Autonomic Pulse Communications for Adaptive Transmission Range in Decentralised Robot Swarms

Liam McGuigan, Roy Sterritt, Glenn Hawe
School of Computing, Faculty of Computing, Engineering and the Built Environment
Ulster University
Jordanstown, N. Ireland
email: mcguigan-l8@ulster.ac.uk, r.sterritt@ulster.ac.uk, gi.hawe@ulster.ac.uk

Abstract— **Robot swarms, consisting of large numbers of individual robots collectively working towards a common goal, must be autonomous in order to carry out their task without regular human input. Further, there is a requirement that such swarms be autonomic, capable of self-management to enable operation in distant, complex or changing environments. Underpinning the ability of the swarm to cooperate and adapt is the communication between individual robots. Wireless communication relying on a fixed transmission range may be subject to connectivity loss, restrain robot motion, or be an inefficient use of energy. This research makes use of robot swarm simulation to develop Autonomic Pulse Communication as a means of adaptively selecting a transmission range, based on the existing concept of Pulse Monitoring to allow individuals within the swarm to estimate the local swarm density. The system is able to successfully share data originating in a single robot with the rest of the swarm within an allotted time period. It is also found to be extremely robust to communications loss, completing the task when the chance of a successful message receipt is as low as 5%.**

Keywords- Swarm robotics; Self-adaptation; Autonomic Computing; Swarm communication; Simulation.

I. INTRODUCTION

Swarm robotics, the study of how individual behaviours within a group of robots may combine through local interactions to create a more complex set of behaviours [1], has potential applications in fields such as space exploration [2], precision agriculture [3], and disaster response [4], where many small, simple robots can cover a much larger area than a single monolithic craft.

The size of the swarm, its decentralised nature, and the conditions in which it may potentially operate mean that a swarm should be able to act on its own, adjusting its behaviour according to a changing situation without the need for any external guidance [5]. Autonomic Computing concepts [6][7] can assist in achieving swarm self-adaptation, making use of a Monitor, Analyse, Plan and Execute loop, with a shared Knowledge base, known as MAPE-K, as described in [6] to assess the situation, identify any changes necessary, and implement them.

As swarms are decentralised, their ability to adapt depends on their cooperation through sharing information on which to base decisions and come to an agreement on actions to be taken. When the swarms are reliant on local communication with neighbouring robots, the effective range of that communication matters. Too small, and robot behaviour may need to be constrained to maintain communication links with other members of the swarm. Too large, and it may be an inefficient use of battery power, lead to communication interference, or even be detrimental to overall performance.

In previous work, a decentralised swarm made use of an autonomic system to help adjust a range over which robots would broadcast for help in a foraging task [8]. This worked by using a fixed range pulse message between robots to help estimate the density, but it was found that the range of this pulse message needed to be set for differing swarm densities. If this is not initially known, performance would be degraded.

The objective of this work is to implement an adaptive system for setting the range over which a robot broadcasts information, according to the local density of the swarm, detected at run-time.

The rest of this paper is structured as follows. Section II discusses related work in swarm self-adaptation and autonomic systems used to develop the Autonomic Pulse Communication (APC) system presented. Section III discusses the design of the APC system and how it estimates local density. Section IV describes the data sharing task used, Section V describes the test scenarios used to evaluate the system, and Section VI presents the results of those tests. Section VII discusses the results, and Section VIII concludes the paper with a summary and directions for future research.

II. RELATED WORK

In the context of a robot swarm, a distinction can be made between the adaptation of individual robots, and that of the swarm as a whole. This can be related to the idea of *self-expression* [9][10], in which the swarm at large can be reconfigured. Such swarm-level adaptation can then take advantage of wider knowledge to make changes to swarm composition [11], or cooperative strategies [12].

To achieve swarm-level adaptation, however, cooperation and communication becomes essential. Individuals must share data in order to collectively recognize the need to adapt, and then to decide on the new course of action. Consensus problems, typified in swarm research as the best-of-*n* problem [13], in turn require some means of communicating the currently held opinion of any one robot to neighbours.

Direct communication between neighbours requires a degree of connectivity between the robots in the swarm. All-time connectivity uses approaches such as control laws to balance both the task at hand and the need for connectivity [14][15]. Such approaches necessarily restrict the movement of individual robots, and may be detrimental to performance [16]. Relay approaches may help with this, by delegating the job of providing connectivity to only some portion of the swarm [17][18].

