

SMARTER ROBOT SWARMS COULD CHANGE WARFARE

小兵立大功-靈敏無人機器載具群

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前言

Different types of robots suit different missions. For instance, an airborne robot might skillfully maneuver around obstacles better than a ground robot, but a ground robot might have more energy to travel longer distances.

不同型式的無人機器載具，可適應不同的任務；例如，飛行無人機器載具超越各式障礙物的靈活性就優於地面無人機器載具，但地面無人機器載具卻擁有較長距離運動的能力。

Army leaders believe the next stage of warfare will necessitate the support of mixed robot teams that can dynamically adapt to environmental challenges. But for different types of autonomous robots to work together, they need a core strategy that tells each team member how to move, plan and communicate. The Distributed and Collaborative Intelligent Systems and Technology Collaborative Research Alliance (DCIST CRA), a program managed by the U.S. Army Combat Capabilities Development Command Army Research Laboratory, aims to fill that technology gap.

美國陸軍領導階層相信：下一階段的戰爭，將會需要可靈活適應戰場環境挑戰，混合型無人機器載具的協助，方能扭轉戰局，克敵制勝。但要整合這些不同型式的自主性

無人機器載具並發揮功用，需要一套能讓其成員有效的對機器載具發號施令、計畫及溝通的核心策略。

美國陸軍戰鬥能力發展司令部所屬的研究實驗室刻正推動一項，名為分散式協同智能系統暨科技合作的整合計畫(DCIST CRA)，用以填補此項新興科技與傳統之間的落差。



上下圖示：一支由 40 架無人機構成的飛行機器載具群，在美國加州-艾爾堡國家訓練中心的演習中接受測試。

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本文

“A lot of Army-relevant road maps and autonomy strategy documents for multidomain operations rely on heterogeneous mixes of air and ground autonomous systems,” said Brett Piekarski, DCIST collaborative alliance manager. “We’ve done a lot of good work in the Robotics Collaborative Technology Alliance and the Micro Autonomous System[s and Technology] Collaborative Technology Alliance, but the place where we haven’t worked in is collaborative systems. That’s the thread that we see as the next long pole in the tent to enabling Army future concepts.” The collaborative technical alliances are partnerships among the Army, private industry and academia that focus on the rapid transition of innovative science and technology for application to Army needs.

據美國陸軍戰鬥能力發展司令部合作聯盟專案經理布瑞特•皮耶卡斯基(Brett Piekarski)指出：雖然我們在機器載具及微型自主性系統合作聯盟上頗有進展，但若干與支援多重領域作戰有關的軍用地圖及獨立性圖資，係依賴空中及地面圖資混合系統，但此系統本身既存之差異性為目前我們有待改進之處，亦是我們促成陸軍未來作戰概念實現之法寶。另科技合作聯盟與陸軍、私人產業及學術界，彼此為伙伴關係，渠等則專注在陸軍運用新創科技所需的快速轉型。

Partnered with leaders in academia across the nation, the DCIST CRA endeavors to spearhead the science that extends the reach, situational awareness and operational effectiveness of human-robot teams against multidomain threats in complex and contested environments.

分散式協同智能系統暨科技合作整合計畫(DCIST CRA)與全國學術精英機構合作，竭力引領人員與無人機器載具團隊，期能在激烈及複雜環境中對抗多重威脅時，能及時將此科技能力延伸至戰場實地、情境覺知及作戰效率上。

The DCIST program specializes in research on distributed intelligence, heterogeneous group control, and adaptive and resilient behaviors as well as in cross-disciplinary experiments that incorporate aspects of all three research areas. Given the sheer size and scope of the program, the combined progress being made under the collaborative research alliance could significantly accelerate the rate at which the Army achieves technological superiority on the future battlefield.

