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MICRO-CLASS MISSILE ASSAULT BOAT SWARM TACTICS EFFECTIVENESS IN THE TAIWAN STRAIT

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THESIS

MICRO-CLASS MISSILE ASSAULT BOAT SWARM TACTICS EFFECTIVENESS IN THE TAIWAN STRAIT

by

Shuchang Liu

December 2019

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13. ABSTRACT (maximum 200 words)

Taiwan resolves to maintain peace and stability across the Taiwan Strait while the People's Republic of China's rising military capability has challenged the status quo. As a result, Taiwan's military aims to develop asymmetric warfare capability and build up a credible deterrence. Among the new assets in production, the 45-ton micro-class missile assault boat (MicMAB) is designed to carry two anti-surface warfare missiles, and the concept of employment is focused on its stealth, terrain masking, and swarm tactics. The thesis's objective is to analyze the MicMABs' swarm effectiveness against adversary warships in the Taiwan Strait using Hughes's salvo equations and the agent-based modeling tool Map Aware Non-Uniform Automata. In the scenario of 60 MicMABs engaging 50 heterogeneous warships, the results indicate that 60 MicMABs can take 45 adversary warships out of action on average. If selective targeting is not an option due to a lack of sound intelligence, surveillance, and reconnaissance, it is recommended to assign each MicMAB to shoot whichever target is closest. When in direct engagement, the attrition of the MicMABs is high, nearly 35, but taking a high-degree terrain-masking route can successfully lower the attrition to approximately 18.

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MICRO-CLASS MISSILE ASSAULT BOAT SWARM TACTICS EFFECTIVENESS IN THE TAIWAN STRAIT

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

Taiwan resolves to maintain peace and stability across the Taiwan Strait while the People's Republic of China's rising military capability has challenged the status quo. As a result, Taiwan's military aims to develop asymmetric warfare capability and build up a credible deterrence. Among the new assets in production, the 45-ton micro-class missile assault boat (MicMAB) is designed to carry two anti-surface warfare missiles, and the concept of employment is focused on its stealth, terrain masking, and swarm tactics. The thesis's objective is to analyze the MicMABs' swarm effectiveness against adversary warships in the Taiwan Strait using Hughes's salvo equations and the agent-based modeling tool Map Aware Non-Uniform Automata. In the scenario of 60 MicMABs engaging 50 heterogeneous warships, the results indicate that 60 MicMABs can take 45 adversary warships out of action on average. If selective targeting is not an option due to a lack of sound intelligence, surveillance, and reconnaissance, it is recommended to assign each MicMAB to shoot whichever target is closest. When in direct engagement, the attrition of the MicMABs is high, nearly 35, but taking a high-degree terrain-masking route can successfully lower the attrition to approximately 18.

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LIST OF ACRONYMS AND ABBREVIATIONS

C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance
CSIST	National Chung-Shan Institute of Science and Technology
DOE	Design of Experiment
HF	Hsiun Feng
ISR	Intelligence, Surveillance, and Reconnaissance
MANA	Map Aware Non-Uniform Automata
MicMAB	Micro-class Missile Assault Boat
MOE	Measure of Effectiveness
NPS	Naval Postgraduate School
ODC	Overall Defense Concept
OOA	Out of Action
PLA	People's Liberation Army
PLAN	People's Liberation Army Navy
PRC	People's Republic of China
R&D	Research and Development
SSC	Small Surface Combatants
TTP	Tactics, Techniques, and Procedure
U.S.	United States
USN	United States Navy

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EXECUTIVE SUMMARY

Navies around the world have focused on acquiring large warships for multi-mission capacity and steaming range. In the era of great power competition, however, potential maritime conflicts are more likely to happen upon green waters rather than high seas, where large-size, multipurpose warships might be constrained to maneuver and carry out their capabilities. In such situations, a large number of small, fast combatants equipped with robust firepower may bring an asymmetrical advantage to a smaller navy in an engagement against a navy primarily composed of large-size warships.

Taiwan resolves to maintain peace and stability across the Taiwan Strait while the People's Republic of China's rising military capability has challenged the status quo. As a result, Taiwan's military steers to a new approach entitled the Overall Defense Concept, proposed by then Chief of the General Staff, Admiral Lee Hsi-Min in 2017. The Overall Defense Concept aims to develop asymmetric warfare capabilities and build up a credible deterrence. Among the new assets in production, the 45-ton Micro-class Missile Assault Boat (MicMAB) is designed to be stealthy, endure rough sea states, and carry two indigenous anti-surface warfare missiles each. Sixty platforms are planned, and four prototypes will be built and tested in 2020. The concept of employing these small combatants is to leverage swarm and terrain-masking tactics.

The thesis' objective is to analyze the MicMABs' potential swarm effectiveness against adversary warships in the Taiwan Strait in a People's Liberation Army Navy (PLAN) invasion scenario. The analytical tools, Hughes' salvo equations (Hughes 1995) and the agent-based modeling software Map Aware Non-Uniform Automata (MANA), are applied in this study to explore the effectiveness of employing MicMAB swarm tactics by varying target priorities and selecting varied terrain-masking engagement routes. The scenario is assumed in the mid-section of the Taiwan Strait, where Blue deploys a homogeneous force of 60 MicMABs to engage the invading Red task group, a heterogeneous force consisting of destroyers, frigates, and corvettes.

The key assumption for this scenario is that there are no other Red or Blue assets present in this area, assuming the air being dominated by Red, and Blue having its primary forces in preservation out of this area. Hence, 60 MicMABs are set to share targeting information, acquired by Blue mobile radar vehicles ashore. Moreover, Blue is assumed to enjoy a 100-kilometer zone of target detection and acquisition around the islands of Taiwan, and the MicMABs are initially dispersed at small fishing ports in this area, ready to be deployed and fire missiles either in port or to an advantageous position.

The first analytical tool utilized is Hughes' salvo equations, which specializes in surface warfare. The parameters required are number of ships, scouting effectiveness, striking power, readiness, defensive power, and staying power, and thus the resulting force attrition can be calculated for a single salvo force-on-force engagement between Blue and Red. The major finding from this part of the analysis is that having a sufficient number of MicMABs and keeping them stealthy are the most prominent attributes. Specifically, as Red's scouting effectiveness parameter increases, which implies the degree of MicMAB's stealth decreases, the number of MicMABs attrited increases rapidly. In the case when Red has 10 destroyers, 10 frigates, and 10 corvettes with a scouting effectiveness parameter of 0.1, the total number of MicMABs taken out of action is 18. By contrast, if Red's scouting effectiveness is increased to 0.4, all 60 MicMABs are taken out of action.

Hughes' salvo equation is deterministic and highly aggregated, and to add variability and entity-level resolution into this study, the stochastic modeling and simulation tool MANA is utilized. The design of experiment takes a systematic approach to explore the measure of effectiveness of Blue's 60 MicMABs engaging two sizes of Red task groups, consisting of 30 or 50 heterogeneous combatants of destroyers, frigates, and corvettes, respectively. Therefore, the attributes contain two sizes of Red force, three terrain-masking routes, and a variety of target priorities, namely assigning a certain number of small combatants allocated and prioritized to engage with destroyers, frigates, or corvettes. Selecting terrain-masking routes is of particular interest in this study. Consequently, Figure ES-1 illustrates routes A, B, and C, where route A stands for a more direct engagement, and routes B leverages more terrain-masking. Route C adopts an alternative terrain-masking tactic around the scattered mid-strait islands.

Figure ES-1.   Various Terrain-Masking Routes

The simulation results indicate that 60 MicMABs can, on average, attrite 45 out of 60 adversary warships. If selective targeting is not an option due to a lack of sound intelligence, surveillance, and reconnaissance, it is recommended to assign each MicMAB to shoot at whichever target is closest. When in direct engagement (using route A), the attrition of the MicMABs is high, nearly 35, but adopting a high-degree terrain-masking tactic (using route C) can successfully lower the attrition to approximately 18. Because this analysis did not detect statistically significant differences in targeting priorities, the effect of prioritized targeting will require more in-depth exploration with extensive sensitivity analysis. Overall, firing at the closest target is satisfactory based on the outcome of the simulation, and the simulation provides evidence that a swarming force distributed among the mid-strait islands and close to the Taiwan shore leads to a favorable outcome. Hence, use of terrain masking is a critical tactic to employ in order to increase the lethality and survivability of the swarm.

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I.   INTRODUCTION

Navies around the world have focused on building or procuring multipurpose warships of larger size, especially the United States Navy (USN) and the People's Liberation Army Navy (PLAN). With larger size and greater functionality comes increased cost, and thus, fewer ships can be acquired for a given budget.

As large ships are preferred for their multi-mission capacity and steaming range, small combatants seem to be less valued by blue-water navies. Nevertheless, in the era of great power competition, potential maritime conflicts are more likely to happen upon green waters, or littoral zones, instead of high seas. Having a large number of small inexpensive ships equipped with robust firepower may bring an asymmetrical advantage to a smaller navy in an engagement against a larger navy primarily consisting of large-size capital ships.

The major and obvious vulnerability of small combatants is their short operational range, but in the littoral environment, this vulnerability can be mitigated with well-planned logistics. Contemporary potential maritime hotspots are mostly around green waters, such as the South China Sea, East China Sea, Persian Gulf, and Baltic Sea, where small combatants can often enjoy the advantages of terrain and island masking, as well as swift maneuverability while engaging larger capital ships.

A particularly important issue to the international order is the security situation across the Taiwan Strait. The government of the People's Republic of China (PRC) has not abandoned the idea of uniting the PRC and the Republic of China, Taiwan, by force, despite the fact that 23 million Taiwanese enjoy a vibrant democracy and value basic human rights. As a result, the government of Taiwan has always valued the importance of a credible defense and sought to acquire sufficient defense capabilities.

In recent decades, however, PRC's People Liberation Army (PLA) has significantly outnumbered Taiwan's armed forces in areas such as number of soldiers, missiles, tanks, and ships. Furthermore, its force buildup is supported by an enormous defense budget. The growing imbalance of military forces between the PRC and Taiwan has led Taiwan's military decision makers to abandon the concept of war of attrition in favor of developing

asymmetric and innovative warfare tactics, as well as acquiring the needed platforms through the international market or indigenous industries (Thompson 2018).

In 2017, Taiwan's then Chief of the General Staff, Admiral Lee Hsi-Min, proposed a new approach, the Overall Defense Concept (ODC), introducing the concept of maximizing Taiwan's defense advantages and focusing on the PLA's key vulnerabilities with a series of asymmetric platforms, manufactured indigenously, along with existing capital ground, maritime, and air assets, mostly produced by the United States (U.S.) manufacturers (Thompson 2018). One of those indigenous asymmetric platforms is the Micro-class Missile Assault Boat (MicMAB), which is designed to be low cost but highly effective and can be produced in a short timeframe. This small, fast combatant, designed to be stealthy, endure high sea-state, and carry two anti-surface Hsiun Feng (HF) type II missiles, is projected to provide critical and kinetic anti-surface warfare and anti-amphibious warfare capability. Produced with sufficient numbers, the MicMAB will leverage the advantage of swarm tactics.

In 2018, Taiwan's legislators approved this type of platform's Research and Development (R&D) program in the 2019 defense budget, and four prototypes are expected to be built and tested in 2020 by the National Chung-Shan Institute of Science and Technology (CSIST), which is Taiwan's major defense technology developer. Sixty MicMABs are planned to be brought into the order of battle, and because of their small tonnage, they can be positioned inside both military harbors and small fishing ports, as well as fire their missiles inside the port or at sea, depending on the battle situation. Also, the MicMAB is designed to have only simple but robust communication equipment to link with shore-based Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) systems to receive orders on target coordinates and information instead of possessing an advanced long-range radar system. With these design features, questions about their effectiveness against various warships or tactics development are debated among Taiwan's Navy and the Defense Ministry.

This thesis explores these questions using two analytic tools, one deterministic and the other stochastic. Specifically, this thesis' objective is to analyze the MicMAB's swarm effectiveness against PLAN warships in a PLA invasion scenario on the northeast part of

the Taiwan Strait using Hughes' salvo equations (Hughes 1995), established by CAPT Wayne Hughes, USN (Ret.) and the simulation software Map Aware Non-Uniform Automata (MANA), developed by New Zealand's Defense Technology Agency. This study analyzes the MicMAB's tactics and target preferences to inform decision makers on swarm effectiveness and required force structure. Specific research questions are:

- Can naval combat modeling and analysis using deterministic and agent-based simulations inform Taiwan's Navy on the military value of the MicMABs and how best to employ them?

- What is the best allocation of the MicMABs along the Taiwan coast?

- How does the assignment of target priorities for the MicMAB's swarm engagements affect the number of adversary attrited?

- How much more survivable and effective are near shore launch points leveraging terrain-masking than attacking while steaming toward the adversary's fleet?

To address these questions, this thesis is outlined as follows:

- Chapter II provides background and literature reviews on the strategy of using small combatants in future warfare as well as Taiwan's defense strategy. It also highlights several past theses using Hughes' salvo equations and simulation with intelligent design of experiment to explore tactics and questions of force structure.

- Chapter III describes the analytical methodologies this study uses as well as the tactical situation explored.

- Chapter IV provides the analytical results from the salvo questions and MANA simulations.

- Chapter V contains this study's conclusions and recommendations.

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II. BACKGROUND

Although large multi-purpose combatants are favored by the USN for their long-range power projection and weapon capabilities, numerous studies and researchers have concluded that small combatants can be effective in modern maritime conflicts. In this chapter, three papers, one thesis, and Taiwan's ODC are reviewed with regard to the research on the effectiveness of small combatants. It also addresses several theses which used similar analytic methodologies to explore naval tactics.

At the Naval Postgraduate School (NPS), maritime warfare experts CAPT Wayne Hughes, USN (Ret.) and CAPT Jeff Kline, USN (Ret.) have analyzed the utility of small combatants and the future force structure of the USN. The following reviews of their works are based on the papers "Between peace and the air-sea battle" (Kline and Hughes 2012), "Impacts of the robotics age on naval force design, effectiveness, and acquisition" (Kline 2017), and "The advantages of single-purpose warships for littoral combat" (Hughes 2014). These papers provide strong arguments for a navy to acquire small combatants and develop adequate tactics deploying them along with other major combatants.

