## Leveraging swarm capabilities to assist other systems

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Most studies in swarm robotics treat the swarm as an isolated system of interest. Investigations into heterogeneous swarms [1], [2] examine various types of robots working in conjunction, yet these too are considered collectively as a single entity. While there are instances where swarms are supported by external systems [3], it remains rare for swarms to act in service of another system.

We argue that the prevailing view of swarms as selfsufficient, independent systems limits the scope of potential applications for swarm robotics. Specifically, certain scenarios, such as search and rescue operations, might not derive substantial advantage from deploying a robot swarm as an autonomous solution. However, the assistance provided by a swarm could prove invaluable to human rescuers.

Robot swarms are uniquely poised for effective information acquisition. Their distributed nature allows them to rapidly collect environmental data and continuously update this information through peer-to-peer sharing. We refer to this collective data-gathering capability as "swarm perception." In swarm robotics, extensive research has been conducted on collective behaviors [4], [5] and collective decision-making [6], [7], often highlighting the importance of swarm perception. For example, the works of Valentini et al. [8] and Zakir et al. [9], use swarm perception as a tool in a study evaluating collective decision-making.

Swarm perception enables a swarm to dynamically monitor its surroundings, detecting and reporting changes, even in environments whose structure is initially unknown. While the information gathered is typically utilized internally to refine the swarm's collective behavior, it can also be seen as a vast, evolving shared database filled with mission-specific environmental data. By granting external systems access to this database—for instance, through communication between swarm robots and an external robot—the swarm can provide critical information that aids the external system's task. However, there is a notable scarcity of research focused on leveraging swarm perception to benefit external systems.

The potential beneficiaries of swarm support extend be-

<sup>1</sup>IRIDIA, Université libre de Bruxelles. <sup>2</sup>Royal Military Academy of Belgium. <sup>3</sup>Toyota Motor Europe. Correspondence to mauro.birattari@ulb.be. The project has received funding from Belgium's Wallonia-Brussels Federation through an ARC Advanced Project 2020 (Guaranteed by Optimization). MK and MB acknowledge support from the Belgian Fonds de la Recherche Scientifique-FNRS. DGR acknowledges support from the Colombian Ministry of Science, Technology and Innovation – Minciencias.

MK, DGR, GLH, IG and JS contributed equally to this work and should be recognized as co-first authors. The idea was conceived by all authors. The experiments were designed by MK, DGR, GLH, IG and JS, and performed by MK with the assistance of DGR, GLH, IG and JS. The paper was drafted by MK, GLH and KH and edited by MB; The research was directed by MB. yond artificial systems. Indeed, the notion of a swarm aiding another system has already been explored within the realm of human-swarm interaction [10], [11]: the human operator can leverage the information gathered by the swarm to improve operational efficiency or safety. For example, a rescuer could utilize the swarm's data to pinpoint victims' locations, or a speleologist might depend on maps created by the swarm for planning explorations. The concept of a robot swarm supporting firefighters has been previously addressed by Naghsh et al. [12]. However, research on human-swarm interaction remains limited to date.

We anticipate that a heterogeneous architecture comprising a robot swarm would be especially valuable for tasks such as identifying and tracking targets (specifically people), surveillance, and scouting activities. Tracking individuals across multiple cameras, known as multi-target, multi-camera tracking (MTMCT), poses a significant challenge [13]. Person reidentification (Re-ID) techniques are developed to address these challenges, particularly for tracking pedestrians across multiple non-overlapping camera views [14]-[16]. Person Re-ID often relies on low-resolution CCTV cameras; this necessitates the extraction of whole-body features, a process that is affected by variables such as occlusions, lighting conditions, body poses, and clothing alterations [17]. The small size and mobility of individual robots in a swarm afford them the ability to access diverse viewpoints within an environment, enabling close-up observations from multiple angles. This versatility facilitates the implementation of more effective identification systems, such as facial recognition based on combined observations to enhance detection accuracy. Furthermore, in scenarios where environments are unknown and strategies dependent on fixed sensor placements or path planning are impractical [18], identifying and tracking people become exceedingly complex.

