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Robotic Technology in Military Applications: Insights from Portuguese Navy Research

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Abstract:

Robots have been used in a military context for a long time. In recent years, the pace of introducing new systems has increased for several reasons, including the widespread use of robots in civilian applications and the consequent development of a vibrant industrial base. However, adapting robot technology to military applications is not always trivial, and a good interaction between industry and military institutions is key to success. In this paper, we present a review of successful research projects undertaken by our team at the Portuguese Navy (PoN) Research Center in close collaboration with industry. We provide valuable insights that can guide future developments in this field. It is essential to guarantee continuous research and development in the military domain since the obtained knowledge is critical and undoubtedly essential to guide the future. Combining knowledge and capacity for action is crucial for continuously improving robotics, and military robotics is no exception.

Keywords:

robotics, military robotics, research and development, technological innovation, military

1 Introduction

The Armed Forces (AF) have always been a source of technological innovation and scientific development [1, 2]. Technological superiority and proper use of technology have always been critical for military success, and this need for technology has usually been supported by generous funding due to its importance [3]. However, the end of the 20th century and the beginning of the 21st century have shifted to a new reality [1]. Technology

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is evolving faster than ever, and the private sector, fueled by an insatiable demand by society in general, has taken the lead in most technological areas [4]. This is true for robotics [5, 6], as it is for cybersecurity [7, 8], quantum devices [9, 10], and many other emerging and potentially disruptive technologies [11, 12]. The key to success is always striving to stay ahead and develop better, more efficient solutions for existing problems.

With the existing industry investment in research and development, the knowledge is no longer centered only in academia but is spread in multiple institutions and companies. This has made it possible to accelerate research and development since the industry can more easily work directly with the AF as a final customer, developing new services and systems (solutions) that are now more adjusted to the existing needs. Real experimentation exercises have recently allowed industry, academia, and AF to test and explore new products during research and development, bringing the major stakeholders closer together [13, 14].

In the AF, and more particularly in the Portuguese Navy (PoN), we have some cases of research and development success, like the *Sistema INtegrado para a Gestão de Prioirdades de Reparação e Afectação de Recursos* (SINGRAR) software [15], which is a fuzzy, distributed expert system designed to assist with command and control activities in the naval environment [16]. This started as an internal project and rapidly proved its importance as an expert system capable of assisting the ship's command in the priorities during real operations, enchanting the decisions, and decreasing the error rate due to human failure [15, 17]. This project and other similar ones emerged from operational needs that required the search for new or better solutions. The AF have always focused on research and development, taking into account its scale and the existing reality. They understand that technological advancement plays a key role in battle operations, and to be able to guarantee avant-garde is essential to motivate and incentivize research.

It is essential to adopt the most recent technology, trying as much as possible to ensure that it requires acceptable costs. Due to the usual budget constraints, the AF benefits from a close relationship with external entities to develop innovative solutions at lower costs. Even with the current efforts, much more must be done to regain the technological avant-garde needed to ensure a clear advantage in a conflict scenario. The main objective of the AF is to guarantee protection in case of a conflict, and technology can help ensure readiness and action alternatives to deal with external threats. The collaboration among the three major sectors (stakeholders), namely academia, industry, and the military, can lead to the development of superior quality products more suitable for real-world scenarios and operations. This approach can also help reduce the overall research and development costs, as the accountability is shared. This responsibility sharing is essential since each player has their own specialization, skills, and objectives in specific fields. This symbiosis adds more value, decreasing the needed development time and increasing the efficiency and the final product quality. This added value is one of the reasons that leads to the development of projects that can aggregate the three major sectors since the added value is undeniable. Furthermore, production at a national level not only creates economic opportunities but also directly impacts the enrichment of the country's wealth.

The PoN Research Center (*Centro de Investigação Naval* – CINAV) was founded in 2010, and since then, it has struggled to be competitive and active in the research and development field. It creates a research culture and gives the navy personnel the mindset to contribute actively to complex and sometimes time-consuming research tasks. One of its primary focuses is on military robotics, trying to find and develop new solutions to the existing needs and mainly trying to contribute to the research and development of autonomous robots to automate some of the operations performed at sea. Our analysis will focus on our experience and expertise, reviewing existing projects to provide critical insights for future developments.