Likewise, the Singaporean Navy emphasizes the value of small combatants since its country is located on the edge of the Malacca Strait, where large warships are likely constrained in maneuverability, but small combatants enjoy the advantage of agility. A thesis titled "Distributed surface force," written by a group of U.S. and Singaporean students in Systems Engineering at NPS in 2014, is reviewed for its emphasis and analysis on the value of small and distributed surface firepower (Buss et al. 2014). Taiwan's Navy shares some similarities to the Singaporean Navy in terms of self-defense orientation and strait geography. The study's conclusion serves as a reference as Taiwan's military decision makers plan for its future force structure.

A. LITERATURE REVIEW: "BETWEEN PEACE AND THE AIR-SEA BATTLE"

In their paper, Kline and Hughes (2012) propose U.S. political and military leadership adopt a War at Sea strategy as an intermediate approach, between peaceful competition and

full-scale conventional war, against China's military expansion. This strategy confines military actions at sea within the first island chain, avoids land invasion or ground operations, and takes advantage of the U.S. underwater domain capability, and as such, it provides more options for deterrence (Kline and Hughes 2012). With the goal to retain U.S. power projection and maintain peace over the western Pacific, this strategy also serves as a catalyst to strengthen engagements with allies in this region.

Taiwan is located at the geopolitical axis of the first island chain, and so Taiwan's political or military postures are essential to U.S.-PRC relations. The points raised in this paper echo many U.S. strategy guidelines, and as a result, Taiwan should continue to strengthen forces for maritime operations in the potential scenarios of conflicts at sea. Among several means and platforms discussed in this War at Sea strategy (Kline and Hughes 2012), small, missile-carrying surface combatants deployed along with major warships, submarines, and air forces can distract and disrupt PLAN surface forces' targeting capability. In addition, small combatants can provide alternative utility, and three such prominent employments are mentioned in this paper (Kline and Hughes 2012):

- A deterrent to China's maritime actions that violate international law.

- Escort tasks in the South China Sea.

- Cooperation with Japan's coast guard against China's illegal actions around the Senkaku (Diaoyutai) Islands.

B.   LITERATURE REVIEW: "IMPACTS OF THE ROBOTICS AGE ON NAVAL FORCE DESIGN, EFFECTIVENESS, AND ACQUISITION"

Reactivity, robustness, and resilience are the three essential elements suggested in this paper to measure future U.S. naval force design alternatives (Kline 2017). A bimodal force design is described, leveraging unmanned systems and autonomy for an "offensive" sea denial force while more traditional multi-purpose large combatants are used for "defensive" sea control (Kline 2017). This force structure, proposed by Kline, enables the navy to adapt to a variety of potential conflict scenarios (reactivity), sustain operations while experiencing attrition (resilience), and remain relevant in a range of geo-political futures (robustness).

Again, employment of small combatants is emphasized in this paper with the concepts of distributed lethality and offensive-defensive mix (Kline 2017). Distributed, small combatants, which are less expensive but equipped with advanced long-range missiles, can take the advantage of the offense, while large combatants capable of multiple-missions conduct sea-control and sea-denial operations against the adversary (Kline 2017). This is called distributed lethality combined with smart defense.

The concepts of reactivity, robustness, and resilience also apply to Taiwan's Navy force structure, and small combatants with surface-to-surface missiles are key to its force structure alongside aircraft fighters, submarines, and capital ships. Taiwan's Navy has explored the concept of distributed lethality with two generations of guided-missile fast-attack boats and corvettes. In addition, the design of the MicMAB, different from existing fast-attack boats, is focused on its small displacement, which enables it to be placed inside any military, commercial, and fishing ports for more resilience.

C. LITERATURE REVIEW: "THE ADVANTAGES OF SINGLE-PURPOSE WARSHIPS FOR LITTORAL COMBAT"

The MicMAB can be simply defined as a single-purpose combatant whose design is solely dedicated to surface warfare, with no surface-to-air or anti-submarine warfare capabilities. In the paper, "The advantages of single-purpose warships for littoral combat," CAPT Hughes takes the approach of quantitative demonstration to analyze different measures of combat value between multi-purpose and single-purpose warships (Hughes 2014).

In summary, the value of single-purpose small combatants is compared to that of a large multi-purpose warship according to the following three aspects: lost value, salvo equations, and equal-cost numerical value (Hughes 2014). The value of single-purpose small combatants is shown to be higher for littoral combat in each comparison.

First, a single-purpose warship's value of lost combat capability is approximately proportional to that of the number of a multi-purpose warship's capabilities (Hughes 2014). If a multi-purpose warship has four mission capabilities, such as surface warfare, surface-to-air, anti-submarine warfare, and helicopter employment, it will lose all these combat capabilities once it is put out of action by a single hit by a missile or torpedo (Hughes 2014).

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The same applies to a single-purpose warship, but the lost combat capability is 4:1 for the former versus the latter, and as such, a single-purpose ship is favored in the face of attrition (Hughes 2014).

Also, Hughes' salvo equations demonstrate that the number of warships is the most important attribute in a missile exchange. Hughes (2014) illustrates why the number of ships is the dominant attribute from his equations by the following example: if the number of A's ships is three times that of B's, then B's ships must have three times the offensive, defensive, and staying powers in order to have parity in fractional losses. In Chapter III of this thesis, Hughes' salvo equations are applied to analyze the effectiveness of MicMABs against PLAN forces, and thus it is explored in detail later.

Lastly, the equal-cost number of single-purpose ships that can be acquired is much higher than that of a multi-purpose warship, which is critical with constrained budgets (Hughes 2014). In the paper, Hughes explains that with a small portion of the ship-building budget, a sufficient number of missile corvettes can be acquired for littoral combat and the main part of the budget can still support the building of multi-purpose warships for sustained open-ocean operations.

D.   LITERATURE REVIEW: "DISTRIBUTED SURFACE FORCE"

In 2014, an NPS systems engineering team assigned with a distributed surface force capstone project conducted a study of high-level design for small surface combatants (SSC). The team's research focused on the SSC's cost effectiveness and its ability to provide a credible deterrence and project power through anti-area access denial environment (Buss et al. 2014).

The SSC is designed for combat upon green waters and cooperates with other types of warships in a heterogeneous squadron, which the team calls the armada (Buss et al. 2014). More specifically, the armada consists of two air-defensive Arleigh Burke-class destroyers, two anti-submarine capable Littoral Combat Ships, and 15 SSCs, which are to deliver distributed lethality inside a contested environment. As in this thesis, the technique of modeling and simulation is applied in the capstone project, and the team's finding is that the

armada could defeat the adversary's force of four destroyers, two frigates, five submarines, 10 missile boats, and one aircraft, with only marginal losses (Buss et al. 2014).

The team conducted numerous sensitivity analyses of the SSC's characteristics to study measures of performance, and determined the SSC's detection and classification range as the most important factor for the armada's combat effectiveness (Buss et al. 2014). Increasing an SSC's sensor range by five nautical miles greater than the adversary's enables the SSC's ability to target and attack the adversary's ships first, and thus lowers the average casualties to less than one unit on the U.S. side (Buss et al. 2014). Furthermore, since the armada is a heterogeneous squadron of mixed ships, air defense and anti-submarine capabilities are considered. The team analyzed the impact on the adversary's air and underwater attacks in the scenarios with the armada having varied degrees of air defense or anti-submarine measures (Buss et al. 2014). Lastly, logistics such as fuel endurance, supportability refueling, and construction cost estimation are also explored in this project, which provides a comprehensive understanding of the SSC's effectiveness to the USN (Buss et al. 2014).

In contrast to the SSC's design requirement of an organic detection range of 60 nautical miles, a MicMAB is designed to rely on a robust shore-based C4ISR system to acquire target assignments and attack, instead of organically detecting and classifying targets. A scenario of a homogeneous force of MicMABs against the adversary's mixed surface forces is assumed in this thesis to focus on MicMAB's effectiveness with the factors of allocations, target priority, and terrain-masking tactics. The MicMAB's developing background and design concept is discussed in the following section on reviewing Taiwan's ODC.

E.   LITERATURE REVIEW: TAIWAN'S "OVERALL DEFENSE CONCEPT"

In Taiwan, the Overall Defense Concept (ODC) has been widely discussed and recognized among military decision makers since it was proposed by then Chief of the General Staff, Admiral Lee Hsi-Min, in 2017 (Thompson 2018). While continuing to strengthen or upgrade major armed forces platforms such as Cheng-Kung class frigates, equivalent to Perry class, and F-16V fighters, Taiwan has also accelerated its pace to

indigenously develop asymmetrical measures and build necessary sensors, weapons, and platforms.

It is undeniable that PLA has outnumbered Taiwan's armed forces with its tremendous defense budget and resources. As a result, the ODC first proposes that Taiwan's armed forces should abandon the traditional way of defending the invading PLA through force attrition on the waters around Taiwan and the strait (Thompson 2018). Instead, the armed forces should secure the range of operations within 100 kilometers around the main island of Taiwan, where its joint surveillance and firepower can be better leveraged (Thompson 2018).

Furthermore, the innovative and asymmetrical measures in the ODC are developed in order to maximize Taiwan's defense advantages within a relatively limited budget. The asymmetrical measures generally feature mobility, stealth, resilience, low cost, easy and quick to produce, but robust and lethal.

The MicMAB design and employment concept comes from the ODC. Its concept of deployment is described as follows, starting with the possible PLA invasion scenario explained:

There are two phases of Taiwan's defense operations: fighting the decisive battle in the littoral area and annihilating at the beach zone, which may also be seen as Taiwan's interdiction operations and anti-landing operations (Thompson 2018).

Once the PLA initiates invasion with its massive forces, primarily from the Eastern Theater naval forces, it is quite possible that PLA will firstly seek to dominate air and sea. In response, Taiwan's forces will try to preserve major fighters and combatants in the beginning phase of defense operations, instead of deploying them under unfavorable conditions (Thompson 2018).

Thus, MicMABs will be deployed using swarm tactics and swiftly launch their missiles as a saturation attack to interdict the PLAN's major surface combatants within a 100-kilometer range during the phase of interdiction operations, or engage with the PLA's landing forces during the phase of anti-landing operations.

Based on the MicMAB's design concept, here are its main features and advantages:

- Low operations range, sufficient for littoral and in-port operations

- Ability to be dispersed into all fishing ports, free from worry of military harbor denial, even under the condition PLA dominates air and sea

- Size of a fishing boat, hard to detect and identify at sea

- Ability to utilize island or shore terrain-masking easily

- Low need for detection equipment, only need to require target coordinates via diverse ways of communication

- Indigenously built ship body and missile system

- Short production timeframe to magnify the quantity

Besides four destroyers and three flotillas of frigates, Taiwan still owns several types of asymmetrical naval force, including the 500-ton Tuo Chiang-class corvette equipped with eight HF type II and eight HF type III anti-surface missiles, and the conventional Kuang Hua VI-class fast attack missile boat. The 45-ton MicMABs, each equipped with two anti-surface missiles, are expected to be brought into the order of battle and magnify the efficacy of Taiwan's asymmetrical warfare tactics.

F.   LITERATURE REVIEW: EXAMPLE ANALYSIS IN TACTICS USING SIMILAR METHODOLOGY

Hughes' salvo equations and MANA simulation have been applied on numerous studies and theses, especially in terms of naval affairs or maritime warfare. Three key theses developed by students at the NPS are reviewed. Their methodologies are valuable to this thesis in developing the approaches to explore the MicMAB's tactical effectiveness.

First, in 2007, Mahon studied the interaction between warships at sea and anti-ship cruise missile batteries on land. The Littoral Combat Model was developed to examine the question of whether a modern warship is capable of littoral operations. The Littoral Combat Model was derived from both Hughes' salvo equations and Lanchester's area fire differential equations to examine the effect on force attrition caused by aimed fire with missiles or area

fire weaponry (Mahon 2007). The author concluded the following key points: preemptive and effective attacking is an important advantage, and a warship's direct fire weaponry can often effectively take down batteries ashore. A sea-based force's area fire, however, is vulnerable in littoral engagements (Mahon 2007).

Kaya (2016) applied MANA to explore the combat capability requirement for a frigate in an anti-air warfare environment via MANA modeling and simulation, and the analysis yields both technical and tactical recommendations for ship design. The author set frigates equipped with a variety of weaponry and missile systems, as well as a prospective ship-based unmanned aerial vehicle, modeled the combat environment, and acquired the measures of force attrition from both sides. The result showed that a Point Defense Missile System with long and medium surface-to-air missiles can successfully enhance survivability, while the unmanned aerial vehicle has very little effect (Kaya 2016).

Similarly, Zaman Khan (2017) studied the maritime convoy screening problem through MANA. Based on the two screening methods, zone defense and close escort, several types of combat platforms were modeled, with various sensors and weaponry, against two Red submarines to determine the best combination of combat capabilities (Zaman Khan 2017). Through output analysis, one recommendation was to deploy anti-submarine warfare helicopters in the intermediate screen against submarines and their torpedoes (Zaman Khan 2017).

Even though the methodologies are similar between the aforementioned theses and this study of the MicMAB's effectiveness, there are noteworthy differences in this thesis' approaches. First, this thesis applies Hughes' salvo equations solely to explore the force-on-force attrition between Blue's homogenous force of the MicMABs and Red's heterogeneous force, consisting of destroyers, frigates, and corvettes. Hence, the ship design of the MicMAB has been determined. As a result, the study does not model a variety of combat capabilities and examine their effectiveness. Instead, the emphasis is on exploring the tactics for these 60 MicMABs, such as force allocation, target prioritization, and terrain masking.

III. METHODOLOGY

Small combatants can be widely dispersed or gathered in swarms; they can be employed alone or with other types of major combatants; they can attack alone or with coordinated fire from other surface forces, shore batteries, or air missile platforms. All the tactics and their efficacy need to be examined separately, along with different force presence. In this thesis, the main focus is the effectiveness of the MicMABs in the scenario of facing a PLAN invasion in the Taiwan Strait. One deterministic model and one stochastic model are defined and set up with certain assumptions applied to study this wartime scenario. This is done because deterministic and stochastic models can have complimentary advantages (Lucas 2000). In the following description of the methodology and analysis, the Taiwan Navy's 60 MicMABs are set as the Blue force, designed to counter the Red force, which represent the PLAN invasion force.

Blue deploys 60 MicMABs to engage with the invading Red task group, consisting of destroyers, frigates, and corvettes, across the Taiwan Strait, as shown in Figure 1. The key assumptions for the scenario are as follows:

- This area is dominated by Red air superiority, and there are only Red destroyers/ frigates/ corvettes present in this area to initiate PLA invasion operations.