分散式協同智能系統暨科技合作整合計畫，係擅長研究分散式智慧、異質群組控制以及具備適應性與彈性行為等能力，並藉整合上述三個領域各項細節之跨領域實驗。鑑於此計畫的全盤規模與範圍，研究合作聯盟的整合進展，將大幅提升陸軍在未來戰場上掌握科技優勢的速度。

As evidence of this potential, a DCIST team within the Adaptive and Resilient Behaviors Division of the program presented a new framework for distributed intelligence at this year's IEEE International Conference on Robotics and Automation (IEEE stands for the Institute of Electrical and Electronics Engineers). Supported in part by Boeing Co., this latest milestone in the DCIST program introduced a new approach to distributed information-gathering called Distributed Local Search, which optimizes the trade-off between information gain and energy cost for heterogeneous robot teams.

有鑑於該實驗的潛能，分散式協同智能系統暨科技合作整合計畫所屬的適應性與彈性行為研究小組，於本(2021)年在電機及電子工程師協會針對機器化與自動化的國際會議上，提出分散式智慧的新計畫架構。獲得波音公司的部分支持，此一劃時代的分散式協同智能系統暨科技合作整合計畫，引介一項稱為分區局部搜索的新型分散式情報資料蒐集手段，有助於不同性質的機器載具團隊在權衡情報資料酬報與人力付出之取捨時，發揮最大作用。

“Most of the current approaches have been to basically send out a team where robots myopically search like ants trying to find the closest food they can locate,” said George Pappas, professor of electrical and systems engineering at the University of Pennsylvania and team lead for DCIST. “One of the challenges for us is to determine how to make the robot swarm more strategic as a team and think more longer term and look for targets that are farther out. This is the first real push toward considering factors like energy costs, which introduces a new class of optimization problems to address.”

賓州大學電機系統工程教授並擔任分散式協同智能系統暨科技合作整合計畫小組負責人的喬治・帕柏斯(George Pappas)表示：目前大部分作法是派出操作團隊至所望地點，然後讓機器載具像螞蟻在近處尋覓食物般執行搜索任務。然而我們面臨的挑戰之一，即是如何讓機器載具群體成為有效率的作戰團隊，並思考未來如何讓它們尋獲位於遠方的目標，而不是只會在近處尋覓，如此才是衡量成本資源付出與發揮最大功能的首要考慮之處。



圖示：戰士們利用科技優勢在複雜及獨立自主的環境中進行溝通。

Balancing Energy, Performance

得失之間

In order to accomplish important Army missions, autonomous robot teams need a strategy that maximizes the capabilities of each member of the swarm without wasting energy or time on unnecessary actions.

為了達成陸軍交付的重要任務，自主機器載具團隊需要一套能讓每一部機器載具發揮最大效能，而不會浪費時間與人力在非必要行動上。

A centralized approach may offer a large degree of control over the robot swarm, but having one command station direct the behavior of the robots leaves the operation vulnerable to a single point of failure.

集中指揮或許可對機器載具組作最大程度之掌控，但讓單一指揮單位掌握所有機器載具，卻有把雞蛋全部放在同個藍子內的缺點與風險。

A distributed approach where each robot plans its own motions demonstrates greater resilience to such risks, but a complete lack of coordination will lead to redundant movements that drain the team's resources.

分散式手段能讓每一機器載具自主行動，享有最大彈性並能避免前述風險發生。若完全缺乏有效的協調，卻可能導致無關緊要的行動，虛耗掉團隊的寶貴資源。

In 2014, DoD funded researchers from top universities to create a new kind of information-gathering strategy that enables autonomous robots to make smart decisions in the long run instead of chasing after short-term benefits. In response to this challenge, Pappas and his team initially devised a new approach in the form of a coordinate descent algorithm, where the robots plan their actions one at a time.

2014 年美國國防部贊助來自各頂尖大學的研究員，研擬情報資料蒐集的新方法，使自主機器載具不只是追求階段性的短期效益，而是能從長遠方面做出明智的決策。為能有效解決此項挑戰，帕柏斯教授及所屬團隊著手以協調式下降演算法，設計一套程式，讓所有載具一次只能執行一個行動。

In this approach, the first robot plans its own motion to minimize uncertainty from its own perspective, then shares this information with the second robot in the team. The second robot takes the first robot's plans into account when it makes its own plans, which guarantees the second robot will not go in the same direction the first robot plans to go. The second robot then passes the information to the third robot, which takes into account what the first two plan to do.

