RAND AUSTRALIA

Research Report

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Supporting the Royal Australian Navy's Campaign Plan for Robotics and Autonomous Systems

Emerging Missions and Technology Trends

A rapidly evolving technology landscape provides Australia with many opportunities to apply robotics, autonomous systems and artificial intelligence (RAS-AI) in the defence context. In the maritime domain, specifically, RAS-AI technologies have been recognised as key enablers of future maritime capabilities. Consequently, the Royal Australian Navy (RAN) has recently launched a strategy establishing a framework for developing and employing RAS-AI out to 2040 (RAN, 2020).

The delivery of the RAN's *RAS-AI Strategy 2040* is to be facilitated through a campaign plan that will seek to identify the activities necessary to assist the RAN in achieving its ambitions. The RAND Australia research team is supporting the RAN in this endeavour by building an evidence base to help identify and shape those activities. This support has provided research on experimentation, innovation, human-machine teaming, emerging technologies and other areas, such as the potential role of industry and academia in helping the RAN leverage RAS-AI capabilities.

KEY FINDINGS

- A rapidly evolving RAS-AI technology landscape has enabled an expansion of uncrewed aerial, surface and underwater vehicle missions in the maritime domain.
- Across all platforms, maritime RAS-AI missions are likely to expand in the near term, enabled by advances in several key technology areas.
- RAS-AI missions may significantly change in the far term, though technological as well as non-technological barriers may constrain certain missions.

From a technological perspective, there are various opportunities for the RAN to leverage RAS-AI in different missions to achieve its ambitions in the maritime domain and improve how it operates (Dortmans et al., 2021). RAS-AI technologies span uncrewed aerial, surface and underwater vehicles and enabling technologies—although the *RAS-AI Strategy 2040* focuses predominately on autonomous systems and only on artificial intelligence (AI) insofar as it enables those autonomous systems to operate independently. As the strategy points out, significant advances that could enable or otherwise shape future opportunities are expected in these technologies over the next two decades (RAN, 2020).

To support the formulation of a campaign plan to advance the implementation of the RAN's *RAS-AI Strategy 2040*, this report describes the current landscape and trajectory of maritime RAS-AI technologies in the near and long term (out to 2040). The team primarily focused on uncrewed aerial vehicles (UAVs), uncrewed surface vehicles (USVs) and uncrewed underwater vehicles (UUVs). In line with the emphasis in the RAN's *RAS-AI Strategy 2040* on autonomous systems, the research team focused on advances in missions and technologies underpinning uncrewed platforms and autonomous systems rather than a wider integration of AI in maritime operations (e.g., on crewed platforms or to support back-office functions at naval installations on land). The authors focused on three underpinning research objectives for this research:

- Characterise the landscape of RAS-AI technologies and missions in the maritime domain.
- Characterise the likely trajectory of RAS-AI technologies and missions in the maritime domain out to 2040.
- Identify the likely technological enablers shaping future RAS-AI missions in the maritime domain.

The remaining sections of this report describe the high-level findings from this research. First, the methodology used in the development of this report is described. Next, high-level findings regarding the mission and technology trends for each category of RAS-AI platforms (i.e., uncrewed aerial, surface and underwater platforms) are presented and high-level findings in relation to advances in enabling technologies are outlined. This is followed by concluding remarks.

Abbreviations

AI	artificial intelligence
ASW	anti–submarine warfare
C2	command and control
C4ISR	command, control, communications, computers, intelligence, surveillance and reconnaissance
CBRN	chemical, biological, radiological and nuclear
ECM	electronic counter measures
EW	electronic warfare
ISR	intelligence, surveillance and reconnaissance
MCM	mine counter measure
ML	machine learning
RAN	Royal Australian Navy
RAS-AI	robotics, autonomous systems and artificial intelligence
S&T	science and technology
SAR	search and rescue
UAV	uncrewed aerial vehicle
USV	uncrewed surface vehicle
UUV	uncrewed underwater vehicle

Methodology

The research team used a mixture of qualitative methods to address the project's overarching research objectives. Specifically, the team produced qualitative evidence by generating a database of maritime RAS-AI technologies through a two-pronged analytical approach that consisted of the following:

- *A top-down, mission-centred activity* that was carried out through desk research and review of open-source literature. This was done with the intention of capturing key high-level findings from existing literature regarding technology maturity and emerging technology trends for RAS-AI in different mission contexts. Specifically, the research team reviewed past RAND Corporation reports on RAS-AI technologies along with relevant open-source

academic and grey literature (i.e., government publications and conference proceedings) identified through searches in relevant databases.
- *A bottom-up, technology-driven activity* that leveraged RAND Europe's horizon-scanning database of emerging science and technology (S&T) trends to identify key advances in emerging technologies to complement the desk research and add granularity to the analysis.[1] The research team used relevant search terms in the database to produce a long list of new and emerging RAS-AI technologies.

Drawing on data collected through this two-pronged analytical approach, the research team conducted crosscutting analysis to identify high-level mission and technology trends.

The analysis and findings presented in this report were produced with the following assumptions and scope-related constraints:

- The research was conducted under significant time- and resource-related constraints that limited the methodological options available in exploring potential technology and mission-related trajectories. Because of these constraints, an approach focusing on desk research and a broad mapping of open-source data was prioritised over other futures and foresight methodologies (e.g., development of technology and mission scenarios or more in-depth engagement with relevant stakeholders). As a result, this research is intended to provide nuance and further depth to the RAN's existing understanding of technology and mission trajectories; the team did not explore a wider variety of potentially disruptive future RAS-AI missions, technologies and tactics through which these technologies could be used. It should be recognised that the RAS-AI missions and technology landscape is characterised by a level of uncertainty that this research only partially explores.
- The analysis of the technology trends was guided by the taxonomy of current and potential future RAS-AI missions in the maritime domain (see Table 1) and enabling technologies (see Table 2) provided in the RAN's *RAS-AI Strategy 2040*.[2] The two taxonomies represent the RAN's expectations for how (and by when) RAS-AI systems capabilities might contribute to Navy missions, assuming that the RAN chooses to invest in these capabilities. The research team adopted the existing taxonomies provided in the RAN's strategy to facilitate interpretation of the mission and technology trends and to ensure coherence of the evidence base, though examples of additional potential RAS-AI missions are provided in footnotes.
- The research team did not make explicit assumptions concerning the size or cost of RAS-AI systems used in the near or far term. However, to ensure coherence of the analysis, the team sought to provide greater detail about systems that appeared, based on the RAN's RAS-AI strategy, to be of likely interest (e.g., tactical UAV capabilities). It should be noted that the nature of technical and financial enablers and barriers could vary depending on the size and complexity of the system being considered. Similarly, systems of different sizes might be suited for different mission contexts. For example, medium-sized USVs might be preferred for intelligence, surveillance and reconnaissance (ISR); developments of large USVs might focus on anti–submarine warfare (ASW).
- The analysis is intended to illustrate the breadth of S&T developments occurring across all types of RAS-AI technologies and the technological and wider operational opportunities stemming from complementary S&T advances. The research also covers common enabling technologies that could underpin key future RAS-AI missions. The analysis did not seek to assess which RAS-AI missions might be best prioritised or to provide a road map for implementation. Further research would be required for a detailed examination of the impact or implementation of individual technologies of interest to the RAN. The conclusions at the end of this report provide further reflections that might assist the RAN in this endeavour.

