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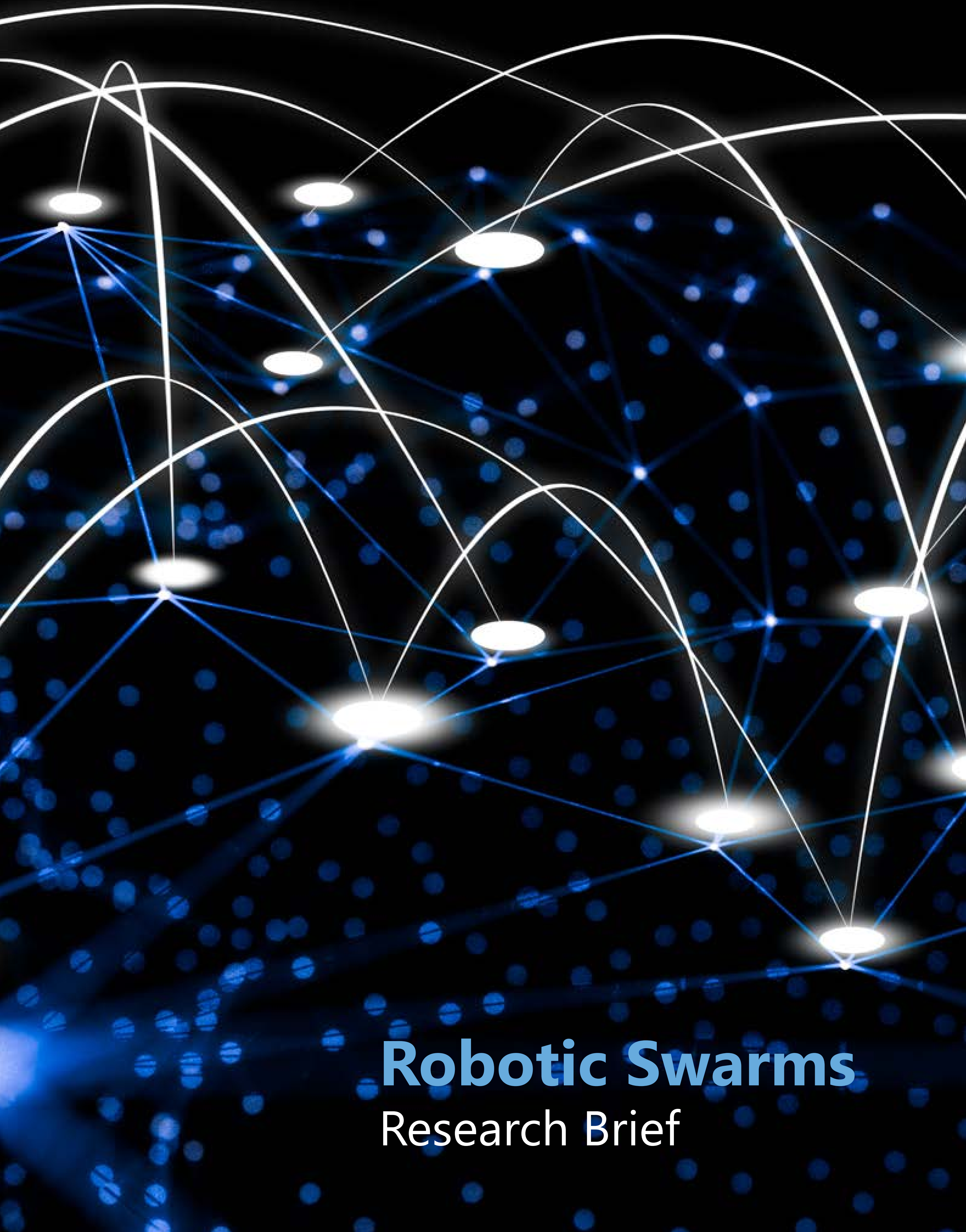

Robotic Swarms

Research Brief

INTRODUCTION

Swarming as a concept is not new. Swarms can be found in nature, such as schools of fish (for foraging and defending against predators), bee colonies (reproduction) and bird flocks (foraging and migration). Swarming is also a long-standing military tactic, where several units converge to attack a target from multiple axes in a deliberately structured, coordinated way. But a new type of swarming is on the horizon: robotic swarms.