在此種手段中，第一部機器載具規劃其行動時，會自行斟酌並減少行動的不確定性，然後將此一資訊分享予團隊中第二部機器載具。後者會在規劃自身的行動時，將前者的規劃列入考慮。如此，便能確保第二部機器載具不會重蹈第一部機器載具所規劃的方向。然後第二部機器載具，再將此一資訊傳遞給第三部機器載具，並將前二部機器載具的規劃列入考量範圍。

“It's called ‘coordinate’ because each robot is like a different coordinate, and we're ‘descending’ because we're minimizing the uncertainty by proceeding with one robot at a time,” said Nikolay Atanasov, assistant professor in electrical and computer engineering at the University of California, San Diego and a principal investigator for the DCIST program. “And the interesting part about this algorithm is that we can prove that this kind of decentralized planning will perform at least 50% as well as the optimal centralized performance even in the worst-case scenario.”

聖地牙哥加州大學助理教授，同時也是分散式協同智能系統暨科技合作整合計畫首席研究員的尼克萊・阿塔納索夫(Nikolay Atanasov)表示：此一模式被稱為協同行動，係因為每一載具皆是不同的協同行動者，而我們則是藉由一次只對一部載具下達指令，以減少不確定性的逐降式指揮。而且此種演算指令最有意義的部分是，我們確認分散

式規劃模式，即使在最惡劣狀況下也有 50% 的任務達成率，相較集中指揮模式在最佳狀況下之達成率，也不遑多讓。

Exploratory, Economical

探索與效益之間

Distributed Local Search builds on top of the coordinate descent approach by factoring in the trade-off between energy and uncertainty reduction, a key element in real-life missions that most information-gathering algorithms tend to neglect.

分區局部搜索建立在協調式下降模式上，係將人力付出與減少不確定性之間的酬報列入考量，此乃是實際執行情報資料搜集任務時之關鍵要素，亦是常被忽略之處。

“We want agents to be more exploratory so that they can acquire information and reduce uncertainty as a team, but we also want them to be economical about their resources, whether that is their battery or the amount of time they have,” Pappas said. “This new algorithmic challenge on how to balance both in a scalable way across many robots is one of the key innovations that we are pursuing with our colleagues as part of the DCIST program.”

帕柏斯教授表示：為了獲取所望情報資料，我們期待各單位在探索如何獲取所望情資並減少其不確定性的同時，亦期望他們在其資源管控上能更節約實惠，如電池容量效能與探索研製可運用的時間。此外，施行這項大量用於權衡整個機器載具投資與報酬的新式計算挑戰，亦是身為分散式協同智能系統暨科技合作整合計畫全體研究團成員所追求的關鍵創新作法之一。

With Distributed Local Search, individual robots communicate with their teammates on a regular basis and recommend smarter trajectories for the team as members obtain more information about their surroundings. During each brainstorm session, the robots evaluate proposed movements based on their knowledge about the environment and determine whether the energy costs of their future actions will outweigh the potential information gain. Once all the robots come to an agreement, the swarm swiftly adopts the updated team plan. 採用分區局部搜索的作法，讓各別機器載具能持續與其機群成員溝通，建議精算過之航路，讓群體乃至各別機具能獲取周遭更多情資。在每次的腦力激盪研討會議上，機器載具會依據它們對環境的認知，來評估其耗費的能量是否與所得情報資料價值相符，以及是否繼續進行後續的動作。一旦所有機器載具取得共識，機器載具群組即靈巧採用最新的團隊計畫。



圖示：隸屬美國陸軍第一騎兵師第一裝甲戰鬥隊的偵察員薩切利・布里雷中士，在立陶宛的訓練任務中正準備發射掠奪者無人機。

“The solutions generated by the swarm are much more physically realizable and much more meaningful,” Pappas said. “This research is not just about how to get robot teams to move from one place to another but also how to get them to learn things about the environment, about the adversary and about each other—that’s the new frontier.”