TABLE 1

Taxonomy of RAS-AI Technology Missions in the Maritime Domain

Vehicle	Today[a]	Likely Near Term[b]	Potential Far Term[c]
UAVs[d]	• Communications relay • ISR in permissive environments • CBRN detection • Small-scale cargo delivery in permissive environments	• Cargo delivery in hostile environments • Maritime interdiction • ASW tracking • Air defence	• C4ISR in a contested environment • Medium-enduring ISR • Counter surface vessel • Ship-in-port antipersonnel operations
USVs	• ISR in permissive environments • Mine sweeping • SAR • Bathymetry and hydrography[e]	• Mine countermeasures • Armed escort • Military deception; EW • ASW sanitisation • Air and missile defence (sensing, nonkinetic operations) • Counter fast attack craft (remote operations)	• ISR in hostile environments • Mine laying • Counter fast attack craft (autonomous) • Ground attack • Air and missile defence (kinetic operations)
UUVs	• Mine countermeasures • Counter deployed sensor; sensor array • Near-land monitoring • Oceanography • Undersea infrastructure monitoring • Inspection; identification of hulls and piers • Communications, navigation and networking • UUV decoys	• Tracking submarines in support of ASW • Long-endurance ISR • Navigation and networking • Counter surface vessel	• Short timeline TCS from a submerged UUV against a land-based target • Self-propelled mine swarms (autonomous)

SOURCE: RAN, 2020.

NOTE: C4ISR = command, control, communications, computers, intelligence, surveillance and reconnaissance; CBRN = chemical, biological, radiological, nuclear; EW = electronic warfare; SAR = search and rescue; TCS = time critical strike.

[a] This is defined as 'missions that could be accomplished with today's technology, albeit with the need for adaptation to military applications or the maritime environment' (RAN, 2020, p. 11).

[b] This is defined as 'missions that could be accomplished with near-term technologies and are expected to be available for projects currently in planning' (RAN, 2020, p. 11).

[c] This is defined as 'missions that can be accomplished in the far term and will require significant technological development' (RAN, 2020, p. 11).

[d] Other potential missions could involve air-to-air refuelling and countersubmarine engagements (e.g., through airdropping of torpedoes from UAVs).

[e] The research team added bathymetry and military survey to this list to reflect the options being considered under SEA 1905 Phase 1.

Technology Mission Trends

Although the recent technology development, experimentation and acquisition experiences of navies around the world have demonstrated a variety of maritime missions for which RAS-AI might be suited (Dortmans et al., 2021), Australia's development and deployment of RAS-AI for the RAN is less mature. However, the RAN plans to invest in and expand its capabilities in this area (comprising RAS-AI systems, workforce, data infrastructure and training) and integrate those capabilities into the broader fleet alongside crewed vessels and aircraft.

Evidencing this growing ambition and interest, the RAN's *RAS-AI Strategy 2040* lists several current and potential missions for RAS-AI across three principal types of platforms: UAVs, USVs and UUVs (see Table 1). The following sections expand on the identified mission and technology trends for each category.

UAVs

Existing international efforts to develop maritime RAS-AI include the use of UAVs for a growing variety of missions. These efforts often treat UAVs as a 'force multiplier' that offers, among other benefits, improved persistence on task; increased mass; and improved force resilience, range and ISR capabilities (Allison, 2021). In Australia, the *2020 Force Structure Plan* has recognised this through characterising maritime UAVs as a priority investment area for the RAN.

A particular focus of the *2020 Force Structure Plan* has been tactical maritime UAVs, underpinned by a planned investment of up to $1.3 billion over

TABLE 2

Taxonomy of RAS-AI Enabling Technologies

Field	Today[a]	Likely Near Term[b]	Potential Far Term[c]
Autonomy	Able to carry out simple and well-defined missions with human oversight	Able to independently carry out missions using general information and automatically adapt to changing circumstances	
Sense	Object recognition, full spectrum sensing	Additional sensing, integrated perception and contextual cognition	Scene understanding
Think or decide	Rule-based decisions, earning from training data	Anomaly detection, values-based reasoning	Abstraction, judgement, strategic and ideas-based reasoning
Act	Routing navigation, obstacle avoidance	Agile navigation and obstacle avoidance	Navigation in dense and dynamic environments
Team	Human oversight of machines	Emergent swarming behaviour,[d] armed wingman	Fully adaptive coordinated swarm, understanding of intent
Interoperability; communications	Current C2 standards, stovepiped systems Centralised data management	Seamless C2 support for human-machine and machine-machine collaboration, onboard data processing[e] Smart push of data to the right user	
Secure computing; networking	Cyberdefence in depth Stovepiped RF systems elected LPI and LPD	Autonomous cyber defence, cyber-resilient design Efficient and agile use of RF spectrum, pervasive LPI and LPD, self-healing mesh networking paths[e]	
Other enabling technologies	Propulsion Energy storage and harvesting Sensor technology (size, type, sensitivity, resolution) Materials and methods to enable long-term remote operations on and below the surface Underwater communications		

SOURCE: RAN, 2020.

NOTE: C2 = command and control; LPD = low probability of deception; LPI = low probability of interception; RF = radio frequency.

[a] This encompasses ‘mature technologies available for integration into projects, albeit with the need for adaption to military applications or the maritime environment’ (RAN, 2020, p. 10).

[b] This encompasses ‘technologies that are on a path to maturity and are expected to mature in time for projects currently in planning’ and might be integrated in military applications by 2030 (RAN, 2020, p. 10).

[c] This encompasses ‘technologies that will require further research and development before their application are fully understood and available for military use’ and thus might be integrated in military applications by 2040 (RAN, 2020, p. 10). Potential additional technologies to mature in the far term might include set-and-forget autonomous weapons systems.

[d] For the purpose of this research, swarms are defined as ‘multi-robot systems within which robots coordinate their actions to work collectively towards the execution of a goal’ (Ekelhof and Paoli, 2020, p. 24).