Relaxing the need for all-time connectivity, path planning approaches [16] or ferries [19] may allow for an intermittent approach, but add complexity to swarm behaviour and require some or all robots to halt their task periodically.

The absence of explicit attempts to maintain communications link may be described as opportunistic, with robots transferring data to others in range when their paths happen to cross. This is the least restrictive approach and does not require dedicated roles or periodic rendezvous, but at the expense of guaranteed connectivity.

A crucial factor, regardless of the approach taken, is the communication range. The further apart any two robots may be when maintaining a communication link between them, the freer the robots are to move, and the fewer the number of robots that may be critical to network connectivity. As higher ranges may require more power and result in network interference [20], and lower ranges may decrease connectivity, finding a suitable broadcast range becomes desirable.

The mechanism for achieving this, described in the next section, is based on the existing concept of Pulse Monitoring (abbreviated to PBM due to its extension of Heart Beat Monitoring, HBM) [21], in which a periodic heartbeat message has a pulse encoded within it, allowing a component in a system to indicate its current health status. The concept has been explored in applications such as personal computers [22], telecommunications [23], and cluster management [24]. In order to support a reflexive reaction by minimising the processing required by a recipient, health-related data may be included in the message [23].

Pulse monitoring may be applied to a robot swarm, such as in [25], where it may be a means for a ruler craft during the Prospecting Asteroid Mission to monitor the health of workers under their control. However, another perspective may be used. In a dynamic swarm, where there is a need for scalability, it may be undesirable for one robot to track another's health over a significant period of time, and it cannot be expected that any one robot would rely upon another *specific* robot to assist in a task. Instead, pulses received during a small interval may represent the health of the local neighbourhood, allowing a robot to determine if its own status is abnormal, or provide early-warning of danger by noting problems developing in neighbouring robots.

Pulse monitoring is typically concerned with reporting on the health of whatever aspect is being monitored, as a form of failure management. In this paper, the concept is adapted to allow an individual robot to measure the local density of the swarm through the receipt of pulse messages from neighbouring robots that contain information about the source robots' positions. In this way, the "I am healthy" signal is replaced with one saying "I am here". The design of the APC system is described in the next section.

III. AUTONOMIC PULSE COMMUNICATIONS

The goal of the APC system described in this paper is to provide a mechanism for the adaptive adjustment of the transmission range used for inter-robot communication, in order to avoid the pitfalls that come with needing to set the range used at the start of the mission.

To achieve this, the concept of PBM described in the previous section is adapted to repurpose the regular signal sent by each robot. In the Decentralised Autonomic Manager described in [8], robots used periodic pulses to determine the local density of the swarm, but the pulse required a fixed transmission range used by each robot. If different transmission ranges were to be used, the density could not be easily calculated.

This problem is resolved by having each pulse also contain the position of the sending robot, allowing the distance from the pulse origin to the receiving robot to be calculated. Alternatively, situated communication [26] may be used to derive distance information from the received signal. Whichever approach is taken, the distance may be used to estimate the local density.

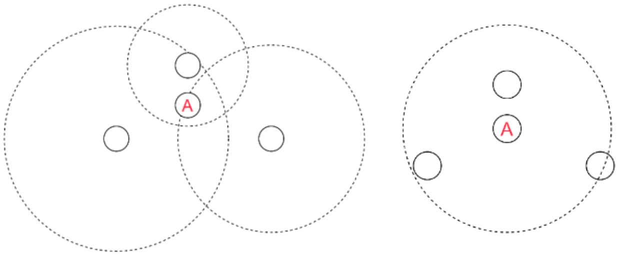
Fig. 1 (a) shows a case in which Robot A has a number of neighbours, all broadcasting pulse messages at different ranges, each of which is transmitted far enough to reach the robot. To simplify the example, all robots are shown to be sending their messages simultaneously, but the same process applies as long as all messages are received within the same short period of time. Each pulse contains the position of its sending robot.

By totalling the measured ranges of the received pulses, the APC system is able to calculate the average distance of pulse messages received. The local density, ρ, is then calculated as:

$$\rho = n / \pi \bar{d}^2, \tag{1}$$

where n is the number of received pulses in the time period, and $\bar{d}$ is their mean distance.