帕柏斯教授指出：如此，機器載具群組所採取的方案，會更具體可行且不同於以往。另外，本研究不僅是讓機器載具由一地移動至另一處，同時也是讓機器載具感測環境變化，知天、知地亦能夠知己、知彼，讓情報蒐集作為及作戰方式進入嶄新的境界。

Muddy Side, Windy Side

風雨展信心

To illustrate the power behind Distributed Local Search, the DCIST researchers performed a computer simulation that placed ground and aerial robots in an environment divided in half with a muddy side and a windy side. Ground robots had to expend more energy to move on the muddy side, while aerial robots had to use more energy to fly on the windy side. Once equipped with the Distributed Local Search algorithm, the ground robots learned to search for targets on the windy side while the aerial robots learned to stay on the muddy side.

為了展現分區局部搜索的實力，分散式協同智能系統暨科技合作整合計畫的研究員進行了電腦模擬測試，將地面機器載具及飛行機器載具分別安置在一半泥濘地形及一半強風的環境中。地面機器載具需要耗費更多的能量方能在泥濘地形中通行，同時飛行機器載具亦得使用更多能量，始能飛越強風地區。一旦配備了分區局部搜索的程式，地面機器載具可以感知搜索位於強風地區的目標，而空中機器載具則順勢在泥濘地形區上空執行搜索任務。

“We can see that, over time, the Distributed Local Search algorithm finds solutions which assign the aerial robots and the ground robots to the areas that respectively optimize their movements,” Atanasov said. “In contrast, myopic algorithms would only try to maximize information gain and fail to take motion costs like the mud and wind conditions into account.”

隨著時間的推移，我們見證了分區局部搜索程式的效能，解決問題的方法即是派遣地面機器載具及飛行機器載具，分別至它們各自最能發揮效能的地區。

阿塔納索夫教授指出：反之，如果採用近距離搜索模式，它們只在乎最大量獲取情報資料，而不會將泥濘地形及強風等狀況的通行代價，列入考量。

Just as teamwork plays a crucial role in mission success for soldiers on the battlefield, the ability for robot swarms to jointly devise and modify a plan during the mission serves as a major technological advantage for the Army. This revolutionary artificial intelligence (AI) behavior framework could lead to development of large-scale robot teams that can quickly adapt to unexpected mission threats and intelligently formulate an appropriate counterresponse.

就像士兵在戰場上，團隊合作係任務成功的關鍵要素，無人機器載具群組執行任務時擬訂及修正計畫的能力，成為陸軍的主要科技優勢。此一人工智慧行為架構有助於研發出，可以快速調整不預期方面之敵情威脅，並可靈巧地擬定適當的反制手段的大規模機器載具群組。



圖示：一架小型無人機飛越美國猶他州的杜格威試驗場。

“The ability of intelligent autonomous systems to collaboratively plan in highly dynamic situations will open the doors for the Army to consider and employ robot teams in increasingly complex missions and operational environments,” Piekarski said.

皮耶卡斯基指出：智能型自主系統在瞬息萬變的動狀況下協同計畫的能力，將為陸軍面對繁雜任務及艱困作戰環境時，仍能思考與部署機器載具團隊，創造克敵制勝契機。For the Army, solutions such as Distributed Local Search represent only one of countless breakthroughs within this technical thrust of the DCIST program.

對陸軍而言，像分區局部搜索這樣的解決方案，只是象徵在分散式協同智能系統暨科技合作整合計畫的科研專案，無數的突破性進展中的一項。

Striving for Autonomy

自主性的展現

Jonathan Fink, the Army lead for the Adaptive and Resilient Behaviors Division, said some of the brightest minds in academia are working diligently with Army researchers to tackle the most challenging, Army-relevant problems in robust, multiagent autonomous behavior.

陸軍適應性與彈性行為研究小組負責人喬納森・芬克(Jonathan Fink)指出：一些學術界的頂尖學者正孜孜不倦地與陸軍研究人員，為了解決與陸軍無人機器載具相關問題，最具挑戰性的多智能體自主性行為等問題。

“There is work at the University of Pennsylvania where researchers are looking at how to use machine learning to accelerate the computation behind wireless communication between autonomous agents across networks,” Fink said.

