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Integrating Systems Methodologies for Australian Undersea Surveillance: A Systematic Literature Review

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ABSTRACT

Australia is a maritime nation, relying on access to its surrounding oceans for its economy and security. The Royal Australian Navy conducts undersea surveillance to monitor this vital maritime environment and gain insight into activities beneath the ocean's surface. Australia's maritime jurisdiction is vast, with the world's third-largest Economic Exclusion Zone, but its resources are constrained, with only 5% of the United States' defense budget and navy personnel. Fortunately, advancements in unmanned vehicles and networked sensors can address this disparity by increasing the capacity of Australia's naval fleet at a fraction of the cost of manned platforms. However, current applications of unmanned systems only address simplified scenarios without defining how the plethora of unmanned systems should be applied across the full spectrum of surveillance operations. A new naval fleet architecture must be designed using systems methodologies to integrate unmanned systems into this holistic "system of systems". Systems engineering, systems architecture, system modeling, system dynamics, operations research, and design for Six Sigma are complementary methodologies with unique techniques to solve this complex problem. This systematic literature review critically analyzed current unmanned systems and the utility of systems methodologies to design their application in undersea surveillance. It contributes insights into the benefits and challenges of unmanned systems in Australia's maritime context, whilst demonstrating shortcomings with the currently disparate application of methodologies to design unmanned fleet architectures. Further research is justified to design an integrated framework of systems methodologies that designs fleet architectures for Australian undersea surveillance.

1 | Introduction

Australia is a maritime nation, relying on access to its surrounding oceans for its economy and security. Sea transport accounts for 99% of Australia's trade by volume, including over $600 billion of imports and exports from 2017 to 2019 [1]. Australia's economy, security, and sovereignty depend on sea lines of communication (shipping lanes) extending from Australia's borders into international waters and beyond. Additionally, Australia depends on critical infrastructure within the maritime environment, including local assets such as ports and oil rigs, and international assets such as undersea cables for global connectivity. Whilst space-based satellite communication provides an alternate communications mechanism, undersea cables account for 97% of the world's data traffic [2].

Thus, Australia has a vested interest in monitoring and protecting this vital maritime environment, including areas that

Summary

- This work is a review article of systems methodologies in designing fleet architectures for undersea surveillance.
- It provides justification for continuing research into integrating systems methodologies for the Royal Australian Navy as it pivots to a fleet architecture incorporating unmanned systems. Designing a fleet architecture for this real-world application is a complex "system of systems" problem.
- Current literature does not address the compounding complexity of physics-based constraints combined with the dynamic surveillance needs, budget and resource constraints, and new technology adoption evidenced in the Australian context.
- This systematic literature review assesses the complementary characteristics of different systems methodologies and the benefits of designing an integrated framework, thereby shaping avenues of further research.

may be prone to piracy, terrorism, and access denial by state and nonstate actors. Maritime surveillance provides persistent situational awareness to deter (and, if needed, respond to) events that could adversely impact Australia's security, safety, economy, or environment. Undersea surveillance is a subset of maritime surveillance, providing insight into activity below the ocean's surface. Undersea surveillance can yield more extensive intelligence than surveillance performed at the surface but is significantly more challenging due to the underwater environment, where sensor detection methods are more complex and communications are limited. The Australian Department of Defence [3] has emphasized the importance of undersea capabilities for safeguarding Australia's maritime approaches and sea lines of communication, prioritizing investment in persistent undersea surveillance.

The national importance of undersea surveillance is evident; however, Australia's maritime jurisdiction is vast. Australia's Exclusive Economic Zone (EEZ) encompasses approximately 10 million square kilometers, extending up to 200 nautical miles from the continent, offshore territories, and the Australian Antarctic Territory [4, 5]. Nevertheless, given the end-to-end, intercontinental connectivity required for shipping lanes and submarine cables, Australia's interests in undersea surveillance extend well beyond its own waters. Furthermore, as an original signatory to the International Convention for the Saving of Life at Sea (SOLAS) 1974, Australia has Maritime Search and Rescue responsibilities for a region of approximately 45 million square kilometers or roughly one-tenth of the Earth's surface [6, 7]. Within this region, Australia's search and rescue authorities have rescued an average of 2000 people per year across a range of environments [8]. Evidently, the breadth of coverage for Australia's maritime surveillance is immense, with significant contributions from undersea surveillance.

The Royal Australian Navy (RAN) is Australia's primary organization responsible for undersea surveillance. Like most other navies, the RAN has traditionally conducted undersea surveillance through crewed platforms such as submarines, surface ships, anti-submarine helicopters, and maritime patrol aircraft [9]. However, these expensive and heavily manned platforms are limited in quantity and cannot readily scale to cover the extent of the maritime environment [10]. This challenge is further compounded for the RAN, as its fleet is relatively small compared to nations of similar geographic size. For example, the USA has a total EEZ area of roughly 11.3 million square kilometers, and the US Navy boasts a battle force fleet size of approximately 297 ships with 330,000 personnel [11]. In contrast, for Australia's similar-sized EEZ, the RAN has a total fleet of only 46 ships with 16,000 personnel [9]. With limited resources to address such an extensive maritime environment, the RAN is forced to do "more with less".

Fortunately, modern technological advancements in unmanned systems and the proliferation of unmanned vehicles (UxVs) across a spectrum of applications [12–14] offer a paradigm shift in addressing the challenges of undersea surveillance. This disruptive technology provides an opportunity to supplement the existing RAN fleet with a step-change in capability and capacity (quantity). Whereas crewed platforms, such as submarines, can leverage their highly skilled crews to perform cognitive-intensive and targeted tasks, their unmanned counterparts can provide inexpensive capacity at scale and may be expendable to keep defense personnel out of harm's way.

Recent research [10, 15] acknowledges the necessity of a mix of both crewed platforms and unmanned systems will be required to realize the undersea surveillance capabilities essential for modern navies. As we stand at this turning point in adopting unmanned technologies, the challenge remains in designing a valid fleet architecture for the RAN. A fleet architecture is the foundational design of the navy's fleet to fulfill its operational goals. It encompasses the fleet structure with its composition of assets (including vehicles, sensors, and personnel), the behavior of the fleet and its interaction with the external environment, and performance characteristics with associated design constraints.

Determining the mix of unmanned and manned systems within the navy's fleet architecture is a complex "System of Systems" problem, requiring engineering methodologies that can address multiple, often competing, dimensions of the need. Whilst a system comprises numerous interconnected elements in a unified whole, a system of systems is far more complex, as it consists of multiple systems working together to achieve a common purpose. There are many systems methodologies well-suited to tackling this class of complex problems [16], including systems thinking and the related disciplines of systems engineering, systems architecture, systems modeling, system dynamics, operations research (OR), and design for Six Sigma. Arnold and Wade [17] define systems thinking as "a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects." Existing literature uncovers the current application of these methodologies to elements of the undersea surveillance domain, such as UxV routing, sensor placement, and design of individual platforms.

Nevertheless, the literature has yet to prove the merits of applying systems methodologies to the holistic problem of fleet architecture design. There are gaps in the current research where individual methods are applied disparately without realizing their complementary benefits. Additionally, the existing research only addresses individual elements of undersea surveillance without improving the overall system-of-systems fleet architecture. The systematic literature review described in this article critiques the existing body of knowledge in the domains of undersea surveillance, unmanned systems, and systems methodologies for application in the Australian maritime environment. In doing so, this article identifies gaps in the literature and demonstrates that further research is required to develop an integrated framework of systems methodologies to design fleet architectures for undersea surveillance, leveraging modern advancements in unmanned systems.

1.1 | Existing Literature

To inform this literature review, we initially conducted a systematic search for relevant literature using "Web of Science" and "Scopus" databases. The search results were then filtered to a primary set of scholarly, peer-reviewed publications relevant to this topic. Table 1 summarizes the search parameters and corresponding literature yield from this initial search of the databases. Applicable literature in the search results was identified based on relevancy to the research topic, journal metrics, and quantity of citations. When the applicable literature referenced additional important literature, we searched for specific titles and authors in the databases. If the literature could not be found in the primary databases, a secondary search was conducted using "Google Scholar" and "ProQuest", and applicable standards and textbooks were located. While the primary search focused on publications from the last five years to ensure they reflected the current knowledge, some secondary literature (often foundational materials and highly cited papers) was 10–20 years old. In addition to the scholarly literature, we supplemented our literature review with Australian, US, and UK Government publications sourced from government websites, including the Australian Department of Defence website and the US Congressional Research Service website. These government publications contribute essential context for understanding current needs, plans and budgets for Australian undersea surveillance, as well as recent trends by the US Navy, an early adopter of unmanned systems. A total of 128[1] relevant pieces of literature informed this literature review and the distribution of sources is summarized in Figure 1.

1.2 | Contributions

This article introduces a systematic approach to designing a new naval fleet architecture that integrates unmanned systems specifically for Australia's undersea surveillance needs. Unlike previous research, which often applies unmanned systems to simplified scenarios, this paper uniquely identifies the challenge of applying a diverse array of UxVs and networked sensors across the full scope of surveillance operations. By using a combination of systems methodologies, the study moves beyond traditional approaches and lays the foundation for a "system of systems" architecture tailored to Australia's unique maritime and resource constraints.

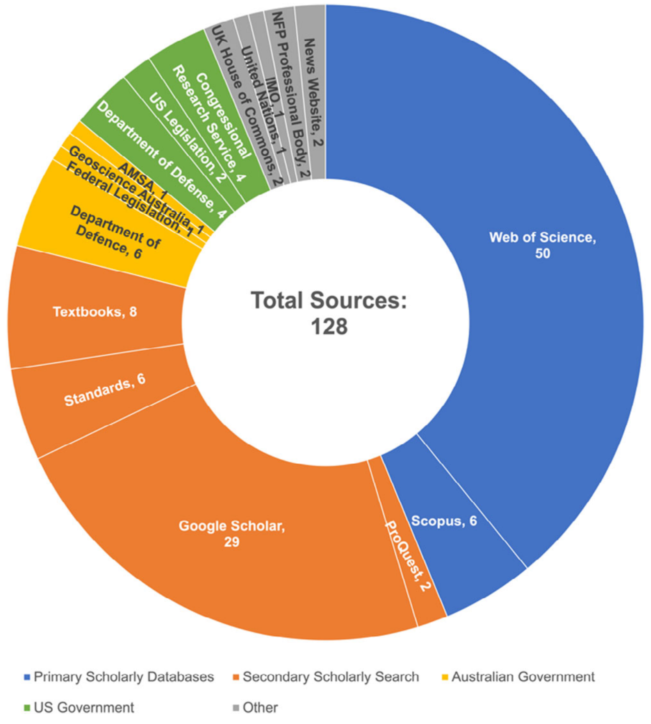

FIGURE 1 | Literature sources.

The main contribution of this paper is a critical analysis of current unmanned systems and the potential of various systems methodologies in designing undersea surveillance fleet architectures. The paper provides valuable insights into the operational benefits and limitations of unmanned systems in Australia's maritime domain, highlighting gaps in current methodologies and the need for an integrated framework to achieve a cohesive and efficient fleet architecture. This work offers a pathway to future research aimed at creating a robust, cost-effective undersea surveillance system that enhances Australia's defense capabilities within its vast maritime jurisdiction.

This article is structured as follows. Section 2 further details the critical need for undersea surveillance by exploring the literature, including recent government publications. Section 3 outlines the application of unmanned systems for undersea surveillance and analyses the foundational technology benefits, constraints, characteristics, and gaps in the literature. Section 4 explores systems methodologies for designing a solution and identifies current gaps in their existing application. Finally, Section 5 summarizes the remaining open problems stemming from gaps in the literature and discusses how further research in this domain should address them.