- Blue deploys only MicMABs to meet this initial force, while Blue's major combatants, as well as underwater and air assets, are designated with other tasks, such as countering amphibious operations.

- Red underwater and air assets are not present in this scenario, assuming that they are deployed for invasion operations outside this area.

- Blue has 60 MicMABs, and each carries two indigenous anti-surface warfare HF type II missiles.

- Each MicMAB weighs 45 tons, and its speed can reach 35 knots. In the model, a MicMAB has a very low rate to be detected due to its small size and enjoys the advantage of radar terrain-masking.

- Blue's MicMABs acquire target designation from Taiwan's command centers, which employ fixed/mobile radar sites for target acquisition.

- Blue enjoys a 100-kilometer zone of target detection and acquisition.

- Initially, Blue's MicMABs disperse at all small fishing ports, ready to be deployed. They either stay in port or sail to an advantageous position at sea, then fire their missiles and return for rearm.

Adapted from https://www.google.com/maps/place/Taiwan/@23.6629757, 116.5030323,2378812m/data=!3m1!1e3!4m5!3m4!1s0x346ef3065c07572f: 0xe711f004bf9c5469!8m2!3d23.69781!4d120.960515
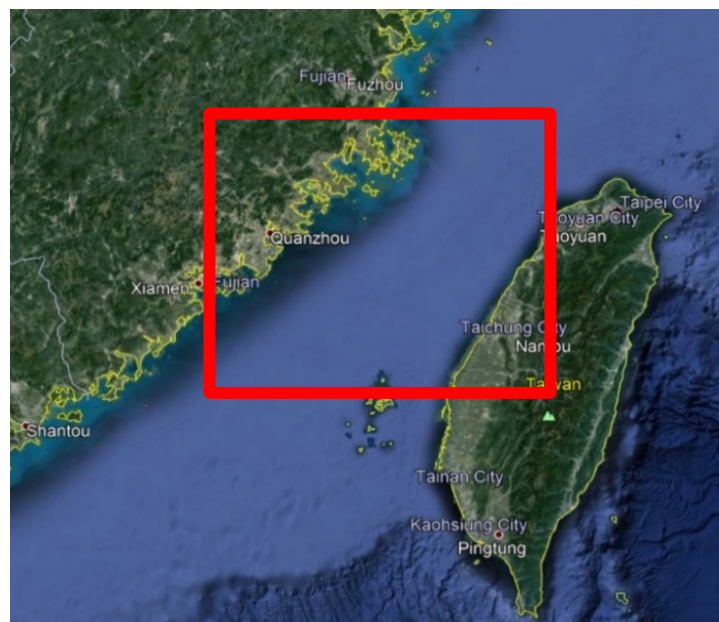
Figure 1.   Scenario Map

A.   HUGHES' SALVO EQUATIONS

Sixty MicMABs are expected to bring the advantages of quantity and distributed lethal fire. The deterministic Hughes' salvo equation is a useful analytic tool for surface

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warfare. It is used in this study to explore the best allocation of MicMAB groups against Red destroyers, frigates, and corvettes, with the consideration of Red or Blue force attrition, or the number of ships out of action (OOA). The parameters of Hughes' salvo equations are set and calculated based on the following parameters, such as both sides' staying power, striking power, defensive fire, scouting effectiveness, and readiness effectiveness.

For the attrition of Red force:

$$\Delta B = \frac{\sigma_A a_2 A - \tau_B b_3 B}{b_1}$$

For the attrition of Blue force:

$$\Delta A = \frac{\sigma_B b_2 B - \tau_A a_3 A}{a_1}$$

ΔB = number of Red ships OOA	ΔA = number of Blue ships OOA
σ_A = scouting effectiveness of Blue ships	σ_B = scouting effectiveness of Red ships
a_2 = striking power of Blue ships	b_2 = striking power of Red ships
A = number of Blue ships	B = number of Red ships
τ_B = readiness of Red ships	τ_A = readiness of Blue ships
b_3 = defensive power of Red ships	a_3 = defensive power of Blue ships
b_1 = staying power of Red ships	a_1 = staying power of Blue ships

In this model, the measures of effectiveness (MOEs) are the attrition of Blue and Red forces, and to reduce the Blue attrition and increase Red attrition implies a better outcome for Blue. More specifically, the value of taking a Red destroyer out of action is higher than that of a mission kill on a corvette. Therefore, linear programming is applied to maximize Red attrition with different weighting factors assigned for successful hits on destroyers, frigates, and corvettes, as well as minimizing Blue MicMAB attrition. With

different requirements, decision variables and constraints are specified. This linear programming problem is formed and solved in Chapter IV.

In addition, the MicMAB's feature of stealth near land is considered to be essential, and its effect on force attrition when it loses its stealth feature is also explored and compared by changing Red ships' scouting effectiveness parameter.

B.   MANA SIMULATION

To add variability and entity-level resolution into this analysis, the stochastic agent-based model MANA is used in simulating these engagements. In these simulations, the MOEs are again the attrition of Blue and Red forces. For the convenience of comparison, the complete matrix of the design of experiment (DOE) is shown in Chapter IV.

The DOE is constructed based on a systematic approach instead of common design methods such as fractional factorial (Montgomery 2017) or Nearly Orthogonal Latin Hypercube (Cioppa and Lucas 2007). Because MicMAB's prototype characteristics and features have been determined and are in production, the DOE is thus constructed to explore the aspects on certain tactical employments. The DOE's variables are primarily changing Tactics, Techniques, and Procedure (TTP) and selecting terrain-masking routes, both qualitative attributes. Exploring the ranges of the MicMAB's combat capability enhancement, such as number of missiles carried and radar cross section improvement, which are quantitative attributes, is recommended for follow-on work.

The first part of the DOE is shown in Table 1, and the attributes explored are the number of Red forces and the number of Blue MicMABs assigned for certain target priority or simply for whichever target is closest.

The rationale of the design's purposes is explained as follows. Regarding Red forces' design, two different sizes of PLAN task force are selected for exploration: the first one consists of 10 destroyers, 10 frigates, and 10 corvettes, and the second has 10 destroyers, 20 frigates, and 20 corvettes. The first Red task force is designed to determine Blue's 60 MicMABs' effectiveness when Blue significantly outnumbers Red's 30 warships but Red has stronger firepower. The second Red task force is designed to explore whether

Blue's 60 MicMABs are still sufficiently effective when Red has a large force, consisting of 50 warships, with much stronger firepower. This study's analysis focuses on pairwise differences between design points.

Table 1.   Cases 1 to 22 of the DOE

Case	MicMAB	TTP	Destroyers-First MicMAB	Frigates-First MicMAB	Corvettes-First MicMAB	Red Destroyer	Red Frigate	Red Corvette	Route Scenario	Remark	Simulation Stop Condition
1	60	mix	n/a	n/a	n/a	10	10	10	A		Blue casualties reach 60, or Red casualties reach 30, or combat duration reaches 2000 time steps (5.56 hours)
2	60	ttp	60	n/a	n/a	10	10	10	A		
3	60	ttp	n/a	60	n/a	10	10	10	A	MicMABs changing TTPs v.s. Medium Red force	
4	60	ttp	n/a	n/a	60	10	10	10	A		
5	60	ttp	20	20	20	10	10	10	A		
6	60	ttp	30	20	10	10	10	10	A		
7	60	ttp	30	10	20	10	10	10	A		
8	60	ttp	20	30	10	10	10	10	A		
9	60	ttp	20	10	30	10	10	10	A		
10	60	ttp	10	20	30	10	10	10	A		
11	60	ttp	10	30	20	10	10	10	A		
12	60	mix	n/a	n/a	n/a	10	20	20	A		Blue casualties reach 60, or Red casualties reach 50, or combat duration reaches 2000 time steps (5.56 hours)
13	60	ttp	60	n/a	n/a	10	20	20	A		
14	60	ttp	n/a	60	n/a	10	20	20	A	MicMABs changing TTPs v.s. Large Red force	
15	60	ttp	n/a	n/a	60	10	20	20	A		
16	60	ttp	20	20	20	10	20	20	A		
17	60	ttp	30	20	10	10	20	20	A		
18	60	ttp	30	10	20	10	20	20	A		
19	60	ttp	20	30	10	10	20	20	A		
20	60	ttp	20	10	30	10	20	20	A		
21	60	ttp	10	20	30	10	20	20	A		
22	60	ttp	10	30	20	10	20	20	A		

Another design's attribute is to explore a range of changes in TTPs in order to probe into the research question of what the effect of assigning target priorities is on the outcome. Of particular interest is to examine whether a certain number of MicMABS allocated and prioritized to engage with destroyers, frigates, or corvettes will have a better outcome than if no priority is assigned. In the DOE, the combination of 10, 20, and 30 is designed to group the MicMABs in assigning target priorities in the convenience for tactical decision making.

In MANA, changing TTPs is simulated implicitly by setting a specific squad of agents with a particular target priority, and the squad of agents will shoot at those specific targets first if acquiring multiple adversary agents simultaneously. In the DOE, certain numbers of MicMABs are set to have different prioritized targets, from among destroyers,

frigates, or corvettes, compared with the case of all 60 MicMABs that fire at the closest target regardless of target type.

More specifically, the 22 cases in the DOE are sorted into the following categories:

- Numbers of Red destroyers, frigates, and corvettes are 10, 10, 10 or 10, 20, 20, respectively. The first half of the 22 cases is designed to have Blue's 60 MicMABs engaging Red's heterogeneous force of 30 warships, and the second half is designed to have Blue's 60 MicMABs engaging Red's heterogeneous force of 50 warships.

- TTPs are mixed, equal numbers (20 each), or combinations of 10, 20, and 30, indicating the number of MicMABs that engage with prioritized targets of Red destroyers, frigates, or corvettes. Thus, there are 11 combinations and 22 cases in total for engagements with two different Red force sizes. The reason to select groupings of 10, 20, or 30 is to scale the DOE appropriately for this thesis and to acquire noticeable differences in the output. In addition, this grouping is considered more straightforward for tactical decision making for employing 60 small combatants.

- Stop conditions are when Blue reaches 60 casualties or Red reaches its maximum casualties, 30 or 50, to observe the outcome of force-on-force attrition.

Furthermore, the level at which the terrain-masking tactic is exploited is also explored through simulation, and this part of the DOE is shown in Table 2. In order to answer the research question of whether near shore launch points leveraging terrain-masking results in a better outcome, two additional engagement paths are designed in the setting of the MANA scenario map, as routes B and C. For this part of the DOE, only the mixed TTPs and three specific TTPs are selected along with varying routes. This selection is driven by the statistical insignificance between the cases adopting mixed TTPs and those with specific TTPs, which was found from the first part of the DOE's output during development of this study.

Table 2.　Cases Taking Various Terrain-Masking Routes in the DOE

Case	MicMAB	TTP	Destroyers-First MicMAB	Frigates-First MicMAB	Corvettes-First MicMAB	Red Destroyer	Red Frigate	Red Corvette	Route Scenario	Remark	Simulation Stop Condition
12	60	mix	n/a	n/a	n/a	10	20	20	A	Lower Level of Terrain Masking	Blue casualties reach 60, or Red casualties reach 50, or combat duration reaches 2000 time steps (5.56 hours)
13	60	ttp	60	n/a	n/a	10	20	20	A		
14	60	ttp	n/a	60	n/a	10	20	20	A		
15	60	ttp	n/a	n/a	60	10	20	20	A		
23	60	mix	n/a	n/a	n/a	10	20	20	B	Medium Level of Terrain Masking	
24	60	ttp	60	n/a	n/a	10	20	20	B		
25	60	ttp	n/a	60	n/a	10	20	20	B		
26	60	ttp	n/a	n/a	60	10	20	20	B		
27	60	mix	n/a	n/a	n/a	10	20	20	C	Higher Level of Terrain Masking	
28	60	ttp	60	n/a	n/a	10	20	20	C		
29	60	ttp	n/a	60	n/a	10	20	20	C		
30	60	ttp	n/a	n/a	60	10	20	20	C		

Illustrations of various terrain-masking routes are shown in Figure 2. The MicMABs' engagement paths set for the aforementioned cases are depicted as route A, representing a more direct force-on-force engagement, and routes B and C, with more near-shore launch points set as engagement paths. The latter two are designed to simulate cases in which the MicMABs have better terrain-masking tactics than route A. Namely, in route B, all 60 MicMABs are deployed to stay close to Taiwan's coastal area, with terrain-masking and under friendly covering fire, and then fire when they can. In route C, some of the MicMABs are deployed to stay near the Penghu Islands, which are scattered and centrally located in the Taiwan Strait, and then fire when they can. These two routes are compared to determine whether selecting tactical positions enhances the MicMABs' MOEs against the PLAN warships.

Figure 2.   Various Terrain-Masking Routes

Besides the DOE, the combat entities' parameters in Blue's and Red's forces are set based on the simulation's assumptions previously addressed, which are based on the data acquired from Jane's Fighting Ships database (Jane's 2019) and discussions with U.S. and Taiwan subject matter experts. The model parameter matrix for simulation is shown as Table 3.

Table 3.   Model Parameter Setting

MANA Model Setting	Sensor Range	Speed	Number of Missiles	Missile Range	Missile Hit Rate	Number of Hits to kill	Concealment Factor	Terrain Masking Factor
Blue Mobile Radar	100 km (deterministic)	0 kts	0	0	0	1	0.5	0.9
Blue MicMAB	20 km (deterministic) 100 km (inorganic)	30 kts	2	150 km	0.8	1	0.9	0.9
Red Destroyer	within 10 km: p = 0.5, within 50 km: p = 0.2, within 100 km: p = 0.1 (probabilistic)	20 kts	8	150 km	0.8	6	0	0.9
Red Frigate		20 kts	6	150 km	0.8	4	0.1	0.9
Red Corvette		30 kts	4	150 km	0.8	2	0.5	0.9

Blue's radars have a deterministic detection range of 100 kilometers, and this is implicitly designed to simulate Taiwan's military's joint C4ISR capability. This enables the 60 MicMAB agents, each with a 20-kilometer detection range, to share and acquire target information inorganically from three Blue shore-based mobile radar facilities. In addition, a concealment factor is used to mimic each agent's radar cross section and ease of detection. It is fixed for each ship class and proportional to the combatant's displacement. With a 0 to 10 scale, the higher on the scale the harder it is to be detected by the adversary's entities. Similarly, the terrain-masking factor applies when a Blue or Red combatant is within the littoral zone, which is manually designed along the Taiwan coast, Penghu islands, and Mainland China coast in the model. This factor decreases a combatant's detectability if within those zones.

