SWARMING LOGISTICS FOR TACTICAL LAST-MILE DELIVERY

Sam Thornton, Guy Edward Gallasch
Land Division
Defence Science and Technology Group
Edinburgh, South Australia, Australia
Guy.Gallasch@dst.defence.gov.au

***Abstract*— Last-mile delivery in a military context can often be dangerous, putting personnel and the supplies they carry at risk. The emergence of aerial 'delivery drones' from the commercial delivery sector highlights the possibilities of uncrewed vehicles being used in last-mile delivery. However, demonstrations of such technology have been limited to single vehicle deliveries, where only small portions of supplies can be delivered at once. This paper explores the concept of low-cost, uncrewed vehicle swarming for tactical last-mile delivery in a deployed setting. The benefits of uncrewed swarming systems over conventional methods of resupply are discussed, as well as the vulnerabilities and challenges faced by such systems.**

Keywords—Last-mile Logistics, Swarming, Drone Delivery

I. INTRODUCTION

Last-mile delivery (LMD) in a military context is the distribution of supplies from the last point of bulk disaggregation to dispersed forces located in the area of operations. It is a critical Combat Service Support (CSS) process. The last-mile is not actually reference to a fixed distance, but it is generally within a range of 30km [1]. While there is scepticism of the potential for swarming to be applied to LMD, it has many potential benefits over conventional methods of resupply, most notably its scalability, flexibility, and robustness against single point failure. The use of uncrewed delivery vehicles also reduces risks to personnel transporting supplies in contested environments, and can provide extended delivery capabilities to locations inaccessible by humans. This paper explores the concept, including strengths and weaknesses, of using swarms of low-cost, uncrewed platforms for last-mile military resupply.

II. SWARMING

Swarming can be defined as the collective physical behaviour (often emergent and complex) of a group or 'swarm' of physical agents, where each agent's own behaviour is based on simple rules for interaction with other agents within the swarm, and the environment. Biological examples of swarming can be seen in social insects such as ants and honey bees, in birds ('flocking'), fish ('schooling'), and many other organisms [2]. Swarming can occur both with and without the use of explicit communication between agents, making it an attractive concept to explore for technological operations in electromagnetically contested and degraded environments [2].

Sam is an undergraduate student with the University of Adelaide. He undertook this work while on a Summer Vacation Placement with Land Logistics Group, Land Division, over the 2017/18 vacation period.

III. LAST-MILE DELIVERY

A. *Military versus Civilian Contexts*

LMD in a military context differs greatly from that of a civilian context. Supply delivery to the tactical edge in contested environments poses the threat of delivery systems being disrupted by adversaries. Whether this is to hijack provisions, or to simply stem the flow of supply, military delivery systems can often be considered 'soft' targets and require appropriate countermeasures for protection. The result is the need for increased complexity of delivery platform design and delivery planning, and/or the necessity of security escort units. Additionally, military environments tend to be less structured that civilian environments, and can change throughout the course of an operation. High bandwidth connectivity is also problematic close to the tactical edge.

B. *Changing Nature of the Battlespace*

The call for new LMD methods originates in part from the nature of modern warfare. The 'front lines' of the battlespace have evolved from describing the literal front lines of opposing forces (such as trench warfare in the First World War), to forces fighting in more dispersed and highly mobile tactical groups. This in turn has forced (and will continue to force) LMD methods to become more versatile and precise. As stated in [3]: "Supplying widely dispersed units without traditional CSS battalions present is a difficult problem that will probably need to be addressed by a package of fixes" (p. 71).

C. *Current Last-mile Delivery Methods*

Current modes of direct delivery in military operations primarily involve the use of crewed supply vehicles and air drops. Due to the increasingly dispersed nature of modern warfighting, delivery vehicles are required to undertake multi-stop routes for distribution of supplies to ever more widely dispersed forces. This is an inefficient way of operation, as supplies after the first delivery are not transported directly to their delivery points. The result of this indirect delivery is increased delivery times and wasted resources. Air drop methods such as the Joint Precision Air Drop System (JPADS) can be expensive, requiring recovery on delivery by the receiver so that they can be returned and reused [4]. Air drops systems also need to be taken up to altitude before they can be deployed, further increasing delivery times, and requiring crewed cargo aircraft to fly over potentially contested areas.