2 | Australian Undersea Surveillance

Understanding the Australian context for undersea surveillance is an important dimension of this literature review, as it informs research application. Australia's extensive surveillance coverage, coupled with its limited resources, adds a unique dimension of complexity in designing a valid fleet architecture for the RAN. Whilst the physics of undersea surveillance techniques is universal, consideration of Australia's needs and constraints

TABLE 1 | Initial literature search parameters.

Database	Search terms	Date range	Literature yield
Web of Science	navy surveillance unmanned systems	Last 5 Years	10 articles, 1 relevant
Web of Science	undersea survaillance unmanned systems	Last 5 Years	3 articles, 0 relevant
Web of Science	undersea surveillance	Last 5 Years	24 articles, 3 relevant
Web of Science	"systems engineering" AND "operations Research"	Last 5 Years	30 articles, 5 relevant
Web of Science	"system architecture" AND "operations research"	Last 5 Years	3 articles, 0 relevant
Web of Science	"systems architecture" AND "operations research"	Last 5 Years	0 articles
Web of Science	navy AND "fleet mix"	Last 5 Years	0 articles
Web of Science	navy AND "fleet Mix"	Any	1 article, 1 relevant
Web of Science	anti submarine warfare	Last 5 Years	51 articles, 7 relevant
Web of Science	underwater surveillance	Last 5 Years	354 articles (too broad)
Web of Science	"underwater surveillance" AND "navy"	Last 5 Years	5 articles, 1 relevant
Web of Science	"underwater surveillance" AND "systems engineering"	Last 5 Years	0 articles
Web of Science	"underwater surveillance" AND "unmanned"	Last 5 Years	44 articles, 10 relevant
Web of Science	"systems thinking"	Last 5 Years	2470 articles (too broad)
Web of Science	"systems thinking" AND "navy"	Last 5 Years	3 articles, 1 relevant
Web of Science	"systems thinking" AND ("unmanned" OR "autonomous")	Last 5 Years	22 articles, 1 relevant
Web of Science	"systems thinking" AND ("underwater" OR "undersea") AND "surveillance"	Last 5 Years	0 articles
Web of Science	"systems thinking" AND "underwater"	Last 5 Years	2 articles, 1 relevant
Web of Science	Australia AND "underwater surveillence"	Last 5 Years	2 articles, 0 relevant
Scopus	navy AND surveillance AND unmanned	Last 5 Years	13 articles, 2 relevant
Scopus	navy AND surveillance AND underwater	Last 5 Years	8 articles, 2 relevant
Scopus	navy AND "fleet mix"	Last 5 Years	1 article, 1 relevant
Scopus	navy AND "fleet architecture"	Last 5 Years	4 articles, 2 relevant

shape the complex "system of systems" problem and thereby inform the selection of technology and fleet design techniques in later sections of this article.

In 2020, the Australian Government publicized the vital importance of maritime and undersea surveillance, stating, "Protecting Australia's large EEZ requires an understanding of the maritime environment under our control, sustained presence, and adapting to new technological developments that could increasingly complicate our ability to keep Australian interests safe in the Maritime domain" [3]. To support this need, the Force Structure Plan 2020 [3] proceeded to commit $7.4 billion to develop an

Integrated Undersea Surveillance System. More recently, the Defence Strategic Review [18] reinforced this need by describing the deteriorating geopolitical environment throughout the Indo-Pacific with a further decline since 2020. This regional instability includes the proliferation of “gray-zone” tactics; a reduction in the warning period for military conflict; military modernization and expansion by other regional countries; and increasing climate change escalating the risk of environmental disasters. Clearly, the demand for undersea surveillance throughout the Indo-Pacific is on the rise. The Defence Strategic Review reinforces the criticality of “undersea warfare capabilities (crewed and uncrewed) optimized for persistent, long-range subsurface intelligence, surveillance and reconnaissance (ISR) and strike”.

Nevertheless, the need for undersea surveillance in the Indo-Pacific region is not unique to Australia. Other nations, such as the USA, are also responding to the geopolitical situation in the Indo-Pacific, including by investing in improved undersea surveillance capabilities. A recent report by the US Congressional Research Service [11] presented the need for a greater naval presence in the Indo-Pacific due to China’s military modernization efforts. The report claimed that China’s military modernization aims to assert a greater degree of control in the South China Sea and potentially implement anti-access/area-denial (A2/AD) measures in the region. The analysis contained in the report asserted that China now boasts the World’s largest navy, with a battle force of approximately 340 platforms, surpassing the US Navy sometime between 2015 and 2020. In response, the US Navy is shifting a greater percentage of its fleet to the Pacific to maintain an increased operational presence. O’Rourke [11] connects the geopolitical situation with the US Navy’s shift to a distributed fleet architecture using UxVs.

Whilst undersea surveillance is a capability in itself for addressing the geopolitical environment, it is also an enabler for various naval missions applied in a variety of operations. Existing research reports and their associated literature reviews [15, 19–21] revealed a vast range of naval operations supported by undersea surveillance. These operations are synthesized into the following list:

1. Combat operations, including:
   a. Intelligence, Surveillance, Reconnaissance (ISR);
   b. Anti-Submarine Warfare (ASW);
   c. Anti-Surface Warfare (ASuW);
   d. Mine Warfare and Mine Counter Measures (MCM);
2. Protection of sea lines of communication, including the assurance of maritime trade, protection of merchant shipping and anti-piracy;
3. Protection of maritime infrastructure, including undersea cables and offshore oil and gas rigs;
4. Monitoring of ports, harbors, and maritime borders;
5. Maritime search and rescue;
6. Humanitarian and natural disaster response;
7. Environment and resource protection;
8. Oceanography.

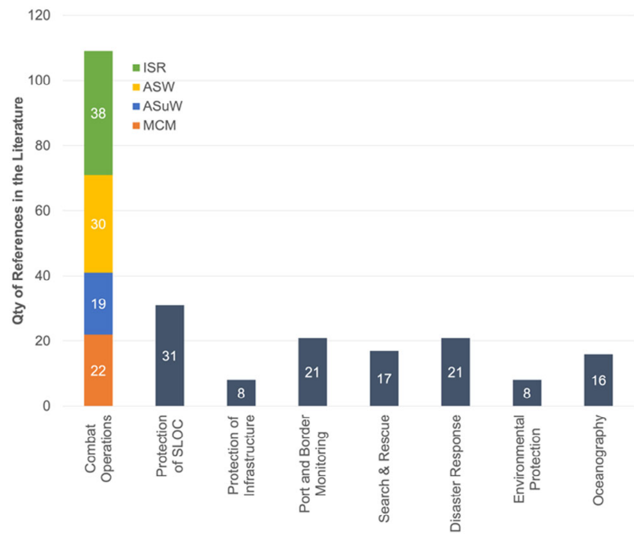

FIGURE 2 | References to undersea surveillance operations.

Figure 2 presents the quantity of literature in this review that identified each naval operation supported by undersea surveillance. Although the majority of the literature focused on support for combat operations, particularly ISR and ASW, there are also numerous references to other naval operations.

Although the purpose of undersea surveillance for these types of operations is similar to that of other nations, Australia’s area of interest for undersea surveillance is unique. Australia’s area of interest encompasses its ports, harbors, and coastline, expanding into its sovereign Economic Exclusion Zone and stretching further into its Maritime Search and Rescue region. Beyond Australia’s jurisdiction, surveillance is required in international waters to maintain security and accessibility. In order to accommodate this varying scale of surveillance, undersea surveillance is categorized as follows:

1. Local surveillance, performed in nearby regions such as Australia’s coastal waters.
2. Remote surveillance, performed at locations away from territorial waters and isolated from fixed infrastructure, such as in international waters.
3. Wide-area surveillance, performed over a significantly larger region, generally in the Open Ocean.
4. Integrated undersea surveillance, including all the above categories and may be undertaken simultaneously. Integrated undersea surveillance can only be managed at a fleet level by allocating surveillance assets to dynamic locations of need.

Australia has a substantially smaller budget to invest in undersea surveillance capabilities when compared to other allied nations. Australia’s FY24 defense budget of AU$52 billion [22] is roughly half of the UK’s FY24 defense budget of GB£54 billion (AU$101 billion) [23] and is merely 5% of the US FY24 defense budget of US$842 billion (AU$1.24 trillion) [24].

Guided by recurring themes in the literature, such as operational requirements, geographic considerations, and budgetary constraints, we have identified the following quality attributes as derived "measures of goodness" for Australian undersea surveillance:

1. *Scale* of coverage area over which surveillance is conducted;
2. *Persistence* or duration for which the required surveillance is uninterrupted;
3. *Cost* of procurement and operation of the capability;
4. *Performance* including accuracy and effectiveness of the capability;
5. *Availability* and resilience of the capability's effect; and
6. *Flexibility* and modifiability of capability to adapt to evolving needs.

Ultimately, Australia's future fleet architecture must provide value for money for conducting undersea surveillance. Value for money is identified in the Defence Capability Manual [25] as the government's core rule when procuring new defense systems. In the context of candidate RAN fleet architectures, value for money can be evaluated by comparing the above quality attributes to annual procurement and operations costs.

3 | Unmanned Systems

3.1 | Unmanned Systems in the Literature

Unmanned systems are a disruptive technology for undersea surveillance, providing asymmetrical capabilities at a fraction of the cost of traditional crewed naval platforms. Many nations are recognizing the significance of this technology and investing substantially in research and development for their navies. In FY23 alone, the US Government budgeted US$550 million for the development of just three variants of UxVs [26–28]: the Large Unmanned Surface Vehicle (LUSV); Medium Unmanned Surface Vehicle (MUSV); and Extra-Large Unmanned Undersea Vehicle (XLUUV). Similarly, Pillar 2 of AUKUS (the defense and security partnership between Australia, the United Kingdom, and the United States) includes an advanced capability workstream for autonomous underwater vehicles, which the three nations have stated is a "significant force multiplier for our maritime forces" [29–31]. A recent joint statement [32] clarified that this AUKUS workstream for autonomous vehicles will jointly operate and provide real-time maritime domain awareness to support decision-making.

Australian industry is also investing in developing UxVs for defense applications [33]. Notable examples include the recent Australian development of Boeing's MQ-28 Ghost Bat, Anduril's Ghost Shark, C2 Robotic's Speartooth, and Ocius' Bluebottle.

Sustaining the Undersea Advantage: Disrupting Anti-Submarine Warfare Using Autonomous Systems [10] is a foundational work that offers a modern baseline understanding of the benefits of unmanned systems in the naval undersea domain. Building upon related research [34–38], Clark et al. [10] proposed a new fleet architecture for ASW operations that augments existing manned platforms (submarines, surface ships, and maritime aircraft) with unmanned and autonomous systems (unmanned underwater/surface/aerial vehicles and networked sensors). The authors argued that their proposed fleet architecture significantly improves scale, persistence and cost of operations compared to the current ASW approach, which relies on a smaller quantity of manned assets. They emphasized that the current approach is becoming increasingly ineffective in dealing with the scale of potential undersea threats during a conflict with modern adversaries. By modeling two historical scenarios with US budget data for the new fleet architecture cost [39, 40], Clark et al. quantified significant cost reductions. For these two ASW scenarios, they claimed unmanned systems would reduce procurement costs from US $40 to US $3.4 billion and reduce operations and support costs from US $272 to US $82 million per month.