Given a density, the APC system may then use a density-pulse range relationship provided in its knowledge base,



(a) (b)

Figure 1. A robot receives pulse messages from neighbours, and uses them to calculate a suitable range for its own pulse.

calculated based on the needs of the task. In Fig. 1 (b), Robot A sends out its own pulse, with the range determined by that relationship, enabling its pulse message to reach its neighbours.

The APC system is only able to calculate a suitable local density if it receives pulse messages during the period between sending its own pulses. If none are received, the robot is considered to be isolated from the rest of its swarm, and so it gradually increases its broadcast range on subsequent pulses. This increases the chance that the robot will later reconnect with the other robots, in turn influencing future selections of the transmission range.

In addition to the distance information required by the APC system, pulse messages may also share arbitrary data, sent on each broadcast, for the purpose of spreading information throughout the swarm. In this work, the data packet is small and does not grow with size, so a simple strategy of sharing data with neighbouring robots is used, in which no individual robot needs to care about which robots receive a broadcast. This approach scales with the swarm size, as the underlying behaviour of the robots does not need to change for larger swarms.

IV. DATA SHARING TASK

This research employs a time-stepped simulation of a homogeneous swarm of agents tasked with sharing a piece of data throughout the swarm. The purpose of this task is to determine how well a swarm of robots may share a single piece of information, initially held by only one robot in the swarm, with the rest of the members. The swarm of robots, each using an APC system configured with a pulse period of 10 simulation ticks, and a fixed pulse range of 10 units, is placed in a circular map.

Each robot stores a Boolean flag, initially set to false. At the start of each run, a robot is selected at random from the swarm and their flag is set to true. Any robot whose flag is true will share this data via the APC system. Receipt of the flag will cause a robot to set its own flag to true, and commence its own sharing.

During the test, the robots may wander freely throughout the map. Each tick of the simulation, a robot picks a random direction in two dimensions. If the robot is able to move forward one unit distance without leaving the map, the robot moves to that location, otherwise it will not move in this simulation update.

The test is left to run for 250 simulation ticks, and at the end, the success of the swarm in sharing the data is scored by the percentage of robots with their flag set to true. The test duration used will impact the density-range calculation, as the ideal range data used will be that which enables the swarm to reliably share the data with all members within 250 ticks.

All tests were run with the APC system set to stagger pulse times, rather than having all robots pulse simultaneously. This removes any requirement of the APC system to synchronise robot behaviour, while also avoiding flooding the available bandwidth with messages sent simultaneously.

V. TEST SCENARIOS

The following subsections describe the particular test scenarios run. Each test was run 50 times, and the results averaged across all runs.

A. *Density-Pulse Range Relationship*

To determine the relationship between the swarm density and the ideal pulse range to use, a set of simulations was run, for swarm sizes of 50, 100, 200, 500 and 1,000 robots, and maps with radii of 25, 50, 75 and 100 units.

The ideal pulse range for a given combination was determined by taking the lowest pulse range for which over 99.5% of the swarm, on average, received the data.

B. *Pulse Period*

This test explores how the APC pulse period affects the ability of the swarm to share the data. A map with a radius of 100 units was used, with the pulse range fixed at 10 units. The test was repeated with the five swarm sizes from the previous test, and pulse periods of 2, 5, 10, 15, 20 and 25 ticks. Each combination of swarm size and pulse period was tested, and the scores from each scenario are compared to evaluate the effects.

C. *Adaptive Pulse Range*

The equation relating density and pulse range derived from the previous test is now used in the APC system to adaptively adjust the pulse range, based on the local swarm density. This test looks at the ability of this adaptive APC system to set an appropriate pulse range, and therefore share the data throughout the swarm.

The maps and robot counts are the same as those listed from the Density – Pulse Range tests. Each APC system starts with a pulse range of one unit, and uses a period of 10 ticks. The score for each combination of map and swarm size is measured, and compared against the best performing fixed range communication established in the previous test.

D. *Communications Loss*

To explore the impact of communications no longer being guaranteed to arrive, a swarm of 200 robots is tested in a map with a radius of 100 units. The simulation is configured with a probability of any robot receiving a broadcast range, and the test is run with probabilities of 20%, 15%, 10%, 5%, 4%, 3%, 2% and 1%, together with a test of the fixed range communications with a probability of communication success set to 5%. Every 10 ticks, the number of robots that have the flag set to true are recorded, and the results compared.

VI. RESULTS

The following subsections discuss the results of the tests described above.

