Reshaping the Ocean Battlespace with Naval Mining

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1. **Summary.** Naval Mine Warfare (MIW) includes two distinct, different missions: active mining and mine countermeasures (MCM). Exponential progress in robotics, sensor networks, autonomy and sustainable logistics present new opportunities for Naval mining to deliberately defend against steadily increasing global threats. Splitting sensor suites from munition sets can enable active mining to reshape and change the operational battlespace. Judicious employment of Naval mining can allow U.S. forces to "***attack effectively first***" when overseas aggressors threaten freedom of navigation, international maritime commerce, national boundaries, and vital U.S. interests. Deliberately applying a mining focus to feasible theater capabilities is a **Hedge Strategy** for emerging concepts in future fleet force design. This work proposes building a new software tool that supports quantitatively assessing new mining concepts, providing a realistic basis for in-depth cross-disciplinary analytic understanding.

2. **Problem.** Naval mining has played an important role for nearly every major maritime conflict in the modern age. However, contemporary U.S. naval forces no longer have the ability to execute significant active mining operations that can shape potential conflicts. In recent years, steady developments in underwater vehicles offer encouraging signs of progress. New programs related to active mining have been announced but tend to be expensive high-technology updates of classic designs, neither surgable nor scalable. It is possible to move past customary thinking about mines as individual solitary devices, instead considering future minefields as a **system of *distributed robots,*** made up of split ***sensor suites*** plus controllable ***munition sets***. Splitting sensors from effectors can enable potent, low-cost, repeatable solutions. Software support to conduct careful analysis of such paired sensor-munition systems is needed to examine and explore how Naval mining might affect theater operations most effectively.

3. **Goal**. Naval mining aligns conceptually with modern subsea seabed defense imperatives. An integrated-deterrence approach to theater mining as a ***surgable, sustainable, attritable,*** distributed robotics capability can lead to potent new capabilities. Splitting sensor suites from munition sets, with a few simple logical states sequenced by command and control (C2), can become a major enabler to shape the boundaries and chokepoints of the ocean battlespace. The overall objective is to show how theater-scale active mining supports national imperatives to ***deter, deescalate, and defeat*** near-peer aggressors, as necessary. Over time, force design gains significant advantages from secure weapons systems that are separately deployed forward. Such approaches add missing capabilities for short-range *sea control* and long-range *sea denial*. Integrating available advanced system technologies with existing munition capabilities, both bound together using simple effective C2, can guide new operational strategies. Mining offers the potential to sustain allied use of the seas, while preventing an adversary from denying freedom of navigation and international commerce.

4. **Background.** Support of maritime commerce and forward-deployed expeditionary operations are core Naval missions. Whether covert or overt, deliberate mining offers significant national advantages, in many ways similar to historic Naval mining efforts and outcomes of eras past (O'Hara 2022). Many strategic issues relate to active mining that remain relevant today.

   a. *National imperatives*. The United States is a maritime nation that must steadfastly defend Freedom of Navigation (FON) for competitive trade and commerce in the global commons. Multinational partnerships and alliances are essential to ongoing economic stability as part of freedom of trade and rules-based international commerce. These fundamental imperatives have remained relevant since first expressed in *The Influence of Sea Power upon History* by Alfred Thayer Mahan (Mahan 2022). Contemporary analysis reaffirms and reinforces these principles. For example, *Anti-Access Warfare* (Tangredi 2013) summarizes how maritime mining by Iraq changed the course of coalition response from sea to land in Operation Desert Storm, and further shows the role of active mining in the larger context of Anti-Access Area Denial (A2/AD) strategies. *Considering the Carrier* (Vandenengel 2023) describes "Mine Warfare Today" at length, noting that the mere threat of a $20K weapon can deter deployment of a $12B aircraft carrier, and further inhibits deployment of ships in an accompanying (or independent) naval strike group.

   b. *Sweep of history*. Restrictions and permissions regarding the potential use of ocean mines have been carefully codified in international law for centuries. The outcomes for eight of nine global conflicts since 1905 have been dominated or determined by active mining at sea: Russo-Japanese War, World War I, World War II, Korean War, Vietnam War, Operation Desert Storm, Russia-Ukraine War, and the US-Iran War. For example, absent the sudden conclusion of World War II using atomic weapons, the Operation Starvation mining and bombing campaign against Japan was credited by the Japanese as likely to end the war in the Pacific (Mason 2002). The recent book *Innovating Victory* (O'Hara 2022) provides a cogent analysis of how technical advancements require adaptation and adoption to be effective, insightfully explained across multiple warfare domains (including mines) for the U.S. Navy. The potential impact of mining for current expeditionary operations is carefully examined in (Price 2025). An ongoing bibliography of mines and countermeasures simply lists relevant publications and is now approaching 600 pages (Marlatt 2024). Regrettably, and perhaps remarkably, despite a plethora of evidence and undisputed strategic thinking, little change in the status quo has resulted. Such a powerful role for Naval mining is not a current U.S. capability (Winnefeld 2023), who succinctly notes:

   "Our most advanced mines are no more capable than those used in World War II, except some can be delivered more accurately using precision-guided capability. They still have primitive fusing devices and are only effective in shallow water. We should bring these mines into the twenty-first century using technology that would enable them to be positively controlled, be frequently updated, act as a sensor, use machine learning for acoustic discrimination, and be lethal in deeper water. The ability to selectively seal off Chinese naval assets or commercial shipping from leaving or entering port would be truly disruptive, presenting a new dilemma to Chinese ambitions in its neighborhood. Sadly, this capability has no constituency." (Winnefeld 2023)

c. *National capabilities for mobilization*. Long-term naval operations are dominated by tandem logistics and maneuver for preparation and concentration of power, embodying the Hughes' precept to "attack effectively first" (Hughes 2018). As an existence proof, the United States was able to rapidly mobilize its industrial base during World War II to support surgable, sustainable, attritable logistics despite long odds (Herman 2013). For naval forces, logistics and maneuver are inseparably intertwined, as described in *Fighting the Fleet* (Cares 2021). The current Russia-Ukraine War has made it obvious to all that sustained production and delivery of munitions is essential. A similar industrial framework might be established for Naval mine warfare, which then might effectively "shape the battlespace" for economic stability by paralyzing opponent threats while protecting friendly commercial assets. Aggregate weapons-system effectiveness is a dominating factor for risk analysis, and forward-deployed mines provide ordnance in theater that do not have to be carried on board when ships and aircraft deploy. Thus corresponding costs for enhancing and amplifying the combat power of a hybrid fleet might be much less than corresponding shipbuilding costs. Imposition of asymmetric costs on adversaries can ***deter*** conflict, ***deescalate*** hostilities, and ultimately ***defeat*** opponents if necessary while reinforcing the reliable stability of maritime commerce for a rules-based international order throughout.

d. *Strategic insights informed by computational analysis are needed*. A fresh look at active mining that is based on first principles of warfighting, along with a broader strategic perspective for peacetime protection of allied commerce, is needed and missing. Such an endeavor offers excellent potential for computationally powerful modeling and simulation (M+S) that complements existing (typically classified) analytic tools. Shared understanding of theater-scale mining relationships provides further deterrent influence on opponents while simultaneously strengthening allied resolve. Theater-wide reconsiderations for naval mining that include sea lines of commerce and communications (SLOCs), choke points, harbors, safety lanes (i.e. Q routes), safe havens, and expeditionary operations are likely to reveal multiple new opportunities for coalition stability through subsea mining defenses.

e. *Hedge Strategy*. The pillars of the hedge strategy are *small and low cost*, *unmanned*, *many*, and *smarter* designs (Brown, Selby 2023). These attributes exactly match the potential of massing low-cost smart mines assembled using modern unmanned systems technology. Adaptation, innovation, and ingenuity are essential for success. Failure to adapt leads to irrelevancy (Selby 2021). Principles of the Hedge Strategy continue to grow in influence and impact, and are now central to CNO Daryl Caudle's *Fighting Instructions* for the fleet.

"We find ourselves operating in an era with other great powers, an era in which the speed of decision ruthlessly punishes delay. The requirement for a strong, resilient, and globally present Navy has never been more important to our Nation's defense. […] Our Navy's approach to combat can no longer be based on capability overmatch and winning by mass dominance alone. The Nation needs a Navy that can hedge lethal effects aggressively, innovate continuously, fight [with] distributivity, and command with clarity across a global network of battlespaces." (Caudle 2026)

5. **Operationalizing Mine Warfare**. Multiple game-changing considerations are relevant.

a. *Deployment with minimal risk*. Sustainable, relatively covert delivery of in-water effectors for active mining is needed in order to keep human warfighters out of harm's way. Multiple programs with strategic impact for naval sea power are already possible (Winnefeld 2025). For example, Low Profile Vessels (LPVs) – sometimes called "narco subs" – might also handle surreptitious deployment of ocean assets across (and delivery into) any Weapon Engagement Zone (WEZ) indefinitely (Sierra 2024). This requirement steadily becomes ever-more urgent as the range and intensity of opponent WEZ challenges continue to grow. Thus forward stockpiling of targetable mine munitions, with allies or *in situ*, is possible in peacetime or wartime. The ability to avoid placing human operators (and major assets) in harm's way offers compelling motivation. Another advantage: once deployed, naval mines effectively become a complementary weapons inventory for forward-operating submarines, surface ships and aircraft that do not need to be carried onboard. Whether active or latent, minefields are "smart" munitions – essentially robotic systems – that can be delivered across long distances only once, and then remain in place for long (perhaps indefinite) periods of time. As shown in World Wars I and II, and the Russia-Ukraine war, sustained national endurance is crucial during years-long extended conflicts among great powers.