[e] These technologies are more likely to mature in the near term rather than far term.

the next two decades (Australian Department of Defence, 2020b, p. 45; Chanthadavong, 2020). The initial phase of this capability development program is being defined and procured under SEA 129 Phase 5. Block 1 will add capability—particularly communications and ISR support—to ANZAC-class frigates and the Arafura-class offshore patrol vessel. This block will be seeking to achieve operational capability in the mid-2020s. Block 2 will focus on supporting the new Hunter-class frigates as they come into service starting around 2030 and is anticipated to consist of a broader variety of RAS-AI missions to complement the enhanced C4ISR capabilities that this new class of frigate is expected to offer (July, 2020). At least initially, this program will be the focal point for delivering maritime UAV capabilities, with payloads developed to operate with small fixed- and rotary-winged autonomous platforms.

Current UAV Technologies and Capabilities

Although the focus of tactical UAV capability development under these programs has been on C4ISR in permissive environments, advances in the maturity of UAV technologies are enabling the deployment of UAVs for other important missions, such as **CBRN detection and small-scale cargo delivery in per-**

missive environments. In these contexts, the use of UAVs internationally has grown in recent years, particularly because of increasing (though still relatively limited) reach, adaptability and survivability of UAVs (e.g., to navigate harsh and complex environments). Some recent technology advances in relation to these missions have been

- *improvement of UAV-based communications relays* through improvements in wireless communications, ground-to-relay link optimisation, maximisation of uplink network data rates and the quality of uplink communications and network performance for end-to-end and multiuser communications (Zhan, Yu and Swindlehurst, 2011)
- *integration of advanced sensing capabilities onto UAVs* (such as radar, acoustic and optical sensors that can sense with greater accuracy) and multisensor data fusion to enable the integration of multiple data streams (Uppal, 2016)
- *development of UAVs with improved rotary or jet-powered vertical take-off and landing technology,* which enables UAVs to travel at higher speeds and achieve greater survivability (such as through obstacle avoidance) when being employed in counterpiracy, SAR and cargo delivery missions (Alexander, 2018; 'Silent Arrow Cargo Delivery . . . ', 2019).

Despite these advances, the maturity of current systems is still limited in several key regards, such as limited endurance, ability to carry large payloads and travel at high speeds and defence against jamming and other forms of nonkinetic attack (Dortmans et. al., 2021). These limitations emphasise the key role of such enabling technologies as propulsion, energy harvesting and sensing (discussed in the next major section). Although these areas pose significant barriers to key RAS-AI missions today, they could also enable rapid (and potentially disruptive) future developments in RAS-AI missions should significant advances be made in enabling technological areas.

Potential Near-Term UAV Missions

In the near term, maturing technologies might enhance UAVs' capabilities for more-complex missions, such as **cargo delivery in contested environments, maritime interdiction, ASW tracking and air defence**. These technology-dependent missions rely particularly on advances in the following areas:

- *Ability of UAVs to navigate complex, cluttered and contested environments:* Enhanced obstacle and collision avoidance (e.g., sense and avoid) and advances in UAV sensing capabilities to detect potential targets (e.g., other UAVs, ships, small boats or submarines) from greater distances are both likely to serve as key technology enablers in this area. Particularly for ASW and air defence missions, maturing UAV technologies could draw on advancements in acoustic and nonacoustic sensing and on integration of deep learning to improve automated feature extraction and the situational awareness capabilities of UAVs (Carrio et al., 2017).
- *Operational reach and endurance:* Future missions will require enhancing the reach and endurance of UAVs to engage in long-distance or loitering missions (e.g., for maritime interdiction). This consists of a need to (1) transit between designated search or operational areas and distant launch and recovery points, (2) operate at greater speeds with larger payloads and (3) function with enhanced agility to make rapid course alterations or evade incoming munitions (Kaymal, 2016; Tate, 2016). This will be key to enabling UAVs to operate in and return from hostile environments while delivering a variety of useful effects through their onboard payloads. Advances in heterogenous teaming (e.g., enabling UAVs to operate from USVs) could also facilitate greater reach and endurance for UAVs (e.g., through allowing autonomous launch and landing of UAVs from deployed USVs).
- *Swarming:* Future capability developments are likely to target collaborative, highly manoeuvrable multivehicle systems. This will require advances in swarming technologies to enable autonomous collaborative operation of homogeneous and heterogeneous systems (Ekelhof and Persi Paoli, 2020). Although collaborative

homogeneous systems could help increase mass of counter-UAV systems (e.g., to help identify and respond to potential incoming threats), heterogeneous swarms could—as mentioned in the previous section—help extend the reach of UAVs for such missions as ISR and cargo delivery.

Potential Far-Term UAV Missions

Building on these potential near-term advances, other missions could become feasible over time, depending largely on how quickly progress is made in the key enabling technology areas already highlighted (i.e., operating in complex environments, enhancing reach and endurance and swarming). Such missions are **C4ISR in contested environments, medium-enduring ISR and countersurface vessel missions**. Reflecting the increasingly contested nature of environments in which these missions are carried out, additional technical enablers might be needed. Advances in signal processing and electronic countermeasures (ECM) could, for example, enable UAVs to operate in a contested electromagnetic environment. Enabling the use of UAVs in ISR missions in contested environments is also likely to require further advances in autonomy, propulsion, stealth and survivability, energy management and recharging technologies (e.g., UAV perching). These advances could involve the development of novel kinds of propulsion systems and energy sources (e.g., UAVs leveraging solar power and hydrogen fuel cells) (Baerson, 2021).

In sum, several crosscutting technological enablers can be identified that will support the increased use of UAVs in existing missions (such as SAR or ISR in permissive environments) and in new missions and tasks in more-hostile environments. The key examples are summarised in the text box.

It should be noted that, beyond technological advances, realising the envisaged use of UAVs for Navy missions in contested environments will also depend on **nontechnical factors, such as regulation, policy and ethics**. This is especially sensitive as regards the use of RAS-AI for missions involving the use of force. Nontechnical factors are therefore also likely to shape the timelines in which certain offensive missions are realised or whether they ever are realised at all.

Key Technology Enablers: UAVs

Communications and information exchange: Developing communication protocols and improving the quality of information exchange that can enable UAVs to autonomously navigate complex environments and harsh terrains; enhancing data transmission capabilities to enable UAVs to communicate outside their local network; improving communications to mitigate the need for enhanced autonomy[a]

Survivability (e.g., obstacle and collision avoidance): Improving the survivability of UAVs in congested airspace or complex terrain, such as littoral environments, through enhanced obstacle avoidance capabilities (e.g., autonomous obstacle avoidance through such computational navigation models as nonlinear predictive control) or leveraging of biomimicry to create innovative UAV designs (e.g., AI-enabled soft robotic systems which are highly resilient to external impacts)[b]

Swarming and multivehicle cooperation: Developing machine learning and advanced swarming technologies, which will be critical to identifying and targeting specific targets at longer distances and to creating a greater variety of applications (such as offensive and defensive missions)

Propulsion and energy management: Leveraging innovative propulsion designs, such as those leveraging biomimicry and novel energy sources (e.g., solar power, lasers and hydrogen fuel cells) to enable long-duration missions.