Following the lead of the civil and commercial sector, military organizations are increasingly investing in swarms of robotic systems. As this technology will progressively enter the battlefield, it will have the potential to bring disruptive change in the conduct of military operations.

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WHAT IS A SWARM?

Swarm demonstrations often make headlines in mainstream media, particularly when involving large numbers of robotic units.

Swarm behaviour is based on the use of local rules and relatively simple robots that, when organized in a group, can perform complex tasks in a way that a single robot would be incapable of, thereby giving robustness and flexibility to the group. The simplest description of a robotic swarm is that there are **many (identical or different) robotic units** and that there are only **a few people involved in controlling** them. However, there is no magic number: in theory, swarms may vary from as few as two units tos thousands of units. Each robotic unit within the swarm can be considered an **autonomous** member that reacts according to internal rules and the state of the environment. The algorithm used to program a swarm is **distributed**, meaning that the algorithm of the swarm runs separately on each robot in the swarm. For a swarm to be more than simply a group of individual, autonomous robots, its robots need to exhibit **collective behaviour through collaboration between individual units and with the environment** to perform a given task. To achieve collaborative behaviour, some form of **communication** to allow information exchange between the robots – such as co-observation or wireless signalling via Bluetooth or Wi-Fi – is necessary.

There is no single or agreed-on definition of a swarm. The meaning of the term is far from settled, both within the international community and in the private sector, academia and technical communities. While conscious of these technical and political contexts, for the purpose of this brief, we propose the following working definition of swarms: **multi-robot systems within which robots coordinate their actions to work collectively towards the execution of a goal**.

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WHY SWARMS MATTER FOR DISCUSSIONS ABOUT HUMAN CONTROL?

The prospect of military swarms is real, although they are not yet operational and the technology is rather brittle. Yet how to exercise effective and responsible levels of human involvement over swarms remains a nascent area of research. The main challenges relate to the design and implementation of appropriate human-machine and machine-machine interactions. Researchers and developers have taken numerous approaches to injecting human involvement into a swarm. Human involvement or control in the context of swarming typically refers to either command, control or cordination.

In general, direct control of individual units of a swarm would not only be counterproductive but also, most likely, impossible. As the number of robotic units in a swarm grows larger, it becomes increasingly difficult to design for appropriate **human-machine interaction**. Therefore, for human involvement to remain effective, it must focus increasingly on the swarm as a whole rather than on its individual units.

