Quantum Robotic Swarms: What, Why, and How

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Abstract
What is quantum computing, why do we need it, and how can we use it? Similarly: What is swarm robotics, why do we need it, and how can we use it? We try to briefly answer these questions, discussing some possibilities to apply quantum computing to swarm robotics, to get the best out of them. We also discuss a possible application of sonification as human-friendly feedback, and possible directions to be undertaken in future research.

Keywords
quantum computing, robotic swarms, sonification

1. Introduction

Nature inspires the brush of the artist and the pen of the scientist. Robotics is a research area that owes a lot to nature, from the complexity of sensory cognition to the grace of movements. In particular, the observation and investigation of self-organization in natural swarms paves the way toward robotic swarm development. Another part of nature, the "physics of the small," inspires computational tools. It is the case of quantum computing, whose basics are rooted in the superposition principle, destructive measure, and entanglement in quantum mechanics.

Here, we provide synthetic explanations of *What*, *Why*, and *How* in quantum computing and in swarm robotics (Sections 2 and 3, respectively), including some essential references. Then, in Section 4, we discuss the pros and cons of mixing them up. The article is ended with a discussion on the possible role of sonification in this endeavor (Section 5), an example of application (Section 6), and some hints toward future research. In sections 2–4, we present with a jargon-free language the core ideas on these topics. Then, we narrow down the explanation to present our specific work, discussing its key points in Section 6.

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2. Quantum computing

What? Quantum Computing is a branch of computer sciences, inspired by the principles of quantum mechanics. The idea of the classical bit (the basic unit of memory), with the two values 0 or 1, is extended to the qubit, which can assume all possible values between 0 and 1. We can create a superposition of 0 and 1 with different probability amplitudes. The quantum bit is called *qubit*. Logic gates developed in classic computer sciences can be used in quantum computing, provided their re-writing with reversible gates, in analogy with invertible operators.

Why? Quantum Computing is mostly exploited to speed up algorithms, improving their efficiency and reducing computational complexity. Current research mainly aims to prove the fastness of quantum algorithms and develop stronger and safer quantum computers. A specific branch of research deals with the 'translation' itself of classic algorithms in terms of reversible logic gates, and the definition of completely new ones. Many algorithms are based on applications of the *entanglement* [1, 2], that is, the connection between particles, influencing each other non-locally. The entanglement is one of the most striking quantum effects. Thus, theoretical knowledge in physics can lead to computational applications. Conversely, research developed with quantum computers can help better understand the interaction between individual particles, constituting a benchmark for new theories and experiments.

Several advantages of quantum computing have been proven, but they come with a main drawback: decoherence. This is the loss of information due to the interaction of the quantum system with the environment. Scientists are currently working to minimize the risk of decoherence, and design error-free quantum computers. Promising results and new algorithms are continuously appearing. The so-called *quantum supremacy* is yet to be proven, but it seems that scientists are on the right track.

How? In the latest years, researchers have had access to a variety of computing centers and interfaces that would have been unthinkable, let's say, ten years ago. There are physical quantum computers, owned by major research centers and companies such as IBM and Amazon. These companies often allow researchers to remotely access a small portion of their computational power for free. However, there are some limitations to these free-access options: the number of possible qubits in a circuit is limited, and there is an online queue to run the circuit.

As an alternative to real computers, there are simulators. The number of available qubits is higher, and there are limited waiting times. A simulator runs on a classic computer, and it approximates the behavior of a quantum device. In so doing, the simulator's outputs present a lesser quantum rumor than its 'real' version. It means that the results obtained with a simulator are much closer to theoretical expectations than those coming from real quantum computers.

Concerning hardware, a quantum computer is a device different from a classic one. The qubits are recreated through physical systems: for instance, the orientation of a photon or the spin of an electron. The initial idea of quantum computers came from physics, with Benioff and Feynman [1].

3. Swarm Robotics

What? Swarm robotics is a branch of robotics, focusing on hardware and software of small, simple, autonomous, interacting, and self-organized multiple robots [3, 4, 5, 6, 7]. In a swarm, global behavior is a complex phenomenon. It emerges from local interactions of the swarm members, governed by simple rules. Robotic swarms and their organizational principles are often inspired by natural swarms, such as flocking birds [8], schooling fish [9], and foraging ants [10, 11] and termites [12]. Other sources of inspiration are morphogenesis processes, with the self-organization of cells [13].