[a] Wu et al., 2019.

[b] Brogan, 2018; and Fadelli, 2020.

It could be that Australia opts not to realise the full potential applications of RAS-AI technologies for certain missions (e.g., because of legal and ethical concerns) while other competitors (both state and nonstate actors) choose to be less constrained. In such a scenario, the RAN will need to consider how to mitigate any capability gaps that arise from these **differing rules of engagement and approaches to using RAS-AI.**

There is also a technical dimension to this legal and policy question: The Navy will need to consider how best to employ RAS-AI to help it **deter and defeat adversaries' own RAS-AI.** RAS-AI might be among the most efficient means of dealing with adversaries' RAS-AI, including hostile swarming attacks that might otherwise overwhelm the defences of crewed platforms. There might be fewer legal and ethical constraints on the RAN developing and deploying RAS-AI to counter and destroy other uncrewed platforms—given the minimised risk to life and the operational imperatives involved—much as close-in weapon systems are already used on Navy vessels to target and destroy incoming missiles with significant autonomy. In this context, it should be recognised the future S&T landscape might feature highly disruptive, unconventional, asymmetric, breakthrough or 'surprise' adversarial applications of RAS-AI that will require close monitoring by the RAN to maximise the utility of its own uncrewed or autonomous capabilities.

The RAN will similarly need to consider the **implications for interoperability** if its approach to RAS-AI technologies and their applications diverges substantially from the approach taken by allies and partners. This applies not only to UAVs but also across the other platform categories discussed in this report.

USVs

Australia's recently released *2020 Defence Strategic Update* recognised the growing threat that mines and associated new technologies pose in geographic areas of strategic interest (Australian Department of Defence, 2020a). As a result, the Australian government has noted the need to consider the opportunities that USVs might provide in mine countermeasures (MCM) missions. The government therefore intends to bring forward the acquisition of an MCM capability to the mid-2020s rather than wait until the mid-2030s for an uncrewed capability to replace the Huon-class minehunters.[3] As currently described, the intent is to use a mothership, to be based on the Arafura-class offshore patrol vessel, and use standoff systems to deliver mine clearance and perform bathymetric tasks. Central to this approach—and to other similar approaches from Australia's international allies[4]—is employing a mixture of small USV and UUV capabilities alongside a crewed mothership (Vavasseur, 2021).

Current USV Technologies and Capabilities

USVs' current level of maturity allows vehicles to be used in support of a variety of navy missions, such as **mine sweeping, bathymetry, ISR in permissive environments, hydrography and SAR.** Several recent technological advances have enabled these RAS-AI missions to be realised, although further maturing of key enabling technologies is likely to continue to play a key role in enhancing the effectiveness of USVs in these and other mission contexts. The key enabling technologies are:

- *Communications, data storage and data analytics:* Such missions as ISR and mine sweeping require capabilities for USVs to transfer, process, store and exploit greater amounts of data. The development of assured and accredited communications between USVs and other vessels (crewed or uncrewed) has therefore played a critical role in enabling USVs to navigate more-complex and more-contested environments, conduct mine sweeping and cooperate with crewed vessels (Savitz et al., 2013). An emerging focus on modularity in conjunction with increasing volumes of data have emphasised opportunities associated with harnessing AI for USV data analytics (GlobalData, 2021).
- *Payloads and modularity:* As USVs are increasingly explored for a wider variety of missions, including through multimission vehicles, many concepts have relied on improvements in USV payloads (e.g., to enable USVs to carry supplies in SAR or replenish-

ment duties or transfer remotely collected data to another platform for processing). As USVs are being matured for multimission deployments, there have also been opportunities to leverage modular robotics or heterogeneous teaming concepts (e.g., integrating an uncrewed capsule within a larger uncrewed platform) to conduct SAR and similar RAS-AI missions more effectively (Matos et al., 2017).

Despite these advances, uses of USVs, including multimission vehicles, remain largely constrained by the reliance on remote control from a crewed platform (e.g., a ship, aircraft or shore station). In part, this is because of existing ethical safeguards implemented in relation to meaningful human oversight: Australia, along with most allies and partners, requires RAS-AI to retain a human operator 'in' or at least 'on the loop' for important decisions, perhaps even for the entire mission (Scharre, 2018). Enduring technical barriers that impede integrating multiple vehicles (i.e., integrating USVs with multiple other USVs or with other uncrewed systems in the air or below the waterline) also present a challenge to USV missions (Matos et al., 2017).

Potential Near-Term Missions and Associated Technology Enablers for USVs

Noting these constraints, potential near-term missions for USVs might include **mine countermeasures, armed escort, military deception and electronic warfare, ASW sanitation, nonkinetic air and missile defence operations and remote counter fast attack craft operations.** Delivering such missions effectively with RAS-AI is likely to rely on the following technological advances (also summarised in the text box):

- *Interoperability:* Advances in interoperability and multivehicle cooperative system designs could increase the effectiveness of mine countermeasure searches or similar tasks carried out by USVs. That's because such advances will allow USVs to place additional sensors in areas of interest and reduce the need for highly reliable or survivable individual platforms. Currently, however, environmental disturbances, uncertainties and communication limitations hinder the abilities of USVs to cooperate operate autonomously in close proximity with other uncrewed and crewed platforms (Liu et al., 2016).
- *Autonomy in complex environments:* Deploying USVs in more-contested environments, such as for armed escort and EW, will require advances in USV autonomy (such as seakeeping and maritime traffic avoidance) and ability of vehicles to self-deploy and self-recover from a communication-limited operating area. Recent advances in underway refuelling and in autonomous platform control and preventative maintenance systems might enhance overall USV autonomy and

Key Technology Enablers: USVs

Interoperability: Interoperability of USVs with a wide variety of crewed and other uncrewed platforms (e.g., UUVs, UAVs, crewed platforms) is a key factor in determining potential future missions. Recent efforts have successfully demonstrated interoperability (e.g., with 'mothership' USVs deploying smaller remotely operated vehicles for subsurface activities (ECA Group, 2019).

Autonomy and optional manning: Future advances in USV missions will be enabled by advancing the ability of USVs to operate autonomously (notably in seakeeping and maritime traffic avoidance) and the optional manning of vessels to (1) mitigate potential challenges with autonomy and (2) enhance mission tailoring and situational awareness.

Multimission systems and modular payloads: Near- and far-term USV missions will require both advances in USV adaptability and availability for rapid configuration and enhanced modularity of payloads.