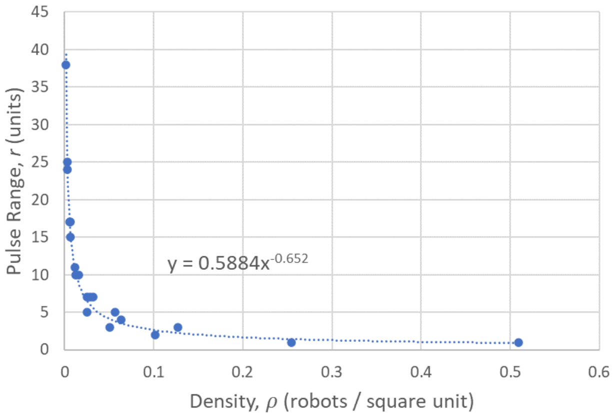


Figure 2. Plot of ideal pulse range against swarm density.

A. *Density-Pulse Range Relationship*

Table I shows the best performing ranges and their respective scores for each combination of map radius and swarm size, while Fig. 2 shows the relationship between swarm density and best performing pulse range.

Fitting a trend line to the plot leads to an equation for determining the pulse range to use, given the density of the swarm:

$$r = 0.5884 \times \rho^{-0.652}, \tag{2}$$

where r is the pulse range, and ρ is the swarm density.

B. *Pulse Period*

Fig. 3 shows the performance for each size of swarm, as the pulse period is increased. Increasing the period results in a drop in the score achieved, which is less prominent in the largest swarms, and is most clearly seen with a swarm of 200 robots.

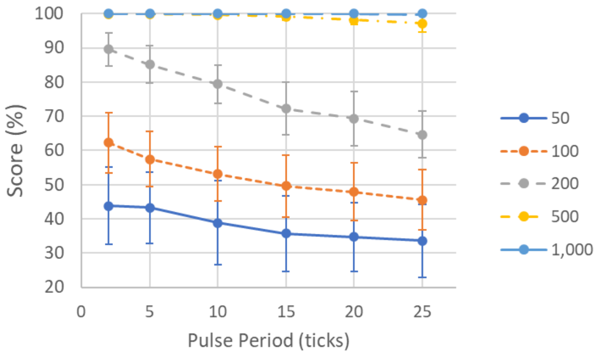


Figure 3. Score achieved by the swarm for each pulse period tested.

C. *Adaptive Pulse Range*

Table II shows the performance of the swarm, and average pulse range used, for each combination of map radius and swarm size. All scenarios achieved greater than the 99.5% score used as a benchmark in the fixed range tests, and all but three of the scenarios received a perfect score. The average pulse range used by the swarm can be compared against the ideal fixed ranges shown in Table I, and shows that higher density swarms make use of shorter range pulses on average.

D. *Communications Loss*

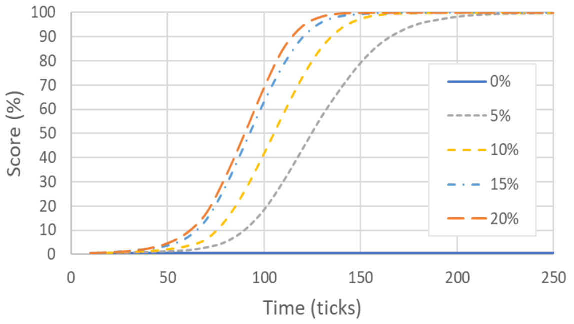
Fig. 4 shows the performance of the swarm of 200 robots on a map with a 100-unit radius, in scenarios where the probability of a communications broadcast being received by a robot was 20% or lower. In addition, the chart shows the performance of the APC system running with a fixed pulse range, where communications have a 5% probability of succeeding.