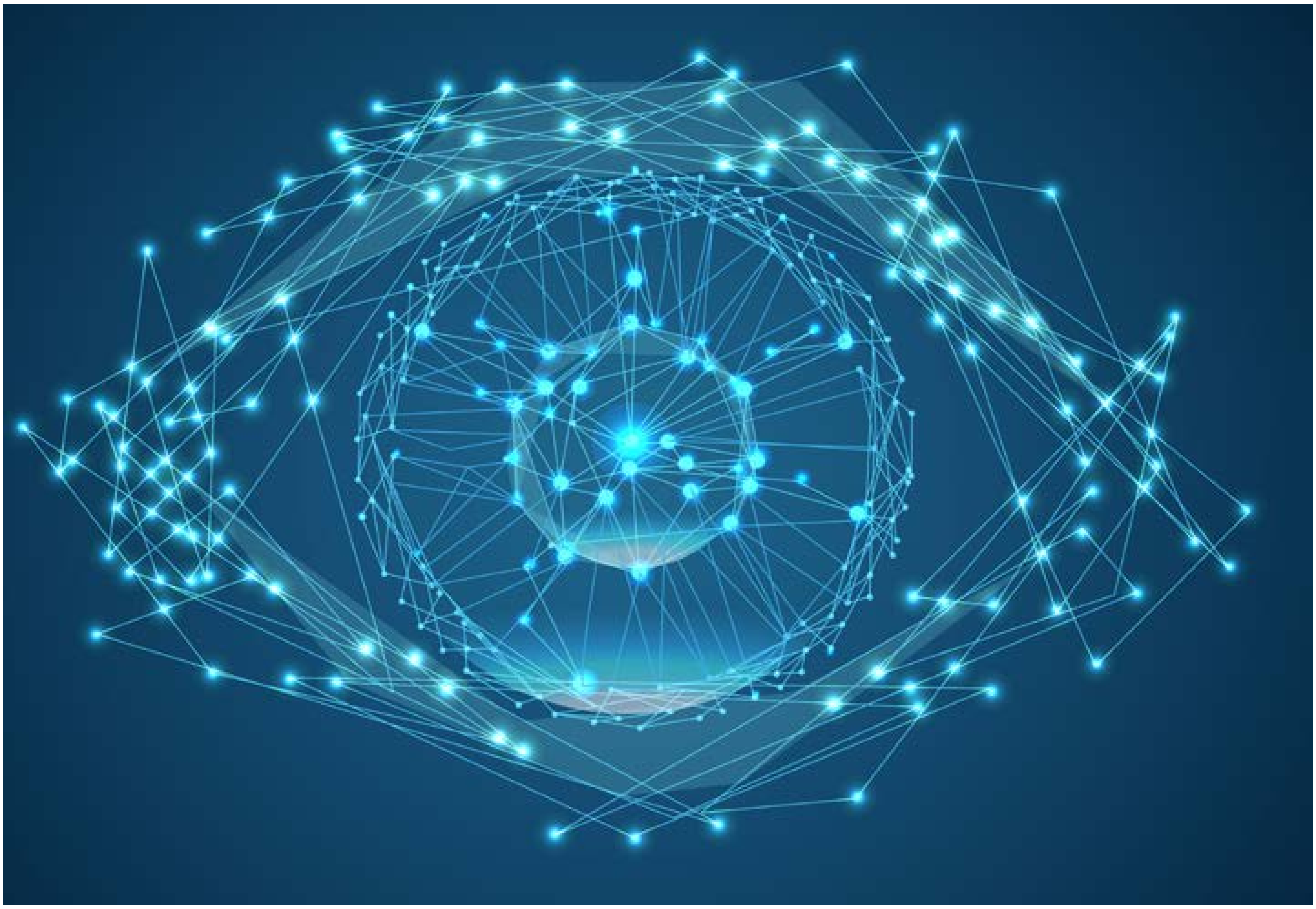
Swarms of robotic units necessarily rely on algorithms for formation, monitoring, spacing, flight path, task distribution, target identification and more. This means that swarms inevitably engage in **machine-machine interaction**. The individual robots interact with other robots in the swarm to achieve a task and, through this interaction, collective behaviour may arise. This collective behaviour will, in turn, affect the manner in which humans can command, control and coordinate the swarm's behaviour.

There is currently a dearth of studies investigating how humans can effectively design and implement appropriate human-machine and machine-machine relationships, and many open questions and issues remain. These questions require significant further study before the potential of swarm robotics can be harnessed and – ultimately – swarms can be deployed effectively and responsibly in military operations.

UNIDIR's study on robotic swarms contributes to filling this gap in the literature by bridging the technical element of this emerging technology with its operational use and resulting implications for international security and arms control.

INTERESTED IN LEARNING MORE ABOUT SWARMS?

You can access the full report "Swarm Robotics: Technical and Operational Overview of the Next Generation of Autonomous Systems" at www.unidir.org/publications



COMMAND

What kind of instructions could humans give a swarm?

While swarms for the most part are expected to operate autonomously, they do not operate in a vacuum or without instructions. **Robotic swarms ultimately operate at the direction of human decision makers.** These commands may come in various forms.

Low-level commands have already been proven to work in swarm robotics, at least in research and development, testing, and simulation. Various projects have examined methods to command a swarm by providing **high-level commands**, while delegating lower-level decision-making to the robotic units.