芬克表示：賓州大學正負責一項任務，該校研究人員觀察如何透過網路，讓無人機器載具以無線通訊，學習在自主性機器載具間，加快電腦運算速度。



圖示：美國陸軍第 25 步兵師的步兵及工兵人員在夏威夷雪弗堡地下作業訓練

任務中，共同操作一具地面無人機器載具。

“We’re also investing new techniques to enable communication in the presence of jamming technologies. We have the algorithmic tools that allow us to do the autonomous planning for these agents, but the end goal for a lot of this work is figuring out new ways to accelerate or improve the scaling of those algorithms so that they perform well even with a large number of agents.”

我們也研發新技術讓通信手段在受到干擾時，仍能有效運作。另我們的數據處理工具，讓我們能執行機器載具的自主性計畫行為，但這些工作的最終目標係找出加快或改進處理大規模數據的新方法，如此在無人機器載具數量增大時，仍能正常運作。

The DCIST CRA presents a range of technological milestones, but for Piekarski, the true value of the program stems from how its research targets the specific needs of the U.S. military in order to achieve dominance over its adversaries.

分散式協同智能系統暨科技合作的整合計畫勾勒出新科技的里程碑，但對皮耶卡斯基經理而言，該專案的價值來自於這些研究，如何符合美軍的特定需求，以超敵勝敵。

Unique Environment

特殊境遇

While robotics and AI technologies produced by commercial industry may satisfy the needs of the average consumer, soldiers on the battlefield face a uniquely challenging environment in which they won’t have guaranteed access to global communications, infrastructure or other resources.

私人企業所生產的機器載具及人工智慧，雖然可滿足一般客戶的需求，但戰場上的軍人卻要面對嚴苛的環境，且不見得有全球通訊、基礎設施及其他資源可予支援。

“This focus on the complexity of Army-relevant missions, unique operational environments and adversarial settings drives the research to develop data sets and fundamental methods that extend commercial approaches beyond where they may fail under these Army constraints and conditions,” Piekarski said. “It helps identify technology gaps that would not normally be addressed by commercial market drivers and use cases.”

皮耶卡斯基另指出：本項專注於陸軍所屬任務複雜性、獨特作戰環境與料敵從寬的專案計畫，驅動研發案朝數據機及商業運算基本方法等方向，但若未將陸軍的限制條件列入，往往會功虧一簣。因此本專案，有助於確認軍方與商業供需雙方，通常不會注意到的科技差距。

To many of the contributing researchers outside DoD, the DCIST program provides them with an opportunity to help soldiers in their own meaningful way.

對許多非屬國防部而學有專精的研究者而言，分散式協同智能系統暨科技合作的整合計畫，提供渠等奉獻所學，造福官兵的機會。

“There are many, many collaborative efforts that are available to many of us researchers out there, but the DCIST program is unique in that it is one of the very few programs that can steer the research community toward problems that have a national impact on the security and safety of the nation,” Pappas said. “I’m very optimistic that, in a five-year horizon, we will be able to see large teams of land and air vehicles performing long-term missions over large areas.”

對研究人員而言，眾志必然成城，但分散式協同智能系統暨科技合作的整合計畫，雖是眾人集思廣義，卻是悠關國家安全及福祉的少數特殊案件。帕柏斯教授表示：我個人甚感樂觀，五年內我們將可見到大規模的地面及空中無人機器載具群組，在廣闊地域執行長時程任務。

Steven Park is the science adviser for the Public Affairs Office, U.S. Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory, Maryland. Previously, he was an Oak Ridge Associated Universities Journeyman Fellow under the DEVCOM Army Research Laboratory chief scientist.

史帝芬・派克

美國馬里蘭州陸軍戰鬥能力發展司令部所轄陸軍研究實驗室公共關係室科技顧問。渠任職目前職務之前，曾擔任橡樹嶺大學俱樂部國家實驗室的首席科學家。