The main contributions of this article are (*i*) the review of some of the experiences of research projects in military robotics that our team has been successful, in (*ii*) the description of some of the past and current actions that led to the success of the projects, and (*iii*) the description and highlight of the importance of the military experimentation exercises.

This article is organized as follows. Section 2 briefly describes joint research projects developed in the defense area and provides vital insights about their development. Section 3 focuses on some of the most critical military experimentation exercises, detailing lessons learned. Finally, in Section 4, we present the conclusions and explore additional ideas for further developments in the field.

2 Joint Research Projects

In Portugal, the AF research centers have outlined the purpose and objectives of the research and development of each AF branch, being able to organize and guide the existing necessities of research and development in near real-time. As in any other state sector, the lack of human resources brings an additional challenge to these tasks, but a clear focus must exist on the present and future of AF research and development. Each AF branch has its research center, which mainly focuses on the research and development of its priorities being coordinated by a central research center named *Centro de Investigação do Instituto Universitário Militar* (CIDIUM) [18]. This coordinated approach allows for better understanding and coordination of AF research and development. Existing resources can be allocated or adjusted promptly to improve efficiency in some particular instances.

The development of military robotics is crucial for the present and future of any country's AF. This development follows a standard process, as illustrated in Fig. 1. The initial stage of developing operational requirements is crucial as it sets the direction for the entire development process. It is critical to accurately assess the technological feasibility of the defined requirements, as an incorrect assessment can make it impossible to develop the desired product. Once the operational requirements are defined, the research and development process begins, aiming to adapt or find innovative solutions to meet the proposed requirements. After completing this phase, it is essential to perform final prototype operability checks. Military experimentation exercises are particularly relevant during this and the research and development phases, as the scenario and test conditions should closely resemble reality in these exercises. After each phase is concluded, a commissioned product with a standard lifecycle is expected. This process generates new knowledge and experience, which can contribute to the organization's aggregate value and directly to developing new projects and solutions.

Some of the most recent military robotics projects developed by the PoN Research Center focus on Unmanned Aerial Vehicles (UAVs) [19-35], Unmanned Underwater Vehicles (UUVs) [36-38] and Unmanned Surface Vehicles (USVs) [19, 36, 39-41]. Research and development in mobile robotics, particularly autonomous vehicles, is critical for PoN, as illustrated in Fig. 2. Being capable of performing autonomous operations can help overcome the challenge of scarce human resources by allowing robots to perform tasks

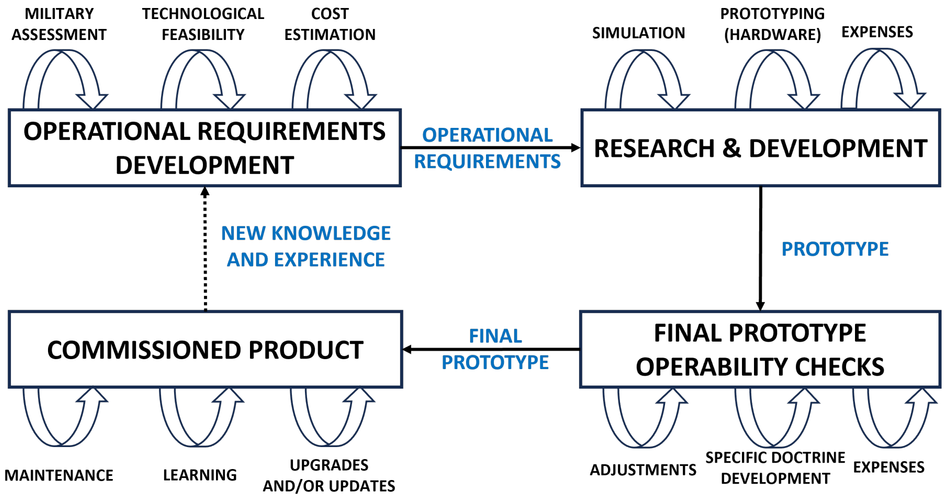

Fig. 1 Military robotics development simplified schematic

that would otherwise require human intervention. Traditionally, robotics are beneficial to perform dull, dirty, and dangerous operations [42, 43]. Robotics can be helpful in various military operations, specifically in navy operations to perform mine warfare [44], hydrographic surveys [45], environmental monitoring [46], search and rescue [47], piracy combat [48], among many others. Various challenges need to be addressed when accomplishing tasks with autonomous systems. These include the requirement for accurate sensor measurements and their proper fusion to execute tasks correctly [49, 50]. Additionally, there is a need to optimize multiple aspects of these systems, such as time [51, 52], energy [53-55], autonomy [56, 57], and safety [58, 59], among several others that have already been identified. Furthermore, as technology evolves, new requirements must be addressed.