b. *Sensor-suite capabilities for target identification*. Long-duration sonobuoy fields are technically feasible that might apply artificial intelligence machine learning (AI/ML) algorithms in order to continuously monitor and learn "signs of life" that discern friend from foe (Winnefeld 2021). Maritime domain awareness (MDA) and ocean surveillance sensor reports are already available from a wide variety of data-collection sources. Any of these sensor networks is orders of magnitude more effective than a single sonar transducer acting as the targeting and triggering mechanism for a mine in isolation. Most modern sensors now have the ability to further discriminate Identification Friend Foe Neutral Unknown (IFFNU), thus avoiding unintended attacks and protecting friendly assets. The sensor-suite "whole" is much greater than the sum of its many different parts.

c. *Command and Control (C2)*. Ironically, the threat of active mining has at least as big an impact on the decision making of opposing forces as the detonation of a given mine itself. Worth considering: perhaps the simplest C2 order is to arm or disarm a weapon. If friendly minefields can be enabled/disabled as directed, then national command authorities can gradually ratchet up (or else reduce) the degree of opposition applied, all in a way that encourages deterrence and de-escalation as an alternative to directly engaging in fleet combat. Complementing the primary role of mine placement as part of a minefield's design, adding local command and control (C2) for **on/off (enable/disable) authorization** makes "shaping the battlespace" a practical option for *deterrence*, *de-escalation*, and *defeat* capabilities. This approach also changes the inherent difficulty of arduous MCM clearance into deliberately controllable minefield neutralization. Such control offers a diplomatic advantage that discourages aggressors, rather than operational impediments that discourage deployment. Simple minefield Command and Control (C2) with minimal Communications (C3) is the key to actionable fleet concepts of operations (CONOPS).

d. *Network-Optional Warfare (NOW)*. Naval forces do not have to be engaged in constant centralized communication (Brutzman 2010-2024). Since they can operate unattended, minimum-essential communication needs are exceedingly simple for minefields. Typically, minefield planning and placement decisions establish the potential scope and effect of these weapons against opposed targets, without requiring repositioning of munitions in response to updated target data. Indeed, since the overarching purpose of a minefield is to prevent hostile shipping traffic from proceeding, classical minefield laydown patterns do not require constant monitoring or even precise targeting information in order to be effective. Such covert capabilities greatly reduce (and practically eliminate) the need for real-time tactical communications. Ordering a minefield on/off is relatively simple as long as delivery of short messages is reliable, thus offering numerous potential communications channels. For example, given a reliable but occasional low-capacity communications channel, command messages might merely be represented via Morse code as "ON" (dash-dash-dash, dash-dot) or "OFF" (dash-dash-dash, dot-dot-dash-dot, dot-dot-dash-dot), perhaps adding a simple day-of-the-month checksum for authentication. Delivery might occur via fiber, acoustic signal, radio-monitoring local buoy, or various other means. Three-letter trigraphs can also express a comprehensive vocabulary securely, with potential encryption. "Long" time delays (even on the order of days) to command a tactical shift in minefield modes are operationally advantageous and actually much faster than expectations, historical capabilities, or international law requirements. For naval mining, necessary communications for simple C2 are thus also simple, utterly terse, and only need to occur occasionally (Brutzman 2023, 2024). Minimalist minefield communications exemplify the principles of Network-Optional Warfare (NOW) through proper prior planning and covert stealth (Augier 2025).

e. *Minefield munitions and mine placement*. Many weapons options are possible, since separation of sensor suites from munition sets allows a mix of both simple and sophisticated hardware devices. Careful early geographic placement of triggerable munitions is a key factor for these potentially first-fired weapons. Such advanced prepositioning at forward munitions depots and allied-partner strongholds supports preparation for possible future hostilities, along with mutually advantageous shared defense strategies. If positioned carefully, even with some spatial randomness, munition placement epitomizes "fire effectively first" imperatives. Logistics for effective disposition of each weapon in a minefield also matter. The Russia-Ukraine War has shown the critical nature of resupply and logistics chains towards overall success, indeed driving the Russian Navy from the Black Sea. Meanwhile, suggested capabilities for propulsion disablers (PDs) as mine effectors can offer a nonlethal "mission kill" alternative against opponent vessels that attempt to traverse a minefield (Dismukes 2025), and vessels so stranded immediately present a stark warning against other attempts to ignore the minefield. Low-cost scalability for repeatable, attritable sustainment offers crucial advantages during long-term conflict. For example, a few weeks after the 2024 Key Bridge mishap in Baltimore, NPS students were asked to describe how many mines might be needed to threaten operations and actually close a harbor. One student officer immediately pointed out that only one mine might be necessary, if positioned in proximity to a bridge.