Individual robots can be equipped with an internal library that contains a pre-programmed set of behaviours. In those cases, humans command the swarm to execute a **specific pre-programmed behaviour**.

Another, perhaps more collaborative method to command a group of robotic units is by **communicating specific plans**.

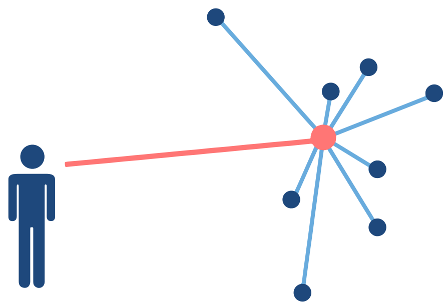
In all cases, an operation will be limited by a **set of parameters**, such as spatial or temporal limitations. Even though these parameters may not directly influence the behaviour of the swarm, they may limit the time and space within which the swarm can operate and, as such, they may indirectly affect the swarm behaviour through interaction with its environment.

CONTROL

How are tasks distributed to the different robots in the swarm?

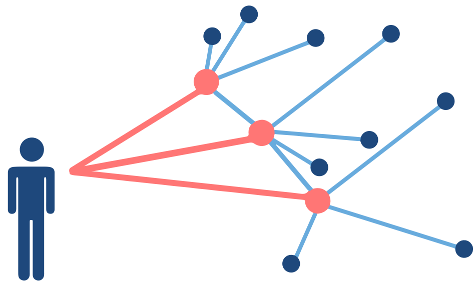
After human-issued commands, the swarm relies on algorithms for formation, monitoring, spacing, flight path, task distribution, target identification and more. These algorithms, or "control architectures", determine the task distribution within the swarm.

Commands can go to one robot that acts as a central controller. This architecture of **centralized control** means that each robot is tasked individually and there is no collaboration between the units directly, except that which goes through the central controller.



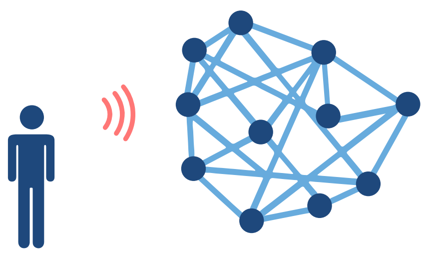
Centralized control

A human may transmit commands to several "leaders" in a swarm. In this architecture of **hierarchical control** individual robots may be controlled by several lower-level ("squad" level) agents, which are in turn directed by higher-level controllers, and so on.



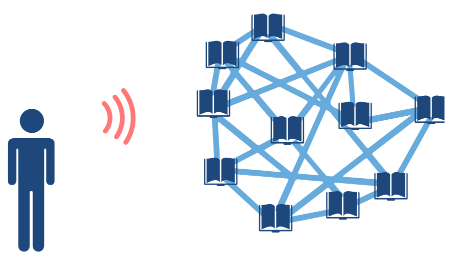
Hierarchical control

Ensemble-level control is a decentralized method that allows humans to broadcast commands to a swarm as a single group (not to specific robots in the group), after which the individual robots make decisions on how to execute that command.



Ensemble-level control

In **behavioural control** architectures, each robot has a library of behaviours, and operators command the system which behaviour to execute or, in other words, which program to run.



Behavioural control

COORDINATION

How does the swarm execute those tasks?