Enhanced stealth: Solutions for enhanced stealth will be key for such missions as ASW sanitation or ISR in contested environments. USV stealth might be enhanced by new designs (e.g., semisubmersible USVs).

platform availability in the near term (Navy League of the United States, 2021; Scott et al., 2015). Although enhanced autonomy represents a key enabler, potential alternative solutions for missions in complex environments include optional crewing of large USVs to enhance mission tailoring and situational awareness (O'Rourke, 2021). It should be noted that although these alternatives could mitigate potential challenges (including legal and ethical ones) with USV autonomy, designing a platform to be optionally crewed rather than uncrewed could entail design compromises that would likely increase acquisition costs.

- *Payload modularity:* Integrating platforms with modular payloads tailored to specific missions (e.g., EW and strike payloads) and facilitating rapid reconfiguration of mission packages are likely to serve as additional key enablers for many near-term technology missions (O'Rourke, 2021; Scott, 2021). Recent advances, particularly with enabling large USVs to carry such modular payloads, signal progress towards such UUV missions as EW, ASW and air and missile defence (O'Rourke, 2021).
- *Stealth:* Enhanced stealth is a similarly important enabler for many near-term missions, particularly for those requiring USVs to avoid detection by submarines (e.g., in ASW sanitation). In this context, semisubmersible USV designs could serve to enhance stealth, survivability and mission performance. Similar enhancements could arise if USVs had the ability to operate a towed array carrying sonar so that they could take advantage of acoustic propagation conditions and separate acoustic sensors from noisy USV platforms.

Potential Far-Term USV Missions

Building on advances in these areas, potential far-term USV missions might include further deployments of USVs in contested environments and in offensive autonomous and kinetic applications, such as **ISR in hostile environments, mine laying, autonomous counter fast attack operations, ground or surface attack and air and missile defence.** Although advances in these mission contexts are likely to similarly rely on the technological enablers outlined in the text box on the previous page (and on selected additional technical enablers, such as target acquisition), legal, ethical and regulatory challenges also might significantly shape the adoption of increasingly autonomous USVs in attack roles.

UUVs

The employment of UUVs is a topic of ongoing debate in Australia, particularly in relation to how and where these technologies are used. The RAN has taken initial steps to integrate UUVs into its capabilities: The SEA 1905 Phase 1 project, for example, is anticipated to employ small UUVs to support MCM and oceanography. And although it is in its early stages, the SEA 5012 Phase 1—Integrated Undersea Surveillance System project is expected to use UUVs to help detect adversary submarines and to enable C2 for theatre ASW (Australian Department of Defence, 2020b). The Defence Science and Technology (DST) Group is focusing one of its nine STaR (Science, Technology and Research) Shots initiatives on remote undersea surveillance in hopes of rapidly advancing this field over the next decade (DST Group, 2020). Recent discussions in the media have urged Australia to explore acquiring the Orca extra-large UUVs to support undersea warfare capabilities and potentially to employ this vessel as a hedge if there are delays with the Attack-class submarine program or the Collins-class submarine upgrade.[5] Therefore, the size and functionality of UUV capabilities remain under consideration.

Current UUV Technologies and Capabilities

At their current level of maturity, UUVs are available for a wide variety of maritime missions, particularly **MCM, counterdeploying sensors, near-land monitoring, oceanography, undersea infrastructure monitoring, inspection and identification of hulls and piers, communications, navigation and networking and as decoys**. Coupled with improvements in onboard sensors (e.g., distributed sensing), advances in the ability of UUVs to operate at greater depth; over longer ranges; and with increased endurance, speed and payloads have all been key to these missions.

Beyond the current level of maturity, advances in stealth, navigational accuracy, endurance and communications are expected to enhance UUV capabilities in the missions already described. This includes advances in navigation and sensing to enable UUVs to operate at longer distances and in complex (e.g., deep water) environments; advances in imaging and data processing, such as rapid data processing and broadening of parameters that UUVs can capture and measure (e.g., in the context of oceanography); and improvements of energy harvesting and management systems (Wynn et al., 2014). Advances in these areas are likely to be driven not only by military research and development but also by civilian sectors (such as oceanographic institutes and the oil and gas industry), given (1) the 'dual use' nature of UUVs and enabling technologies and (2) the commercial and scientific opportunities associated with employing UUVs on such civilian missions as infrastructure inspection, surveying and civilian oceanography.

Potential Near-Term Missions and Associated Technology Enablers for UUVs

Deploying UUVs far from shore still generally requires a crewed vessel to be present nearby, notably for launch and recovery (Alkonis, 2020), although existing technologies might already enable alternative launch and recovery approaches, such as airdropping UUVs from transport aircraft.[6] Pairing UUVs of different sizes and operating UUVs in denied areas (e.g., through launching them from crewed vessels manoeuvring within denied areas) also pose challenges. Likewise, today's UUVs are hampered by relatively limited endurance and by unresolved barriers that hobble underwater communications, networking and deepwater navigation (Alkonis, 2020). In the near term, addressing these challenges through advances in the areas outlined here and in the text box could enable such UUV missions as tracking submarines in support of ASW, long-endurance ISR, navigation and networking and counter surface vessel missions. Key advances include the following:

- *Data transfer and signal processing:* Such missions as UUV-based tracking of submarines in support of ASW or long-endurance ISR require systems capable of high-bandwidth sensor data transfer and payloads that can accommodate more-sophisticated sensor suites and signal processing. Improving onboard processing power and machine autonomy to sufficient thresholds to reliably separate various kinds of signals from noise at greater distances is also likely to advance submarine tracking and ISR (Brixey-Williams, 2020).
- *Sensing:* Advances in sensor resolution and range, multifrequency measurements and modern acoustic sensor arrays and distributed remote sensing networks are likely to advance UUV capabilities across different

Key Technology Enablers: UUVs

Underwater communications and networking: Underwater communication remains a challenge for UUV-enabled tracking because radio waves are heavily absorbed by water and acoustic signalling is limited by high cost and processing power requirements.

Advanced sensing and data fusion: Advances in sensor payloads (including higher sensor resolution and range), onboard data fusion, signal processing, multifrequency measurements and distributed remote sensing networks are likely to advance key UUV missions, such as deepwater navigation, ASW tracking and long-endurance ISR. Increases in onboard processing power and machine autonomy represent important adjacent technical enablers in this context.

Energy harvesting, power management, propulsion and autonomous refuelling: Advances in energy harvesting and power management (e.g., algorithmic systems), long-enduring propulsion and autonomous refuelling might enable greater UUV operational range.

mission contexts. Advances in sensing could, for example, facilitate linking interoperable crewed and uncrewed platforms together as nodes in a larger system-of-systems, allowing persistent coverage across wider areas (Brixey-Williams, 2020).