In contrast, robot swarms can continuously share information about identified individuals, enabling effective tracking as individuals move through the environment. This shared intelligence allows for real-time updates on the locations of identified individuals, enhancing the swarm's capability to support the navigation of other robots within the system. For instance, a hospital robot tasked with delivering medications or supplies could utilize the swarm's data to pinpoint and navigate directly to the requesting doctor's location, showcasing the practical utility of swarm-assisted operations in dynamic environments. In surveillance or monitoring, it is typical to deploy multiple CCTV cameras that relay information back to a central surveillance unit. Robot swarms could complement traditional CCTV systems and offer a significant enhancement to such traditional setups by swiftly communicating any incidents to the security or monitoring team, including those that occur within the cameras' blind spots. Crucially, swarm robots possess the capability to not just detect but actively manage events. Unlike passive camera systems, a robot swarm can initiate immediate, localized responses to mitigate incidents as they await the arrival of specialized personnel, or they might even resolve the situation independently.

As early as 2006, Schmickl et al. [19] envisioned a scenario in which a robot swarm could gather environmental data to create a map. This foresight has since evolved into the development of swarm-based simultaneous localization and mapping (swarm SLAM), a sophisticated form of swarm perception. Despite its potential [20], it was only recently that Lajoie and Beltrame [21] introduced the first swarm SLAM framework by integrating existing SLAM technologiesspecifically RTABMap [22] and GTsam [23])-with an innovative, decentralized technique for prioritizing inter-robot loop closures. However, the current implementation of this method primarily generates pose graphs and demands structured navigation characterized by long, straight movementsconditions that are not typically associated with swarm behavior, which often relies on random walks. Generally, robot swarms excel at creating abstract or coarse maps swiftly rather than detailed occupancy grids, a trait that somewhat restricts their utility within the swarm itself. Nevertheless, this mapping capability is exceptionally well-suited to scouting tasks, where the swarm's objective is to relay information to another system. In such applications, a robot swarm can rapidly produce a basic map of a vast, unexplored area. This preliminary mapping provides valuable navigational assistance to other robots or offers a comprehensive overview for human operators, showcasing the unique strengths of swarm SLAM in exploratory and reconnaissance missions.

While robot swarms hold promise as support mechanisms for other systems, several challenges hinder their widespread adoption. First, the exploration into enabling technologies for robot swarms, such as SLAM and computer vision, is a relatively recent development. Although some initial successes have been recorded, the reliability of current solutions does not yet meet the standards required for practical applications.

Moreover, the field of swarm robotics has been limited by a scarcity of experiments conducted in real-world environments. Much of the research to date has been confined to simulations or carried out in simplistic settings using robots like the E-Puck [24] and the Kilobot [25], which are designed specifically for research. While these platforms are costeffective and suitably compact for large-scale experiments, their capabilities fall short of what is needed for realistic environmental testing. Recently developed, more advanced platforms such as the S-Drone [26], the Mercator [27] or the Summit XL [28], offer enhanced capabilities but have yet to see widespread adoption. There is also uncertainty regarding whether findings from existing research platforms will be applicable to the advanced robots necessary for real-world tasks. Despite the success of automatic design



Fig. 1: A swarm of robots, depicted in white, navigates through an office setting, identifies individuals, and logs both their locations and the times of detection. This information is shared among the swarm to maintain updated records and is also communicated to another robot, shown in black, that requests this information.

methods in simulations, they often struggle with the reality gap [29], [30], making it challenging to anticipate how these methods will perform with more sophisticated robots. However, approaches like AutoMoDe [31], [32] have shown some promise in bridging the reality gap [33], [34], and the broader transfer gap [35].

Another critical consideration is the secure storage and sharing of information collected by the swarm [36]. The inherent decentralized and distributed nature of robot swarms provides a measure of data security, as information is not centralized. Nonetheless, practical applications may necessitate reliance on more centralized and potentially vulnerable infrastructures, especially when swarms need to share data with other systems. Additionally, robot swarms could be susceptible to various attack vectors, including the threat of byzantine robots [37]. Blockchain technology has been identified as a potential solution to offer transparency, security, and trust within robot swarms [38].