f. *Mining limitations and maritime context*. While active mining to shape the ocean battlespace offers multiple powerful capabilities, it is not a superweapon. During an era dominated by missile warfare (Klein 2017) (Hughes 2018), the primary limitation of minefields for friendly shipping is that they offer no direct protection to surface ships from missiles. Nevertheless, controlled denial of ocean access to missile-capable warships, and providing Q-route safety lanes for merchant shipping that is otherwise protected by anti-missile defenses, both remain relevant defenses to reduce risks from missile attack. In other words: *transit access for friendly shipping offers <u>sea control</u>, while blocked transit for hostile shipping offers <u>sea denial</u>, simultaneously*. Fine-tuning sensors and munitions so that operational minefields might also offer defensive protection against underwater and surface robots is another opportunity for further improvement. Minefield limitations can be best addressed when it is properly considered as part of a broader theater capability for littoral or open-ocean subsea warfare that, in turn, can provide a compelling expression of national determination as part of an Integrated Deterrence strategy (DoD 2022).

g. *Operational considerations by near-peer pacing threat*. Other nations do not share the relative lack of interest in mine warfare evidenced during recent decades by the U.S. Navy. The following translated quote is by a Captain in the Peoples Liberation Army Navy (PLAN).

"*Looking back at past naval battles, sea mines have a stellar record in performing blockades and countering amphibious landings. Sea mines have five main advantages:*

1) they are difficult to detect, and their attacks are invisible and sudden;

2) they are capable of autonomously biding time, waiting for the right opportunity to strike; they are a weapon of sea control; they can remain in place for long periods of time, presenting an enduring threat;

3) they are easy to deploy: naval ships, fishing vessels, merchant ships, aircraft, and submarines can all lay mines;

4) they possess comparatively strong offensive capabilities, and have the ability to serve both offensive and defensive functions;

5) they are difficult to remove/sweep; at present there is no MCM approach that can completely eliminate the threat of sea mines.

[...] *developing effective MCM remains an eternal difficulty for the navies of the world. At present, many countries have invested heavily in research on sea mines. In particular, they have pursued breakthroughs in the variety and destructiveness of sea mines. These efforts have led to the development of neural network sea mines (shenjing wangluo shuilei), program controlled sea mines (biancheng zikong shuilei), hidden missile sea mines (chenfu daodan shuilei), intelligent self-guided mines (zhineng zidao shuilei), sound-magnetic induction mines (shengci ganying shuilei), sonobuoy mines (shengna fubiao shuilei), and other highly intelligent sea mines. Their performance, destructiveness, invisibility and resistance to MCM have all reached unprecedented levels.*" (CMSI 2026)

6. **Exploitable Advantages**. Mining changes the balance between *sea control* and *sea denial*. Reshaping the ocean battlespace "changes the playing field" for maritime operations.

   a. *Split and separate sensor suites from munition sets*. Embedding impressive computational capabilities in new mines is no longer a limiting factor. Student capstone work at NPS found that commercially available cellphones (i.e. simple small computers) have more than enough computational capability for LPV and mine task requirements, and are also able to operate for long durations of time when operational-energy endurance needs are met. Indeed, deployed sonobuoys and other remote-sensor fields can apply AI/ML techniques to learn (and later determine) either IFFNU or uncommon outlier signals with high precision. Such relationships are vividly illustrated by the article "AI Surprise in the Black Ditch" (Winnefeld 2021). Minefield alertment and triggering via alternative Maritime Domain Awareness (MDA) sensor networks further diversifies the wide range of sources for ocean-going ship information that can credibly be composed and analyzed together. An essential design principle for robotics is that when a necessary capability cannot be easily engineered into a robot, then it might be possible to "engineer the environment" instead. Shaping the robotic battlespace with mining also shapes the operational environment.

   b. *Treat friends differently than foes*. Current Naval mines are typically the dumbest robots on the planet, computationally less capable than an automated home vacuum cleaner. Simply adding remote "on/off" (enable/disable) controllability is sufficient to throttle lethality for mission requirements during conflict, also meeting legal requirements for Rules of Engagement (ROE) in the maritime commons. Similarly, adding simple IFFNU discernment allows friendly commerce to continue with confidence while placing opponent assets at risk. Blue force tracking and transponders capable of responding to interrogation signals with time-varying identification passcodes can provide further protections for friendly assets. All of these factors support internationally agreed-upon Laws of Armed Conflict (LOAC), thus adding further long-term reinforcement for allied resolve to maintain stable international economic trade. Empowering national and coalition decision makers to be fully "in charge" of minefield activation (and neutralization) fundamentally changes the balance between international economic competition and extended Naval conflict.