The PoN Research Center has participated in several completed projects related to mobile robotics. Some of the most relevant projects can be described as:

- **Integrated Components for Assisted Rescue and Unmanned Search Operations (ICARUS) [2012–2016] –** This project aimed to enhance crisis management by providing first responders with a suite of unmanned search and rescue tools, including air, ground, and sea vehicles equipped with human detection sensors. These tools aimed to improve situational awareness, assist in locating survivors, and ensure optimal collaboration between human crisis managers and unmanned systems, ultimately reducing the overall human and financial costs of significant crises like earthquakes and floods [60-63];
- **UAV-based maritime situational awareness support systems (Seagull) [2013–2015] –** This project used UAVs to monitor and safeguard Portugal's extensive maritime domain. Equipped with advanced sensors, the project aimed to enhance maritime safety through the automated detection of vessels, hazards, and environmental pollutants [24, 64];
- **Fixed-wing UAV automatic landing system on a moving platform (AUTO-LAND) [2012–2015] –** This project aimed to develop Computer Vision (CV)-based

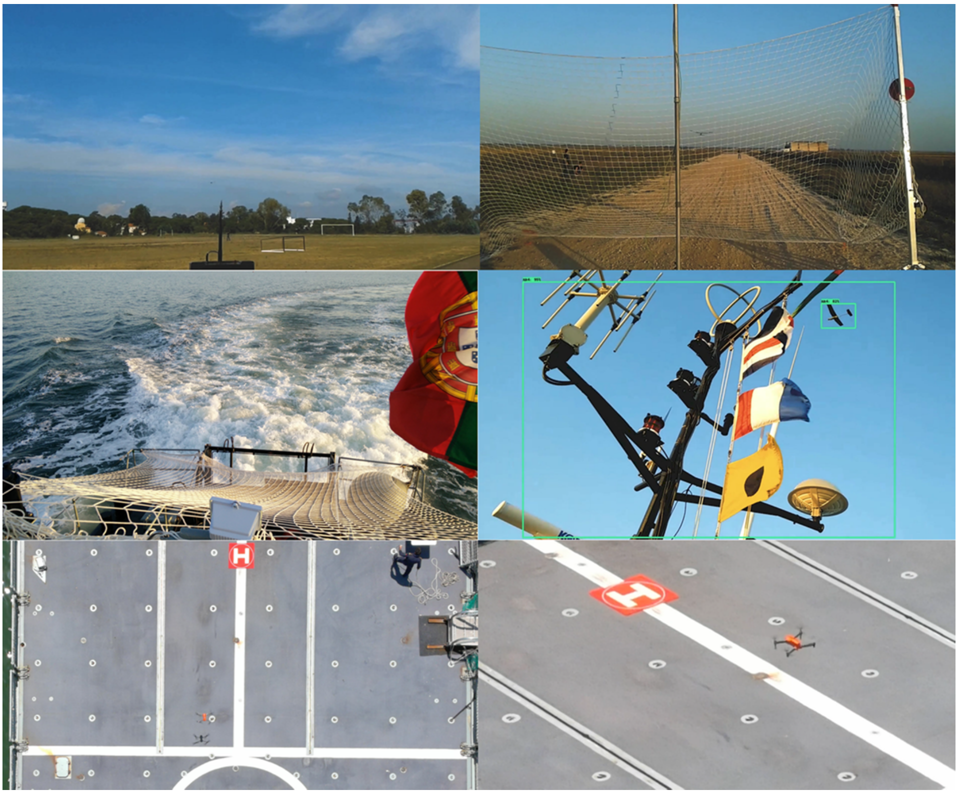

Fig. 2 Experimental development and tests – Some examples

systems that enable the autonomous landing of a fixed-wing UAV on a Fast Patrol Boat (FPB) in a jamming-prone military environment [20-23, 25, 27-32];