To overcome these obstacles, collaboration with industry could play a crucial role by aligning research with practical needs. With the support of Toyota Motor Europe, we realized a demonstration of the ideas presented in this article. The demonstration<sup>1</sup>, showcases a swarm of Mercators [27] aiding a Toyota Human Support Robot (HSR) in delivering an item to a person in an unknown location. The concept is illustrated in Figure 1. Our vision is that further experiments in this direction would open the field of swarm robotics to new perspectives and eventually enable concrete applications.

<sup>1</sup>The video, also submitted to this workshop, is available at https://www.youtube.com/watch?v=8vkeuyJllY8.

## References

- M. Dorigo, D. Floreano, L. M. Gambardella, F. Mondada, S. Nolfi, T. Baaboura, M. Birattari, M. Bonani, M. Brambilla, A. Brutschy, D. Burnier, A. Campo, A. L. Christensen, A. Decugnière, G. A. Di Caro, F. Ducatelle, E. Ferrante, A. Förster, J. Martinez Gonzales, J. Guzzi, V. Longchamp, S. Magnenat, N. Mathews, M. Montes de Oca, R. O'Grady, C. Pinciroli, G. Pini, P. Retornaz, J. Roberts, V. Sperati, T. Stirling, A. Stranieri, T. Stützle, V. Trianni, E. Tuci, A. E. Turgut, and F. Vaussard, "Swarmanoid: a novel concept for the study of heterogeneous robotic swarms," *IEEE Robotics & Automation Magazine*, vol. 20, no. 4, pp. 60–71, 2013.
- [2] F. Ducatelle, G. A. Di Caro, C. Pinciroli, and L. M. Gambardella, "Self-organized cooperation between robotic swarms," *Swarm Intell.*, vol. 5, pp. 73–96, 2011.
- [3] W. Zhu, S. Oguz, M. K. Heinrich, M. Allwright, M. Wahby, A. L. Christensen, E. Garone, and M. Dorigo, "Self-organizing nervous systems for robot swarms," https://arxiv.org/abs/2401.13103, 2024.
- [4] V. Trianni and A. Campo, "Fundamental collective behaviors in swarm robotics," in *Handbook of Computational Intelligence*, ser. Springer Handbooks, J. Kacprzyk and W. Pedrycz, Eds. Heidelberg, Germany: Springer, 2015, pp. 1377–1394.
- [5] M. Brambilla, E. Ferrante, M. Birattari, and M. Dorigo, "Swarm robotics: a review from the swarm engineering perspective," *Swarm Intell.*, vol. 7, no. 1, pp. 1–41, 2013.
- [6] V. Strobel, E. Castello Ferrer, and M. Dorigo, "Managing byzantine robots via blockchain technology in a swarm robotics collective decision making scenario," in AAMAS 2018. Richland, SC, USA: International Foundation for Autonomous Agents and Multiagent Systems (IFAAMAS), 2018, pp. 541–549.
- [7] G. Valentini, E. Ferrante, H. Hamann, and M. Dorigo, "Collective decision with 100 kilobots: Speed versus accuracy in binary discrimination problems," *Autonomous agents and multi-agent systems*, vol. 30, pp. 553–580, 2016.