Clark et al. [10] compiled a significant piece of literature that integrates unmanned technologies, naval operational contexts, proposed fleet composition, and budget constraints. Whilst the paper did not delve deeply into each of these individual areas, it provided a broad and integrated understanding to act as a foundation upon which other literature builds and extends. Notably, the three authors have established that unmanned systems can provide undersea surveillance capabilities for the same (or less) budget as existing manned platforms but can scale to larger areas of operation and remain on station for longer periods of time. The larger quantity of unmanned assets enables a distributed fleet architecture, yielding increased capacity for undersea surveillance.

However, the ability to scale surveillance to larger search areas is not the only benefit of increased capacity. Martin et al. [15] argued that an additional benefit of increased capacity is the ability to speed up undersea surveillance. Where a single multi-role manned vessel would perform surveillance tasks sequentially, a coordinated group of UxVs can perform these tasks simultaneously. This benefit is significant for time-critical missions, such as ASW and maritime search and rescue.

By definition, unmanned systems conduct their operations without direct human involvement. Unmanned systems can be remotely operated or fully autonomous from human control but tend to be singularly focused on a particular role/task. Clark et al. [10] proposed the removal of an opportunity cost, where expensive, manned, multi-role platforms can be freed up for other missions that require higher-order decision-making and skills such as military engagement. O'Rourke [26] described UxVs as being particularly suited for the "three D" missions being those that are dull, dirty, or dangerous. Operators are not only separated from tasks that are repetitive and low-cognitive load but are also kept out of harm's way, allowing unmanned systems to be deployed into areas that would traditionally be avoided due to the high risk of injury or death.

Unmanned systems comprise a broad spectrum of vehicles, sensors, and their enabling technologies [41]. In the maritime context, UxVs include Unmanned Aerial Vehicles (UAVs), Unmanned Surface Vehicles (USVs), and Unmanned Underwater Vehicles (UUVs). These may be larger vehicles that deploy directly from a pier or land, or smaller vehicles that are generally deployed from large vehicles due to their portability and limited

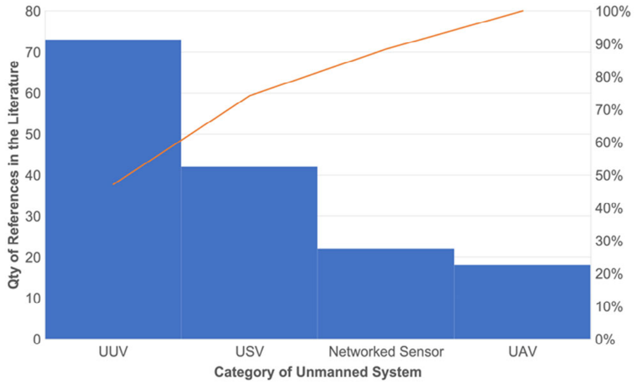

FIGURE 3 | References to core categories of unmanned systems.

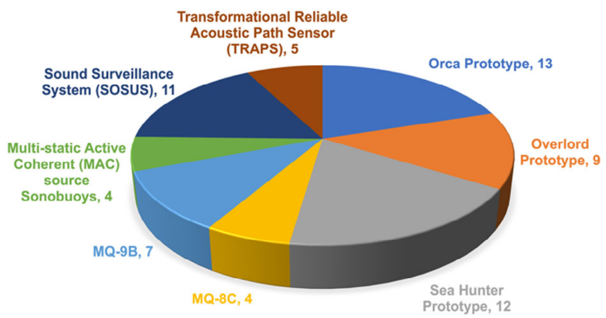

FIGURE 4 | Highly cited unmanned systems.

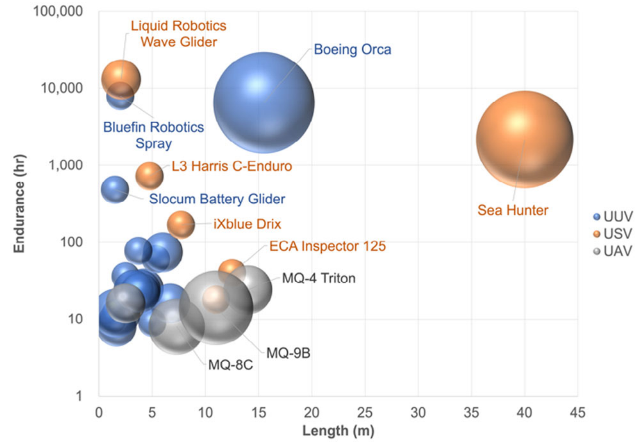

FIGURE 5 | Spread of unmanned vehicle size and endurance.

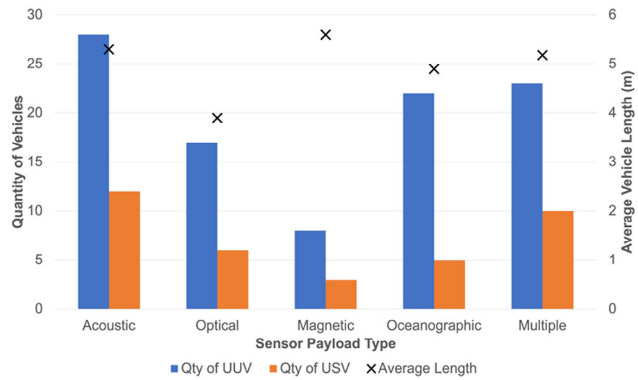

FIGURE 6 | Unmanned Underwater Vehicles (UUV) and Unmanned Surface Vehicles (USV) sensor payloads.

range/speed. The contribution of maritime sensors to unmanned systems includes UxV-mounted payloads and networked sensors that operate independently of a vehicle. Networked sensors can be installed at a fixed location or deployed as the operation requires.

Numerous research and commercial organizations have already conducted extensive literature reviews and published catalogues of existing UxVs and sensors. For example, Martin et al. [15] identified 178 UUVs and 89 USVs; Savitz et al. [20] identified 63 USVs; Hunt [42] lists over 144 UUVs; Button et al. [21] list 45 UUVs; and AUVSI [43] catalogues over 1180 UUVs and USVs. Therefore, this article does not aim to replicate a comprehensive survey of existing products. Instead, Figures 3–6 provide a summary of the analysis of UxVs and self-contained networked sensors mentioned explicitly in the literature related to naval undersea surveillance. This literature included scholarly journal articles, research reports, and government publications but excluded catalogues and manufacturer data sheets promoting an individual product.

It is important to note that any survey of existing unmanned systems will quickly become outdated as new products are developed and released in both the defense and commercial sectors. Therefore, the specific products are less significant to this research than the trends in technology and gaining an understanding of the available capabilities (including limitations) that can be applied to undersea surveillance. Figures 3–6 summarize some of these trends. Figure 3 is a Pareto chart showing the quantity of literature referencing each category of unmanned systems, where UUVs are most dominant (accounting for almost half the references) followed by USVs. Figure 4 identifies the specific systems most highly cited in the literature, indicating a strong interest in these systems for naval undersea surveillance. Figure 5 shows the spread of vehicle endurance and size (length) for a sample of UUVs, USVs, and UAVs in the literature. The significant outliers in size and endurance are labeled, whilst the bubble size indicates the relative quantity of citations (interest in specific vehicles). UxVs with substantially higher endurance tend to be larger or gliders. Lastly, Figure 6 summarizes the quantity of UUVs and USVs in the literature identified with specific sensor payloads (accounting for some vehicles with multiple sensors). Interestingly, it highlights that for the identified vehicles, there was no strong correlation between vehicle size and the selection of sensor payload.

Just as there is a broad spectrum of different unmanned technologies, there are numerous needs and threats that require varying capabilities. For example, Eleftherakis and Vicen-Bueno [2] summarized the threats to undersea cables and their geographical location. More than 75% of the cable faults in 2017–2018 were due to anchors and fishing (nonmalicious), of which more than 80% occurred at a depth of 100 m or less [44]. Eleftherakis and Vicen-Bueno [2] demonstrated that appropriate sensor payloads and UxVs could be selected for undersea surveillance based on the location, size, and speed of different threats.

3.2 | Limitations, Constraints, and Challenges

Although the use of unmanned systems for land and surface surveillance has been widely adopted in modern militaries, their integration into operational naval fleets for undersea surveillance has been noticeably slower [26]. This is partly due to the limitations and challenges placed on the technology in the underwater environment.

The placement of networked sensors and deploying UxVs into the area of operations is a clear challenge, particularly when conducting wide-area or remote surveillance. Whilst smaller assets may be delivered by larger vessels of opportunity, large UxVs must transit from land to the required location.

UxVs require power for propulsion during transit to the area of operation and for manoeuvring within that area. Thus, a significant constraint for unmanned systems is the generation and storage of power, particularly when performing undersea surveillance in remote locations [15]. Alidaee et al. [45] characterized vehicle range as a function of fuel and payload. Power is vital not only for manoeuvring UxVs but also for operating sensors and processing sensor data. Acoustic data processing is particularly demanding and can draw significant power if performed onboard the UxV or at the networked sensor site.

Additionally, underwater communication remains a significant challenge [46, 47], with acoustic communication being the only method currently able to communicate over a few hundred meters underwater. Whilst acoustic communication underwater is covert and direct, the data rate for such communications is very limited [15]. This necessitates performing long-range RF-based communications at the ocean surface, where the platform is more vulnerable to detection. Hamilton et al. [48] proposed that closer integration of acoustic propagation modeling with autonomous navigation in underwater vehicles would allow improvements in the positioning of vehicles and their use in meshed communications networks. However, these improvements are limited to the context of a single vehicle or small group of vehicles rather than offering a significant fleet-level solution. Wettergren and Costa [49] explored an alternate avenue of relying on physically retrieving data from remote sensors, assuming that communication is not always possible. Clark and Patt [33] reinforced the reliance of unmanned systems on command, control, and communications across the whole fleet architecture.

The interrelation between power and communications constraints yields an important trade-off in selecting unmanned systems when designing a fleet architecture. On the one hand, performing organic (edge) processing at the sensor location reduces the burden of high-bandwidth communications, as only postprocessed data is transmitted. Alternatively, remote or externally centralized processing reduces the power demands of sensor/vehicle hardware but burdens the communications network with raw sensor data. Depending on the role of the unmanned systems within the fleet architecture, performing processing at the sensor may or may not be desirable. A related consideration is the resiliency of the fleet architecture, where centralized processing (such as sensor data fusion) by a single asset or node may introduce a localized single point of failure, thereby reducing overall fleet resiliency.

The resiliency of a fleet architecture incorporating unmanned systems also depends on the underlying control of those unmanned systems. Extensive research has been conducted to improve the control dynamics of individual vehicles, including reviews of alternate designs and control models for UxVs [50, 51] and the development of novel models for controlling and stabilizing UxVs [52–54]. Furthermore, the recent promulgation of common autonomy architectures, such as the Unmanned Maritime Autonomy Architecture (UMAA) [55, 56], unifies interfaces and supports the reuse and interoperability of vehicle autonomy components and software. However, autonomy and control dynamics in support of individual vehicle design have been excluded from the scope of this literature review, which is focused on the fleet-level architecture. For the purposes of designing a fleet architecture, it is assumed that the incorporation of unmanned systems will include any necessary vehicle control and its effects will be assessed through the performance characteristics of the unmanned system. Similarly, the provision of command and control (C2) of unmanned systems across the fleet is vital for operations [57] but deemed beyond the scope of this literature review. The impact of C2 on fleet design will be factored into the provision of communications (either continuous or discrete) across the fleet.