   c. *Put time on our side*. Mines are "weapons that wait" (Hartmann, Truver 1991) and thus naval mining is a "long game" enabler. Given that minefields are a hidden threat, always difficult to detect and clear, impacts from a small set of mines can be similar to a large set. Opponents must pause when facing economic risks and opportunity costs due to lost commerce, or operational risks of dangerous transit through harbors and choke points. Longer time frames for transit and delivery of weapon assets are not an impediment for sustained emplacement. Such delays might even be irrelevant if mine assets are already staged forward with allied partners, or when a deployment surge is ongoing (perhaps as periodic minefield replenishment). Similarly, several-day delays to arm or disarm actually emphasizes the power of minefields to ***deter***, ***de-escalate***, and ***defeat***, thus "reshaping the battlespace" over a progression of hostilities while Naval forces defend national objectives.

d. *Playing the long game*. Using a split design for sensor suites and mission sets, a distributed minefield operating with loosely coupled communications has significantly greater operational usefulness than a classic minefield. Over long periods of time it can act either as a sensing system, a weapons system, or both. Preprogrammed sensor abilities can share simple lines of bearing and proximity information that creates a "spiders web" to entrap moving targets, whose own motion actually creates high-probability targeting opportunities and reduces the need for weapon travel. Covert high data-rate connections via optical fiber signaling, across a local sensor suite, can permit an additional processor to compute acoustic beam-forming analysis for greater detection ranges, even aggregating "signs of life" classification and traffic patterns over time. Curiously, longer time delays and operating intervals have some resemblance to the effects afforded by swarm robotics, replacing distance with time. Minefields avoid a swarm's need for long-range travel to achieve concentration, instead laying in wait for the right moment to "fire effectively first."

e. *Outsized effect on adversaries and allies*. Connecting far-broader sensor networks to a single minefield, and considering alternate payloads for mine munitions themselves, offers naval capabilities with a much larger geographic span than the local in-water footprint. Meanwhile operational influences and impacts remain profound. For example, the detonation of a single covert mine might cause a "hard kill." Then, the overt potential presence of additional covert mines can cause a "mission kill" for opponents by deterring port egress/ingress, depleting multiple adversary resources, and even imposing strategic uncertainty as potential psychological warfare. Such uncertainty is amplified by coincidental unrelated events and misinformation. Depletion of opponent resources continues as hostile minefield boundaries are searched. Second-order and third-order reactions might even reshape the perceived battlespace more than the original minefield itself. The influence and impact of all these variations is further multiplied by (covert) IFFNU discrimination and (overt) safe transit of friendly forces throughout.

f. *Navy Force Design considerations*. Currently the Navy and Marine Corps are considering fundamental refactorings of future force design for effective fleet composition of ships, aircraft, submarines, and robots (Kline 2017) (Vandenengel 2023). Emphasis on weapons production, logistics, deployment and delivery is the primary imperative driving force design (Vandenengel 2025a, 2025b) (Hamblet 2025). Hybrid fleet concepts are exploring how lower-cost ships, in combination with a wide range of missiles and other robots, might change both sustainability and combat effectiveness of U.S. force structure. Interestingly, opportunities arise beyond simple cost-ratio optimizations to permit rethinking the larger problem space as well. Mine warfare has potential for profound influence on multiple-year efforts to achieve a balanced, effective, and dominant posture for U.S. and allied Naval forces. Significant robot impact has already been observed in wargames, especially when force-on-force engagements might persist, shifting from short-lived local weapons exchanges to sustained wars of attrition. The "long game" must always be considered when any hostilities occur, since termination of wartime conflict is never guaranteed – "the opponent gets a vote" for when that happens.

g. *USMC Force Design considerations*. Navy and Marine Corps force design is intertwined. (USMC 2024) reports *"Strategic guidance calls for a Marine Corps able to survive and thrive inside contested spaces. Developed concepts are tested through experimentation and wargaming. Integrated planning teams study and analyze the concepts for validation and refinement."* Baseline USMC force-design system inventories already include multiple robots such as the Autonomous Low-Profile Vessel (ALPV), the semiautonomous LRUSV, seven unmanned air systems (UAS), and three different mobile anti-air missile launchers. Quick-response Marine Littoral Regiment (MLR) organization includes combat and logistics teams to control such systems during expeditionary operations. ALPVs can supply mining defenses to confront approaching USV/UUVs and surface ships. Thus USMC minefields can feasibly create expeditionary havens that reshape the battlespace and strengthen lethality.