IV. Swarming for Last-Mile Delivery

A. Benefits of Autonomous Systems for Last-Mile Delivery

The benefits of using uncrewed swarming platforms for tactical last-mile resupply form part of the bigger picture of harnessing autonomous systems for CSS. The use of autonomous systems for LMD could increase the safety of personnel by reducing their exposure to risk. For example, resupply convoys are often seen as 'soft' targets, and hence one argument for autonomous convoys is to reduce the number of personnel travelling in such convoys. Autonomous systems physically integrated with human forces could also provide faster decision making in time critical operations, such as optimal route planning or rerouting in hostile environments [5].

The value of autonomous systems for tactical LMD comes from not only the potential increase in the safety and wellbeing of personnel, but also from the likely increase in LMD efficiency. Autonomous systems do not become physically or mentally tired from carrying out their tasks. This provides potential for more continuous and sustained logistics operations over longer ranges. Autonomous systems could also be used to operate in environments considered too dangerous or inaccessible for humans, extending current CSS capabilities.

B. Benefits of Swarming for Last-Mile Delivery

Although the use of swarming for both offensive and intelligence, surveillance and reconnaissance (ISR) operations is already being explored by militaries around the world, the benefits of using swarms in logistics operations have not been discussed outside of autonomous (and semi-autonomous) ground convoys, which themselves do not exhibit swarm intelligence or emergent behaviour [6].

Coupled with low-cost, potentially expendable individual platforms (swarm agents do not need to be highly intelligent as individuals), swarming offers a force multiplier that is more scalable and flexible than complex, stand-alone systems. Efficiencies can be gained through a better match of payload to platform payload capacity. For instance, a small quantity of supplies could be delivered by a few smaller platforms as opposed to a single larger vehicle which may be transporting empty space. It may additionally be the case that some missions could benefit from having more delivery platforms than needed, such as a way of breaking up valuable supplies, or having some agents act as decoys.

Having scalable delivery swarms also means that multiple locations can be serviced both directly (avoiding the inefficiencies of indirect delivery via milk runs) and in parallel. This also facilitates more 'on demand' delivery due to increased availability of delivery platforms. Swarming also allows for swarm formations and tactics to be altered to suit dynamic and unknown environments. Furthermore, dispersed multi-robot systems can be multi-purpose, e.g. used for both situational awareness and delivery.

As autonomous and automated uncrewed systems become more complex, the cost of staffing required for operation, data management and analysis of the systems also increases [5]. In this regard, another benefit swarming brings to LMD (and automated and autonomous systems in general) is the ability for relatively few humans to control large numbers of autonomous platforms, through relatively simple rules for swarm control and organisation. Multi-robot swarming could act to reduce operating costs, as a single operator would be able to control a large number of platforms – the operator would likely see the swarm as a single entity, placing less investment and attention into the individual platforms that actually make up the swarm.

Finally, the use of decentralised and distributed multi-robot systems increases LMD system robustness over using single, or fewer platforms for delivery. If a single platform used to resupply forces is destroyed or fails in its task, none of the supplies are delivered. However if 100 platforms are used to deliver the supplies in a distributed manner, then the failure of a single platform, or even handful of platforms, has a much smaller impact, as the majority of supplies will arrive. Lt. Gen. Michael Dana, Deputy Commandant of Installations and Logistics for the US Marine Corps, believes that drone swarms for logistics would be especially handy in littoral or island environments [7].

C. Air versus Ground Swarming

LMD for ground forces doesn't need to be constrained to ground platforms. Swarms of UAVs are likely to be the easiest to realise, as they don't have to adapt to changing ground terrain, of particular significance for military environments where there can be little or no pre-existing road infrastructure. Additionally, the sophistication of mechanisms required for ground movement are also greater than that for aerial manoeuvres, further supporting the use of UAVs [6]. Swarm configurations and obstacle avoidance methods are also more flexible in the air domain, due to the freedom of elevation control. Against countermeasures, UAV swarms have the advantage that they are more manoeuvrable and are generally less susceptible to IEDs, land mines, or being obstructed.