Related to resiliency is the security of the fleet architecture for undersea surveillance [58]. Jain and Hussain [59] argued that existing architectures have not adequately addressed the security of communications in underwater sensor networks. Underwater communications require sophisticated encryption and security protocols to avoid modern cyber-attack vulnerabilities. Zukarnain et al. [47] present multiple countermeasure approaches to protect underwater sensor networks from malicious attacks. Furthermore, physical security is vital for assets in remote locations. In a recent news article [60], Bryan Clark was interviewed and stated that as navies move to a more distributed architecture, it had to be accepted that some UxVs will periodically get captured or lost. Thus, the ability to disable sensitive material/capabilities (e.g., cryptographic equipment for communications) is necessary if retrieved by an adversary. Clark also argued that navies could not rely on manned assets to provide continual protection for unmanned systems. If a destroyer is needed to protect the unmanned system, then it is still being diverted from its role and could have performed surveillance duties instead of the unmanned system. Self-protection and resiliency remain key constraints for any fleet architecture developed for undersea surveillance.

3.3 | Evaluation of Existing Applications

The existing literature falls short of exploring the application of unmanned systems for comprehensive undersea surveillance. Individual papers are focused on a single operation at a time, for example, ASW [10, 48], Mine Counter Measures [48], or undersea cable monitoring [2, 34]. Whilst ASW includes a surveillance phase to detect submarines, it is generally localized to a specific area of the ocean. Similarly, undersea cable monitoring encompasses wide-area surveillance due to the inter-continental distances of cable but is always at a fixed, known location. The literature relating to unmanned systems does not explore other vital and unique undersea surveillance operations in sufficient detail, including Intelligence Surveillance and Reconnaissance, maritime search and rescue, monitoring sea lines of communication, or environmental monitoring. Additionally, by only exploring a single operation at a time, the existing literature fails to examine the application of unmanned systems for a holistic fleet architecture with the flexibility to perform all types of undersea surveillance missions, sometimes simultaneously. Furthermore, each paper in the literature only explores one to two specific case studies or scenarios, potentially limiting the evidence of a broad application of unmanned systems in differing maritime contexts. Notably, the literature does not detail undersea surveillance scenarios within Australia's maritime jurisdiction.

The scenarios examined by Clark et al. [10], including the behavior of threats, are based on extrapolation of historical US Navy campaigns and, as such, may be subject to uncertainty and partiality. Other scenarios, including those explored by Eleftherakis and Vicen-Bueno [2], draw similar conclusions and assumptions on threat behavior based on historical data. There are varying levels of scientific rigor used in the literature's exploration of scenarios, but all fall short of detailed operational modeling.

Most of the literature primarily focuses on unmanned systems developed for the US Navy and the UK's Royal Navy, with isolated references to European navies. Whilst there is some overlap with the assets available to the RAN, there are also areas of difference. As outlined earlier, Australia has a substantially smaller budget while retaining a significant maritime area of interest. This compounds the issue of scale for the RAN, and they are forced to do "more with less." The selection of unmanned systems for an Australian fleet architecture is expected to differ when considering the applicable budget limits. This difference limits the quantity and the diversity of selected systems, where Australia seeks flexible systems with a greater return on investment across multiple operations. A report by RAND Australia [19] was developed to guide the RAN's adoption of unmanned systems. It solicited stakeholder input and referenced literature from nations including Australia, the USA, the UK, Israel, France, The Netherlands, Norway, Canada, and Poland. However, it did not translate that input to the selection of specific systems for the RAN. A more recent publication by Clark and Patt [33] reinforced the asymmetrical advantages of unmanned systems. It highlighted the unique challenges of integrating Australian-relevant systems into the RAN fleet, where limited budgets necessitate prioritizing gaps and solutions. Clark and Patt [33] reinforced core concepts for Australia's adoption of unmanned systems, including the value of "system of systems" design to scale coverage of these systems and provide flexibility to service multiple operations. However, they did not extend their recommendations to propose a fleet architecture incorporating unmanned systems for the RAN.

Without a clear justification for selecting specific unmanned systems, the analyses are at odds with the wide variety of unmanned systems available today. For example, there is ongoing conjecture about whether large UxVs (requiring deployment from a pier) should be replaced by a larger quantity of smaller, expendable vehicles launched from other naval platforms. US Chief of Naval Operations, Admiral Mike Gilday, and the US House Armed Services Committee noted that these smaller UxVs are more affordable, provide a greater range of combined sensor payloads, and still provide the required operational picture [61, 62]. Further analysis is necessary to match categories of unmanned systems and their capabilities to specific contributions for undersea surveillance.

Lastly, the literature consistently asserts that undersea surveillance would be improved by utilizing a mix of unmanned systems in conjunction with manned systems. Clark et al. [10] asserted that unmanned technologies are unlikely to achieve the complete autonomy required to conduct ASW missions alone but rather relinquish specific ASW tasks currently conducted by manned platforms. Martin et al. [15] also concluded that unmanned systems are not suited as direct replacements for manned systems but rather offer significant benefits in performing specific tasks as supplementary assets to multirole manned platforms. Despite these agreed conclusions, the literature does not provide conclusive evidence of the mix of unmanned and manned systems required for an Australian undersea surveillance fleet architecture.

This section has demonstrated that the existing literature identifies challenges with applying unmanned systems to undersea surveillance. Still, the literature lacks sufficiently rigorous analysis to draw evidence-based conclusions on their incorporation into a fleet architecture. Table 2 summarizes the fundamental, recurring challenges from the literature and identifies the related parameters that must be analyzed to achieve a valid fleet architecture. These parameters will be utilized in model-based analysis and further research described in Section 5.

4 | Designing a Fleet Architecture With Systems Methodologies

4.1 | Systems Methodologies

Numerous aspects of unmanned systems and their potential benefits to Australian undersea surveillance operations have been outlined in this article. However, simply understanding the operational need and identifying the pivotal technology does not yield a fleet architecture solution. Engineering methods are required to design, optimize, and validate a domain-applicable solution.

The problem domain of undersea surveillance is inherently complex. Consequently, any associated naval fleet architecture inevitably has the structural complexity of numerous compositions of the system elements and the dynamic complexity of needing to perform different tasks as needs change over time. Fortunately, systems methodologies include a range of approaches and disciplines for handling complexity [17], facilitating the transformation of the technology into a domain-relevant solution. Systems thinking is a foundational methodology that can contribute to this problem domain. Gharajedaghi [63] stated, "Systems thinking is the art of simplifying complexity. It is about seeing through chaos, managing interdependency, and understanding choice." Arnold and Wade [17] defined systems

TABLE 2 | Parameters for further analysis.

Unmanned systems challenges	Analysis parameters
Surveillance coverage over a large, dynamic geographical region	Geographical locations, size, and variance; Spectrum of operational scenarios; Quantity of concurrent operations; Vehicle range; Sensor performance.
Timely deployment of unmanned systems	Vehicle range and speed; Vehicle self-deployment vs. delivery; Fleet impact of delivery platforms.
Persistence of unmanned systems	Vehicle endurance; Unmanned systems power source, energy storage, and replenishment; Access to infrastructure; Level of autonomy; System attrition rate.
Communication of surveillance data	Centralized vs. edge sensor processing; Communications networks vs. physical retrieval of data; Data latency requirements; Resiliency of communications networks in maritime environments; Security of data, communications, and unmanned systems.
Resource constraints for Australian application	Procurement and operations costs/budget; Quantity of personnel; National access to unmanned systems/technology.
Defining the mix of unmanned and manned systems in an integrated fleet	Asset roles; Unique system capabilities; Rules governing areas of operation; Fleet-level quality attributes; System deployment interdependencies; System operational interdependencies; System replenishment interdependencies; Constraints imposed by challenges above.

thinking as “a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects.” Thus, systems thinking can be considered a broad “umbrella” of skills and techniques that assist in understanding complex problem domains to develop systems that can address them. Systems thinking offers methods and techniques to handle the complexity of applying unmanned systems to undersea surveillance.

Additionally, it is well suited for designing a fleet architecture as it manages both the parts (the surveillance assets) and the whole (the fleet). The Systems Engineering Body of Knowledge (SEBoK) [16] developed by the International Council on Systems Engineering (INCOSE) stated that “holism has been a dominant theme in systems thinking for nearly a century, in recognition of the need to consider a system as a whole because of observed phenomena such as emergence.” Similarly, Richmond [64] emphasized that Systems Thinkers “position themselves such that they can see both the forest and the trees; one eye on each”.

Moreover, systems thinking includes methods to cope with the diverse Australian operational needs for undersea surveillance and changing requirements. Squires et al. [65] asserted that systems thinking “incorporates multiple perspectives; works where boundary or scope of problem/system may be fuzzy; understands diverse operational contexts; identifies relationships and dependencies; understands complex system behavior; reliably predicts the impact of change to the system.”

Nevertheless, systems thinking is a broad approach that can be complemented by other well-defined systems methodologies, including systems engineering, systems architecture, systems modeling, system dynamics, and systems-related OR, and design for Six Sigma. Some of the key systems methodologies highlighted in the literature are shown in Figure 7, with arrows representing interrelationships between methodologies. It must be noted that this is not a comprehensive list of methodologies but rather an illustrative listing of those recurring in the literature review. Many of these methodologies have overlapping approaches and could be consolidated. However, since the literature has discrete

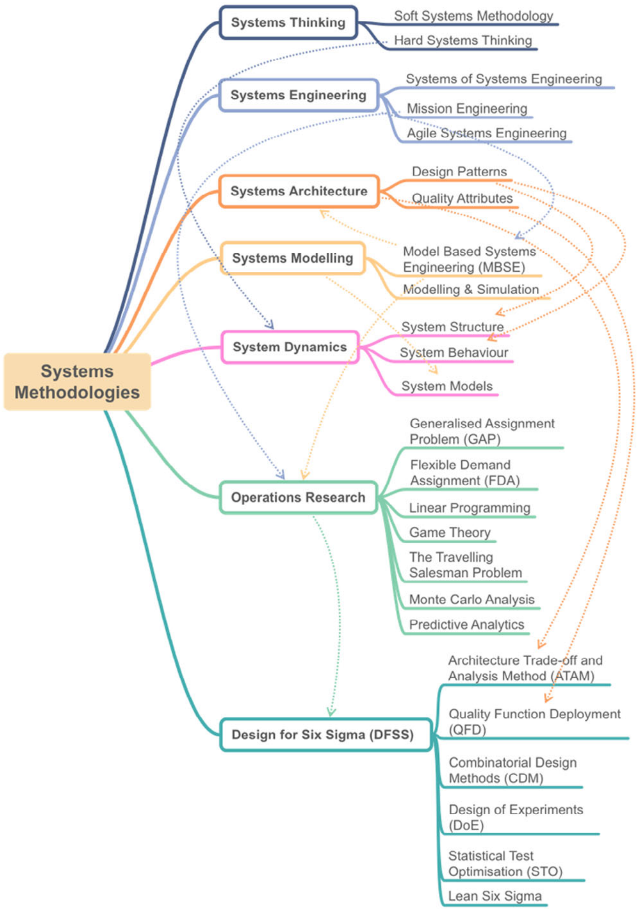

FIGURE 7 | Systems methodologies in the literature.

references to each methodology, this review identifies them independently.

