5, the upcoming missile will be intercepted.

I assume that AI-integrated systems have a higher interception rate of 0.8 due to their advanced capabilities in rapidly assessing and responding to threats. On the other hand, non-AI integrated missile defence systems have a lower interception rate of 0.5, which reflects its reliance on less adaptive and slower response mechanisms.

After running the simulation, here are the results:

Results for System A (AI-Integrated):

Successful interceptions : 70

Failed interceptions : 30

Results for System B (Non-AI Integrated):

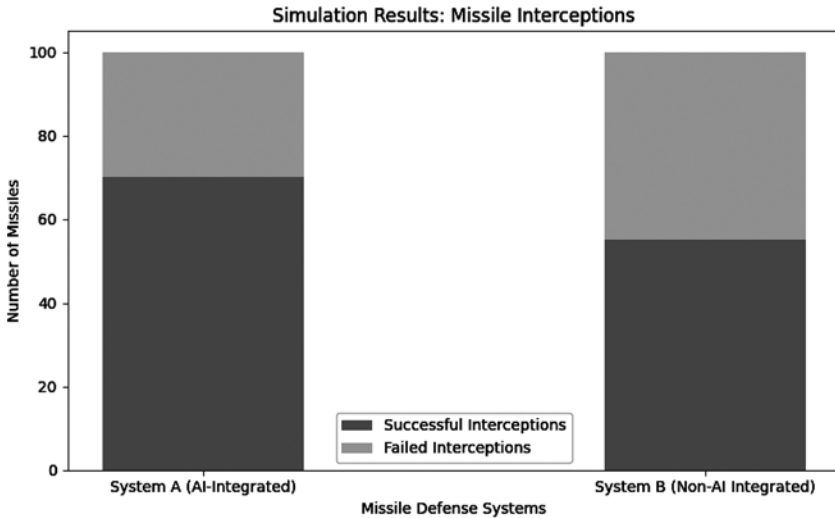
Successful interceptions : 55

Failed interceptions : 45

Out of 100 upcoming missiles, the AI-integrated missile defence system (A) was able to successfully intercept and neutralise 70 missiles, but failed in 30 missile intercepts despite its advanced AI capabilities. These missiles passed through the AI-integrated missile defence and potentially penetrated the intended targets.

On the other hand, the non-AI traditional manual missile defense system (B) was able to intercept 55 missiles successfully, but failed to intercept 45 missiles that could have hit their targets.

Figure 2 The success rate of the AI-integrated missile defence system (A) and the non-AI-integrated missile defence system (B) against saturation attack.



Human in the loop of missile defence decision-making process:

The question of whether humans should be in the loop of missile defence decision-making processes or not is directly connected to AI-integrated BMD systems. AI-based BMD systems have the capability to make rapid decisions based on real-time data analysis and pattern recognition. This section discusses whether or not humans should be in the loop of the missile defence decision-making process.

Humans possess cognitive abilities, instinct and judgement, allowing them to consider various contextual factors and assess the authenticity and reliability of gathered information. In unexpected situations, human participation renders decision-making more flexible and enables consideration of ethical, legal and humanitarian concerns.

For instance, when faced with incoming missile threats targeting densely populated cities, core military facilities (such as nuclear weapon programmes), or border areas, human decision-makers consider real-time information, prevailing political dynamics, anticipated consequences, proximity of the threat to civilians, expected interceptor arrival time, and other pertinent circumstances. However, if the missile targets a border area, decision-makers assess potential negative impacts on neighbouring countries, legal and ethical considerations of not infringing on neighbours' sovereignty, and risks of

collateral damage. Political cost-benefit analyses play a role in decision-making, weighing potential consequences even if civilian lives are at stake. Furthermore, if decision-makers can ascertain information about the missile's payload and range, measures such as mobilising civilians to underground bunkers or protected areas as part of defensive actions may be undertaken.

Despite its advantages, AI has limitations and may introduce errors. AI systems might struggle to accurately interpret data and discern between genuine threats and false alarms. Moreover, lacking geopolitical and strategic context, AI systems pose risks of false negatives or false positives. AI systems are good at making complex decisions by processing vast data volumes and considering multiple factors concurrently. They provide insights and recommendations based on probabilistic analysis and pattern recognition. In contrast, traditional automated processes operate on rule-based determinism, adhering to predefined criteria without the ability to account for nuances or uncertainties. Moreover, human involvement in missile defence decision-making loops is critical for ensuring the credibility and effectiveness of deterrence strategies.³¹

Several missile defence systems are starting to make more decisions on their own, using automation and AI. However, having a system that makes all the decisions without any human involvement is considered extreme. Instead, while humans still oversee the process, more and more tasks within that process are being automated. This means that things like analysing data and planning responses are done by computers to speed things up and make them more efficient.³²

In the context of AI and automation in BMD, things are closely interconnected and mutually dependent. AI technologies, such as machine learning and deep learning algorithms, empower automation in BMD systems. AI enables the automation of various tasks and processes by allowing systems to perceive, analyse, and respond to complex data and scenarios without direct human intervention. For example, AI algorithms can automate the analysis of sensor data to detect and track incoming ballistic missiles, identify potential threats, and generate response plans.

Currently, the Aegis system can fully operate against short-range ballistic missile (SRBM) and medium-range ballistic missile (MRBM) threats.³³ The US missile defence agency also initiated an initiative to build radar which will autonomously acquire persistent precision tracking and discrimination to optimise the defence capability against incoming ballistic missiles.³⁴

Considering the automated decision-making process, humans involved in the decision-making process have some shortcomings which are discussed

here. Humans might be influenced by cognitive bias, heavily influenced by emotion, anchoring, or confirmation bias which impact the judgment and rapid response process of the interceptor. In a high-stress and political pressure situation, there could be a high possibility of making errors and decreasing the overall system reliability.³⁵ For example, considering a situation where large numbers of incoming missiles are heading towards different targets, human decision-makers may hesitate, facing extremely difficult situations, to make decisions in a very short amount of time with accurate judgement because of the overwhelming data and information flow, and pressure for a quick response.³⁶ This may lead to negative influence with huge political consequences, large civilian casualties, and property damage. A complex and large-scale missile defence system requires the involvement of several decision-makers. In such a case, there could be different interests and opinions where individuals take varying decisions.

Experience, political interest and technical expertise can offer different opinions from different individuals, leading to inconsistency in the decision, the vulnerability of the cooperation, mistrust, and decreased effectiveness. When faced with huge amount of incoming data, human decision makers find it challenging to process and interpret the information accurately and precisely. This can increase the likelihood of misinterpretation, specially under time constraints and high-pressure conditions. In the context of missile defence, these challenges could lead to delayed or incorrect decisions, which could likely lead to missed interception opportunities and minimise the systems' effectiveness.

CONCLUSION

The comprehensive analysis of the AI-integrated missile defence system versus traditional non-AI-integrated missile defence systems show significant advantages in the case of AI-integrated missile defence systems. AI-integrated missile defence systems demonstrate superior performance in detecting, tracking and intercepting missiles, with faster detection latencies, lower false positive rates, higher prediction accuracy, and greater interception success rates. The simulation results discussed earlier indicate that AI systems are more effective in handling saturation attacks, successfully intercepting a higher percentage of missiles compared to non-AI systems.

Even though AI brings enhanced capabilities and adaptability, human oversight remains critical for addressing ethical and strategic considerations. Integrating AI into missile defence systems considerably improves efficiency

and reliability, positioning it as a key component of modern defence strategies.

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