UAV swarms do have some downsides, however. One is a need for sensing in 3-dimensional space (although there are less obstacles to avoid in the sky). Another is that UAV swarms, if flying in open skies, may reveal troop locations and/or be actively targeted by countermeasures. In terms of payload, UAVs are more constrained in payload capacity, although the use of scalable swarms somewhat makes up for this, as supplies can be distributed across multiple platforms. Platform cost to payload capacity also tends to be greater for UAVs when compared to UGVs.

Uncrewed maritime vehicles (UMVs), which can be classed as either surface or underwater vessels (or both) do not feature as prominently in LMD for ground forces, though they can play roles in amphibious operations and when forces operate close to bodies of water.

D. Use of UAV Swarming in Last-mile Delivery

Due to physical constraints, UAV swarms for LMD are likely to be constrained in the near future to lighter, smaller items such as medical supplies, small electrical components, and bulk commodities that can be broken down into smaller payloads (e.g. food, water, ammunition). Swarming would allow the overall delivery of meaningful quantities of such items. It is conceivable that UAVs could work in teams to collectively transport larger, heavier items, but it may be the case that conventional delivery methods for such items are more efficient. Scalability and flexibility of tasking provides the capability for parallel delivery to dispersed forces, e.g. simultaneous emergency resupply of ammunition to dispersed fighting elements engaged in a contested urban combat setting – a time critical delivery of valuable supplies to a high risk or denied environment. Another use case could be the delivery of emergency medical supplies, similar to the RQ-7 Shadow UAV demonstration of the QuickMEDS system [5]. However, currently, we note that swarming for LMD is not technologically feasible. We come back to this in Section VI.

E. Type of UAV

The type of UAV used for LMD swarming would depend on the functional requirements of the swarming platforms. There are two main variants: multi-copter (rotary wing) and fixed-wing. We refer the reader to [8] for a more detailed discussion of this, including Vertical Take-Off and Landing (VTOL) platforms and gliders.

F. Size of UAV

Swarming platforms for LMD would need to be small enough to be low-cost and expendable, but large enough to be able to carry at least a few kilograms in payload weight (depending on how divisible supplies are). Larger UAVs generally have greater range capabilities, and for LMD a radius of operation would be up to 30km. Smaller UAVs designed with hybrid or even hydrogen fuel cell power systems (as opposed to purely electric) could reach this target, at the cost of greater running expenses. Smaller UAVs would be preferred for swarming, as the decentralised functional benefits of swarming increase with agent numbers, and smaller, cheaper platforms would be easier to mass produce than larger ones. Larger, less agile heavy-lift UAVs (e.g. [9]) would be more suited to standalone deliveries. Smaller UAVs also have increased resilience against collision due to having less momentum [10]. The precise trade-off between effective throughput, range, and operating costs of small vs. large UAVs is beyond the scope of this paper.

G. Vulnerabilities

As with all uncrewed systems, data security is a vulnerability of swarming systems. The potential for communications jamming, spoofing and hijacking are all things that must be considered when implementing swarming systems, especially since the task of LMD places these systems in contested zones. The physical protection of LMD swarms is also an important consideration, as even though the individual platforms may be considered expendable, the swarm as a whole cannot be. The use of distributed control systems for swarm interaction somewhat alleviates the risk of single point of failure (both data-wise and physically) for entire swarms, but the risk still exists nonetheless. Further adding to these vulnerabilities is the fact that militaries have already begun looking into and implementing anti-drone swarm technologies (e.g. [6, 11]). There is also the threat that opposing weaponised drone swarms could intercept and destroy delivery swarms.

V. State-of-the-Art

UAV LMD is a relatively new area that has only recently gained prominence in the civilian and military logistics. Because of this, there is little material in the open literature around the idea of applying swarming to UAV LMD. The UK's Defence Science and Technology Laboratory (dstl) are currently holding an Accelerator competition to challenge private organisations to develop and demonstrate autonomous last-mile resupply systems. Winners of the competition's first phase included Marble Aerospace, with their proposed project titled "Swarm of high speed and small payload UAS with robotic hangars, for high speed long range resupply of small size item", although details of the project have not been publicly released [12]. Similarly, two first phase winners, 2iC and Blue Bear Systems Research, have partnered for the second phase of the competition to deliver "Autonomous UAV swarm operation", with Blue Bear Systems Research focusing on developing modular UAVs for a "fractionated" last-mile resupply system [13,14].