The SEBoK [16] defines systems engineering as "a transdisciplinary approach and means to enable the realization of successful systems. Successful Systems must satisfy the needs of their customers, users, and other stakeholders." Thus, systems engineering can be considered a discipline that abstracts the traditional engineering disciplines (electrical, mechanical, software, etc.) to combine individual elements into a holistic solution (system) to achieve an intended purpose. Systems of systems engineering is a related discipline that extends systems engineering to manage multiple layers of abstraction and the complexity of systems within systems. These multiple layers of abstraction often result in additional considerations, such as socio-technical or socio-economic phenomena [16]. A naval fleet architecture can be considered a system of systems, encompassing or interacting with vehicles, sensors, communication bearers, operators, algorithms, government bodies, the environment, national infrastructure, and many other elements. Systems engineering is a well-established discipline applied to various industries, including defense, mining, healthcare, pharmaceutical, space, transport, and utilities [16]. However, its implementation varies and is generally tailored to the application. Blanchard and Fabrycky [66] asserted the need for tailoring by citing the numerous governing standards for systems engineering, including but not limited to ANSI/EIA 632 [67], IEEE 1220 [68], and ISO/IEC/IEEE 15288 [69].

Lately, agile software development practices have been adopted in systems engineering, resulting in agile systems engineering with an incremental lifecycle process model well-suited to modern software-centric systems [16].

Some literature considers systems architecture as a method within systems engineering, while others regard it as a discipline of its own. The SEBoK [16] defined systems architecture as "a model representation of the fundamental organization of a system in terms of the structural elements and their behaviors." In contrast, Maier and Rechtin [70] defined it as a fundamental discipline, likening systems architecture to classical (building) architecture. They described systems architecture as an "art" concerned with the characteristics of a system that are observable by customers as either meeting their needs and desires or not. Maier and Rechtin [70] claimed that this is a separate skillset and focus from systems engineering, which by contrast, is concerned with the detailed "science" of design, quantitative optimization, and implementation. Due to its unique perspective and promising benefits, this article treats systems architecture as an independent discipline. An essential tool used by systems architecture is design patterns that are known to contribute (positively or negatively) toward quality attributes (or "ilities") expressed by customers or stakeholders [16, 70]. Systems architecture's concept of quality attributes and supporting patterns can be applied to a fleet architecture for undersea surveillance, where the navy's needs are loosely defined, subject to variation, and challenging to capture as quantifiable requirements. Further emphasizing the importance of systems architecture, Maier and Rechtin [70] cited examples where the success of complex systems is determined by the architecture (and associated patterns) at the conceptual phases of development, regardless of whether the systems architecture was consciously selected or merely by happenstance. Hence, systems architecture is a crucial methodology for developing a naval fleet architecture for undersea surveillance.

Systems modeling is a fundamental systems methodology because the practical application of systems methods often hinges on the use of system models [16]. INCOSE et al. [16] defined a system model as "a simplified representation of a system at some particular point in time or space intended to promote understanding of the real system. As an abstraction of a system, it offers insight into one or more of its aspects, such as its function, structure, properties, performance, behavior, or cost." The benefits of systems modeling have led to the adoption of model-based systems engineering (MBSE) as a discipline closely related to systems engineering and systems architecture. MBSE extends the systems engineering process by replacing the traditionally document-centric approach with a coherent model of the system, becoming the primary engineering artefact [71]. Friedenthal et al. [71] asserted that replacing document-based specifications with a model as the "single source of truth" for engineering baselines results in enhanced specification and design quality, reduced development risk, increased productivity through the reuse of design artefacts, improved communications, and enhanced knowledge transfer via unambiguous and standardized capturing of engineering outputs.

To support standardized adoption, the Object Management Group has defined the System Modeling Language (SysML) [72], which has become the universal language for systems modeling and is published as the ISO/IEC 19514:2017 standard. A recent survey of 661 MBSE practitioners by the University of South Alabama [73] highlighted the leading adoption of MBSE in the defense industry (representing over 40% of the industry participants) but with less than 5% of practitioners being from Australia. 77% of survey participants concluded that system architecting is where MBSE holds the most promise for yielding benefits. Beyond architecting, the SEBoK [16] described the modeling and analysis of MBSE as crucial for complementing testing, which typically occurs later in the engineering lifecycle. This approach allows the performance of a proposed system to be evaluated without the physical implementation, thereby validating the architecture and design. The literature indicates that MBSE methods would benefit an engineering framework for designing a naval fleet architecture ahead of physical implementation.

System dynamics is sometimes considered analogous to systems thinking and is often regarded as the foundation of modern systems modeling approaches [16, 17]. System dynamics was created by Jay Forrester and refined by the System Dynamics Group at Massachusetts Institute of Technology in the 1960s and 1970s. As one of the core members of this group and a seminal author, Donella Meadows [74] wrote, "The system dynamics paradigm assumes that things are interconnected in complex patterns, that the world is made up of rates, levels and feedback loops, that information flows are intrinsically different from physical flows, that nonlinearities and delays are important elements in systems, that behavior arises out of system structure." In her more recent book on system dynamics [75], Meadows stresses the critical relationship between system structure and behavior that allows us to understand how they work and thereby improve their behavior patterns. Thus, system dynamics focuses on the "hard" (definable) elements of the system itself and is related to hard systems thinking, as opposed to soft systems methodology [76], which analyses the "soft" human aspects of system design and use. System dynamics is clearly aimed at tackling complex system-based problems. Hence, its methods should be considered alongside any systems modeling for designing a fleet architecture for undersea surveillance.

Whilst system dynamics and systems modeling focus on the construct and behavior of the system, OR delves deeper into mathematical models to quantitatively support decision making [77]. OR offers a suite of mathematical techniques for optimizing a problem's solution. In the literature, several OR techniques and reference scenarios were identified for assigning a collection of fleet assets. These include the generalized assignment problem (GAP) with numerous documented solution approaches [78]; flexible demand assignment (FDA) as an extension of the GAP [45]; linear programming [79, 80]; game theory [79]; the travelling salesman problem [49]; Monte Carlo analysis [79, 80]; and predictive analytics [81]. Some literature claimed improvements in developing valid solutions from integrating OR techniques with other systems techniques. This included integrating OR with MBSE using SysML [82], refining systems architecture through architecture frameworks and simulation [83], and integrating linear programming with systems engineering-based stakeholder objectives [80]. Similarly, mission engineering applies the systems engineering discipline to operational problems and incorporates OR techniques [84].

Furthermore, design for Six Sigma (DFSS) practices leverage OR-related statistical methods originating from Lean Six Sigma, specifically for developing new systems. Mackertich and Cleotelis [85] demonstrated that these practices are readily integrated with the systems engineering lifecycle for improving the development of increasingly complex systems. DFSS practices include quality function deployment (QFD); architecture trade-off and analysis method (ATAM) developed by the Software Engineering Institute at Carnegie Mellon University [86]; combinatorial design methods (CDM); design of experiments (DoEs) [87]; and statistical test optimization (STO).

4.2 | Existing Applications of System Methodologies

The reviewed literature included numerous materials that described the benefits of systems methodologies for managing the complexity associated with systems of systems. However, only a small quantity of material explicitly explored the application of these methods to naval fleet architecture and its contributing elements.

Clark and Patt [33] proposed using systems methodologies to assist with determining the integration of unmanned systems into the RAN fleet. They asserted the merits of system modeling, systems engineering, and mission engineering methodologies to determine the integration of unmanned systems into an existing manned fleet. Importantly, Clark and Patt [33] also outlined the need for methods to validate that the new fleet architecture meets the operational needs. Their paper forms a supporting argument for further research in this field, as it characterizes the issues and important considerations but does not reach evidence-based conclusions on candidate fleet architecture or a comprehensive methodology to design the fleet architecture.

Lopes et al. [88] outlined a case study of applying systems engineering methods to design an USV. It demonstrated the benefits of systems engineering in a methodical approach to overcome multi-criteria design challenges. However, the application was limited to a single vehicle and did not explore the application of systems engineering for fleet architecture system of systems.

Similarly, Courts and Broadbent [89] explored the application of systems architecture to Royal Navy surface vessels, focusing on the quality attributes of adaptability, flexibility, and modularity. However, much of the paper addressed the individual vessel with only minor extrapolation to claim that vessels with these quality attributes provide an opportunity to design the fleet structure for cost-effectiveness. The paper demonstrated the application of systems architecture to a single system but did not directly investigate the application of these methods to systems of systems at the fleet level. Additionally, Hamilton et al. [48] explored a service-oriented architecture for improved integration between autonomy and communications in UxVs for undersea surveillance applications. Nevertheless, whilst this application benefited the overall fleet, it did not directly apply the systems architecture methods at the fleet architecture level.

A recent research paper by Rogers and Mitchell [90] described the application of MBSE to a complex system of systems. In this case, it was the Submarine Warfare Federated Tactical System (SWFTS) fitted to all variants of US Navy and RAN submarines. SWFTS contains many complex computer-based systems, including multiple sensor types for conducting undersea surveillance. Although this application is not fleet architecture for undersea surveillance, it mirrors some of the complex characteristics. Rogers and Mitchell [90] claim a quantitative financial return on investment from adopting MBSE compared to prior document-centric systems engineering. The benefits detailed in the paper focus on managing change in requirements or design with minimal downstream impacts on the engineering implementation, configuration management, and system defects. However, of more relevance to fleet architecture, Rogers and Mitchell [90] demonstrated that MBSE allows engineers to deal with more complex problem domains in early architecture and design work with a greater likelihood of producing higher-quality solutions that meet the customer's needs.

Numerous materials in the literature explore the application of OR methods for optimizing the placement of vehicles or sensors for surveillance. Laan et al. [79] demonstrated the use of linear programming and game theory for the optimal placement of a small number of assets to protect a single high-value unit from a submarine attack. Craparo and Karatas [91] proposed an improved model for placing multistatic sonar sensors for optimal coverage in undersea surveillance with defined detection locations (such as fixed locations for undersea cables or port entries). Wettergren and Costa [49] developed an optimization approach for positioning sensors in an underwater sensor network, where the level of coverage is treated as a constraint, and the travel distance to a sensor is minimized. Alidaee et al. [45] proposed a model to optimize UAV assignment to targets based on location, priority, and minimum service levels. Jensen et al. [81] proposed an intruder preference model for analyzing illicit border crossings in the USA. Whilst the research by Jensen et al. [81] was unrelated to undersea surveillance, the proposed predictive analytics method could be applied to a naval fleet architecture to optimize asset placement based on the likelihood of a target being present. Importantly, Jensen et al. integrated their statistical model into a broader systems engineering approach for developing a surveillance system.

The disparate applications of OR methods reflect two shortcomings in the literature. Firstly, there was conjecture over what is considered optimal for surveillance, driving the divergent application of optimization techniques to different parameters and criteria. This potentially indicates a lack of integration with other systems methodologies that capture the customer's needs. Secondly, the papers generally focused on localized surveillance using relatively simple scenarios encompassing less than a dozen surveillance assets and only one or two detection targets. This isolated application does not consider the compounding complexity of performing wide-area or integrated undersea surveillance that must deal with multiple competing dimensions of need. Without exploring overall fleet architecture design, the literature did not emphasize the importance of emergent fleet-level characteristics and how the methods could systematically improve them.

Oughton et al. demonstrated the benefits of techno-economic analysis for global coverage of satellite [92] and cellular networks [93, 94]. Oughton et al. integrated quantitative cost assessments with technical performance measures for system evaluation. Their research proves the utility of this approach in assessing the value for money of infrastructure coverage. Whilst their research has similar geospatial coverage considerations to Australian undersea surveillance, it is a different application domain and has not addressed the quality attributes listed in Section 2 nor the analysis parameters in Table 2. However, their research highlights the benefits of techno-economic analysis as a technique for incorporating economic evaluation into system development, which Blanchard and Fabrycky [66] asserted is a crucial consideration for successful systems engineering. This approach could be suitable for assessing the value for money of fleet architectures in accordance with the Defence Capability Manual [25].