Overall, there are 30 cases in the DOE, and 100 repetitions are run for each case. In the MANA simulation, the random seeds for the 100 repetitions are all different and this results in each output being stochastic and conditionally independent. Since the attributes in the DOE are all qualitative instead of quantitative, analytic tools such as descriptive statistics, selection method, task success probability, and partition tree are applied to examine the output, with the use of Tukey multiple pairwise-comparisons to test statistical significance (Rushing et al. 2013), and the analysis results and findings are elaborated in Chapter IV.

IV. ANALYSIS

A. HUGHES' SALVO EQUATIONS RESULT

The first part of the analysis focuses on the results obtained by Hughes' salvo equations with application of linear programming. According to the U.S. Department of Defense's annual report to Congress "Military and Security Developments Involving the People Republic of China 2019," PLAN's Eastern and Southern Theater owns 23 destroyers, 43 frigates, and 33 corvettes. Consequently, the first exploration is to determine how many Red ships should Blue MicMABs engage with in order to achieve the best attrition result, and it is expressed and solved as follows:

Decision Variable:

Number of Red destroyers, frigates, and corvettes to engage with

B_i , *i = Destroyer, Frigate, Corvette*

Number of Blue MicMABs grouped in 10, 20, or 30 to engage with

A_i , *i = MicMAB vs Destroyer, Frigate, or Corvette*

A_i *= 10, 20, or 30*

Objective Function:

$$Max\ 5\Delta B_{Destroyer} + 3\Delta B_{Frigate} + \Delta B_{Corvette} - \Delta A_{MicMAB}$$

s.t.

$$\Delta B_i = \frac{\sigma_A a_{i2} A_i - \tau_{Bi} b_{i3} B_i}{b_{i1}}\ ,\ i = Destroyer,\ Frigate,\ Corvette$$

$$\Delta A_i = \frac{\sigma_B b_{i2} B_i - \tau_{Ai} A_{i3} A_i}{a_{i1}}\ ,\ i = MicMAB\ vs\ Destroyer,\ Frigate,\ or\ Corvette$$

$$\Delta A_{MicMAB} = \Sigma\ \Delta A_i\ ,\ i = MicMAB\ vs\ Destroyer,\ Frigate,\ Corvette$$

$$\Sigma A_i = 60\ ,\ i = MicMAB\ vs\ Destroyer,\ Frigate,\ Corvette$$

$$B_i \geq \Delta B_i\ ,\ \Delta B_i \geq 0\ ,\ i = Destroyer,\ Frigate,\ Corvette$$

$$\Delta A_i \geq 0\ ,\ i = MicMAB\ vs\ Destroyer,\ Frigate,\ or\ Corvette$$

$$B_{Destroyer} \leq 23 \qquad A_{MicMAB\ vs\ Destroyer} = 10,\ 20\ or\ 30$$

$$B_{Frigate} \leq 43 \qquad A_{MicMAB\ vs\ Frigate} = 10,\ 20,\ or\ 30$$

$$B_{Corvette} \leq 33 \qquad A_{MicMAB\ vs\ Corvette} = 10,\ 20,\ or\ 30$$

With these inputs, it is shown in Table 4 that 30 MicMABs can take out 9 destroyers, 20 can take out 8 frigates, and 10 can take out 5 corvettes, with attrition of 7.2, 4.8, and 2 MicMABs, respectively. In Hughes' salvo equations, the number of units is the most important attribute, and thus in this case the large number of MicMABs are able to take out 39.1% of the destroyers, 18.6% of the frigates, and 15.2% of the corvettes among PLAN's Eastern and Southern Theater, with an allocation of 30, 20, and 10, respectively. In this linear programming problem, variables and constraints can be adjusted for different task requirements in future exploration.

Table 4.   Hughes' Salvo Result 1

		Destroyer	Frigate	Corvette						10	20	30	Σ	Constraint
PLAN	B	9	8	5										
		<=23	<=43	<=33										
staying	b1	2	2	1										
striking	b2	8	6	4										
defensive	b3	4	2	1										
scouting	σ_B	0.1	0.1	0.1										
readiness	τ_B	1	1	1										
										10	20	30	Σ	Constraint
MicMAB	A	30	20	10	60	<=	60	vs Destroyer		0	0	1	1	1
staying	a1	1	1	1				vs Frigate		0	1	0	1	1
striking	a2	2	2	2				vs Corvette		1	0	0	1	1
defensive	a3	0	0	0										
scouting	σ_A	0.9	0.8	0.5										
readiness	τ_A	1	1	1										
						Max	60							
PLAN OOA	ΔB	9	8	5										
	Factor	5	3	1		Σ	74							
MicMAB OOA	ΔA	7.2	4.8	2										
	Factor	1	1	1		Σ	14							

Area in green highlights the decision variables: number of Red warships and Blue MicMABs grouped in 10, 20, or 30 (binary variables).

Area in gray highlights the calculation of the linear programming.

Area in pink highlights the output of the value of the linear programming.

A design strength of the MicMAB is its stealth. Its low radar cross section is represented in the previous salvo analysis by setting Red's scouting effectiveness to 0.1 against this 45-ton small combatant. The second exploration is to determine how a MicMAB becomes vulnerable when it gets closer to Red ships and thus is more likely to be detected and identified as a threat. In contrast to the first exploration using the concept of linear programming, the second exploration uses Hughes' salvo equations to calculate the outcome of 60 MicMABs engaging three force sizes of Red destroyers, frigates, and corvettes while varying Red's scouting effectiveness from 0.1 to 0.5.

The result from Hughes' salvo equations is shown in Table 5. It is clear that as Red's scouting effectiveness parameter increases, implying the degree of MicMAB's stealth decreases, the number of MicMABs put out of action increases rapidly. In the case when Red has 10 destroyers, 10 frigates, and 10 corvettes with scouting effectiveness parameter 0.4, a total of 60 MicMABs are taken out of action. As a result, the concept of deploying MicMABs stealthily is essential to Blue's tactics.

Table 5.   Hughes' Salvo Result 2

Red Scouting Effectiveness Enhancing (Blue Losing Stealth)	Red Ships Engaged	Destroyer	Frigate	Corvette	Destroyer	Frigate	Corvette	Destroyer	Frigate	Corvette
		5	5	5	8	8	8	10	10	10
	Blue MicMAB Engaged	30	20	10	30	20	10	30	20	10
0.1	Blue MicMAB OOA	4	3	2	6.4	4.8	3.2	8	6	4
0.2	Blue MicMAB OOA	8	6	4	12.8	9.6	6.4	16	12	8
0.3	Blue MicMAB OOA	12	9	6	19.2	14.4	9.6	24	18	10
0.4	Blue MicMAB OOA	16	12	8	25.6	19.2	10	30	20	10
0.5	Blue MicMAB OOA	20	15	10	30	20	10	30	20	10

The figures in the black frame indicate Blue MicMAB attrition, and those highlighted in red denote that the particular subgroup of the MicMABs is completely attrited by Red.

B.   MANA SIMULATION RESULT

The complete DOE matrix is shown in Table 6. There are 30 cases in total, and each case is run for 100 repetitions. These 30 cases are divided into four groups for comparison and analysis:

- The first group, cases 1 to 11, is highlighted in light blue in the table, where Blue's MicMABs use different TTPs in each case, taking the routes of scenario A, against Red's 30 warships.

- The second group, cases 12 to 22, is highlighted in light green in the table, where Blue's MicMABs use different TTPs in each case, taking the routes of scenario A, against Red's 50 warships.

- The third group, cases 23 to 26, is highlighted in light orange in the table, where Blue's MicMABs with TTPs selectively changed in each case, taking the routes of scenario B, against Red's 50 warships.

- The fourth group, cases 27 to 30, is highlighted in light yellow in the table, where Blue's MicMABs with TTPs selectively changed in each case, taking the routes of scenario C, against Red's 50 warships.

Table 6.   Design of Experiment

Case	MicMAB	TTP	Destroyers-First MicMAB	Frigates-First MicMAB	Corvettes-First MicMAB	Red Destroyer	Red Frigate	Red Corvette	Route Scenario	Remark	Simulation Stop Condition
1	60	mix	n/a	n/a	n/a	10	10	10	A		Blue casualties reach 60, or Red casualties reach 30, or combat duration reaches 2000 time steps (5.56 hours)
2	60	ttp	60	n/a	n/a	10	10	10	A		
3	60	ttp	n/a	60	n/a	10	10	10	A	MicMABs changing TTPs v.s. Medium Red force	
4	60	ttp	n/a	n/a	60	10	10	10	A		
5	60	ttp	20	20	20	10	10	10	A		
6	60	ttp	30	20	10	10	10	10	A		
7	60	ttp	30	10	20	10	10	10	A		
8	60	ttp	20	30	10	10	10	10	A		
9	60	ttp	20	10	30	10	10	10	A		
10	60	ttp	10	20	30	10	10	10	A		
11	60	ttp	10	30	20	10	10	10	A		
12	60	mix	n/a	n/a	n/a	10	20	20	A		Blue casualties reach 60, or Red casualties reach 50, or combat duration reaches 2000 time steps (5.56 hours)
13	60	ttp	60	n/a	n/a	10	20	20	A		
14	60	ttp	n/a	60	n/a	10	20	20	A	MicMABs changing TTPs v.s. Large Red force	
15	60	ttp	n/a	n/a	60	10	20	20	A		
16	60	ttp	20	20	20	10	20	20	A		
17	60	ttp	30	20	10	10	20	20	A		
18	60	ttp	30	10	20	10	20	20	A		
19	60	ttp	20	30	10	10	20	20	A		
20	60	ttp	20	10	30	10	20	20	A		
21	60	ttp	10	20	30	10	20	20	A		
22	60	ttp	10	30	20	10	20	20	A		
23	60	mix	n/a	n/a	n/a	10	20	20	B	Medium Level of Terrain Masking	
24	60	ttp	60	n/a	n/a	10	20	20	B		
25	60	ttp	n/a	60	n/a	10	20	20	B		
26	60	ttp	n/a	n/a	60	10	20	20	B		
27	60	mix	n/a	n/a	n/a	10	20	20	C	Higher Level of Terrain Masking	
28	60	ttp	60	n/a	n/a	10	20	20	C		
29	60	ttp	n/a	60	n/a	10	20	20	C		
30	60	ttp	n/a	n/a	60	10	20	20	C		

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The output of these 30 cases is first analyzed with descriptive statistics. The means and standard deviations of Blue attrition and Red attrition, including each subgroup, are compared to determine if any particular TTP changes enhance the MicMABs' MOEs. Here, a lower Blue attrition or a higher Red attrition mean value is desired, as well as a small value of standard deviation. Table 7 shows the means of each attribute for all 30 cases, and their standard deviations are shown in Table 8.

Table 7.   Means of Each Attribute for All 30 Cases

Means / Case	MicMAB Casualty	Destroyers-First MicMAB Casualty	Frigates-First MicMAB Casualty	Corvettes-First MicMAB Casualty	Red Casualty	Destroyer Casualty	Frigate Casualty	Corvette Casualty	Combat Duration (hours)
1	32.08				29.36	9.75	9.74	9.87	2.57
2	32.94	32.94			29.12	9.67	9.65	9.8	2.54
3	35.33		35.33		28.43	9.39	9.36	9.68	2.57
4	35.76			35.76	28.98	9.55	9.49	9.94	2.66
5	34.77	11.57	11.64	11.56	29.12	9.65	9.56	9.91	2.62
6	35.56	17.99	11.61	5.96	28.65	9.46	9.43	9.76	2.64
7	35.8	17.98	5.84	11.98	28.73	9.48	9.42	9.83	2.62
8	34.68	11.57	17.37	5.74	29.06	9.57	9.53	9.96	2.62
9	38.79	12.7	6.67	19.42	28.23	9.27	9.14	9.82	2.81
10	36.84	6.34	12.22	18.28	28.66	9.38	9.42	9.86	2.72
11	34.53	5.71	17.13	11.69	28.73	9.42	9.49	9.82	2.57
12	44.21				45.14	8.57	17.36	19.21	2.63
13	46.24	46.24			43.16	8.21	16.64	18.31	2.63
14	44.47		44.47		43.83	8.39	16.89	18.55	2.53
15	44.65			44.65	43.61	8.34	16.92	18.35	2.64
16	47.53	16.01	15.83	15.69	40.99	7.67	15.37	17.95	2.63
17	43.51	21.85	14.54	7.12	45.95	8.87	17.75	19.33	2.63
18	46.76	23.64	7.69	15.43	42.48	8.03	15.99	18.46	2.55
19	45.28	15.31	22.66	7.31	44.32	8.53	16.89	18.9	2.65
20	45.62	15.42	7.62	22.58	43.31	8.38	16.46	18.47	2.59
21	43.74	7.35	14.45	21.94	44.8	8.71	17.24	18.85	2.51
22	43.68	7.61	21.78	14.29	44.34	8.57	17.1	18.67	2.58
23	23.81				44.51	8.57	17.15	18.79	2.61
24	25.21	25.21			44.11	8.48	17.11	18.52	2.66
25	24.88		24.88		44.44	8.65	17.17	18.62	2.60
26	22.68			22.68	45.45	8.8	17.66	18.99	2.62
27	17.05				47.55	9.23	18.67	19.65	3.19
28	18.7	18.7			45.13	8.77	17.46	18.9	3.32
29	17.73		17.73		45.51	8.86	17.69	18.96	3.29
30	18.14			18.14	45.96	8.91	17.81	19.24	3.32

Overall, the result of Blue and Red forces' attrition in Table 7 shows that selecting the tactical routes has the most impact on the outcome. Blue is able to attain the best MOE in scenario C's route (cases 27 to 30) with lowest MicMAB casualty and highest Red

casualty, compared to other cases taking routes A and B. Although the MicMABs' MOEs in scenario A's route is not as satisfactory as the other two, varying the attribute of change TTPs provides some valuable insights, which will be discussed in depth later.

In Table 8, the standard deviations of each attribute for all cases are shown. From the perspective of military decision makers, a smaller standard deviation implies less uncertainty. If Blue engages with 50 Red warships, case 17 has the lowest standard deviation on Blue attrition, and case 27 has the lowest value on Red attrition. This will also be discussed later in detail by grouping separately.