h. Consider OODA loops at every level. Perfect comprehensive monolithic systems are not needed in advance when sensor suites and munition sets can each be augmented in tandem. Taking a rapid-acquisition approach towards building a Minimum Viable Product (MVP) can support two-track development of diverse components without wasted effort. Field experimentation and learning from any failures leads to continuous improvement. As John Boyd repeatedly demonstrated, apparent "failures" actually offer lessons learned and potentially rapid improvement when responsive Observe Orient Decide Act (OODA) loops are achieved (Coram 2004). The simplicity of this approach offers maximum operational flexibility. Reshaping the ocean battlespace using minefields can thus be steered and adjusted to achieve evolving national military and diplomatic objectives. When real-world presence of a minefield is initially revealed (or triggered), the individual weapons composing a minefield nevertheless remain clandestine. Thus the scope of minefield effectiveness is limited only by the opponent's imagination and uncertainty. Such battlespace-shaping effects also present allied partners with major opportunities to compatibly contribute remote-sensing contact reports, or even further defensive/offensive minefield activations, for shared asymmetric advantages.

i. *Minefield detonations as combat sensors*. Explosions from active mines that detonate in response to opponent activity provide immediate sensor alertment to friendly forces in the region, without requiring explicit communication links. Such events are underwater "bell ringers" that an operational flank or back-door barrier is being breached. Remote mine detonation can be accompanied by a minefield's sensor suite overtly transmitting a notification message that provides classification details about the attacked target, without loss of covertness for other nearby systems. Damaged ships that avoid sinking provide further opportunities for targeting, seizure, or rescue responses as the ongoing tactical situation unfolds. Attacked ships that avoid damage and retain mobility unavoidably provide widely communicated evidence regarding minefield system effectiveness to friendly forces. Minefield detonations can thus provide an important addition to battlespace awareness, illustrating further potential roles for in-theater operations.

j. *Information Operations (IO)*. The existence, boundaries, density, and likely lethality of any minefield together provoke great uncertainty among adversaries, neutral shipping, economic markets, and even friendly forces. As a consequence, Naval mining emphatically reshapes the information battlespace as well as the ocean battlespace. A credibly declared minefield does not even have to physically exist to have a major impact. Such characteristics correspond directly to concepts integral to Information Operations: public or private sharing of ***valid information***, sharing misleading mistaken ***misinformation***, and disseminating deliberately deceptive ***disinformation***. Perhaps surprisingly, such operations are typically associated with cyber or political activity, and only rarely with maritime defense (Demchak 2025). If Naval forces have a known capability to deploy active minefields, then naval mining provides a potentially kinetic enabler for executing effective information operations afloat and abroad. Information operations based on minefield operations offers new lines of attack and defense for Naval forces and national leadership.

- **Navy**. "Information dominance is the key enabler in this new form of maneuver warfare, by which we confound the adversary's ability to find, fix, and attack our forces." [...] "We continue to innovate with robotic and autonomous warfare and expand our Information Warfare capabilities to ensure decision advantage." (Franchetti 2024)
- **USMC**. "*Influence capabilities and activities.* Power is the capacity or ability to direct or influence the behavior of others or the course of events. The relationship between informational power and physical combat power is such that the commander combines both forms of power to influence relevant actors (enemy, friendly, adversary, neutral), shape the environment, gain advantage, or defeat enemies in battle. The commander uses all available means to implement influencing behavior." (USMC MCWP 8-10)

k. *Clearing the minefield promptly, on command*. "Self-destruct" is a useful third command for the minefield C2 repertoire, and implementation is technically similar to support for on/off commands. Given the simple autonomy capabilities of each mine, each mine in a minefield can be required to individually respond by reporting time of message receipt, and confirming planned time for expected self-detonation. Later fail-safe fallback reporting of failure to self-destruct is also possible, building confidence in minefield clearance and alerting allied forces if follow-up actions are needed. Such simple design requirements greatly facilitate deliberately controlled minefield destruction. This avoids the necessity for dangerous, costly, complex, and time-consuming Mine Countermeasures (MCM) clearance once minefield operations are complete. Once again, simple C2 and elementary "smart robot" design offers new and powerful asymmetric advantages for active mining.

l. *Hardware endurance*. The ocean environment is harsh and unforgiving. Achieving deterrence, de-escalation and defeat capabilities over the longer operational time frames envisioned here will require ocean-going systems that are resistant to corrosion, wide ranges of temperature, bio-fouling, persistent wave action, entanglement, and other environmental factors. Applied engineering work that selects appropriate materials and construction will be necessary to ensure reliability and avoidance of degradation. Much current work demonstrating battery capacity and hardware robustness for maritime robots can streamline rapid, scalable and low-cost improvements for mine design and production.