More broadly, this literature review highlights that existing research applied systems methodologies at a "micro" level. In doing so, the literature addressed only a simplified version of the problem, a contributing sub-problem, or only dealt with a single dimension of the problem at a time. By not addressing the "macro" level problem of a holistic fleet architecture for undersea surveillance, the literature hid the complexity of scale, concurrent operations, and competing dimensions of need. This is despite the literature's indication that systems methodologies are well-suited for solving systems of systems problems [16, 65]. As Meadows asserted [75], "Systems happen all at once. They are connected not just in one direction, but in many directions simultaneously."

Finally, the literature identified some existing overlap and pairing of methodologies but did not articulate an integrated framework for realizing the emergent benefits of combining the methods. Table 3 summarizes the existing systems methodologies in the literature with their individual benefits and limitations when applied in isolation. This further proves the merits of integrating these methodologies when designing a fleet architecture.

5 | Open Problems and Further Research

This literature review has explored several aspects of undersea surveillance, the utility of unmanned systems, and existing methodologies to design a naval fleet architecture employing these technologies. However, gaps in the existing research were identified that remain open problems.

A clear understanding of Australia's needs in undersea surveillance is a vital starting point for furthering knowledge in this domain. A deeper investigation is required to derive the specific capabilities needed for the RAN's predicted profile of operations and associated quality attributes. Although an initial set of quality attributes has been identified in this article, the set could be further refined and validated by applying systems engineering, systems architecture, and design for Six Sigma methodologies. A comprehensive characterization of Australia's needs and constraints for undersea surveillance bounds the problem space whilst ensuring that non-technical dimensions (such as budgets, personnel, resources, and technology access) are factored into the holistic "system of systems" design, thereby ensuring further research can be applied by the RAN.

A broad survey of unmanned systems relevant to undersea surveillance has been outlined in this article. Future research

TABLE 3 | Comparison of individual systems methodologies.

Methodology	Benefits	Limitations
Systems Engineering	Provides a structured approach to defining, designing, and testing a system to meet requirements; Handles layers of abstraction and encapsulation for "system of systems"; Extendable and integrates with other methodologies.	Varied implementation; Lacks mathematical techniques for optimization of fleet parameters.
Systems Architecture	Integrates multiple perspectives and operational contexts; Stakeholder-focused; Leverages reusable design patterns with known attributes; Existing frameworks for handling complexity.	Abstract nature of Systems Architecture lacks focus on design/implementation detail; Lacks mathematical techniques for optimization of fleet parameters.
Systems Modeling	Provides a virtual representation of a real system and its environment; Can be partitioned or abstracted to examine isolated details; MBSE integrates models with Systems Engineering and Architecture practices; Tests and evaluates complex systems where otherwise infeasible or cost/time prohibitive; Standardized languages and tools.	Lacks techniques for the complete system development lifecycle; Greater focus on system structure and behavior with fewer mathematical techniques for quantitative performance optimization.
System Dynamics	Provides foundational concepts for modeling systems.	Lacks techniques for the complete system development lifecycle; Fewer applications in recent defense systems compared to Systems Engineering.
Operations Research	Includes mathematical techniques for quantitative testing and optimizing system parameters in a modeling environment; Proven techniques for addressing common optimization problems.	Lacks techniques for designing systems or eliciting stakeholder needs; Relies on other methodologies for defining the characteristics of a system to optimize.
Design for Six Sigma	Leverages statistical methods from Operations Research to develop optimized systems; Readily integrates with systems engineering and architecture methodologies.	Only targets specific threads of system development for optimization and stakeholder satisfaction; Lacks techniques for the complete system development lifecycle.

should extend this survey to understand the key technological trends and the capabilities offered by different systems for undersea surveillance. This research should determine the unique capabilities offered by unmanned systems compared with manned platforms to inform the roles each should play within a mixed fleet architecture. Additionally, this avenue of research should distill the systems available to Australia to forecast a roadmap for adopting maturing technologies.

A significant gap in the existing research is the focus on "micro" sub-problems rather than addressing the holistic "macro" problem of comprehensive, integrated undersea surveillance across the full spectrum of Australian operations. A crucial area of further research is to build a model that explores this "macro" problem and thereby design a fleet architecture that meets Australian needs. This research should examine system dynamics, OR, and design for Six Sigma methodologies to design the fleet architecture to deliver the required surveillance capabilities whilst maximizing the quality attributes. Additionally, value for money must be addressed, accounting for the Australian personnel and budget constraints using economic evaluation techniques like techno-economic analysis. Through systems modeling, this body of research should determine how the mix of different assets will work together within the fleet. It should analyze the trade-offs between edge processing and centralized processing to determine its impact on the fleet's quality attributes.

To substantiate the research, the "macro" model must not only design and optimize a fleet architecture but also validate it. Future research must validate that the proposed fleet architecture applies to Australian operations in its geographical areas of interest. This research could leverage DoEs to develop model simulations when proving the asserted conclusions. To advance the existing body of knowledge, this research must provide conclusive guidance for building an Australian naval fleet architecture, including what

TABLE 4 | Comprehensive issues in the literature.

Comprehensive issues	Proposed solutions
Australia's ongoing needs in undersea surveillance are not sufficiently characterized to design a fleet architecture.	Perform deeper analysis and elicitation of the capabilities needed, the profile of operations, and derived quality attributes of the system of systems. This should utilize systems architecture and systems engineering approaches that integrate stakeholder needs with technical modeling.
Correlation has not been established between different unmanned technologies and their specific role in undersea surveillance.	Survey and capture the capabilities of unmanned technologies that differentiate them from manned platforms for application in undersea surveillance. The utility of unmanned technologies within the fleet architecture should be measured and tested through system modeling, system dynamics, and operations research methodologies.
Design of unmanned technologies for undersea surveillance has only occurred with individual systems or for localized scenarios.	Model the comprehensive system of systems including dynamic complexity and full spectrum of undersea surveillance operations, as outlined earlier in Table 2. Apply design and optimization techniques at the fleet level as directed by the defined quality attributes of the fleet, whilst factoring cost constraints. The quality attributes provide an unambiguous definition of Australia's ongoing needs in undersea surveillance.
Fleet architectures mixing manned and unmanned assets for undersea surveillance have not been validated.	Measure the performance of candidate fleet architecture models using simulations of operational scenarios for undersea surveillance. Quantify the performance difference between candidate fleet architectures and their improvement over today's predominately manned fleet. Design for Six Sigma techniques should be used to improve test efficiency and coverage, whilst ensuring that validation of the candidate architectures are aligned with the stakeholders' intent for undersea surveillance.
The current application of systems methodologies for developing fleet architectures is disparate and suboptimal.	Design an integrated framework of systems methodologies that combines best practices from the individual disciplines. Document the meta-methodology and its supporting models for broad reuse in "system of systems" problems in any application domain.

assets should be used, where they should be deployed, and when they are needed.

Ultimately, the open problems warrant further research in designing an integrated framework of systems methodologies that apply best practices to developing fleet architectures for undersea surveillance. By combining systems methodologies with domain-applicable data, further research could produce reusable techno-economic system models far superior to the current disparate use of singularly focused decision methods. To extend the value of this research, it could explore the utility of the integrated framework for addressing similar needs across the broader class of "systems of systems" problems beyond maritime surveillance.

5.1 | Future Direction

The systematic literature review has clearly identified gaps in the existing body of knowledge, open problems to solve, and the need for further research. Table 4 summarizes the comprehensive issues in the literature with the proposed solutions to these issues for doctoral research undertaken by the corresponding author. Furthermore, the following research questions have been developed to guide subsequent research in addressing these issues:

1. How should the RAN utilize unmanned systems to improve their undersea surveillance operations?
2. How can systems methodologies help to design a fleet architecture for the RAN, which accounts for dynamic undersea surveillance needs and Australian budget constraints?
3. Which candidate fleet architecture offers the most value for money[2] when applied to Australian undersea surveillance?
4. How can the disparate collection of systems methodologies be integrated to realize their collective benefits for fleet architecture design?

5.2 | Conclusion

This article analyzed 128 pieces of literature on improving naval undersea surveillance through unmanned systems, as designed by systems methodologies. The literature review concludes that unmanned systems offer significant benefits in terms of scalability, persistence, cost-effectiveness, and safety for undersea surveillance operations conducted by the RAN. Applying unmanned systems to undersea surveillance requires further analysis and modeling to overcome the challenges with unmanned systems identified in Table 2. The literature establishes that systems methodologies offer best practices for performing this analysis and managing the complexity inherent in this "systems of systems" problem. However, the spectrum of unmanned technologies is substantial, and the available systems methods are disparate, as highlighted in Table 3. Further research to address the open research questions and issues in Table 4 will extend the existing body of knowledge into designing fleet architectures whilst creating a reusable framework of methodologies for addressing this class of complex problems. These research outcomes are of national significance to Australia as their application in naval undersea surveillance will support the ongoing protection of the nation's surrounding oceans for its economy and security.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Endnotes

[1] A complete listing of the sources that informed this literature review is included in Table A.1 in Appendix A.

[2] Value for money is referenced in the Defence Capability Manual and should be defined in consideration of the quality attributes in Section 2.

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113. K. Bhattacharjya and D. De, "IoUT: Modelling and Simulation of Edge-Drone-Based Software-Defined Smart Internet of Underwater Things," *Simulation Modelling Practice and Theory* (May 2021): 109102304, https://doi.org/10.1016/j.simpat.2021.102304.

114. G. L. Maglione, L. Berretta, S. B. Godfrey, et al., "M&S Based Testbed to Support V&V of Autonomous Resources Task Coordinator" Conference paper, in *Modelling and Simulation for Autonomous Systems (MESAS 2020)* (2021), 12619, 123–138, https://doi.org/10.1007/978-3-030-70740-8_8.

115. G. Macrina, L. D. Pugliese, F. Guerriero, and G. Laporte, "Drone-Aided Routing: A Literature Review," *Transportation Research Part C-Emerging Technologies* (November 2020): 120102762, https://doi.org/10.1016/j.trc.2020.102762.

116. E. V. Carrera and M. Paredes, "Analysis and Evaluation of the Positioning of Autonomous Underwater Vehicles Using Acoustic Signals" Conference paper, in *Developments and Advances in Defense and Security* (2020), 152, 411–421, https://doi.org/10.1007/978-981-13-9155-2_33.

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119. D. A. Helgerson, "Systems Engineering in Naval Ship Design Introduction," *Naval Engineers Journal* 133, no. 2 (June 2021): 36–49.

120. F. Di Ciaccio and S. Troisi, "Monitoring Marine Environments With Autonomous Underwater Vehicles: A Bibliometric Analysis," *Results in Engineering* (March 2021): 9100205, https://doi.org/10.1016/j.rineng.2021.100205.

121. T. Aruna Jacintha and T. Jaya, "Optimization of Adaptive Queuing System With Priority-Based Scheduling in Underwater Sensor Networks," *Cognitive Science and Technology* (2022): 485–499, https://doi.org/10.1007/978-981-19-2350-0_47.

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123. R. A. Holler, "The Evolution of the Sonobuoy From World War II to the Cold War," *US Navy Journal of Underwater Acoustics* 2014 (January 2014), JUA_2014_025_N.

124. R. McCargar and L. M. Zurk, "Depth-Based Signal Separation With Vertical Line Arrays in the Deep Ocean," *The Journal of the Acoustical Society of America* 133, no. 4 (2013): EL320–EL325, https://doi.org/10.1121/1.4795241.