- [8] G. Valentini, D. Brambilla, H. Hamann, and M. Dorigo, "Collective perception of environmental features in a robot swarm," in *ANTS* 2016, ser. LNCS, M. Dorigo, M. Birattari, X. Li, M. López-Ibáñez, K. Ohkura, C. Pinciroli, and T. Stützle, Eds., vol. 9882. Cham, Switzerland: Springer, 2016, pp. 65–76.
- [9] R. Zakir, M. Dorigo, and A. Reina, "Robot swarms break decision deadlocks in collective perception through cross-inhibition," in *ANTS* 2022, ser. LNCS, vol. 13491. Cham, Switzerland: Springer, 2022, pp. 209–221.
- [10] A. Kolling, P. Walker, N. Chakraborty, K. Sycara, and M. Lewis, "Human interaction with robot swarms: a survey," *IEEE Transactions* on Human-Machine Systems, vol. 46, no. 1, pp. 9–26, 2016.
- [11] A. Hussein and H. Abbass, "Mixed initiative systems for humanswarm interaction: Opportunities and challenges," in 2018 2nd Annual Systems Modelling Conference (SMC). IEEE, 2018, pp. 1–8.
- [12] A. M. Naghsh, J. Gancet, A. Tanoto, and C. Roast, "Analysis and design of human-robot swarm interaction in firefighting," in *RO-MAN* 2008-The 17th IEEE International Symposium on Robot and Human Interactive Communication. IEEE, 2008, pp. 255–260.
- [13] T. I. Amosa, P. Sebastian, L. I. Izhar, O. Ibrahim, L. S. Ayinla, A. A. Bahashwan, A. Bala, and Y. A. Samaila, "Multi-camera multiobject tracking: a review of current trends and future advances," *Neurocomputing*, vol. 552, p. 126558, 2023.
- [14] S. Tang, M. Andriluka, B. Andres, and B. Schiele, "Multiple people tracking by lifted multicut and person re-identification," in 2017 IEEE Conference on Computer Vision and Pattern Recognition (CVPR). Piscataway, NJ, USA: IEEE, 2017, pp. 3539–3548.
- [15] E. Ristani and C. Tomasi, "Features for multi-target multi-camera tracking and re-identification," in 2018 IEEE/CVF Conference on Computer Vision and Pattern Recognition. Piscataway, NJ, USA: IEEE, 2018, pp. 6036–6046.
- [16] B. Gaikwad and A. Karmakar, "Smart surveillance system for real-time multi-person multi-camera tracking at the edge," *Journal of Real-Time Image Processing*, vol. 18, no. 6, pp. 1993–2007, 2021.
- [17] M. Ye, J. Shen, G. Lin, T. Xiang, L. Shao, and S. C. H. Hoi, "Deep learning for person re-identification: a survey and outlook," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 44, no. 6, pp. 2872–2893, 2022.
- [18] C. Robin and S. Lacroix, "Multi-robot target detection and tracking: taxonomy and survey," *Auton. Robots*, vol. 40, no. 4, pp. 729–760, 2016.