Table 8.　Standard Deviations of Each Attribute for All 30 Cases

Standard Deviations / Case	MicMAB Casualty	Destroyers-First MicMAB Casualty	Frigates-First MicMAB Casualty	Corvettes-First MicMAB Casualty	Red Casualty	Destroyer Casualty	Frigate Casualty	Corvette Casualty	Combat Duration (hours)
1	7.40				3.09	1.26	1.19	0.69	0.56
2	9.14	9.14			3.75	1.38	1.43	1.09	0.43
3	10.64		10.64		5.01	1.95	2.03	1.23	0.52
4	10.22			10.22	3.14	1.48	1.52	0.31	0.62
5	10.16	3.52	3.60	3.88	3.11	1.21	1.55	0.49	0.60
6	10.05	5.18	3.60	2.02	4.44	1.74	1.82	1.06	0.65
7	10.24	5.30	1.94	3.77	4.23	1.70	1.79	0.93	0.59
8	10.05	3.86	5.28	1.82	3.05	1.34	1.57	0.24	0.55
9	11.17	3.94	2.09	5.76	4.49	1.82	2.12	0.76	0.77
10	10.53	1.99	3.78	5.45	3.83	1.75	1.65	0.60	0.65
11	9.75	1.89	5.19	3.51	4.45	1.95	1.74	0.88	0.46
12	9.26				9.32	2.58	4.83	2.40	0.68
13	9.09	9.09			12.06	3.05	5.74	3.64	0.70
14	8.96		8.96		11.42	2.88	5.51	3.39	0.52
15	9.40			9.40	12.43	3.12	5.78	3.82	0.72
16	9.72	3.47	3.51	3.45	12.61	3.10	6.04	4.08	0.70
17	9.05	4.61	3.37	1.87	8.52	2.35	4.52	2.05	0.57
18	9.32	4.82	1.78	3.41	11.17	2.86	5.75	3.03	0.53
19	9.67	3.14	5.15	2.01	9.65	2.45	5.09	2.68	0.61
20	9.04	3.19	1.84	4.58	12.13	2.85	6.06	3.65	0.64
21	8.95	1.78	3.46	4.45	10.22	2.48	5.21	2.97	0.46
22	9.32	1.75	4.63	3.64	11.60	2.84	5.67	3.46	0.58
23	22.27				11.13	2.81	5.57	3.01	0.56
24	23.34	23.34			11.66	2.99	5.66	3.25	0.67
25	22.83		22.83		11.09	2.64	5.46	3.37	0.56
26	22.14			22.14	9.64	2.46	4.92	2.54	0.63
27	10.83				7.20	2.18	3.65	1.76	1.19
28	10.79	10.79			11.23	2.74	5.66	3.16	1.25
29	11.60		11.60		10.57	2.66	5.36	2.79	1.21
30	11.52			11.52	9.70	2.52	4.94	2.73	1.25

The following analysis is divided into six aspects:

- Cases 1 to 11: Blue's 60 MicMABs engage against Red's 10 destroyers, 10 frigates, and 10 corvettes with various TTPs using scenario A's route.

- Cases 12 to 22: Blue's 60 MicMABs engage against Red's 10 destroyers, 20 frigates, and 20 corvettes with various TTPs using scenario A's route.

- Cases 12 to 15, 23 to 26, and 27 to 30: Blue's 60 MicMABs engage against Red's 10 destroyers, 20 frigates, and 20 corvettes using routes in scenarios A, B, and C.

- Combat Duration of Cases 12 to 15, 23 to 26, and 27 to 30

- Task Success Analysis of Cases 12 to 15, 23 to 26, and 27 to 30

- Partition Tree on MicMAB Attrition

(1)   Cases 1 to 11: Blue's 60 MicMABs Engage Against Red's 10 Destroyers, 10 Frigates, and 10 Corvettes with Various TTPs Using Scenario A's Route

Figure 3 is the boxplot of the MicMAB casualties from cases 1 to 11, and Figure 4 shows these cases' Red casualties. There are 60 MicMABs against Red's 30 warships in these cases, and Figure 4 shows Blue effectively eliminates all 30 Red warships on average with various TTPs changes. However, cases 1 and 8 have the smallest variance, or the least outliers present. Case 1 adopts mixed TTPs, and case 8's TTP consists of 20 MicMABs targeting the destroyers first, 30 MicMABs targeting the frigates first, and 10 MicMABs targeting the corvettes first. Comparing the MicMAB casualties, Figure 3 shows that case 1 has the lowest mean casualty, and case 2 has the second lowest, as case 2's TTP consists of all 60 MicMABs targeting the destroyers first.

Based on the data from this section, Blue's 60 MicMABs with mixed TTPs achieves the best MOE outcome. In a real world combat situation, knowing the adversary's force components requires effective intelligence, surveillance, and reconnaissance (ISR) measures. If Blue's ISR capability is sound, an allocation plan of deploying MicMABs with certain target priorities will work successfully. If selective targeting is not an option

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due to a lack of ISR, it is recommended to assign each MicMAB to shoot at whichever target is closest.
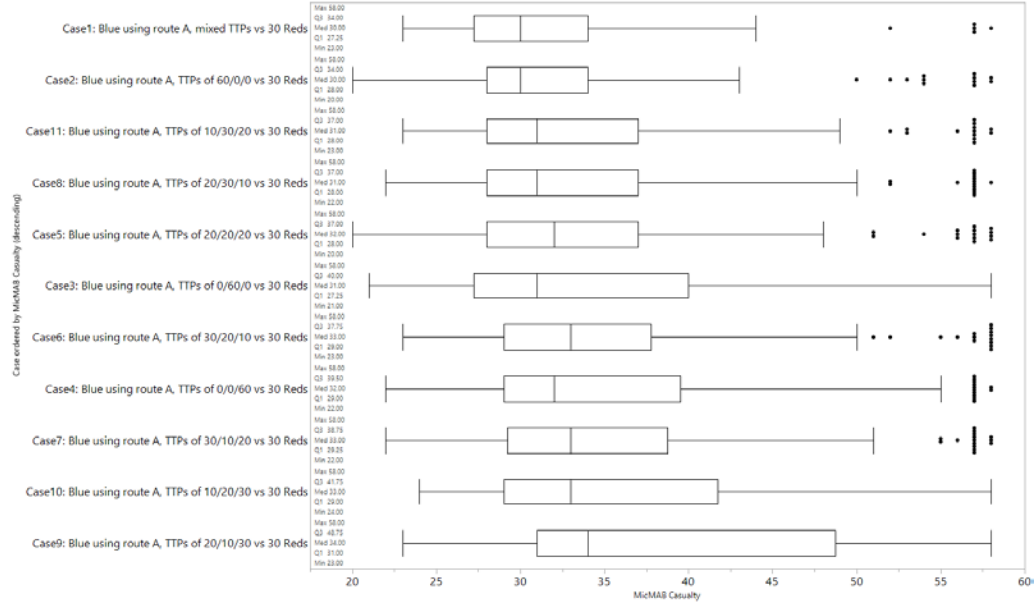
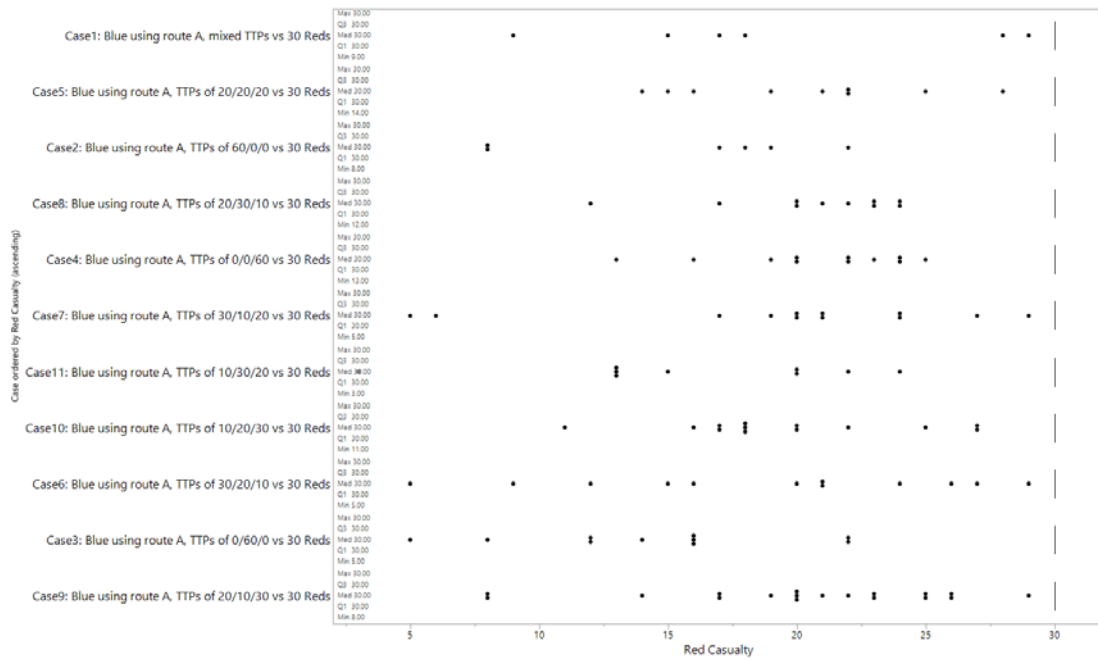

Figure 3.   MicMAB Casualties for Cases 1 to 11

Figure 4.   Red Casualties for Cases 1 to 11

With Tukey multiple pairwise-comparisons on MicMAB attrition, it shows there is statistical significance between case 1 (mixed TTPs) and case 9 (TTP of 20/10/30), case 1 and case 10 (TTP of 10/20/30), as well as case 2 (TTP of 60/0/0) and case 9, where the p-values are much lower than 0.05 among those pairs. All other pairs are statistically insignificant. However, on Red attrition, there is no statistical significance among all pairs. This result indicates that regardless of TTPs, 60 MicMABs are effective in the engagement against 30 adversaries, but the TTPs in cases 9 and 10 should be avoided.

     (2)   Cases 12 to 22: Blue's 60 MicMABs Engage Against Red's 10 Destroyers, 20 Frigates, and 20 Corvettes with Various TTPs Using Scenario A's Route

When Red deploys a large force of 50 warships, the uncertainty of the fight's outcome rises. Figure 5 shows at least 40 MicMABs lost on average taking scenario A's route with varied TTPs in cases 12 to 22. In this group of cases, the best MOE, 43.51 units of attrition, appears in case 17, where Blue's TTP are for 30 MicMABs to target destroyers first, 20 frigates first, and 10 corvettes first. This TTP is reasonably understandable because Red's destroyers possess both strong offensive and defensive fire, such that a large portion of the MicMABs should be dedicated to take them out of action in priority. Case 12, where 60 MicMABs adopt mixed TTPs, is shown to have the fourth lowest mean value of MicMAB attrition, 44.21, among these 11 cases. On the tactical aspect, the tactic of mixed TTPs is easier to execute and requires less training as well as less precise ISR, which is also worth considering to adopt besides case 17's tactic.

Overall, due to the large variance of the outcomes with no outlier being identified, the scene is highly uncertain, and few specific conclusions can be drawn, other than to expect high attrition on both sides when the adversary's force is 50 combatants.

Red casualties from cases 12 to 22 are shown in Figure 6. The means range from between 40 and 46, indicating that 80% to 92% of the Red force is taken out of action. Again, however, the variance is wide, and there are many outliers in the statistics, implying there is a great uncertainty about the combat outcomes. The highest and second highest mean values of Red casualties appear in cases 17 and 12, which are 45.95 and 45.14, respectively.
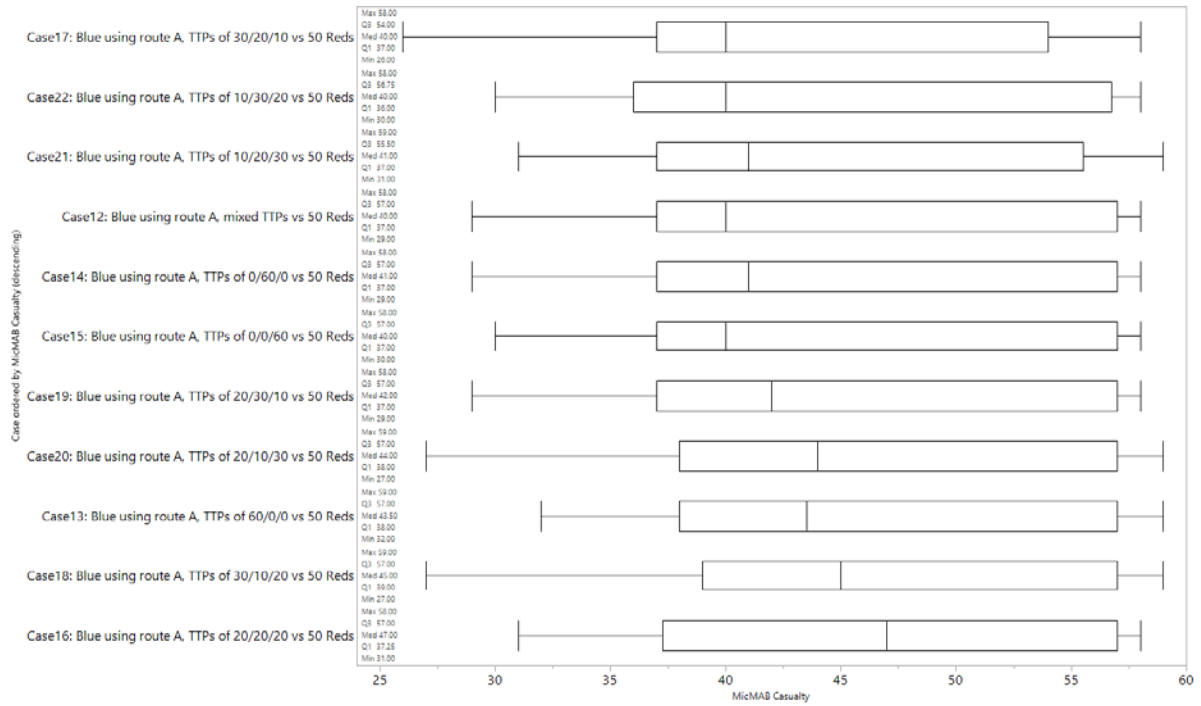
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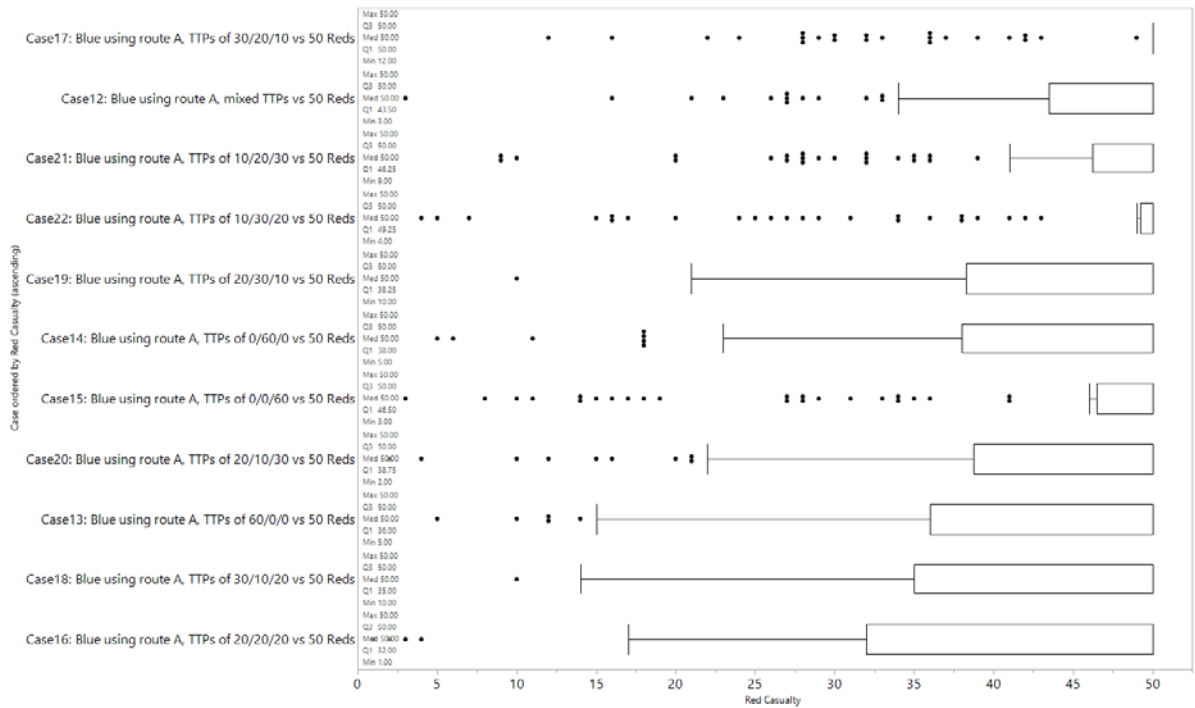Figure 5.   MicMAB Casualties for Cases 12 to 22