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126. M. Hopper and K. A. Stave, "Assessing the Effectiveness of Systems Thinking Interventions in the Classroom," in *26th International Conference of the System Dynamics Society* (2008), 1–26, https://proceedings.systemdynamics.org/2008/proceed/papers/STAVE390.pdf.

127. K. Stave and M. Hopper, "What Constitutes Systems Thinking? A Proposed Taxonomy," in *25th International Conference of the System Dynamics Society* (2007), 29, https://proceedings.systemdynamics.org/2007/proceed/papers/STAVE210.pdf.

128. J. Wade, "Systems Engineering: At the Crossroads of Complexity," in *Kongsberg Systems Engineering Event* (University of South-Eastern Norway, 2011), https://ksee.no/?p=793.

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130. R. Patel, *Surveillance of Marine Resources by Use of Stationary Platforms and Autonomous Underwater Vehicle (AUV)*. (Norwegian University of Science and Technology, 2007).

131. G. Brown, J. Kline, A. Thomas, A. Washburn, and K. Wood, "A Game-Theoretic Model for Defense of an Oceanic Bastion Against Submarines," *Military Operations Research* 16, no. 4 (2011): 25–40, https://doi.org/10.5711/1082598316425.

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Appendix A: Literature Search Results

Table A.1 lists all the literature sources that informed this literature review, including the search category indicating where the literature was first identified. Table A.1 informs the literature sources summary shown in Figure 1.

TABLE A.1 | Literature sources.

Index	Author(s)	Year	Title	Search category
1	Muller, W.; Reinert, F.; Haferkorn, D.; Essendorfer, B.; Arecchi, A.; Svensson, K.; Rieter-Barell, Y.; and Ditzel, M.	2019	Tailored Information Provision for Multinational Naval Operations [95]	Web of Science
2	Munafo, A.; Canepa, G.; andLePage, K. D.	2019	Continuous Active Sonars for Littoral Undersea Surveillance [96]	Web of Science
3	McGeachy, H.	2022	The Changing Strategic Significance of Submarine Cables: Old Technology, New Concerns [97]	Web of Science
4	Wettergren, T. A. and Costa, R.	2021	Optimal Configuration Planning for Sensor Network Serviceability Under a System Coverage Constraint [49]	Web of Science
5	Ernadote, D.	2019	Ontology-Based Optimization for Systems Engineering [82]	Web of Science
6	Thorisson, H., Pennetti, C. A., Andrews, D. J., Hendrickson, D. C., Polmateer, T. L., and Lambert, J. H.	2019	Systems Modeling and Optimization of Container Ship Berthing With Various Enterprise Risks [80]	Web of Science
7	Ernadote, D.	2019	Managing Sets in Ontology-Based Optimizations [98]	Web of Science
8	Jensen, J., Mathews, G., Parnell, G. S., Pohl, E. A., Richards, J. E., and Buchanan, R.	2022	Preference Mapping and Routing of Illicit Cross-Border Activity [81]	Web of Science
9	Chowdhury, R.	2023	Methodological Flexibility in Systems Thinking: Musings from the Standpoint of a Systems Consultant [99]	Web of Science
10	Czarnecki, K., Grünbacher, P., Rabiser, R., Schmid, K., and Wąsowski, A.	2012	Cool Features and Tough Decisions: A Comparison of Variability Modeling Approaches [100]	Scopus
11	Ernadote, D.	2015	An Ontology Mindset for System Engineering [101]	Web of Science
12	Ernadote, D.	2016	Ontology Reconciliation for System Engineering [102]	Web of Science
13	Hammami, O. and Houllier, M.	2014	Rationalizing Approaches to Multi-Objective Optimization in Systems Architecture Design [83]	Web of Science
14	Oncan, T.	2007	A Survey of the Generalized Assignment Problem and Its Applications [78]	Web of Science
15	Stahlbock, R. and Voss, S.	2008	Operations Research at Container Terminals: A Literature Update [103]	Web of Science
16	Alidaee, B., Wang, H. B., and Landram, F.	2011	On the Flexible Demand Assignment Problems: Case of Unmanned Aerial Vehicles [45]	Web of Science
17	Hung, S. M. and Givigi, S. N.	2017	A Q-Learning Approach to Flocking With UAVs in a Stochastic Environment [104]	Web of Science
18	Wang, B.	2011	Coverage Problems in Sensor Networks: A Survey [105]	Web of Science

(Continues)

Index	Author(s)	Year	Title	Search category
19	Fei, Z. S., Li, B., Yang, S. S., Xing, C. W., Chen, H. B., and Hanzo, L.	2017	A Survey of Multi-Objective Optimization in Wireless Sensor Networks: Metrics, Algorithms, and Open Problems [106]	Web of Science
20	Rains, D. A.	1999	Fleet Mix Mission Effectiveness Analysis [107]	Web of Science
21	Hamilton, A., Holdcroft, S., Fenucci, D., Mitchell, P., Morozs, N., Munafo, A., and Sitbon, J.	2020	Adaptable Underwater Networks: The Relation between Autonomy and Communications [48]	Web of Science
22	Laan, C. M., Barros, A. I., Boucherie, R. J., Monsuur, H., and Noordkamp, W.	2020	Optimal Deployment for Anti-Submarine Operations With Time-Dependent Strategies [79]	Web of Science
23	Berzins, V.	2020	Architecture-Based Security for UxVs [58]	Web of Science
24	Ferri, G., Stinco, P., De Magistris, G., Tesei, A., and LePage, K. D.	2020	Cooperative Autonomy and Data Fusion for Underwater Surveillance With Networked AUVs [108]	Web of Science
25	Craparo, E. and Karatas, M.	2020	Optimal Source Placement for Point Coverage in Active Multistatic Sonar Networks [91]	Web of Science
26	Ding, W. J., Cao, H., Guo, H., Ma, Y., and Mao, Z. Y.	2019	Investigation on Optimal Path for Submarine Search by an Unmanned Underwater Vehicle [109]	Web of Science
27	Yao, H. F., Wang, H. J., Li, Y. M., Wang, Y., and Han, C. S.	2019	Research on Unmanned Underwater Vehicle Threat Assessment [110]	Web of Science
28	Muller, W., Arecchi, A., Fisch, F., and Di Quirico, E.	2022	System Simulation Architecture and Design for Maritime Surveillance With Unmanned Assets [111]	Web of Science
29	Roseela, J. A., Godhavari, T., Narayanan, R. M., and Madhuri, P. L.	2021	Design and Deployment of IoT Based Underwater Wireless Communication System Using Electronic Sensors and Materials [112]	Web of Science
30	Bhattacharjya, K. and De, D.	2021	IoUT: Modelling and Simulation of Edge-Drone-Based Software-Defined smart Internet of Underwater Things [113]	Web of Science
31	Maglione, G. L., Berretta, L., Godfrey, S. B., Apostolidis, S., Kapoutsis, A., Kosmatopoulos, E., and Tremori, A.	2021	M&S Based Testbed to Support V&V of Autonomous Resources Task Coordinator [114]	Web of Science
32	Macrina, G., Pugliese, L. D., Guerriero, F., and Laporte, G.	2020	Drone-Aided Routing: A Literature Review [115]	Web of Science
33	Eleftherakis, D. and Vicen-Bueno, R.	2020	Sensors to Increase the Security of Underwater Communication Cables: A Review of Underwater Monitoring Sensors [2]	Web of Science
34	Carrera, E. V. and Paredes, M.	2020	Analysis and Evaluation of the Positioning of Autonomous Underwater Vehicles Using Acoustic Signals [116]	Web of Science
35	Langreck, J., Wong, H., Hernandez, A., Upton, S., McDonald, M., Pollman, A., and Hatch, W.	2021	Modeling and Simulation of Future Capabilities With an Automated Computer-Aided Wargame [117]	Web of Science
36	Chen, H., Nelson, C., Walker, O., and Boccarossa, J.	2019	LED Communicator in Various Underwater Environments [118]	Web of Science
37	Helgerson, D. A.	2021	Systems Engineering in Naval Ship Design Introduction [119]	Web of Science

(Continues)

Index	Author(s)	Year	Title	Search category
38	Arnold, R. D. and Wade, J. P.	2015	A definition of Systems Thinking: A Systems Approach [17]	Scopus
39	Di Ciaccio, F. and Troisi, S.	2021	Monitoring Marine Environments With Autonomous Underwater Vehicles: A Bibliometric Analysis [120]	Web of Science
40	Lopes, P., Silva Da Pires, P., and Moreira, M.	2018	Design Challenges of a Maritime Multipurpose Unmanned Vehicle [88]	Scopus
41	O'Rourke, R.	2022	Navy Large Unmanned Surface and Undersea Vehicles: Background and Issues for Congress [26]	US Congressional Research Service
42	Aruna Jacintha, T. and Jaya, T.	2022	Optimization of Adaptive Queuing System with Priority-Based Scheduling in Underwater Sensor Networks [121]	Scopus
43	Jain, U. and Hussain, M.	2021	Security Mechanism for Maritime Territory and Frontier Surveillance in Naval Operations Using Wireless Sensor Networks [59]	Scopus
44	Courts, M. and Broadbent, C.	2018	The Implications of Adaptability, Flexibility and Modularity for Royal Navy Warship Design [89]	Scopus
45	O'Rourke, R.	2022	China Naval Modernization: Implications for U.S. Navy Capabilities-Background and Issues for Congress (Updated) [11]	US Congressional Research Service
46	Clark, B., Cropsey, S., and Walton, T. A.	2020	Sustaining the Undersea Advantage: Disrupting Anti-Submarine Warfare Using Autonomous Systems [10]	Google Scholar
47	Toti, W. J.	2014	The Hunt for Full-Spectrum ASW [122]	Google Scholar
48	Clark, B., Haynes, P., McGrath, B., Hooper, C., Sloman, J., and Walton, T. A.	2017	Restoring American Seapower: A New Fleet Architecture for the United States Navy [36]	Google Scholar
49	Office of the Under Secretary of Defense	2019	Fiscal Year (FY) 2020 Department of Defense (DoD) Fixed Wing and Helicopter Reimbursement Rates [39]	Google Scholar
50	Holler, R. A.	2014	The Evolution of the Sonobuoy From World War II to the Cold War [123]	Google Scholar
51	Liedman, S. R.	2017	Taming Sea Dragons: Maintaining Undersea Superiority in the Indo-Asia-Pacific Region [37]	Google Scholar
52	McCargar, R. and Zurk, L. M.	2013	Depth-Based Signal Separation With Vertical Line Arrays in the Deep Ocean [124]	Google Scholar
53	Department of the Navy	2020	Department of Defense Fiscal Year (FY) 2021 Budget Estimates: Other Procurement, Navy [40]	US DoD Website
54	Whitman, E. C.	2005	Sosus: The "Secret Weapon" of Undersea Surveillance [125]	Google Scholar
55	Hopper, M. and Stave, K. A.	2008	Assessing the Effectiveness of Systems Thinking Interventions in the Classroom [126]	Google Scholar
56	Richmond, B.	1994	Systems Dynamics/Systems Thinking: Let's Get on With It [64]	Google Scholar
57	Squires, A., Wade, J., Dominick, P., and Gelosh, D.	2011	Building a Competency Taxonomy to Guide Experience Acceleration of Lead Program Systems Engineers [65]	Google Scholar
58	Stave, K. and Hopper, M.	2007	What Constitutes Systems Thinking? A Proposed Taxonomy [127]	Google Scholar