- **Smart unmanned aerial vehicle sensor network for detection of border crossing and illegal entry (SUNNY) [2014–2018] –** This project aimed to develop comprehensive solutions for border surveillance using UAVs equipped with a range of sensors. The developed system can monitor large border areas and detect and track targets and potential incursions [65-67];
- **Advanced UAV development for Hazardous Environment Monitoring (Gamma-Ex) [2014–2016] –** This project aimed for the creation of dual-purpose UAVs for Nuclear, Radiological, and Chemical reconnaissance, certified for explosive environments, with autonomous features for visual and thermal reconnaissance, human presence identification, logistical support, and enhanced situational awareness in hazardous scenarios [26, 34];
- **Swarm of Biomimetic Underwater Vehicles for Underwater Intelligence, Surveillance and Reconnaissance (ISR) (SABUVIS) [2015–2019] –** This project aimed for the integration and development of biomimetic underwater vehicles and developed effective reinforcement learning techniques for autonomous vehicle control. Additionally, it established a simulation environment for development

purposes and delivered operational prototypes to the AF, identifying operational benefits and laying the groundwork for future advancements in biomimetic UUVs [38, 68];

- **UAV Computer Vision Operation in Maritime and Forest Environments (Voamais) [2019–2022] –** This project aimed to improve target detection and tracking using affordable sensors and neural networks. By utilizing advanced techniques, such as convolutional neural networks and correlation filters, it sought to enhance the detection of forest fires, track sea vessels, and enable aircraft pose estimation from airborne and seaborne images. The project benefited national strategies in the ocean, forest monitoring, and coastal operations, promoting environmental protection [21-23, 25, 29, 31, 33, 35].

After decades of working in mobile robotics and mainly in autonomous vehicles, it was possible to obtain a clear view of the operational requirements and the acquisition of the doctrine and operational procedures. This knowledge is highly valuable but hard to quantify, and its importance is sometimes forgotten or belittled. Despite a few decades of development and participation in projects on military robotics, the AF cannot perform all the stages (from the operational requirements to the final product) of a more demanding research and development project, e.g., for large-scale or more complex products since it is not their primary purpose. So, it is essential to establish partnerships with industry and academia. It is from these partnerships that joint research projects capable of developing state-of-the-art products and implementations will emerge. Military knowledge is not only located directly in the AF. Nowadays, multiple defense-related companies exist worldwide, and many former military personnel provide the needed expertise. The development cycle of military products is never-ending due to the constantly evolving context and unpredictability of military operations. This is because the developed products can quickly become obsolete or experience a decrease in their use due to natural changes in the mission's nature caused by factors like geostrategic shifts [69, 70].

Collaboration on the development of new products and solutions across multiple countries' armed forces is a potential solution that has yet to be fully explored. This approach can help retrieve more aggregate knowledge and avoid errors by leveraging lessons learned from operational and practical experience. As stated before, such knowledge is precious but hard to quantify. The primary mission of the AF is to win wars, and operational advantage is crucial in achieving that objective. Most countries strive to maintain technological advantage or to have some uncertainty in their technological power, as peace can end and conflict may arise, reducing the likelihood of collaborations.

During the commissioned product lifecycle, performing the proper maintenance, upgrades, and updates is essential, when possible, to adapt it to obtain a better performance. Apart from the traditional and expected maintenance, it is essential to learn not only from a technical perspective but also to guarantee a better and more intelligent use of its capacities. To accelerate this learning process, it is essential to have some system simulator that can extend the training to a practical perspective closer to reality, increasing the operators' and technicians' knowledge. For obvious reasons, it is impossible to develop a perfect product. Still, performing the needed research and development is essential to ensure that the solutions provided are better than the current technology can provide at acceptable costs.

Fig. 3 UAV deployment from a ship on the left and UUV performing a mission on the right during a REP exercise

Sharing standardized data [71] throughout the research and development phases can significantly benefit all the stakeholders. It can speed up the development process and minimize the repetition of errors. However, it is not always possible due to maintaining technological advantage and commercial interests. Industry and academia may choose to register patents and keep the information confidential to ensure a proper commercial return. Many companies and industrial partners want to profit from the efforts to develop and maintain highly advanced technological products and solutions, often taking many years to perfect. Acknowledging that all parties involved in the product research and development process must benefit somehow is essential.

3 Military Experimentation Exercises

Military experimentation exercises significantly influence the interaction between academia, industry, and AF. Being on the field experimenting and testing the technology in near-real operational scenarios with military people with operational doctrine is essential to speeding up the development process. The direct consequence is the development of a product that is better equipped to handle real-world challenges and more aligned with potential operational demands. Indirectly, these exercises also give operators experience since they must interact with different personnel and systems.