Figure 6.   Red Casualties for Cases 12 to 22

The effectiveness of 60 MicMABs engaging 10 destroyers, 20 frigates, and 20 corvettes can also be shown via loss exchange ratio, which is shown in Table 9. The loss exchange ratio is to take the adversary attrition number divided by own force attrition number as a measure of performance or effectiveness, and the larger the ratio, the better it is for Blue force. In Table 9, the value of the loss exchange ratio for all 11 cases is approximately between 0.91 to 1.02, and this indicates roughly one MicMAB loss for one Red destroyer, frigate, or corvette, which is deemed to be effective considering the difference of the cost, tonnage, and mission capabilities between Blue's and Red's platforms.

Table 9.   Loss Exchange Ratio for Cases 12 to 22

Case	12	13	14	15	16	17	18	19	20	21	22
Red Attrition	45.14	43.16	43.83	43.61	40.99	45.95	42.48	44.32	43.31	44.8	44.34
Blue Attrition	44.21	46.24	44.47	44.65	47.53	43.51	46.76	45.28	45.62	43.74	43.68
Loss Exchange Ratio	1.021	0.933	0.986	0.977	0.862	1.056	0.908	0.979	0.949	1.024	1.015

With Tukey multiple pairwise-comparisons on both MicMAB and Red attrition, the result shows there is no statistical significance among all pairs of cases, where the p-values are larger than 0.05 among those pairs. Specifically, due to the wide variance present, mixed TTPs or varying TTPs do not have statistically significant effect on the outcome of the engagements.

As with the previous set of cases, it is recommended half the MicMABs give priority to destroyers, but if selective targeting is not an option due to a lack of quality ISR, the tactic of mixed TTPs is recommended. It is noteworthy that the average value of Blue and Red attritions in all these cases do not differ greatly, and simulated combat durations differ by only ten minutes. These imply the tactical robustness of the MicMAB swarm concept. The attribute of the MicMABs' tactical positions that affect terrain masking is discussed in the following section.

(3)   Cases 12 to 15, 23 to 26, and 27 to 30: Blue's 60 MicMABs Engage Against Red's 10 Destroyers, 20 Frigates, and 20 Corvettes Using Routes in Scenarios A, B, and C

In this section, only the cases of the mixed TTPs and three specific TTPs are selected for simulation and examination, varying three tactical routes A, B, and C. In the previous chapter regarding the methodology, it is explained that the design is due to the statistical insignificance among the cases varying TTPs by grouping 10, 20 or 30 MicMABs to target destroyers, frigates, or corvettes first. Thus, there are 12 cases to compare on MicMABs and Red casualties in this section.

Figure 7 shows Blue's casualties in cases 12 to 15, where route A is taken, cases 23 to 26, where route B is taken, and cases 27 to 30, where route C is taken. Recall in route A, the MicMABs leave the terrain-masking area to engage the adversaries. In route B, all the MicMABs head toward the same direction and stay within the terrain-masking area, while in route C, some MicMABs are deployed around the scattered islands located in the middle of the Taiwan Strait. The simulated combat results differ and are noteworthy. The MicMAB casualties are much higher using route A. This is expected since this route exposes the small combatants to Red's ISR and targeting. Although having lower mean casualty rates than route A, route B demonstrates high variability in the results with several outcomes being the elimination of the MicMAB swarm. Employing the MicMAB swarm using route C results in (relatively) low casualty rates between 17.05 and 18.14, and with more consistent outcomes. Overall, the best MOE is achieved in the cases where the MicMABs adopt the tactical path of route C, and the attrition is less than 1/3 of Route A.
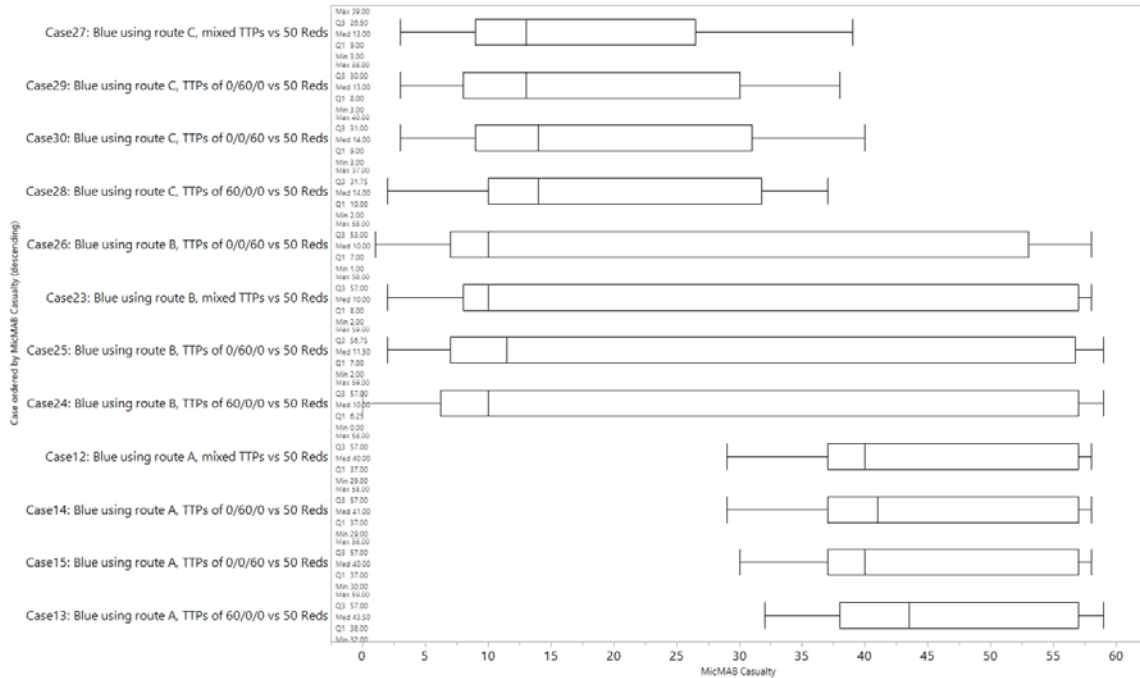
Figure 7.   MicMAB Casualties for Cases 12 to 15 (Route A), 23 to 26 (Route B), and 27 to 30 (Route C)

Figure 8 shows Red casualty rates in each of the MicMAB's route choices. The cases of route C achieve the best MOE with the highest mean Red attrition, followed by the cases of route B and cases of route A, respectively. Hence, the boxplot of Figure 8 indicates the cases of route C and cases of route B have a very narrow variance with plentiful outliers, while the cases of route A have a wider variance with much fewer outliers. Taking the tactical routes with higher degrees of terrain masking is expected to achieve higher Red attrition with higher certainty. Among all, the highest Red attrition happens in case 27, where half of the MicMABs take the route closely along the Taiwan coast, the other half stay around the scattered Penghu islands, centrally located in the middle of the Taiwan Strait, and both are under terrain masking.
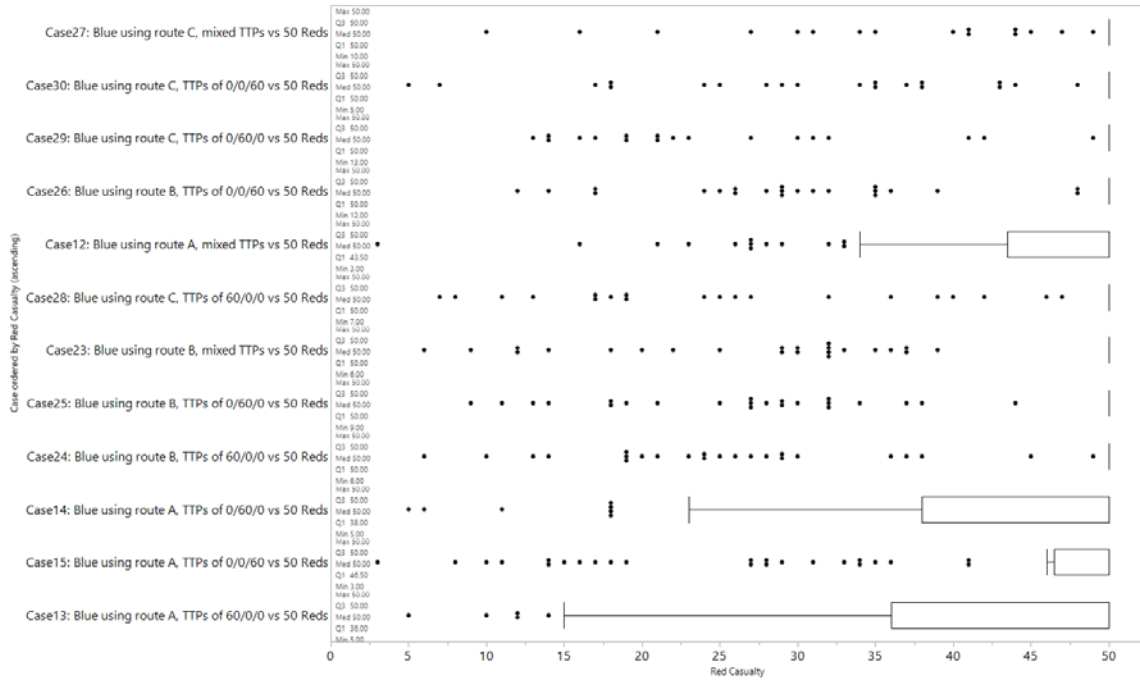
Figure 8.   Red Casualties for Cases 12 to 15 (Route A), 23 to 26
(Route B), and 27 to 30 (Route C)

Table 10 compares the loss exchange ratio of these 12 cases. Corresponding to the results in Figures 7 and 8, cases 27 to 30 using route C have the highest average loss exchange ratio in favor of the MicMABs, followed by the cases using route B and the cases using route A. These data highlight the attribute of terrain masking as the most influential factor to a MicMAB favorable exchange ratio. Among this set, case 27 has the highest MOE showing the value of terrain masking and early engagement with Red due to the tactical position chosen. Then, changing the TTPs has a secondary influence to the MOE, but those cases adopting the mixed TTPs achieve the best outcome overall.

Table 10.   Loss Exchange Ratio for Cases 12 to 15 (Route A), 23 to
26 (Route B), and 27 to 30 (Route C)

Case	12	13	14	15	23	24	25	26	27	28	29	30
Red Attrition	45.14	43.16	43.83	43.61	44.51	44.11	44.44	45.45	47.55	45.13	45.51	45.96
Blue Attrition	44.21	46.24	44.47	44.65	23.81	25.21	24.88	22.68	17.05	18.7	17.73	18.14
Loss Exchange Ratio	1.021	0.933	0.986	0.977	1.869	1.750	1.786	2.004	2.789	2.413	2.567	2.534

With Tukey multiple pairwise-comparisons on Red attrition, there is no statistical significance among all pairs of cases, either using the same or different terrain-masking routes. On the other hand, when comparing MicMAB attrition in those cases using different terrain-masking routes of A, B, and C, these pairs do show statistical significance, implying their p-values are all less than 0.05. This result can simply be summarized as selecting varied degrees of terrain-masking routes can vary MicMAB's survivability, but does not affect their lethality against 50 heterogeneous adversary warships.

(4)   Combat Duration of Cases 12 to 15, 23 to 26, and 27 to 30

Another essential consideration is the length of the combat duration. Figure 9 shows the combat duration of the 12 cases taking the three routes. Interestingly, the cases adopting route C, where half of the MicMABs stay around the Penghu islands, consume the longest time on average to finish the combat, with a wide variance. It can be observed that the MicMABs in routes A and B engage with Red warships in a more direct way, where a large scale of force on force attrition happens, than the MicMABs do in route C. The more dispersed engagement opportunities of route C result in both longer average combat duration and with greater variance.

Here, regarding the result of Tukey multiple pairwise-comparisons on combat duration, there is statistical significance between the cases adopting route C and those adopting routes A or B. Yet, all the pairs between the cases using route A and those using route B show no statistical significance.