(Continues)

TABLE A.1 | (Continued)

Index	Author(s)	Year	Title	Search category
59	Wade, J.	2011	Systems Engineering: At the Crossroads of Complexity [128]	Google Scholar
60	O'Rourke, R.	2023	Navy Force Structure and Shipbuilding Plans: Background and Issues for Congress [28]	US Congressional Research Service
61	Clark, B., Walton, T. A., and Cropsey, S.	2020	American Sea Power at a Crossroads: A Plan to Restore the US Navy's Maritime Advantage [38]	Google Scholar
62	Hunt, J.	2013	Global Inventory of AUV and Glider Technology Available for Routine Marine Surveying [42]	Google Scholar
63	Australian Communications and Media Authority	2007	Submarine Cable Declaration 2007 [129]	Australian Federal Register of Legislation
64	Patel, R.	2007	Surveillance of Marine Resources by Use of Stationary Platforms and Autonomous Underwater Vehicle (AUV) [130]	ProQuest
65	Brown, G., Kline, J., Thomas, A., Washburn, A., and Wood, K.	2011	A game-Theoretic Model for Defense of an Oceanic Bastion Against Submarines [131]	Google Scholar
66	Song, A., Stojanovic, M., and Chitre, M.	2019	Underwater Acoustic Communications: Where We Stand and What Is Next? [46]	Google Scholar
67	Lilley, R.	2014	Recapture Wide-Area Anti-Submarine Warfare [132]	ProQuest
68	Australian Naval Institute and University of New South Wales	2022	Protecting Australian Maritime Trade [1]	Not For Profit
69	Department of Defence	2023	National Defence: Defence Strategic Review [18]	Australian Department of Defence Website
70	Department of Defence	2020	Force Structure Plan 2020 [3]	Australian Department of Defence Website
71	Geoscience Australia	2023	Oceans and Seas [4]	Geoscience Australia Website
72	United Nations	1982	United Nations Convention on the Law of the Sea (UNCLOS) [5]	United Nations Website
73	Australian Maritime Safety Authority	2022	Australia's Search and Rescue Region [6]	AMSA Website
74	International Maritime Organisation	1979	International Convention on Maritime Search and Rescue [7]	IMO Website
75	Whitehead, J.	2015	Search and Rescue in Australia [8]	Google Scholar
76	Savitz, S., Blickstein, I., Buryk, P., Button, R. W., DeLuca, P., Dryden, J., Mastbaum, J., Osburg, J., Padilla, P., Potter, A., Price, C. C., Thrall, L., Woodward, S. K., Yardley, R. J., and Yurchak, J. M.	2013	US Navy Employment Options for Unmanned Surface Vehicles (USVs) [20]	Google Scholar
77	Button, R. W., Kamp, J., Curtin, T. B., and Dryden, J.	2009	A Survey of Missions for Unmanned Undersea Vehicles [21]	Google Scholar
78	Martin, B., Tarraf, D. C., Whitmore, T. C., DeWeese, J., Kenney, C., Schmid, J., and DeLuca, P.	2019	Advancing Autonomous Systems: An Analysis of Current and Future Technology for Unmanned Maritime Vehicles [15]	Google Scholar

(Continues)

TABLE A.1 | (Continued)

Index	Author(s)	Year	Title	Search category
79	US Department of the Navy	2021	Unmanned Campaign Framework [41]	US DoD Website
80	Kordahi, M., Rapp, R., Stix, R., Sheridan, S., Irish, O., Wall, D., Waterworth, G., Perrat, B., Wilson, S., and Holden, S.	2019	Global Trends in Submarine Cable System Faults 2019 Update [44]	Google Scholar
81	US Congress	2022	National Defense Authorization Act for Fiscal Year 2023 [62]	US Legislation
82	US Senate Appropriations Committee	2022	FY2023 Department of Defense Appropriations Act [27]	US Legislation
83	LaGrone, Sam	2022	Navy Rethinking Medium Unmanned Surface Vehicle After Middle East Tests, Says CNO Gilday [61]	News Website
84	Kenney, C. M.	2022	Iran's Attempted Drone Thefts Highlight Challenges of Protecting Unmanned Vessels at Sea [60]	News Website
85	Royal Australian Navy	2023	The Fleet [9]	Australian Department of Defence Website
86	US Department of Defense	2023	Department of Defense Releases the President's Fiscal Year 2024 Defense Budget [24]	US DoD Website
87	Department of Defence	2023	Portfolio Budget Statements 2023–24 [22]	Australian Department of Defence Website
88	Kirk-Wade, E.	2024	UK Defence Spending [23]	House of Commons Library
89	Rogers, E. B. and Mitchell, S. W.	2021	MBSE Delivers Significant Return on Investment in Evolutionary Development of Complex SoS [90]	Google Scholar
90	INCOSE, the Institute of Electrical and Electronics Engineers Systems Council (IEEE-SYSC), and Stevens Institute of Technology	2023	Systems Engineering Body of Knowledge (SEBoK) [16]	Book
91	Gharajedaghi, J.	2012	Systems Thinking: Managing Chaos and Complexity: A Platform for Designing Business Architecture [63]	Book
92	American National Standards Institute (ANSI) and Electronic Industries Alliance (EIA)	2003	Processes for Engineering a System (ANSI/EIA 632) [67]	Standard
93	Institute for Electrical and Electronic Engineers (IEEE)	2005	Application and Management of the Systems Engineering Process (IEEE 1220) [68]	Standard
94	International Organization for Standardization (ISO), International Electrotechnical Commission (IEC), Institute of Electrical and Electronics Engineers (IEEE)	2023	Systems and Software Engineering—System Life Cycle Processes (ISO/IEC/IEEE 15288) [69]	Standard
95	Blanchard, B. S. and Fabrycky, W. J.	2006	Systems Engineering and Analysis [66]	Book
96	Maier, M. W. and Rechtin, E.	2009	The Art of Systems Architecting [70]	Book

(Continues)

TABLE A.1 | (Continued)

Index	Author(s)	Year	Title	Search category
97	Cloutier, R.	2019	2018 Model Based Systems Engineering Survey [73]	Google Scholar
98	Object Management Group	2017	Systems Modeling Language (SysML) Version 1.5 [72]	Standard
99	Friedenthal, S., Moore, A., and Steiner, R.	2015	A practical Guide to SysML: The Systems Modeling Language [71]	Book
100	Loerch, A. G. and Rainey, L. B.	2007	Methods for Conducting Military Operational Analysis [77]	Book
101	Mackertich, N. and Cleotelis, D.	2006	How Do We Win This Game When the Rules Keep Changing? A Case for the Increased Application of Design for Six Sigma in Systems Engineering [85]	Google Scholar
102	Bass, L., Clements, P., and Kazman, R.	2013	Software Architecture in Practice [86]	Book
103	Mackertich, N., Kraus, P., Mittelstaedt, K., Foley, B., Bardsley, D., Grimes, K., and Nolan, M.	2017	IEEE Computer Society/Software Engineering Institute Watts S. Humphrey Software Process Achievement Award 2016: Raytheon Integrated Defense Systems Design for Six Sigma Team [87]	Google Scholar
104	Fletcher, J. L. and Niewood, E. H.	2023	Starting Simple With JADC2 [133]	Google Scholar
105	Stewart, M. S., Pavlos, J., and Boat, E.	2006	A Means to Networked Persistent Undersea Surveillance [134]	Google Scholar
106	Meadows, D. H.	1989	System Dynamics Meets the Press [74]	Web of Science
107	Meadows, D. H. and Wright, D.	2008	Thinking in Systems: A Primer [75]	Book
108	The Association for Uncrewed Vehicle Systems International (AUVSI)	2023	Uncrewed Systems & Robotics Database (USRD) [43]	Not For Profit
109	Naval Sea Systems Command	2020	Unmanned Maritime Autonomy Architecture (UMAA) Compliance Specification [55]	Standard
110	PMS 406 Unmanned Maritime Systems	2019	Unmanned Maritime Autonomy Architecture (UMAA) Architecture Design Description (ADD) [56]	Standard
111	He, Y., Wang, D. B., and Ali, Z. A.	2020	A review of Different Designs and Control Models of Remotely Operated Underwater Vehicle [50]	Web of Science
112	Brook-Holland, L.	2024	AUKUS Pillar 2: Advanced Military Progammes [31]	House of Commons Library
113	Marles, R.	2023	AUKUS Defense Ministers Meeting Joint Statement [32]	Australian Department of Defence Website
114	Department of the Prime Minister and Cabinet	2022	Fact Sheet: Implementation of the Australia—United Kingdom—United States Partnership (AUKUS) [29]	Australian Department of Defence Website
115	Parrish, P. and Nicastro, L. A.	2023	AUKUS Pillar 2: Background and Issues for Congress [30]	US Congressional Research Service
116	Clark, B. and Patt, D.	2023	Raising AUKUS's Second Pillar: Integrating Uncrewed and Other Emerging Technologies into the Australian Defence Forces [33]	Google Scholar
117	US Department of Defense	2023	Mission Engineering Guide [84]	US DoD Website

(Continues)

TABLE A.1 | (Continued)

Index	Author(s)	Year	Title	Search category
118	G. E. M. Abro, S. A. B. M. Zulkifli, M. S. A. Khan, and V. S. Asirvadham	2021	Single dimension-Based Fuzzy Sliding Mode Control Design for the Stabilisation of Underactuated Unmanned Underwater vehicle [52]	Web of Science
119	Z. A. Ali, X. Li, and M. A. Tanveer	2021	Controlling and Stabilizing the Position of Remotely Operated Underwater Vehicle Equipped With a Gripper [53]	Web of Science
120	J. Doornbos, K. E. Bennin, Ö. Babur, and J. Valente	2024	Drone Technologies: A Tertiary Systematic Literature Review on a Decade of Improvements [13]	Web of Science
121	K. Teixeira, G. Miguel, H. S. Silva, and F. Madeiro	2023	A Survey on Applications of Unmanned Aerial Vehicles Using Machine Learning [14]	Web of Science
122	T. R. Beegum, M. Y. I. Idris, M. N. B. Ayub, and H. A. Shehadeh	2023	Optimized Routing of UAVs Using Bio-Inspired Algorithm in FANET: A Systematic Review [54]	Web of Science
123	M. A. Tahir, I. Mir, and T. U. Islam	2023	A Review of UAV Platforms for Autonomous Applications: Comprehensive Analysis and Future Directions [51]	Web of Science
124	Z. A. Zukarnain, O. A. Amodu, C. Wenting, and U. A. Bukar	2023	A Survey of Sybil Attack Countermeasures in Underwater Sensor and Acoustic Networks [47]	Web of Science
125	D. A. Eisenberg, D. L. Alderson, M. Kitsak, A. Ganin, and I. Linkov	2018	Network Foundation for Command and Control (C2) Systems: Literature Review [57]	Web of Science
126	O. B. Osoro and E. J. Oughton	2021	A Techno-Economic Framework for Satellite Networks Applied to Low Earth Orbit Constellations: Assessing Starlink, OneWeb and Kuiper [92]	Web of Science
127	E. J. Oughton, K. Katsaros, F. Entezami, D. Kaleshi, and J. Crowcroft	2019	An Open-Source Techno-Economic Assessment Framework for 5G Deployment [93]	Web of Science
128	E. J. Oughton and A. Jha	2021	Supportive 5G Infrastructure Policies Are Essential for Universal 6G: Assessment Using an Open-Source Techno-Economic Simulation Model Utilizing Remote Sensing [94]	Web of Science