- *Swarming:* Swarming capabilities, in which several UUVs collaborate with each other and with other platforms, could enhance the use of UUVs in various missions, such as MCM and submarine tracking in support of ASW. UUV swarming is already being developed, such as exploration of the ability of multivehicle systems to self-arrange in various swarm formations and simultaneously collect data (Lundquist, 2021). Despite these advances, the lack of an underwater communication standard has remained a barrier for UUV swarming compared with collaboration between aerial or surface systems. Additionally, limited range of communications has constrained the potential areas of coverage that could be achieved through swarming (González-García, et al., 2020).
- *Energy harvesting, power management and propulsion:* Missions such as long-endurance ISR will necessarily require UUVs to operate at greater distances, corresponding to the need for advances in energy and power management and in alternative energy-harvesting methods (e.g., from fuel cells), long-enduring propulsion and refuelling. UUVs might leverage advanced algorithmic energy management technologies to enhance energy efficiency through optimising energy consumption. Innovative propulsion designs (such as acoustic propulsion and untethered self-propelling robotics), autonomous recharging or refuelling systems and modular payloads could also enhance the operational range of UUVs up to months (Weydahl et al., 2020).

Potential Far-Term UUV Missions

Similarly to USVs, in the medium and longer term, addressing technical and nontechnical barriers could enable offensive UUV missions, such as **counter surface vessel and time-critical-strike against land-based assets.** From a technological perspective, advances in the integration of payloads and targeting will be needed to enable UUVs to achieve a sufficient sensor-to-shooter timeline and to discriminate reliably between targets and decoys and between military and civilian targets. From the perspective of nontechnological barriers, **ethical, legal and regulatory challenges** are likely to restrict the use of UUVs in attack missions in similar ways as they restrict the use of UAVs and USVs.

Enabling Technology Trends

Advances in maritime RAS-AI capabilities are not shaped merely by innovations in individual platforms' hardware and software or in tactics and concepts of operation. The extent to (and pace with) which Australia can apply RAS-AI to new mission maritime contexts will also depend on advances made in a wider variety of enabling technologies.

The *RAS-AI Strategy 2040* reiterated the importance of enabling technology areas spanning autonomy, interoperability, secure computing, propulsion and energy harvesting, among others (RAN, 2020). A high-level characterisation of key current and potential future trends in these areas is provided next.

Autonomy

The technology trajectories of maritime RAS-AI significantly depend on maturing AI and machine learning (ML) and related advances in the levels of autonomy that UAVs, USVs and UUVs are able and permitted to achieve. Autonomy levels (e.g., humans are either 'in the loop', 'on the loop' or 'out of the loop' for different decisions[7]) are particularly shaped by advances in four aspects: sensing, reasoning and decisionmaking, acting and teaming.[8] Each of these can be briefly described as follows:

- *Sensing:* At current technology maturity levels, AI systems can conduct autonomous object recognition and full-spectrum sensing—though improvements are continually being made to improve the effectiveness of these capabilities. For example, advances in autonomous sensing are still needed to address sensing and object recognition systems' vulnerability to spoofing and false positives (e.g., seeing nonexistent obstacles) (Yulong and Mao, 2020). Although ongoing technological advances are also occurring in such areas as AI-enabled sensor fusion and in-depth sensing, this sensing typically remains limited to a single event modality. As a result, future efforts are likely to be oriented towards enhancing sensor coverage and adaptability, including through achieving AI-enabled adaptive multivehicle sensor coverage (Reily, Mott and Zhang, 2020).

- *Reasoning:* Future advances in autonomous reasoning might move beyond rules-based 'IF…THEN…ELSE' systems that have limited utility in complex and contested environments. This will rely on enhancing the ability of autonomous systems to navigate uncertainty and imprecise data—for example, through hybrid systems that combine various AI reasoning techniques (such as rules-based and fuzzy AI) within a single system or that use artificial neural network-based systems (Arun et al., 2020). Improving the process through which autonomous systems learn from training data (e.g., through open-ended learning architectures, autonomous multiple-task learning and cooperative multivehicle learning) will be key to future advances in autonomous reasoning, as will improving the speed at which these systems learn (Martineau, 2019; Santucci et al., 2020). Ensuring that humans can interpret and understand autonomous reasoning (e.g., through advances in such areas as 'explainable AI' or symbolic reasoning) will also be essential to allow verification and validation (V&V) testing and provide users with confidence to trust autonomous systems. This is particularly relevant given (1) the challenges associated with traditional V&V processes and approaches (e.g., scenario-based testing) in complex and nondeterministic AI techniques, such as ML and (2) the heightened sensitivities around applying AI in military settings.
- *Acting:* Autonomous acting capabilities in maritime robotics and autonomous systems concern particularly their ability to navigate contested and dynamic environments using such means as adaptive agility and obstacle avoidance. Despite advances in obstacle avoidance, systems continue to struggle with complex environments (Polvara et al., 2017). Advances in deep reinforcement learning and convolutional neural network–based navigation systems, collaborative multivehicle perception and biomimicry-based designs might provide avenues for future improvements in this area.
- *Teaming:* Teaming refers to solutions for human-machine teaming and for machine-machine teaming, such as swarming technologies. Recent advances in the former have been the development of systems that use resonance (i.e., capacity for observation and mirroring) to understand and predict the intent of human operators (ICT Results, 2009). At the same time, more research is required to understand how humans respond and adapt to machines in any integrated team (e.g., through anthropomorphism) and how this affects long-term performance, morale and unit cohesion. For machine-machine teaming, swarming technologies of the kind discussed in this report have been notably maturing through solutions for physical and behavioural heterogeneity, synchronised real-time perception and flexible hierarchical control (i.e., swarming systems that adapt hierarchy between individual vehicles) (Dorigo, Theraulaz and Trianni, 2020).

Interoperability and Communications

From a technological perspective, advances in interoperability and communications for RAS-AI systems are likely to centre on the development of seamless C2 for both human-machine and machine-machine collaboration and onboard data processing. Efforts to develop these capabilities for the Royal Navy in the United Kingdom, for example, have centred on the MAPLE (Maritime Autonomous Platform Exploitation) C2 system, which aims to provide advanced and resilient C2 architectures to allow a controller to operate multiple vehicles (Smith and Biggs, 2018; Smith and Biggs, 2019).

Future advances in interoperability and communications will include **solutions for single-domain and for cross/multidomain C2** and have different military and technical requirements for each. Notably, single-domain C2 might require solutions for developing operational trust while the development of cross/multidomain C2 (to enable multidomain teaming) might need to address technical challenges with integrating multiple real-time data streams from a heterogeneous autonomous system into a single integrated operating picture (see, e.g., Kongsberg Geospatial Ltd, undated). This is a major area of focus for Australia's allies and partners, as reflected in the United States' investment in Joint All Domain Command and Control and the United Kingdom's development of related concepts for multidomain integration using a 'digital backbone' (Black and Lynch, 2020; Lingel et al., 2020). Relevant technologies in this context are resilient mesh networks, advanced data science, analytics, AI and ML and cloud and edge computing to enable an 'any sensor, any shooter' model that combines both crewed and uncrewed platforms.