Adapted from https://www.google.com/maps/place/Taiwan/@23.6629757,
116.5030323,2378812m/data=!3m1!1e3!4m5!3m4!1s0x346ef3065c07572f:
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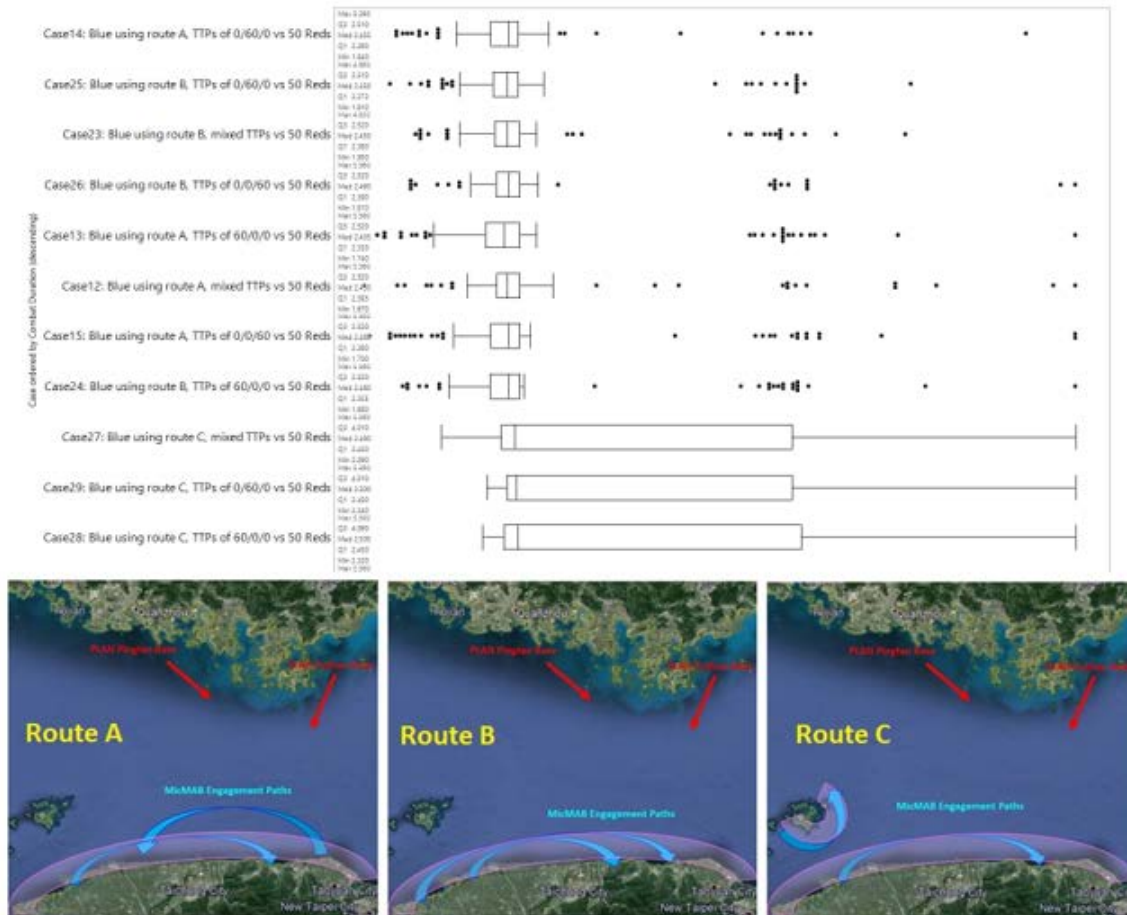
Figure 9.   Combat Duration in Hours for Cases 12 to 15 (Route A), 23
to 26 (Route B), and 27 to 30 (Route C) along with the Figure of the Three
Scenarios of Terrain-Masking Setting

(5)   Task Success Analysis of Cases 12 to 15, 23 to 26, and 27 to 30

In the simulation, the stop conditions are assumed with exhaustive force attrition
for both sides or maximal time step reached. For 30 cases designed in the DOE, each case
is run for 100 repetitions, and the task success probability is extracted by calculating the
times when Blue wins among 100 runs for each case. Similarly, the probabilities of Red
success and draw are acquired by calculating the times when Red wins and when the
maximal time step is reached. This part of the analysis aims to provide military decision
makers a sense of probability in task success, failure, or draw.

First, the calculated result for 30 cases in terms of the probabilities of Blue's success, Red's success, and a draw is shown in Table 11. In the cases where MicMABs engage 30 Red warships using route A, Blue has much higher probability, from 0.82 to 0.94, to win the fight, which means putting all adversaries out of action. By contrast, when MicMABs engage 50 Red warships, the task success probability drops to 0.77, or even 0.56, and this is consistent with the aforementioned analysis on these cases' wide range of variance. Again, taking the tactical routes with higher level of terrain masking enhances MicMAB's success probability. The MicMABs using route B can win the fight with a probability from 0.76 to 0.78, and that probability is brought up to 0.80 or 0.84 when route C is adopted. It is noteworthy that there is a relatively high probability of a draw, but no probability of Red winning when the MicMABs use route C, which the swarm force distributes around the mid-strait islands.

Furthermore, to take a closer look at the engagement end state of the runs when Blue wins or fails, or a draw happens, it is necessary to examine the Red casualties and combat duration for the runs when Blue wins. In addition, the MicMAB casualties and combat duration are also explored for the runs when Blue fails. When the result is a draw, MicMAB and Red casualties are further examined and discussed. Due to the statistical insignificance on the pairs of cases taking the same route and varying TTPs by grouping 10, 20, or 30 MicMABs, only the cases of the mixed TTPs and three specific TTPs are selected to compare with varying the three tactical routes A, B, and C. More specifically, cases 12 to 15, 23 to 26, and 27 to 30 are selected to compare in terms of analyzing the situations that Blue wins or fails, or a draw happens.

Table 11.   Task Success Probability

Task Success Prob / Case	Case Detail	Blue Success Probability	Red Success Probability	Probability of Draw
1	Blue using route A, mixed TTPs vs 30 Reds	0.94	0.04	0.02
2	Blue using route A, TTPs of 60/0/0 vs 30 Reds	0.94	0.06	0
3	Blue using route A, TTPs of 0/60/0 vs 30 Reds	0.90	0.10	0
4	Blue using route A, TTPs of 0/0/60 vs 30 Reds	0.89	0.11	0
5	Blue using route A, TTPs of 20/20/20 vs 30 Reds	0.91	0.07	0.02
6	Blue using route A, TTPs of 30/20/10 vs 30 Reds	0.88	0.11	0.01
7	Blue using route A, TTPs of 30/10/20 vs 30 Reds	0.88	0.11	0.01
8	Blue using route A, TTPs of 20/30/10 vs 30 Reds	0.90	0.10	0
9	Blue using route A, TTPs of 20/10/30 vs 30 Reds	0.82	0.17	0.01
10	Blue using route A, TTPs of 10/20/30 vs 30 Reds	0.87	0.12	0.01
11	Blue using route A, TTPs of 10/30/20 vs 30 Reds	0.91	0.09	0
12	Blue using route A, mixed TTPs vs 50 Reds	0.72	0.27	0.01
13	Blue using route A, TTPs of 60/0/0 vs 50 Reds	0.69	0.30	0.01
14	Blue using route A, TTPs of 0/60/0 vs 50 Reds	0.73	0.27	0
15	Blue using route A, TTPs of 0/0/60 vs 50 Reds	0.72	0.26	0.02
16	Blue using route A, TTPs of 20/20/20 vs 50 Reds	0.56	0.43	0.01
17	Blue using route A, TTPs of 30/20/10 vs 50 Reds	0.77	0.23	0
18	Blue using route A, TTPs of 30/10/20 vs 50 Reds	0.62	0.38	0
19	Blue using route A, TTPs of 20/30/10 vs 50 Reds	0.70	0.30	0
20	Blue using route A, TTPs of 20/10/30 vs 50 Reds	0.70	0.29	0.01
21	Blue using route A, TTPs of 10/20/30 vs 50 Reds	0.75	0.25	0
22	Blue using route A, TTPs of 10/30/20 vs 50 Reds	0.75	0.24	0.01
23	Blue using route B, mixed TTPs vs 50 Reds	0.77	0.23	0
24	Blue using route B, TTPs of 60/0/0 vs 50 Reds	0.76	0.23	0.01
25	Blue using route B, TTPs of 0/60/0 vs 50 Reds	0.77	0.23	0
26	Blue using route B, TTPs of 0/0/60 vs 50 Reds	0.78	0.21	0.01
27	Blue using route C, mixed TTPs vs 50 Reds	0.84	0	0.16
28	Blue using route C, TTPs of 60/0/0 vs 50 Reds	0.80	0	0.20
29	Blue using route C, TTPs of 0/60/0 vs 50 Reds	0.82	0	0.18
30	Blue using route C, TTPs of 0/0/60 vs 50 Reds	0.80	0	0.20

Table 12 shows what the combat duration and MicMAB casualties look like when Blue has task success, namely taking out all Red warships. Here, MicMAB casualties are shown in terms of attrition ratio for the purpose of comparison convenience. Similar to the aforementioned analysis in the previous sections, when 60 MicMABs engage 30 adversaries, they generally have high task success probability. When facing a larger

adversary force of 50 warships, however, the cases taking route C have significantly higher probabilities of winning than those taking routes B and A. Also, selecting routes C and B can lower MicMAB attrition significantly compared to selecting route A.

Nevertheless, the combat duration for those cases taking route C appears to be close to those taking routes A and B when only the runs of Blue winning are examined. With pairwise comparisons, the result shows that there is statistical significance only in the pair of cases 1 and 29. In the runs of all 12 cases when Blue wins regardless of selecting different routes or varying TTPs, the fight only endures over 2.8 hours on average.

Table 12.   Blue Success Analysis

Blue Wins / Case	Case Detail	Blue Success Probability	Combat Duration Mean	Combat Duration St Dev	MicMAB Casualty Ratio
1	Blue using route A, mixed TTPs vs 30 Reds	0.94	2.51	0.36	0.51
2	Blue using route A, TTPs of 60/0/0 vs 30 Reds	0.94	2.54	0.43	0.52
3	Blue using route A, TTPs of 0/60/0 vs 30 Reds	0.90	2.58	0.53	0.55
4	Blue using route A, TTPs of 0/0/60 vs 30 Reds	0.89	2.56	0.47	0.55
12	Blue using route A, mixed TTPs vs 50 Reds	0.72	2.53	0.37	0.65
13	Blue using route A, TTPs of 60/0/0 vs 50 Reds	0.69	2.69	0.57	0.69
14	Blue using route A, TTPs of 0/60/0 vs 50 Reds	0.73	2.57	0.43	0.66
15	Blue using route A, TTPs of 0/0/60 vs 50 Reds	0.72	2.62	0.49	0.66
23	Blue using route B, mixed TTPs vs 50 Reds	0.77	2.65	0.55	0.23
24	Blue using route B, TTPs of 60/0/0 vs 50 Reds	0.76	2.71	0.57	0.25
25	Blue using route B, TTPs of 0/60/0 vs 50 Reds	0.77	2.68	0.55	0.25
26	Blue using route B, TTPs of 0/0/60 vs 50 Reds	0.78	2.63	0.50	0.22
27	Blue using route C, mixed TTPs vs 50 Reds	0.84	2.74	0.62	0.23
28	Blue using route C, TTPs of 60/0/0 vs 50 Reds	0.80	2.76	0.61	0.25
29	Blue using route C, TTPs of 0/60/0 vs 50 Reds	0.82	2.79	0.63	0.23
30	Blue using route C, TTPs of 0/0/60 vs 50 Reds	0.80	2.77	0.62	0.23

Table 13 shows what the combat duration and Red casualties, including destroyers, frigates, and corvettes, look like when Red has task success, namely taking out all Blue MicMABs. Also, casualties are shown in terms of attrition ratio. First of all, it is obvious that Red has low probabilities of success with 30 warships and also that there is no successful outcome for Red in the runs when MicMABs select route C. When MicMABs take route A to engage 50 Red warships, the chance of Blue failing rises, ranging from 0.26 to 0.30. Furthermore, selecting route B can lower the chance of Blue failing to 0.23 or 0.21,

and selecting route C can further reduce that chance to 0.0, which is an interesting outcome and will be further examined.

Another insight found from Table 13 is that even when Red wins, namely all 60 MicMABs are taken out of action, Red still loses on average 60% of its warships. In addition, Red corvettes are taken down in a higher ratio than Red destroyers and frigates because of their lower staying power against missile attacks.

Table 13.   Red Success Analysis

Red Wins / Case	Case Detail	Red Success Probability	Combat Duration Mean	Combat Duration St Dev	Red Casualty Ratio	Destroyer Casualty Ratio	Frigate Casualty Ratio	Corvette Casualty Ratio
1	Blue using route A, mixed TTPs vs 30 Reds	0.04	2.41	0.37	0.49	0.38	0.43	0.68
2	Blue using route A, TTPs of 60/0/0 vs 30 Reds	0.06	2.52	0.45	0.51	0.45	0.42	0.67
3	Blue using route A, TTPs of 0/60/0 vs 30 Reds	0.10	2.49	0.45	0.48	0.39	0.36	0.68
4	Blue using route A, TTPs of 0/0/60 vs 30 Reds	0.11	3.54	0.96	0.72	0.63	0.58	0.95
12	Blue using route A, mixed TTPs vs 50 Reds	0.27	2.86	1.02	0.65	0.49	0.53	0.86
13	Blue using route A, TTPs of 60/0/0 vs 50 Reds	0.30	2.55	0.84	0.59	0.46	0.49	0.74
14	Blue using route A, TTPs of 0/60/0 vs 50 Reds	0.27	2.41	0.69	0.54	0.40	0.42	0.73
15	Blue using route A, TTPs of 0/0/60 vs 50 Reds	0.26	2.51	0.87	0.53	0.39	0.43	0.69
23	Blue using route B, mixed TTPs vs 50 Reds	0.23	2.64	0.72	0.58	0.45	0.45	0.77
24	Blue using route B, TTPs of 60/0/0 vs 50 Reds	0.23	2.61	0.85	0.56	0.44	0.47	0.73
25	Blue using route B, TTPs of 0/60/0 vs 50 Reds	0.23	2.45	0.69	0.56	0.46	0.43	0.72
26	Blue using route B, TTPs of 0/0/60 vs 50 Reds	0.21	2.51	0.80	0.59	0.46	0.47	0.77
27	Blue using route C, mixed TTPs vs 50 Reds	0						
28	Blue using route C, TTPs of 60/0/0 vs 50 Reds	0						
29	Blue using route C, TTPs of 0/60/0 vs 50 Reds	0						
30	Blue using route C, TTPs of 0/0/60 vs 50 Reds	0						

Table 14 shows the detail of those cases where a draw happens, namely the stop condition of a maximal time step is reached during the run. When the MicMABs use routes A and B, the probability of the draw is extremely low, either 0.01 or 0.02, and the resulting casualties on both sides are high. By contrast, that probability is relatively high, from 0.16 to 0.20, when the MicMABs adopt route C. Among those cases where route C is used and a draw happens, case 27 has the lowest MicMAB attrition and highest Red attrition. This result supports the aforementioned recommendation that the tactic of mixed TTPs is more dynamic than other types of TTPs.