DARPA funded research firm Otherlab have taken to exploring LMD through the use of small (about a metre wingspan) GPS-driven gliders named APSARA – Aerial Platform Supporting Autonomous Resupply/Actions – that can travel up to 150 kilometres (when deployed from 35000 feet) and have a 10 metre landing accuracy (presumably in ideal conditions) [15]. The gliders are capable of delivering a one kilogram payload. Their structures are made from cardboard, allowing recipients to leave the airframes to degrade once the gliders have landed (including their electronics). Although these gliders do not display swarm intelligence, they are intended to be deployed in large groups (up to hundreds). The US Naval Research Lab has also developed small GPS-driven gliders intended to be dropped in groups from aircraft [16]. The Close-In Covert Autonomous Disposable Aircraft (CICADA) gliders have 3D printed fuselages, and wings and tail fins constituting of printed circuit boards for on-board avionics. Currently, the gliders are designed to only carry sensory and communications payloads, being able to transmit data back to their launching planes – using the gliders for delivery of supplies is yet to be explored.

VI. Technological Challenges

There are numerous technological challenges to overcome before swarming is viable for meaningful LMD in a military context, beyond the usual Space, Weight and Power constraints forcing a trade-off between range/endurance, payload capacity, size, and cost (in this case largely centred around energy density of batteries or other fuels). Many of these challenges are also applicable to swarming for other purposes.

A. Whole-of-Swarm Positioning

Reliance on positioning systems such as GPS for swarm coordination is a clear weakness when operating in a contested environment where GPS can often be blocked or spoofed, or where satellite coverage isn't sufficient. This will need to be accounted for through the use of inbuilt maps combined with other localisation and positioning techniques including the use of dead reckoning, inertial navigation, and optical-flow.

B. *Internal Swarm Localisation*

There are numerous methods for localisation of individual agents within a swarm and for the detection of neighbours, both active and passive, and each with their own pros and cons. A more detailed discussion is presented in [8], but in brief, these include wireless networking technologies, camera vision, laser rangefinding (3D lidar), infrared sensors, ultrasonic sensors, radar, and audio. From a signature management perspective, passive methods are preferred, however such methods (e.g. vision) are too financially and computationally expensive to be viable for low-cost, small UAVs at the current level of technology maturity (although this is expected to improve rapidly). Furthermore, unless carefully designed, the active sensors of many robots swarming in close formation may interfere with each other in unwanted ways, e.g. the sensors from one platform pick up the transmitted signals from another platform instead of their own reflected signals [17].

C. *Signature Management*

Adding to the problem, any vehicles operating in warzones should ideally have sufficiently low signatures (radio frequency, acoustic, thermal, visual etc.) to avoid detection by adversaries, limiting the number of sensory technologies and acceptable communications bandwidth than can be used.

D. *Human-Swarm Interface*

Another big technological challenge for UAV swarming in LMD, and for coordination of multi-robot systems in general is the operational control of such systems. This not only relates to the human-swarm interface, in which data needs to be optimally presented to operators within human cognitive limits, but also to the degree of autonomy each system exhibits. Higher degrees of autonomy allow lesser needs of operator control, but greater needs in operator analysis of autonomous performance and decision making.

E. *Communications and Networking*

If wireless networks are used for both inter- and intra-swarm communication, suitable networking protocols will need to be developed. These networks must be scalable and adapt to agents both entering and exiting a swarm's network. Separating different data into different channels of communication (e.g. remote piloting of a swarm leader vs. intra-swarm communications) into different channels of communication may help to provide resilience against interference [18].

VII. Conclusion

The concept of swarming enables meaningful volumes of supplies to be delivered by low-cost, uncrewed systems. The use of uncrewed systems for tactical last-mile delivery reduces the exposure of CSS personnel to potentially hostile environments. Furthermore, swarming systems allow supplies that can be divided into smaller parts to be transported in a distributed manner that is scalable, flexible and robust. Swarming delivery systems suit the increasingly dispersed and mobile nature of modern warfighting, where conventional methods of supply delivery can be time and cost inefficient. Military organisations have acknowledged the potential for UAV swarms to be used in future warfare in offensive and ISR roles, and have already begun developing countermeasures. However, numerous technological challenges remain.