Despite advances in the development of relevant C2 architectures, more-complex RAS-AI operations still face technological barriers (regardless of the operational domain), such as the following:

- limited cross-platform standardisation, requiring operators to be trained in the use of individual vehicles[9]
- real-time data analysis and assimilation challenges that stem from production and communication of data in vehicle-specific formats
- limited availability of machine-machine interfaces as well as associated limitations for the use of common controller tools, multivehicle operating strategies, autonomous control and data delivery (Harris et al., 2020).

In addition, policymakers need to consider broader nontechnological factors—such as the challenge of overcoming **bureaucratic, cultural and financial barriers** to implement a new multidomain C2 architecture and associated technical solutions that cut across stakeholder interests in multiple domains (i.e., land, maritime, air, space and cyber), individual services (e.g., Navy, Army, Air Force) and mix of international allies and partners. Because of these technological and nontechnological challenges, various concepts have been explored to improve human-vehicle interaction in various operations scenarios—such as the deployment of uncrewed vehicles in combat with operators remaining in close proximity of a combat area, thus allowing operators to remain at a relatively close communication distance to a vehicle while maintaining force protection. Such concepts might mitigate both technical challenges with communications and nontechnical challenges associated with autonomous target identification and engagement, among others.

Secure Computing and Networking

Cybersecurity, cyber defence and EW constitute key challenges for autonomous systems because of the obstacles involved in securing cyber-physical systems.[10] RAS-AI systems, depending on their level of autonomy, might require real-time control, might be composed of multiple independent systems and might include commercial, off-the-shelf subsystems from different vendors with insecure safety protocols and poor authentication practices. Advances in deploying RAS-AI in contested electromagnetic environments add to these challenges: Systems might be exposed to exploits through various channels, including the communications infrastructure (Madan, Banik and Bein, 2019). Therefore, RAS-AI computing and networking are likely to require the development of **robust cybersecurity and cyber-defence solutions and ECM**, notably novel sensor-security technologies to improve the ability of operators to detect potential threats and vulnerabilities.

The development of autonomous cyber defence and of cyber-resilient designs requires methods for **autonomous response to a variety of possible attacks and vulnerabilities**. To date, research on these potential methods and their requirements remains limited (Kholidy, 2021). However, existing work has proposed several concepts for autonomous cyber defence and for cyber-resilient robotics and autonomous systems designs, such as autonomous response controllers and designs embedding mission-critical, safety-sensitive military effectors, systems and networks with autonomous intelligent cyber-defence agents (AICAs) to enable networks to operate despite cyberattacks. AICAs allow a system to autonomously acquire data from the environment and detect relevant cyber threats, analyse and elaborate on proposed cyber-defence actions, exchange information regarding the action with other agents or an operator across a central cyber C2 and formulate a response plan on basis of the information exchange (Boyd, 2019; Theron and Kott, 2019).

Existing research on autonomous cyber defence also highlights additional potential solutions for such cyber-resilient designs as the following:

- *Blockchain technologies* provide several opportunities for developing cyber-resilient designs, particularly in the form of blockchain-enabled data verification and secure communications architectures in decentralised autonomous networks (Angin, 2020).
- *Advances in ECM* to deal with jamming, spoofing, dazzling and other threats similarly represent important avenues for enhancing secure computing and networking for robotics and autonomous systems.
- *Reversionary modes* could also become increasingly important to ensuring that remotely piloted or autonomous systems are able to operate safely in a contested electromagnetic spectrum when communication and data links to other forces (e.g., human operators) are degraded. This concept refers to tactics, techniques and procedures for how a combined human-machine team should operate when the performance of RAS-AI in the team is degraded. Such tactics, techniques and procedures are likely to have different requirements depending on the level of autonomy and human control in a system—that is, whether humans are ‘in’, ‘on’ or ‘out of’ the loop because of the different challenges that systems with varying levels of autonomy might face in degraded conditions.

Other Enabling Technologies

Future advances in maritime RAS-AI will be underpinned by advances in other, adjacent technologies. Although some advances might be platform-specific, some crosscutting trends in these adjacent technologies can be identified (some examples are summarised in Table 3). It should be recognised that other enabling technologies beyond the ones captured in this report are likely to shape future capability development, including specifically in RAS-AI. Therefore, investments in RAS-AI will necessarily have to be informed by wider changes in the S&T landscape, the full analysis of which is beyond the scope of this research.

In addition to the technologies listed in Table 3, developing new technologies that support the **integration of uncrewed vehicles alongside the human element** is also essential. Advances in immersive virtual, augmented or mixed reality environments could enable such developments in the future. Virtual, augmented and mixed reality technologies can be leveraged for developing human-machine teaming solutions, strengthening trust and enabling effective user-system communication. Synthetic environments and related advances in modelling and simulation capabilities might also enable operators of uncrewed vehicles to better develop concepts of operations involving RAS-AI and to train for operation alongside such systems in different scenarios. Relatedly, human-machine teaming technologies, such as human-computer interfaces (HCIs), are already being explored for RAS-AI control, particularly because of their utility in

- enabling more-accurate and more-rapid decisionmaking by operational personnel, thus improving and accelerating the observe, orient, decide, act (OODA) loop
- facilitating effective and intuitive engagement between operators and RAS-AI systems, thus improving the quality of human oversight and mitigating technological, legal and ethical challenges associated with RAS-AI.

HCI technologies are likely to further improve in the near term, particularly in relation to the speed, scope and accuracy of information transfer, brain-to-machine and brain-to-brain communications, inter-

TABLE 3

Examples of Key Advances in Selected Other Enabling Technologies

Category	Examples of Key Crosscutting Advances
Propulsion	• Developing propulsion systems that can accommodate higher payload payloads at higher speeds and range; i.e., addressing tensions between payload capacity, endurance and speed • Promoting innovative propulsion designs; e.g., inspired by biomimicry, enhancing adaptability and enabling systems to operate in condensed environments
Energy storage and harvesting	• Addressing tensions between persistence and maintenance • Developing and maturing novel energy sources; e.g., photovoltaic cells and fuel cells or solar power-based systems • Developing refuelling, battery docking and battery-switching techniques
Sensor technology	• Enhancing sensor performance at greater speeds and increasing data capture rates • Advancing solutions for data fusion, such as from real-time sensor data streams • Developing ultra-low power and miniaturised sensor designs
Materials and methods to enable long-term operations	• Integrating advances in autonomy, propulsion and energy storage and harvesting • Promoting advances in the variety of sensing and communications technologies
Underwater communications	• Delivering advances in underwater localisation and communication through acoustic signalling/acoustic networks, increased underwater autonomy, flexible communication devices (e.g., acoustic modems) and so-called 'quantum radio' technologies that leverage quantum methods to modulate low-frequency magnetic radio

active task learning and safety (Binnendijk, Marler and Bartels, 2020).