Table 14.   Draw Analysis

Draw Analysis / Case	Case Detail	Probability of Draw	MicMAB Casualty Mean	MicMAB Casualty St Dev	MicMAB Casualty Max	MicMAB Casualty Min	Red Casualty Mean	Red Casualty St Dev	Red Casualty Max	Red Casualty Min
1	Blue using route A, mixed TTPs vs 30 Reds	0.02	48	5.66	52	44	28.50	0.71	29	28
2	Blue using route A, TTPs of 60/0/0 vs 30 Reds	0								
3	Blue using route A, TTPs of 0/60/0 vs 30 Reds	0								
4	Blue using route A, TTPs of 0/0/60 vs 30 Reds	0								
12	Blue using route A, mixed TTPs vs 50 Reds	0.01	47		47	47	48		48	48
13	Blue using route A, TTPs of 60/0/0 vs 50 Reds	0.01	55		55	55	48		48	48
14	Blue using route A, TTPs of 0/60/0 vs 50 Reds	0								
15	Blue using route A, TTPs of 0/0/60 vs 50 Reds	0.02	56	0	56	56	48.50	0.71	49	48
23	Blue using route B, mixed TTPs vs 50 Reds	0								
24	Blue using route B, TTPs of 60/0/0 vs 50 Reds	0.01	52		52	52	49		49	49
25	Blue using route B, TTPs of 0/60/0 vs 50 Reds	0								
26	Blue using route B, TTPs of 0/0/60 vs 50 Reds	0.01	53		53	53	48		48	48
27	Blue using route C, mixed TTPs vs 50 Reds	0.16	33.06	4.15	39	23	34.69	11.50	49	10
28	Blue using route C, TTPs of 60/0/0 vs 50 Reds	0.20	34	2.51	37	27	25.65	12.58	47	7
29	Blue using route C, TTPs of 0/60/0 vs 50 Reds	0.18	34.94	3.37	38	23	25.06	10.52	49	13
30	Blue using route C, TTPs of 0/0/60 vs 50 Reds	0.20	35.15	2.06	40	31	29.80	12.09	48	5

It is interesting that those cases taking the tactical route C, which is a set of paths around the mid-strait islands across the Taiwan Strait, have zero chance of failing but higher chances of a draw. Consequently, the playback method in MANA simulations was used on case 27 for its 100 repetitions in order to determine the possible causes. In each run, the time steps of the three Blue mobile radar facilities are recorded once they are attrited, as well as the remaining ammunition for each surviving MicMAB.

The result shows that there is no significant difference on the surviving MicMABs' remaining ammunition among the runs when Blue wins or fails, or when a draw happens for all cases. However, the results on Blue radar attrition and associated time steps do significantly differ and need to be examined.

Table 15 shows the two kinds of survival time for three Blue radars in the 100 runs of case 27. The first one is the overall average survival time, counting the time for both surviving and attrited radars, and the other is the average survival time when the radar is attrited. The three Blue radars, positioned on the north and south of the Taiwan coast, as well as the coast of the mid-strait Penghu islands, are examined on their vulnerabilities in terms of survival time and attrition probability.

First of all, a draw happens in the simulation when the maximal time step is reached, implying the combat lasts 5.56 hours. From Table 15, it can be observed that three radars are on average attrited in a very early stage of the engagements when a draw happens,

ranging from 1.08 to 2.00 hours. The attrition probability for Blue radars on the north and south of the Taiwan coast is 1.0, and it is 0.81 for the radar on the mid-strait island. For case 27, if three Blue radars are taken down, the combat outcome is guaranteed to be a draw.

In the runs when Blue wins, Blue radars on the north and south of the Taiwan coast have longer average survival time, but the radar on the mid-strait island has shorter survival time and is considered to be vulnerable against Red warships. Corresponding to the result of survival time, the north and south radars have much lower attrition probabilities, 0.14 and 0.19, respectively, than the mid-strait island radar does. The mid-strait island radar's attrition probability is 0.76, with an average overall survival time 2.32 hours. Another insight is that when the radars are attrited in the runs for both when a draw happens and when Blue wins, the north radar is the earliest one to be taken down by Red, followed by the mid-strait island radar and the south radar. This result also corresponds to the sequence of Red warships approaching into the east of the Taiwan Strait.

Table 15.   Radar Attrition in 100 Runs of Case 27

Case 27 Radar Attrition			
When Blue Wins	North Radar	South Radar	Mid-Strait Island Radar
Occurrence Count	16 out of 100 runs		
Average Survival Time (hours)	4.87	4.81	2.32
Average Survival Time When the Radar is Attrited in the Run (hours)	0.73	1.61	1.31
Attrition Probability	0.14	0.19	0.76
Survival Probability	0.86	0.81	0.24
When a Draw Happens	North Radar	South Radar	Mid-Strait Island Radar
Occurrence Count	84 out of 100 runs		
Average Survival Time (hours)	1.08	1.71	2.00
Average Survival Time When the Radar is Attrited in the Run (hours)	1.08	1.71	1.17
Attrition Probability	1	1	0.81
Survival Probability	0	0	0.19

Overall, this part of the analysis reveals that if three simulated agents of mobile radar facilities are taken out in the early stage of the engagements, the engagement most likely leads to a draw in case 27, or an unfavorable outcome in the other cases. The loss of inorganic target sharing results in the MicMABs being unable to acquire targets while ashore under terrain masking, and if the MicMABs take a more direct engagement in order to acquire targets organically, their casualties are expected to be much higher.

(6)   Partition Tree on MicMAB Attrition

To verify the observations on the importance of terrain masking on MicMAB attrition, a partition tree is shown in Figure 10. Similar to a regression model, five splits explain 30% of the data's variability. Granted, this is a low R-squared, due mainly to the high variability across all results. Nevertheless, the R-squared value can be brought up to 96.6% when only the values of each case's average MicMAB attrition are considered because the stochastic nature of the random replications is filtered out.

The first and second splits both relate to the attribute of terrain masking, thus reinforcing that this is the most important factor in determining MicMAB attrition. The first factor for lowering MicMAB attrition is to use a terrain-masking route, and the second split on the left shows it is better to use route C (high terrain masking) than route B (medium terrain masking).

If Route A's more exposed track is taken, the second split on the right is to determine whether the MicMABs have more than 20 frigates-first units, including mixed TTPs or not. Then, if the MicMABs have more than 20 frigates-first units or more, the next split indicates the tactic of mixed TTPs is better, and a lower Blue attrition is desired. However, if the MicMABs have fewer than 20 frigates-first units, the next split indicates having 30 destroyers-first units is preferred, which results in a lower Blue attrition. In this branch, however, these conclusions are weak as the differences in MicMAB attrition for each split is small.
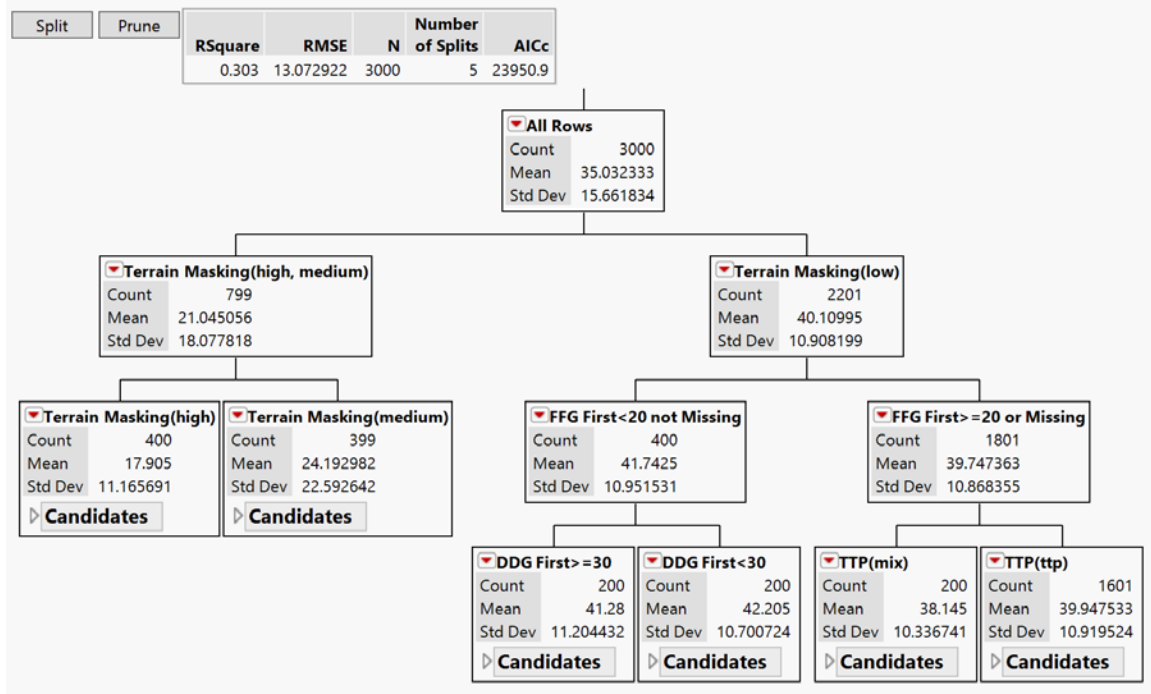
Figure 10.   Partition Tree on MicMAB Attrition

As a result, the partition tree highlights terrain masking as by far the most prominent consideration to reduce MicMAB attrition. Then, the consideration of adopting the tactic of mixed TTPs or prioritizing 30 MicMABs to engage with the adversary's destroyers may be addressed, although this part of the results is inconclusive. In Chapter V, these findings are further elaborated for Blue's decision-making process and to address the original research questions from Chapter I.

V.   CONCLUSION

The peace and stability across the Taiwan Strait is of national interest to both the United States and Taiwan, but the PRC's rising military capability is challenging the status quo. Taiwan, as an indispensable partner to the United States in the Indo-Pacific region and beyond, does not only rely on the defense articles procured from the United States, but also seeks a stronger domestic military industry to build up a credible deterrence capability. In recent years, the military exchange and defense industry cooperation between the United States and Taiwan have continued to grow, and Taiwan will continue efforts to promote regional stability.

Taiwan does not seek conflicts and war. Instead, Taiwan aims to develop asymmetrical and innovative assets and tactics that are so lethal that China would not initiate a war with Taiwan. To that end, having a large number of small, fast, stealthy combatants with advanced anti-ship missiles definitely should be considered as an option in Taiwan's force structure.

First, as verified in this thesis by the application of Hughes' salvo equations, stealth is an essential feature for the MicMABs. Further, this thesis' modeling and simulation suggest 60 MicMABs are effective in countering a PLAN force size of 10 destroyers, 10 frigates, and 10 corvettes. If the adversary's force size increases, such as 10 destroyers, 20 frigates, and 20 corvettes, 60 MicMABs are still effective by taking 45 of them out of action on average. The outcome of such an increase in adversary force size, however, can be much more uncertain, and the MicMABs' attrition also increases. Nevertheless, in a comparison of the total tonnage of both sides' warship attrition, the MicMAB is considered to be a lethal, terrain-utilizing asymmetric asset for maritime operations upon green waters.

Overall, the prominent concern of MicMAB deployment and tactics is the number of adversary destroyers and frigates. As a result, it is important to have sufficient numbers of small combatants targeting the adversary's destroyers and frigates first or to keep all MicMABs flexible to attack whichever warship is closest, in order to achieve a better outcome of the MOE.

Consequently, to address the original research questions in light of these findings:

- Can a naval combat modeling using deterministic and agent-based simulations inform Taiwan's Navy on the military value of the MicMABs and how best to employ them?

  Both Hughes' salvo equations and the agent-based simulation MANA provided insights on the military value of the MicMABs against a more expensive PLAN surface force. Employment tactics were explored with varying targeting priorities for the MicMABs against this force.

- What is the best allocation of the MicMABs along the Taiwan coast?

  The simulation provides evidence that a swarming force distributed among the mid-strait islands and close to the Taiwan shore leads to consistently superior battle outcomes than the alternatives explored.

- How does the assignment of target priorities for MicMAB swarm engagements affect the number of adversary kills?

  Although not statistically significant, certain targeting priorities seem to have an effect on the MicMAB force exchange ratio. Shooting at whichever target is closest is satisfactory based on the outcome of the simulation. More research and at-sea experimentation is required on this topic.

- How much more survivable and effective are near-shore launch points leveraging terrain-masking than attacking while steaming toward the adversary's fleet?

  This research provides clear evidence that the MicMABs' use of terrain masking is a critical tactic to employ to increase the lethality and survivability of the swarm.

Recommendations for Taiwan's Navy include:

- To maintain the MicMAB's small tonnage feature and improve its ship hull material or design to further reduce its radar cross section as well as its operational durability for rough sea state

- To adopt tactics that use the terrain-masking advantage

- To shoot at the closest target if selective targeting is not an option due to a lack of quality ISR

- To ensure having sufficient units of MicMABs for distributed lethality

- To ensure platforms can share targeting information with command centers and acquire targets inorganically

- To strengthen MicMAB's capability to counter helo or guns, and to refuel and rearm in a short timeframe for the purpose of multiple engagements

Recommendations for follow-on work include:

- Simulations on tactics of MicMABs working with other types of combatants as heterogeneous forces, surface and air, as well as varying target priorities along with using different terrain-masking routes

- Simulations on capability improvements of the MicMABs, such as organic detection range and number of missiles carried

- Wargaming on employing MicMABs in different scenarios of the PLA invasion or blockade

- Wargaming on employing MicMABs in peace-time scenarios to explore their effectiveness on other tasks, such as patrolling the South China Sea

- At-sea exercises of the MicMABs with other types of combatants

- Extensive sensitivity analysis of the various inputs to the simulation

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