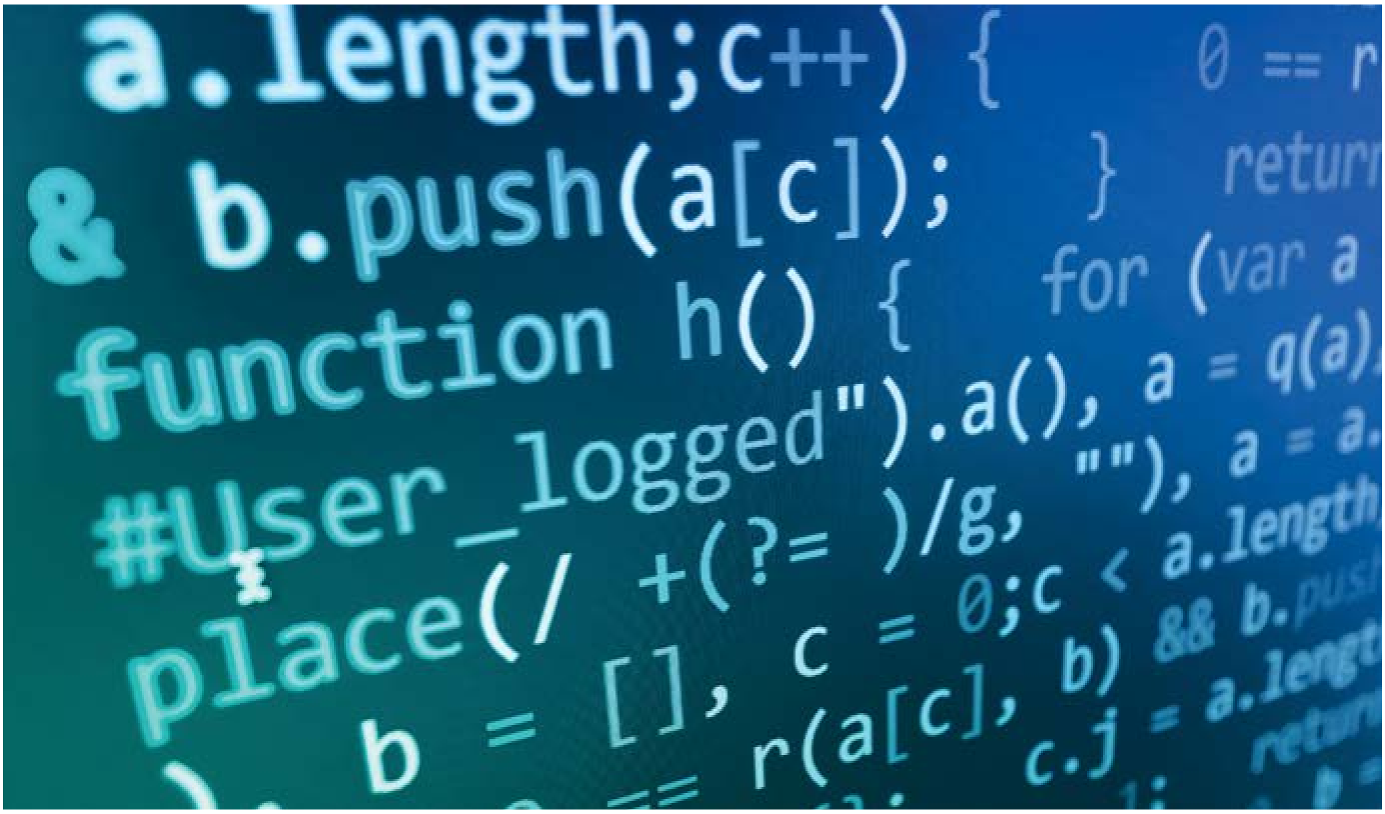
After humans have provided the swarm (or specific units within the swarm) with commands, and control architectures have guided how the commands will be distributed, the swarm has to coordinate its collective behaviour and execute the assigned tasks. How the swarm executes those assigned tasks depends, in part, on the coordination method.

Leader-follower models designate one robotic unit as the leader and the other robots as followers. In this model, robots coordinate by following the leader's trajectory, or the leader can assign specific tasks to individual robots in the swarm.

Utility functions can be used to optimize the swarm's behaviour: the swarm is given a high-level command (a goal), after which the swarm balances the costs and rewards of particular actions and pursues the action that is considered the most utile (with the highest reward).

Another method to coordinate swarm behaviour is the use of **consensus algorithms**: individual robots communicate with one another and converge on a solution through voting or auction-based methods.