7. **Proposed approach for continued work: minefield simulation and analysis**

It is important to realize that missiles, underwater mines, drones and even satellites are robots. Different ways of thinking about future Naval operations are needed. In order for Naval leaders, academics, and strategists to harness mining imperatives effectively, an open-source analytic simulation tool is needed which can quantitatively ground an ongoing campaign of design studies, analysis, and discussions. Sustained efforts in applied research by Naval Postgraduate School (NPS) faculty, working together with warfare-qualified graduate and doctoral students, has repeatedly demonstrated how dedicated multinational efforts can build long-term Decision Advantage for future leaders (Rondeau 2022).

Qualitative, ungrounded opinions about minefield effectiveness offer questionable credibility when long-duration quantitative analysis can be performed. Prior design work shows that comprehensive simulation software supporting careful analytic study of these many imperatives is possible (Brutzman 2023). A broad and detailed description follows for design goals and feature requirements in such a tool suite.

a. Facing forward: discouraging opponents

- Although the U.S. Navy has been intensely focused on mine countermeasure (MCM) clearance challenges over recent decades, the fact that such serious mining difficulties might be similarly applied against opponents is rarely considered or acted upon.
- Mining capabilities are already available for many nations, both friendly and hostile. These potential impacts and implications need to be considered in partnership with allies (such as NPS officer students) in order in order to avoid *asymmetric disadvantage*.
- Separating sensor suites and munition sets actually changes the nature of a minefield.
- Simple (yet diverse) robotic sensors and munitions provide inexpensive asymmetric advantages that are economically repeatable, scalable, and attritable.
- Terse, occasional, limited communications requirements for minefield C2 epitomizes the additional combat power possible with Network Optional Warfare (NOW) despite maintaining presence in denied, contested, and distant operating areas.
- Mining requires no human presence for deployment, operations, or neutralization. Simple robotic systems (sensor suites and munition sets) can be controlled at a distance to perform dull, dirty, dangerous work while human operators (and critical platforms) remain well removed at a safe distance.
- Mining concepts might provide focused purpose across a spectrum of emerging Naval capabilities in robotics, sensors, munitions to support both *sea control* and *sea denial*.
- While the rate of technological change continues increasing more than ever before, actionable capabilities are now available that can change the operational playing field.
- Guided by dominant historical successes and emerging scalable capabilities, such work can take a fresh look at how mining can reshape the contours of the battlespace.
- Workshop scenarios, field experimentation, and at-sea exercises with international participation can directly illustrate the potential relevance and utility of minefields that address combined combatant commander requirements.

b. Analytic enablers: intellectual advantages

- Massive improvements in structured data collection that is analyzed by computationally powerful processing chains can significantly improve upon classic probability studies that are predicated on the effectiveness of simple single-sensor mines in a minefield.
- The reference text *Naval Operations Analysis (NOA)* includes open-source equations and methodology suitable for establishing a codebase with parameterizable settings (Wagner 1999). Separating sensitive parameter values from software that implements openly published mining-assessment algorithms offers a path for international partners to compatibly collaborate intellectually.
- Publicly available software assets originating at NPS include open-source software tools using open data standards that produce data-driven modeling and simulation (M&S) environments. These are suitable for methodical analytics and Extensible 3D (X3D) graphics visualization (Brutzman 2007) (Web3D 2026). Hybrid simulation is possible though rehearsal, real-time or replay data channels for shared state information using the Distributed Interactive Simulation (DIS) Protocol (IEEE 2012).
- NPS experience conducting robotic Field Experimentation (FX) has shown the value of producing repeatable comparable data archives that capture key capabilities, eventually becoming suitable for Live Virtual Constructive (LVC) synthesis and digital-twin comparison. Work carefully conducted in a cross-disciplinary graduate-education context found at NPS is a major capability multiplier.
- Security classification levels are ordinarily determined by real-world operations and scenarios, as well as by actual sensor/munition capabilities. Security classification *per se* rarely arises from the basic nature of the geometric relationships between long-running sensor detections, target motion analysis (TMA), and minefield munition detonations. For example, *Naval Operations Analysis* (Wagner 1999) defines the essential algorithmic relationships needed for straightforward minefield simulation in this context, and has been openly published for a quarter century... such long-available fundamental relationships simply cannot be suddenly classified.
- Unrestricted, sensitive and classified sets of parameter values can each be securely and compatibly stored as independently loaded configuration files, rather than as shared source code. This approach emphasizes the building of sharable understanding while safeguarding information assets holding special interest for each stakeholder.
- Basic, representative exemplar scenarios to establish sharable software capabilities can be parameterized at the unclassified level (using open-source public data) as preliminary proxies for more advanced, militarily sensitive scenarios. Access and classification restrictions must be carefully observed throughout. We expect that principal actors for such analysis can consider scenarios with varying sensitivity restrictions that are also suitable for shared work with international partners.
- The Modular Open Systems Approach (MOSA) offers a technology-business framework that can define requirements for sensing, munitions, communication, coordination, etc. MOSA principles for system engineering of connections between diverse components can help model an evolutionary minefield architecture, enabling many stakeholders in U.S. and allied industrial bases to coherently co-evolve over the long term. (DLA 2026)

c. Reinforcing continued applied research with top-level Naval imperatives (and vice versa)