TABLE I. IDEAL PULSE RANGES FOR EACH MAP AND SWARM SIZE

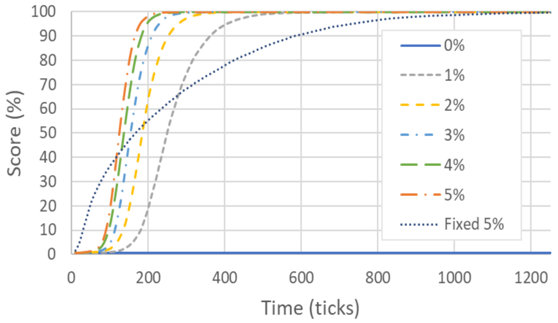
Swarm Size	**Map Radius**							
	25		**50**		**75**		**100**	
	Range	Score	Range	Score	Range	Score	Range	Score
50	5	99.84%	15	99.72%	25	99.67%	38	99.88%
100	3	99.82%	10	99.62%	17	99.54%	24	99.60%
200	2	99.97%	7	99.94%	11	99.57%	17	99.53%
500	1	99.96%	4	99.94%	7	99.90%	10	99.74%
1,000	1	100%	3	100%	5	99.95%	7	99.87%

TABLE II. PULSE RANGES AND SCORES WHEN USING APC

Swarm Size	**Map Radius**							
	25		**50**		**75**		**100**	
	Range	Score	Range	Score	Range	Score	Range	Score
50	7.28 ± 0.32	100%	16.27 ± 0.33	100%	23.34 ± 0.47	99.96%	29.42 ± 0.51	99.64%
100	4.61 ± 0.14	100%	10.68 ± 0.21	100%	16.50 ± 0.18	100%	21.63 ± 0.26	99.98%
200	3.04 ± 0.07	100%	7.14 ± 0.13	100%	11.06 ± 0.17	100%	14.87 ± 0.19	100%
500	1.89 ± 0.02	100%	4.02 ± 0.08	100%	6.35 ± 0.07	100%	8.98 ± 0.11	100%
1,000	1.38 ± 0.00	100%	2.65 ± 0.03	100%	4.18 × 0.05	100%	5.82 ± 0.06	100%



(a) up to 20%



(b) up to 5%, with fixed pulse range

Figure 4. Performance of swarm under communication loss.

VII. DISCUSSION

The results show that a relationship may be established between the performance of the swarm and the pulse range used for transmitting the data, as seen in Fig. 2. This relationship is specific to the task employed, in this case the sharing of data to at least 99.5% of the swarm within 250 ticks. Different tasks, with different requirements for success, will necessarily result in a different relationship being established.

Increasing the pulse period has a detrimental effect on swarm performance, although it would reduce the energy used as fewer pulses would be sent. Balancing the performance needs of the swarm with the energy cost is an important factor, so a pulse period of 10 ticks was chosen for the adaptive APC and communications loss tests. Halving the period to 5 ticks would double the expected energy usage for only a small gain in performance, as seen in Fig. 3. Any performance decrease from using a longer period can be balanced through pulse range selection in the adaptive APC system.

The results in Table II show that the adaptive APC system, when starting with an initial pulse range of just one unit, is able to determine an appropriate range for a robot to broadcast at and enable the sharing of the data throughout the swarm within the allotted 250 ticks.

When comparing the average pulse range in Table II to the best fixed ranges in Table I, the adaptive APC system is found to have a slightly higher range on average in lower density swarms, but in higher density swarms it can reduce the average pulse range, allowing the swarm to expend less energy. In the more dense swarms, not every robot will detect the same local density, so the APC system enables the robots to reduce their pulse range while in higher density areas.

The APC system was also found to be extremely robust to communications loss, being able to successfully share the data within 250 ticks even when the probability of a successful message is as low as 5%, and it performs much better than the fixed pulse range at that level. A lower number of pulses being successfully received will result in a lower density estimate being made by the APC system, and a corresponding increase in the pulse range to reach more robots. While this system balances, increasing pulse ranges will increase energy usage.

It may be preferable for the swarm in cases of extremely high message loss to recognise the problem and find an alternative solution, perhaps contracting the swarm or temporarily increasing the period between pulses. Adaptive adjustment of the pulse period may help reduce energy usage overall, and this may be a topic for future work.

VIII. CONCLUSION AND FUTURE WORK

This research presented a system for adaptively adjusting the range of communications between robots based on the density of the swarm, by adapting the existing concept of Pulse Monitoring. By replacing the “I am healthy” message with one saying “I am here”, a receiving robot can use the aggregate data presented by multiple received pulses to estimate the local density of the swarm.

In a task to share a piece of data with the rest of the swarm, the Autonomic Pulse Communications system was able to adaptively determine the pulse range to use to achieve excellent results, ensuring that 100% of the swarm received the data within the allotted time in all but three scenarios. The results show the system selecting shorter pulse ranges when the swarms are denser, and compare favourably with the best performing fixed pulse ranges used to establish the relationship between density and pulse range that the system uses. Further, the APC system was shown to be extremely robust to communications loss, as the system adapts to a decrease in the number of received messages by increasing the pulse range, thus increasing the chances of the message being received by some robots.