Emergent coordination arises out of the interaction between the individual units in the swarm and can be compared to the behaviour of musicians in a jazz ensemble, where individual musicians coordinate by reacting to the behaviour of the other musicians in the group.



STATE OF PLAY

The deployment of military swarms has the potential to significantly change the role of humans and the way they exercise control over autonomous systems.

Today's swarms – in the civilian and military domain – are either under development or still in a testing and demonstration phase. In the military context, swarm research and development focuses most prominently on the applications described in the table below.

None of the projects in the table are said to have reached the operational stage. Designing, developing and testing swarms in structured environments (e.g. a lab) or relatively uncluttered environments (e.g. controlled airspace) is only the beginning. Deploying that same technology in an senvironment that is uncontrolled, unstructured and potentially hostile presents many more challenges.

Application	Description	Examples
Intelligence, Surveillance and Reconnaissance operations	Swarms may be tasked to search a defined area to, for example, find potential targets, or they may be used to map large areas.	The Strategic Capability Office of the US Department of Defense, in partnership with the Naval Air Systems Commands Perdix project and the Distributed and Collaborative Intelligent Systems and Technology Collaborative Research Alliance (DCIST CRA).
Perimeter surveillance and protection	Swarms could be used as autonomous border surveillance systems.	The European Union initiative Roborder; the US Office of Naval Research's swarm fleet CARACaS; China's 56-boat drone swarm.
Distributed attacks	Swarms could be used as weapon systems that autonomously distribute targets among themselves.	The US Defense Advanced Research Projects Agency (DARPA) Collaborative Operations in Denied Environment (CODE) project; Turkish company STM's Kargu swarm.
Air defence	Swarms can be used to confuse, overwhelm and neutralize enemy air defence by their sheer numbers.	The European Union's Suppression of Enemy Air Defenses Swarm.
Force protection	Swarms could also be used to protect high-end military platforms and troops during missions, such as deployment around a convoy, ships or other assets.	The US DARPA and Air Force Research Laboratory Gremlins project; the US Air Force's XQ-58A Valkyrie or "loyal wingman".
Deception	Swarms may act as decoys, perform false manoeuvres or deceive the adversary into thinking that the swarm is a much larger vehicle moving through an area.	Similar decoy tactics have been deployed by Israeli forces in the Syrian Arab Republic, tricking Syrian radars into believing drones were attacking aircraft. The drones were, however, not said to operate as swarms.
Dull, dirty and dangerous tasks	Swarms could also be used for dull, dirty and dangerous tasks, such as mine detection and cleaning.	Autonomous swarm landmine detecting robots; Rolls-Royce's miniature robots that can perform visual inspections of engines.
Countering other swarms	Given the worldwide availability of small robotic platforms (particularly aerial vehicles such as hobby aircraft), swarms may be used (or even be necessary) to counter other swarms.	The US Naval Postgraduate School's experiments on counter-swarms in the context of the Advanced Robotic Systems Engineering Laboratory (ARSENL).

About UNIDIR

The United Nations Institute for Disarmament Research (UNIDIR) is a voluntarily funded, autonomous institute within the United Nations. One of the few policy institutes worldwide focusing on disarmament, UNIDIR generates knowledge and promotes dialogue and action on disarmament and security. Based in Geneva, UNIDIR assists the international community to develop the practical, innovative ideas needed to find solutions to critical security problems.

This research area of the Security and Technology Programme is supported by the Governments of Germany, the Netherlands, Norway, and Switzerland.

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Inputs for this publication were drawn from:
Ekelhof, Merel, & Giacomo Persi Paoli. *2020. Swarm Robotics: Technical and Operational Overview of the Next Generation of Autonomous Systems*. Geneva: United Nations Institute for Disarmament Research.

Ekelhof, Merel. 2019. 'The Distributed Conduct of War: Reframing Debates on Autonomous Weapons, Human Control and Legal Compliance in Targeting.' Dissertation. VU University Amsterdam.

Design: Kathleen Morf, www.kathleenmorf.ch
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