Once started, a progressively improving software codebase can implement analysis-group products to facilitate ongoing research, helping to generate multiple data products and reports.

- A fresh look based on first principles of naval warfighting, along with a broader strategic perspective for challenged peacetime protection of allied commerce, offers potential for repeatable M+S that complements existing (typically classified) analytic tools.
- Considering theater-wide naval mining that includes sea lines of commerce and communications (SLOCs), harbors, choke points, safety lanes, and expeditionary operations is likely to offer new opportunities for coalition subsea seabed defense.
- Utilizing open-source data as simulation-metadata properties means that all assumptions are traceable, all model variations can be carefully compared, and all simulation anomalies can be repeatably examined (and deliberately resolved).
- Formalize and publish the data model for parameters of interest, facilitating simulator adaptation and unlocking numeric outputs by spreadsheets (or alternative ad hoc programs) that can apply consistent identifiers and reference units for compatible utilization. Quality assurance (QA) filters can then ensure that such external products generate valid, useful products that avoid "Garbage In Garbage Out (GIGO)" syndrome.
- Having reusable data models and training datasets with well-defined terms of reference can accelerate analyst progress, allowing design-thinking projects and simulation experimentation to repeatably tackle problems of interest for longer-term progress… in effect, performing ***analytic campaigning*.**
- NPS assessment efforts can use the annual Joint Campaign Analysis, C2 and other capstone classes, annual Warfare Integration Continuum (WIC) theming, regularly recurring workshops, master's theses, and possible wargame integration. Given the broad applicability of Naval mining, we expect interest from thesis students serving in multiple warfare communities.
- As new best practices begin to mature, further work might adapt portions of the software suite as a decision aid for exploration of Concepts of Operations (CONOPS) and Concepts of Employment (CONEMPS) using representative exemplars of interest.
- Drafting an actionable Navy/USMC Mine Warfare Roadmap that is fully sharable with industry might chart how the strengths and expertise of numerous relevant actors might be coordinated to good effect, in order to deliberately execute such a broad strategy. An analytically grounded roadmap might also crisply capture long-standing uncertainties as solvable problems (rather than perpetually unaddressed conundrums) to stimulate effective cooperation among many stakeholders.
- Understanding and insight improve as computational rigor is repeatedly applied to a steadily growing set of both simple and critical operational problems in naval affairs.

d. Enabling deliberate understanding and execution of potential paths forward

U.S. Navy thinking and action needs to get ahead of these multiple overlapping trends. Modeling and simulation can provide new perspectives for planning and operational effectiveness. Comprehensive approaches are possible that rebalance fleet capabilities within an ocean battlespace that is reshaped by controlled mining.

An open-source modeling and simulation software tool, configured using scenario-description files of varying sensitivity, can integrate and accelerate analytic understanding in a manner that is both sharable and actionable by U.S. services and allied partners alike.

8. Conclusions and Recommendations

Using "weapons that wait" with modern robotics capabilities, split sensors and munitions design, and minefield-wide C2 commands for on/off/disarm, it is now clear that mine warfare can reshape the future ocean battlespace to "attack effectively first" in extended Naval conflict.

Treating mines as robots, and minefields as systems, can provide leadership with new options. Deployment of active minefields that include simple C2 for on/off/disablement also addresses reasonable concerns about placing munitions that later might be difficult to clear.
A progressive approach to deterrence, deescalation and defeat of opponents, exercised as needed during prolonged conflict through deliberate controlled mining, actually reinforces widely shared imperatives for allied defense and dependable international commerce.

Elevating active mine warfare exactly matches Hedge Strategy objectives for Naval power. Further work on simulation-driven analytics for the quantitative study of maritime mining can propel greater understanding that also grows the Naval order of battle for allied armaments. Aligning current work on acquisition, force structure and robots is easily applied to mines.

Reshaping the ocean battlespace to dynamically rebalance *sea control* and *sea denial* through mine warfare amplifies all other Naval capabilities. Active naval mining fully supports perennial global challenges for great-power conflict resolution and unrestricted maritime commerce.

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