- [19] T. Schmickl, C. Möslinger, and K. Crailsheim, "Collective perception in a robot swarm," in *International Workshop on Swarm Robotics*, ser. LNCS, E. Şahin, W. M. Spears, and A. F. T. Winfield, Eds., vol. 4433. Heidelberg, Germany: Springer, 2006, pp. 144–157.
- [20] M. Kegeleirs, G. Grisetti, and M. Birattari, "Swarm SLAM: challenges and perspectives," *Front. Robot. AI*, vol. 8, p. 23, 2021.
  [21] P.-Y. Lajoie and G. Beltrame, "Swarm-SLAM: Sparse decentralized
- [21] P.-Y. Lajoie and G. Beltrame, "Swarm-SLAM: Sparse decentralized collaborative simultaneous localization and mapping framework for multi-robot systems," https://arxiv.org/abs/2301.06230, 2023.
- [22] M. Labbé and F. Michaud, "RTAB-Map as an open-source lidar and visual simultaneous localization and mapping library for large-scale and long-term online operation," *Journal of Field Robotics*, vol. 36, no. 2, pp. 416–446, 2019.
- [23] F. Dellaert and collaborators, "Georgia Tech Smoothing And Mapping (GTSAM)," May 2022. [Online]. Available: https://github. com/borglab/gtsam)
- [24] F. Mondada, M. Bonani, X. Raemy, J. Pugh, C. Cianci, A. Klaptocz, S. Magnenat, J.-C. Zufferey, D. Floreano, and A. Martinoli, "The epuck, a robot designed for education in engineering," in *ROBOTICA* 2009, P. Gonçalves, P. Torres, and C. Alves, Eds. Castelo Branco, Portugal: Instituto Politécnico de Castelo Branco, 2009, pp. 59–65.
- [25] M. Rubenstein, C. Ahler, and R. Nagpal, "Kilobot: A low cost scalable robot system for collective behaviors," in *ICRA 2012*. IEEE, 2012, pp. 3293–3298.
- [26] S. Oguz, M. Allwright, W. Zhu, M. Wahby, E. Garone, and M. Dorigo, "S-Drone: An open-source quadrotor for experimentation in swarm robotics," IRIDIA, Université libre de Bruxelles, Brussels, Belgium, Tech. Rep. TR/IRIDIA/2022-010, 2022.
- [27] M. Kegeleirs, R. Todesco, D. Garzón Ramos, G. Legarda Herranz, and M. Birattari, "Mercator: hardware and software architecture for experiments in swarm SLAM," IRIDIA, ULB, Tech. Rep. TR/IRIDIA/2022-012, 2022.
- [28] M. O. Arregi and E. L. Secco, "Operative guide for 4-wheel Summit XL mobile robot set-up," Acta Scientific COMPUTER SCIENCES Volume, vol. 5, no. 4, 2023.
- [29] N. Jakobi, P. Husbands, and I. Harvey, "Noise and the reality gap: the use of simulation in evolutionary robotics," in *ECAL '95*, ser. LNAI, F. Morán, A. Moreno, J. J. Merelo, and P. Chacón, Eds., vol. 929. Berlin, Germany: Springer, 1995, pp. 704–720.
- [30] K. Hasselmann, A. Ligot, J. Ruddick, and M. Birattari, "Empirical assessment and comparison of neuro-evolutionary methods for the automatic off-line design of robot swarms," *Nat. Commun.*, vol. 12, p. 4345, 2021.
- [31] M. Birattari, A. Ligot, D. Bozhinoski, M. Brambilla, G. Francesca, L. Garattoni, D. Garzón Ramos, K. Hasselmann, M. Kegeleirs, J. Kuckling, F. Pagnozzi, A. Roli, M. Salman, and T. Stützle, "Automatic off-line design of robot swarms: a manifesto," *Front. Robot. AI*, vol. 6, p. 59, 2019.
- [32] M. Birattari, A. Ligot, and G. Francesca, "AutoMoDe: a modular approach to the automatic off-line design and fine-tuning of control software for robot swarms," in *Automated Design of Machine Learning and Search Algorithms*, ser. NCS, N. Pillay and R. Qu, Eds. Cham, Switzerland: Springer, 2021, pp. 73–90.
- [33] G. Francesca, M. Brambilla, A. Brutschy, V. Trianni, and M. Birattari, "AutoMoDe: a novel approach to the automatic design of control software for robot swarms," *Swarm Intell.*, vol. 8, no. 2, pp. 89–112, 2014.
- [34] A. Ligot and M. Birattari, "Simulation-only experiments to mimic the effects of the reality gap in the automatic design of robot swarms," *Swarm Intell.*, vol. 14, pp. 1–24, 2020.
- [35] M. Kegeleirs, D. Garzón Ramos, K. Hasselmann, L. Garattoni, G. Francesca, and M. Birattari, "Transferability in the automatic offline design of robot swarms: From sim-to-real to embodiment and design-method transfer across different platforms," *IEEE Robotics and Automation Letters*, vol. 9, pp. 2758–2765, 2024.
- [36] E. R. Hunt and S. Hauert, "A checklist for safe robot swarms," Nat. Mach. Intell., vol. 2, pp. 420–422, 2020.
- [37] V. Strobel, A. Pacheco, and M. Dorigo, "Robot swarms neutralize harmful byzantine robots using a blockchain-based token economy," *Sci. Robot.*, vol. 8, no. 79, p. eabm4636, 2023.
- [38] M. Dorigo, A. Pacheco, A. Reina, and V. Strobel, "Blockchain technology for mobile multi-robot systems," *Nature Reviews Electrical Engineering*, pp. 1–11, 2024.