Conclusion

As recognised in the *RAS-AI Strategy 2040* (RAN, 2020), exploiting RAS-AI effectively in the maritime domain will require in-depth understanding of a rapidly evolving technological landscape. Ongoing research and investments in S&T continue to increase the maturity of RAS-AI and potential applicability across different mission contexts and in increasingly complex and contested environments.

This report is intended to provide the RAN with a more detailed overview of relevant current, near- and far-term mission and technology trends as part of RAND's ongoing support to the development of the RAN's RAS-AI Campaign Plan.[11] As stated in the beginning of this report, this overview does not seek to predict the precise trajectory or pace in change regarding RAS-AI missions and technologies out to 2040; rather, it is intended to assist the RAN in assessing capability development opportunities regarding maritime RAS-AI through a high-level illustration of the art of the possible in terms of RAS-AI missions and technologies out to 2040.

Beyond the analysis on the key mission and technology trends presented in the body of this report, the following additional principles can be identified that might help guide the RAN's ongoing assessment of opportunities for RAS-AI capability development:

- Future developments in the use of maritime RAS-AI systems are likely to be shaped by the interaction of multiple technologies, including both new and legacy systems, rather than by a single technological enabler or breakthrough (Bellasio et al., 2021). Notably, many RAS-AI systems and the RAN's understanding of appropriate missions are both likely to evolve iteratively through interactions between incremental advances in hardware, software and relevant enabling technologies. That being the case, it is important that the monitoring of future RAS-AI missions and technology trends takes a broad perspective that includes a wide variety of developments spanning different platforms and the wider context of enabling technologies.
- Future RAS-AI mission and technology trends are likely to be shaped by advances in military, civil and commercial RAS-AI systems. As noted earlier, relevant nonmilitary uses are oceanography, the oil and gas industry and the shipping industry. There are various opportunities for the RAN and the wider Australian Defence Force to leverage

advances in civil and commercial RAS-AI applications and close interactions with a wide variety of industry and academia might help maintain good situational awareness of these opportunities (and of any emerging threats, such as from the proliferation of dual-use technologies of both state and non-state actors).

- In addition to technological advances, non-technical factors are likely to shape future RAS-AI mission and technology trends. Evolving regulatory, legal, policy and ethical frameworks (including sensitivities around autonomous uses of force) might significantly determine when RAS-AI technologies are employed in particular missions or whether they are employed at all. It is therefore important to interpret technological advances in RAS-AI in the wider context of regulation, policy, legislation and evolving perspectives on the ethical elements of RAS-AI (e.g., principles of meaningful human control and other ways to address risks associated with algorithmic biases through increasing AI intelligibility and algorithmic transparency).

Notes

1 Using an approach originally developed for the United Kingdom's Defence Science and Technology Laboratory (Dstl) (and used since 2016 by Dstl to provide monthly analyses of emerging developments in science and technology), RAND's database draws on a proprietary software tool and analyst input to scrape and aggregate information on the latest S&T developments from a variety of academic, industry, news media and social media sources from the internet, including non-English language sources (in Mandarin, Russian and French). This database contains more than 6,000 new and emerging S&T items, grows by around 200 entries per month and can be queried to draw out specific disciplines and/or application areas.

2 Note that the strategy considers both autonomy as a whole, as well as the key functions of sense, think and decide, act and team (RAN, 2020, p. 10).

3 This acquisition is planned to occur under Project SEA 1905 Phase 1, which will also feature military survey vessels ('Defence Down-Selects OPV Variant to Replace Huon Class', 2021).

4 For example, the United Kingdom's Royal Navy has plans for an MCM capability that use a similar 'mothership' concept, with the future Type 32 frigate potentially serving as a mothership for uncrewed systems assisting in the launch, operation and recovery of uncrewed maritime systems. Belgium, Japan, the Netherlands, Singapore and other countries have been reported to explore similar concepts (Vavasseur, 2020).

5 For example, see Shoebridge, 2021.

6 For example, the Chinese Aerospace Science and Technology Corporation has recently introduced a concept for airdropping autonomous underwater vehicles (Wong, 2021).

7 'In the loop' refers to systems in which humans make final decisions concerning use of force. 'On the loop' refers to systems that can make autonomous decisions with human supervisions. 'Out of the loop' refers to systems that can make autonomous decisions without supervision (see Wong et al., 2020).

8 These effectively cover the famous observe-orient-decide-act (OODA) loop developed by John Boyd, as well as noting the collaborative nature of many RAS-AI systems (e.g., swarming, human-machine teaming).

9 This has emphasised the need for common streamlined command consoles to be developed to enable the practical deployment of small platforms.

10 A cyber-physical system is a system in which the 'interacting digital, analog, physical and human components [are] engineered for function through integrated physics and logic' (National Institute of Standards and Technology Cyber-Physical Systems, undated).

11 Other research during this effort focused on experimentation, innovation, human-machine teaming and the role that industry and academia could play in helping the RAN leverage RAS-AI capabilities.

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About This Report

The Royal Australian Navy (RAN) recently launched a strategy for developing and employing robotics, autonomous systems and artificial intelligence (RAS-AI) to be delivered through a campaign plan. A RAND Australia research team is supporting the RAN in this endeavour by building an evidence base to help identify and shape the underpinning activities. This report characterises the RAS-AI mission and technology trends. It provides an overview of the current landscape and trajectory of maritime RAS-AI technologies in the near and long term (out to 2040) and a high-level review of the missions that might be possible in the near, medium and long terms in light of relevant technological and nontechnological enablers.

In line with the *RAS-AI Strategy 2040*, this report—rather than focusing on a wider integration of artificial intelligence in maritime operations—focuses on advances in missions and technologies underpinning uncrewed platforms and autonomous systems, including uncrewed aerial vehicles, uncrewed surface vehicles and uncrewed underwater vehicles. In addition to the analysis on the key mission and technology trends presented in the report, the research team identified three other principles that should be taken into account in the ongoing assessment of RAS-AI capability development opportunities: (1) a focus on the interaction of multiple technologies (both new and 'legacy' systems) rather than a single technological solution; (2) consideration of complementary advances in defence and commercial RAS-AI systems, which could create rapid changes regarding what is leading-edge; and (3) monitoring of nontechnical factors, such as evolving regulatory, legal, policy and ethical frameworks that might significantly shape future technology adoption pathways.

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