Regarding the military experimentation exercises, the PoN started the yearly Rapid Environment Picture (REP) exercise in 2010 together with the Faculty of Engineering University of Porto (FEUP) to test the developed systems. This exercise regularly had the participation of other entities and researchers, who took this opportunity to test their systems and be at sea with a multidisciplinary team of scientists and military personnel. This exercise combines UAVs, USVs, and UUVs, as illustrated in Fig. 3. This exercise established a fruitful partnership between the PoN and FEUP, improving and increasing academia's knowledge about the specificity and requirements of military operations. What in that time began as an outstanding achievement for both, fortunately nowadays, is more common, and this approximation between partners is becoming usual.

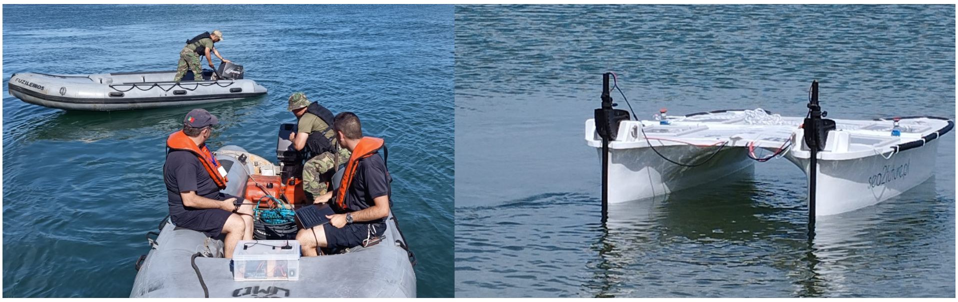

Fig. 4 Towed array experimental tests on the left and USV performing a mission on the right during a REX exercise

Fig. 5 Experiments conducted during a REPMUS exercise. The left side shows a tested UUV, while the right side shows a tested UAV

Nowadays, the most relevant experimentation exercises developed by Portuguese AF, and particularly by the PoN that allow the participation of industry and academia are the Robotics Exercise (REX) [41, 72, 73] and the Robotic Experimentation and Prototyping using Maritime Uncrewed Systems (REPMUS) [13, 14]. These exercises are crucial for researchers to gain sea experience and immerse themselves in military culture, increasing the value and quality of the developed product. The REX exercise is a smaller exercise entirely organized by the PoN Research Center, where the research community can count on all the logistical support from the PoN. This exercise brings several advantages to the participants since it is an opportunity to be in contact with the most recent market technologies and researchers. It also allows the partners to test their systems in a challenging environment, as illustrated in Fig. 4.

On the other hand, REPMUS is a large-scale unmanned vehicle exercise for the military robotics community with almost 2000 participants every year [74]. Here, we test several operational scenarios with many partners, testing several systems (Fig. 5), their robustness, endurance, and capabilities, and also to straighten up and improve operating procedures. Without these synergies between partners (academia, industry, and AF), and especially in a reality where the resources are limited, it is essential to potentialize every opportunity, and these experimentation exercises are crucial. The AF are mainly constituted to guarantee the territory's sovereignty, and being able to cooperate with the research and development of the country is an essential factor and brings an additional purpose, adding value to its existence.

One of the major issues when dealing with several systems from different companies and countries is the interoperability between them. All the systems or systems of systems [75] must ensure interoperability since it is paramount to perform collaborative missions and achieve the desired objective successfully and efficiently. Concerning the AF belonging to the North Atlantic Treaty Organization (NATO), the Standardization Agreements (STANAGs) are the documents that define the norms among the members. Regarding the UAV domain, the NATO STANAG 4586 [76, 77] standardizes the interfaces of the UAV control systems to allow much easier information sharing between the systems. The NATO STANAG 4586 does not intend to develop new technology or perform some operational improvement but aims to increase the interoperability and communication between systems, as stated before. This STANAG should be used in conjunction with others, such as the NATO STANAG 4545 [78, 79], which defines the secondary image formats, the NATO STANAG 4575 [80], which defines the data storage interface, and the NATO STANAG 4607 [81], which defines the ground moving target indicator format. The NATO STANAG 4609 [82] defines the digital motion imagery standards. The NATO STANAG 7023 [83] defines the air reconnaissance primary imagery data standards. The NATO STANAG 7024 [83] defines imagery air reconnaissance tape recorder standards, the NATO STANAG 7085 [84] defines the data links for Intelligence, Surveillance, and Reconnaissance (ISR) systems, and the NATO STANAG 4670 [85, 86] defines the training of designated UAV operators, among many others. It is essential to comply with a specific standard according to the type of system and expected interaction between systems. A commonly used action is to develop gateways that convert the used protocols to compatible ones, interconnecting several systems without performing major system changes [87, 88]. To ensure smooth interoperability between existing systems, companies should focus on adapting their protocols to meet the standards outlined in the STANAGs or developing gateways (software or hardware) that can be easily adapted or installed. This would allow faster and more efficient communication between different systems, improving collaboration and productivity.