The APC system therefore shows promise, allowing a swarm to maintain communication links between its members while imposing fewer restrictions on the behaviour of the robots. Should the swarm suffer loss of robots over the course of the mission, the resulting lower density of the swarm may be compensated for automatically by the system.

Individual pulse messages used in this work were simplified, by considering them to be atomic actions. Larger amounts of data may take longer to broadcast than small packets, and this will impact the ability of a robot to successfully receive all of the data in a single broadcast. The motion of the robots may result in a recipient moving out of range before the transmission is completed. Additionally, communications failure was simply modelled as a random chance of failure, not taking into account the operating conditions or physical obstructions in the path.

Future work may investigate the impact of those aspects on the system, as well as applying the APC system in a more complex task, such as the foraging scenarios used in [8], or a collective decision-making task, where the data being transferred has a specific use that impacts performance of the wider task. Another avenue of interest may be the mechanism by which data is shared. As information grows in complexity, it may be desirable to selectively share only a portion of data in order to minimise the time and energy costs of data transfer, keeping the pulse messages short.

Further work may also investigate the impact of other factors in the ability of the swarm to share data. In this work, the data to be shared was fixed, so a changing data set that requires frequent reporting should be investigated. Also of note is the movement of the swarm, which supports data sharing through changing the set of neighbours receiving a robot's pulse. Different robot speeds, more limited mixing, and the absence of motion altogether may impact the performance of the system.

REFERENCES

[1] E. Sahin, 'Swarm robotics: From sources of inspiration to domains of application', in *Swarm Robotics*, vol. 3342, E. Sahin and W. M. Spears, Eds. 2005, pp. 10–20.

[2] M. G. Hinchey, R. Sterritt, and C. Rouff, 'Swarms and Swarm Intelligence', *Computer*, vol. 40, no. 4, pp. 111–113, Apr. 2007.

[3] V. Trianni, J. IJsselmuiden, and R. Haken, 'The SAGA concept: Swarm Robotics for Agricultural Applications', Technical Report, 2016. Accessed: Dec. 21, 2022. [Online]. Available: http://laral.istc.cnr.it/saga/wp-content/uploads/2016/09/saga-dars2016.pdf.

[4] L. Abraham, S. Biju, F. Biju, J. Jose, R. Kalantri, and S. Rajguru, 'Swarm Robotics in Disaster Management', in *2019 International Conference on Innovative Sustainable Computational Technologies (CISCT)*, Oct. 2019, pp. 1–5.

[5] G. Beni, 'From Swarm Intelligence to Swarm Robotics', in *Swarm Robotics*, Berlin, Heidelberg, 2005, pp. 1–9.

[6] J. O. Kephart and D. M. Chess, 'The vision of autonomic computing', *Computer*, vol. 36, no. 1, pp. 41–50, Jan. 2003.

[7] E. Vassev, R. Sterritt, C. Rouff, and M. Hinchey, 'Swarm Technology at NASA: Building Resilient Systems', *IT Prof.*, vol. 14, no. 2, pp. 36–42, Mar. 2012.

[8] L. McGuigan, R. Sterritt, G. Wilkie, and G. Hawe, 'Decentralised Autonomic Self-Adaptation in a Foraging Robot Swarm', *Int. J. Adv. Intell. Syst.*, vol. 15, no. 1 & 2, pp. 12–23, 2022.

[9] M. Puviani, G. Cabri, and L. Leonardi, 'Enabling Self-Expression: The Use of Roles to Dynamically Change Adaptation Patterns', in *2014 IEEE Eighth International Conference on Self-Adaptive and Self-Organizing Systems Workshops*, Imperial College, London, United Kingdom, Sep. 2014, pp. 14–19.

[10] F. Zambonelli, N. Bicocchi, G. Cabri, L. Leonardi, and M. Puviani, 'On Self-Adaptation, Self-Expression, and Self-Awareness in Autonomic Service Component Ensembles', in *2011 Fifth IEEE Conference on Self-Adaptive and Self-Organizing Systems Workshops*, Ann Arbor, MI, USA, Oct. 2011, pp. 108–113.