References

[1] Gov.uk, "Competition document: autonomous last mile resupply" last accessed 22 May 2018, Available via https://www.gov.uk/government/publications/accelerator-competition-autonomous-last-mile-supply/accelerator-competition-autonomous-last-mile-resupply

[2] Wikipedia, "Swarm behaviour", last accessed 22 May 2018, available via https://en.wikipedia.org/wiki/Swarm_behaviour

[3] Edwards, S., "Swarming on the Battlefield: Past, Present, and Future", Monograph Report, RAND Corporation, 2000, available via https://www.rand.org/pubs/monograph_reports/MR1100.html

[4] Ackerman, E., "U.S. Marines Testing Disposable Delivery Drones", IEEE Spectrum, 17 April 2017, available via https://spectrum.ieee.org/automaton/robotics/drones/marines-testing-disposable-gliding-delivery-drones

[5] Ivanova, K., Gallasch, G. E., and Jordans, J., "Automated and Autonomous Systems for Combat Service Support: Scoping Study and Technology Prioritisation", DST Group Technical Note DST-Group-TN-1573, October 2016.

[6] Sanders, A., "Drone Swarms", Master's Thesis, School of Advanced Military Studies, United States Army Command and General Staff College, Fort Leavenworth, Kansas, 2017.

[7] Seck, H., "Marines Want Swarming Delivery Drones for Resupply, Disaster Relief", Military.com, 25 July 2017, available via https://www.military.com/defensetech/2017/07/25/marines-want-swarming-delivery-drones-resupply-disaster-relief

[8] Thornton, S. and Gallasch, G. E., "Swarming Logistics for Tactical Last-mile Delivery" draft DST Group General Document, 21 February 2018, unpublished.

[9] Aitken, R., "What do China's Delivery Drones Look Like? - JD.Com Spotlight", UnmannedCargo.org, 26 October 2017, available via http://unmannedcargo.org/chinese-delivery-drones/

[10] Kumar, V., "The Future of Flying Robots", last accessed 23 May 2018, available via https://www.youtube.com/watch?v=ge3--1hOm1s

[11] Lockheedmartin.com, "Technology that Counters Drone Swarms", last accessed 31 January 2018, available via https://lockheedmartin.com/us/innovations/061416-webt-laser-swarms-drones.html .

[12] Gov.uk, "Accelerator funded contracts 1 April 2017 to 31 March 2018", last accessed 8 December 2017, available via https://www.gov.uk/government/publications/accelerator-funded-contracts/accelerator-funded-contracts-1-april-2017-to-31-march-2018

[13] 2icworld.com, "News | 2iC", last accessed 20 December 2017, available via http://www.2icworld.com/news/11/45/UK-SMEs-partner-to-develop-Autonomous-Last-Mile-Logistics-Solution-for-MoD

[14] Scott, R., "Innovative modular UAS concept [DSEI17D2]", Janes 360, 13 September 2017, available via http://www.janes.com/article/73890/innovative-modular-uas-concept-dsei17d2

[15] Ackerman, E., "Swarms of Disposable Drones Will Make Critical Deliveries and Then Vanish", IEEE Spectrum, 1 Feb. 2017, available via https://spectrum.ieee.org/automaton/robotics/drones/otherlab-apsara-aerial-delivery-system

[16] Ackerman, E., "Naval Research Lab Tests Swarm of Stackable CICADA Microdrones", IEEE Spectrum, 25 July 2017, available via https://spectrum.ieee.org/automaton/robotics/drones/naval-research-lab-tests-swarm-of-stackable-cicada-microdrones

[17] Turgut, A., "Self-organised flocking with a mobile robot swarm", Ph.D thesis, Graduate School of Natural and Applied Sciences, Middle East Technical University, 2008.

[18] Etter, W., Martin, P., Mangharam, R., "Cooperative Flight Guidance of Autonomous Unmanned Aerial Vehicles", CPS Week Workshop on Networks of Cooperating Objects (CONET), April 11-14, 2011.