One of Portugal's most recent advances in technology experimentation is the creation of Technological Free Zones (TFZs), which are designated test sites for innovative technologies, products, services, and processes [74, 89]. These zones provide a secure environment for promoters to test their ideas with support from competent authorities. In 2022, the PoN introduced the first Portuguese TFZ named *Infante Dom Henrique*, significantly improving new systems' research and development capacity. The zone provides a regulated and easily accessible platform for conducting tests and currently hosts the REPMUS exercise in its facilities, as illustrated in Fig. 6. With an area of 2 590 km^2, the PoN TFZ offers a sea and land area with conditions close to reality for military robotics experimentation and testing. Creating TFZs for military purposes has been a successful case, and it can create synergies among defense partners. This model should be replicated in different places with varying area characteristics to expand the experimentation possibilities. In Portugal, many companies and universities request the creation of their TFZs as they recognize their importance in achieving their goals.

Despite the collaborative efforts of all parties involved, the country needs to provide support, as every test and action must comply with existing laws. Partners may invest their time and resources in other regions worldwide if a country has strict regulations on specific experimentation scenarios. Therefore, it is crucial to maintain a balance between

Fig. 6 TFZ Infante Dom Henrique support facilities in the Tróia Peninsula [74]

strict compliance with laws and allowing research and development in a safe environment. With the creation of the TFZs, among other actions, Portugal is contributing decisively to the proliferation of science and technology.

4 Conclusions

The only important future is successful and sustainable development, which can only be achieved if academia, industry, and AF work together to decrease costs and develop products with the functionality and reliability needed to handle a real operational scenario. Collaboration between different AF countries exists in some international projects, but it needs to be fully explored to generate even more knowledge and better final products.

The AF research centers are of utmost importance as they are vital in centralizing and defining the correct path for military development. They have a clear understanding of the needs of each military branch in almost real-time. To ensure a prompt response to research and development and the bureaucratic needs of participating in several national and international projects, it is essential to provide the research centers with the required human resources. While a multidisciplinary military team can handle minor research and development projects, collaboration with academia and industry is crucial. This can bring more scientific knowledge for developing new solutions, given that the industry is usually more product-oriented. This is especially important during the research and development process of building or creating a unique solution.

The military experimentation exercises are essential, and the creation of TFZs are advantageous since they are designated test sites for innovative technologies, products, services, and processes. They provide a safe and secure environment for research and development in a near-real operational scenario. When testing and using multiple systems simultaneously, it is crucial to ensure interoperability between them. To achieve this, we must ensure that all systems comply with the same normative standards. Developing gateways or converters can be a simple and easy-to-implement solution in cases where it is impossible to adapt the system entirely to comply with the existing normative.

The future lies in continuously developing new systems that gather synergies between partners and ensure the developed products are designed and optimized for the desired mission types. Mission types change with time, as political interests and the geostrategic environment also change. Therefore, the systems must be able to adjust and not be too specifically adapted to a particular type of mission.

The development of autonomous mobile robotics is crucial for military operations, as it ensures the execution of dull, dirty, and dangerous tasks while protecting human life. Despite years of development in various domains, such as air, surface, and underwater, the field still lacks a clear operational product. However, a squadron of unmanned vehicles may soon be deployed for real operations. Although it is not yet a reality, it is a dream that is becoming increasingly closer to reality with each passing day.

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Our team has developed the projects discussed in this article and many others not mentioned here. These projects have involved outstanding institutions and researchers, and we are grateful for their collaboration and knowledge-sharing throughout the years. We look forward to maintaining these fruitful partnerships in the coming years, which will help us generate knowledge essential for significant advancements in military technology.

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