[11] J. Zelenka, T. Kasanický, and I. Budinská, 'A Self-adapting Method for 3D Environment Exploration Inspired by Swarm Behaviour', in *Advances in Service and Industrial Robotics*, Cham, 2018, pp. 493–502.

[12] C. Saunders, R. Sterritt, and G. Wilkie, 'Autonomic Cooperation Strategies for Robot Swarms', in *Adaptive 2016: The Eighth International Conference on Adaptive and Self-Adaptive Systems and Applications*, Rome, Italy, Mar. 2016, pp. 20–27.

[13] G. Valentini, E. Ferrante, and M. Dorigo, 'The Best-of-n Problem in Robot Swarms: Formalization, State of the Art, and Novel Perspectives', *Front. Robot. AI*, vol. 4, 2017, Accessed: Jan. 03, 2023. [Online]. Available: https://www.frontiersin.org/articles/10.3389/frobt.2017.00009.

[14] B. Capelli and L. Sabattini, 'Connectivity Maintenance: Global and Optimized approach through Control Barrier Functions', in *2020 IEEE International Conference on Robotics and Automation (ICRA)*, May 2020, pp. 5590–5596.

[15] B. Capelli, H. Fouad, G. Beltrame, and L. Sabattini, 'Decentralized Connectivity Maintenance with Time Delays using Control Barrier Functions', in *2021 IEEE International Conference on Robotics and Automation (ICRA)*, May 2021, pp. 1586–1592.

[16] Y. Kantaros, M. Guo, and M. M. Zavlanos, 'Temporal Logic Task Planning and Intermittent Connectivity Control of Mobile Robot Networks', *IEEE Trans. Autom. Control*, vol. 64, no. 10, pp. 4105–4120, Oct. 2019.

[17] N. Majcherczyk, A. Jayabalan, G. Beltrame, and C. Pinciroli, 'Decentralized Connectivity-Preserving Deployment of Large-Scale Robot Swarms', in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Oct. 2018, pp. 4295–4302.

[18] V. S. Varadharajan, D. St-Onge, B. Adams, and G. Beltrame, 'Swarm Relays: Distributed Self-Healing Ground-and-Air Connectivity Chains', *IEEE Robot. Autom. Lett.*, vol. 5, no. 4, pp. 5347–5354, Oct. 2020.

[19] P. Smith, R. Hunjet, A. Aleti, and J. Barca, 'Data Transfer via UAV Swarm Behaviours', *J. Telecommun. Digit. Econ.*, vol. 6, pp. 35–57, Jun. 2018.

[20] P. Gupta and P. R. Kumar, 'The capacity of wireless networks', *IEEE Trans. Inf. Theory*, vol. 46, no. 2, pp. 388–404, Mar. 2000.

[21] R. Sterritt, 'Pulse monitoring: extending the health-check for the autonomic grid', in *IEEE International Conference on Industrial Informatics, 2003. INDIN 2003. Proceedings.*, Banff, AB, Canada, 2003, pp. 433–440.

[22] R. Sterritt and S. Chung, 'Personal autonomic computing self-healing tool', in *Proceedings. 11th IEEE International Conference and Workshop on the Engineering of Computer-Based Systems, 2004.*, May 2004, pp. 513–520.

[23] R. Sterritt, D. Gunning, A. Meban, and P. Henning, 'Exploring autonomic options in an unified fault management architecture through reflex reactions via pulse monitoring', in *Proceedings. 11th IEEE International Conference and Workshop on the Engineering of Computer-Based Systems, 2004.*, Brno, Czech Republic, 2004, pp. 449–455.

[24] W. Truszkowski, M. Hinchey, and R. Sterritt, ‘Towards an Autonomic Cluster Management System (ACMS) with Reflex Autonomicity: Workshop on Reliability and Autonomic Management in Parallel and Distributed Systems (RAMPDS-05) at ICPADS-2005’, *Unkn. Host Publ.*, pp. 478–482, Jul. 2005.

[25] E. Vassev and M. Hinchey, ‘Self-Awareness in Autonomous Nano-Technology Swarm Missions’, in *2011 Fifth IEEE Conference on Self-Adaptive and Self-Organizing Systems Workshops*, Ann Arbor, MI, USA, Oct. 2011, pp. 133–136.

[26] K. Støy, ‘Using Situated Communication in Distributed Autonomous Mobile Robotics’, *SCAI*, vol. 1, pp. 44–52, Feb. 2001.