Why? Robotic swarms achieve complex goals with several simple robots, where each unit accomplishes a simple task. Advantages of swarm robotics include autonomy, cooperation, scalability, cost-effectivity, and adaptability. Robots in a swarm are autonomous because each of them takes local decisions according to their perception of the environment and the messages exchanged with their peers. Robots in a swarm cooperate to achieve a complex task, be it search and rescue or shape formation. Thanks to the scalability, even in the case of loss of a single unit, the behavior of the whole is not compromised [5, 4]. Thus, they present an economic advantage with respect to single, less expensive, and complex robots, especially in risky situations, leading to a cost-effectiveness of the whole system. A robotic swarm can also constitute a model to test theories on natural swarm formation and behavior. Another application involves small-sized robots entering the human body and locally and precisely delivering a drug [14].

How? Quantum computing can be approached with real devices and simulators. The same applies to robotics: there are tangible devices and simulated ones. Working in a simulation environment allows one to design new robots, check their feasibility, make tests taking into account the physics of the system without damaging any expensive device, and check the effectiveness of a prototype or of an algorithm to achieve a task.

4. Quantum + Swarm Robotics

What? Mixing the quantum with swarm robotics means applying quantum algorithms to robotic controllers. A classic robotic controller can be enhanced with a faster quantum version. We have to bear in mind that robots live and act in the domain of classical physics: thus quantum effects, such as the Heisenberg indeterminacy, do not apply. For this reason, the quantum paradigm can enter details of the decision-making process, or we have to mathematically quantize some variables, or make some probabilistic assumptions. For instance, we can start with the definition of probability amplitudes and superposition of different conditions (such as positions and rewards), in analogy with quantum states (up, down) in quantum mechanics [15].

Why? The two things together, swarms of robots and quantum computing, allow a computational speed-up for missions of simple, interacting robots. Thus, the advantages of efficiency and scalability sum up. We may say that, ideally, they help save “time and money”: computational time and money to buy robots.

More conceptually, the operation of ‘quantum translation’ of classic algorithms does apply to swarm-robotic controllers as well. Such a translation is based on reversible logic gates and measurements as the constitutive elements of quantum circuits. We can thus explore potentialities and applicability limits of quantum computing for swarm robotics. As mentioned while discussing the advantages of quantum computing, also in the case of the swarm we can use the new tools to deepen our knowledge of natural phenomena. For instance, we can enhance our understanding of complex systems using robots to represent particles and agents, and quantum computing to model emerging behaviors out of simple local rules. There are already some studies on quantum particle swarm optimization [16]; however, the aim of future research is broader than just an improved optimization system. This is why we are not delving here into a detailed comparison with typical methods for swarm robotics.

Quantum effects such as indeterminacy, superposition, and entanglement may lead to improvements in swarm robotics. Entanglement may enhance swarm's communication strategy and cohesiveness, letting single robots act as particles of the same system and modifying their configuration according to the changes made to one of them. Single-robot configurations, such as space distribution and exploration-success feedback, can be modeled via eigenstate superposition (Section 6) with suitable probability amplitudes. Their variation for all robots leads to the emergent behavior. Distributed control may be achieved via a system of quantum gates taking as inputs the current robotic configurations at t and giving as outputs, e.g., positions suggestions at $t + 1$.

How? Some pioneering studies aim to join robotics with the quantum world [17, 18, 19], and only a few concern swarm-robotic applications [20, 21]. The quantum paradigm can shape the decision-making system of a single robot, e.g., to make more efficient the path-planning task [22]. The quantum can also inform pairwise interactions between the elements of the swarm, influencing their individual decisional process and emerging behavior. In Section 6, we summarize our approach.

4.1. *Caveats*

Drawbacks mainly concern the availability of quantum computers or simulators the units (or a computing center) have (has) to connect with, and the issue of decoherence, that is, the loss of entanglement due to the interaction with the environment [1]. In addition, the use of quantum requires the access to online computational resources.

5. Some magic: sonification

Sonification is the transformation of given data into auditory information, using a suitable mapping strategy. The choice of mapping must be motivated by data typology, properties to be highlighted, possible auditory limitations, and aesthetic reasons. For scientific applications, sonification is an alternative or an addition to visualization, enriching data understanding by one more sensory dimension. There are entire conferences on sonification, for each one of the mentioned research areas. We are particularly interested in sound renditions of swarm-robotic movements. Existing examples are limited concerning other sonification applications. They consist of: rhythmic patterns generated according to neighboring interactions [23]; robotic-role identification through sound [24] and pre-composed polyphonic music playing; harmonic structures translated into swarm geometries [25]. There are also studies on the feedback of multi-robot behavior [26] with user-selected songs played with different timbres according to robots' proximity. In Section 6, we discuss our proposed example of sonification for a quantum-driven robotic swarm. Basically, sound can convey information regarding robots' position, with convergence as an emerging effect from sound superpositions. In addition, sounds can provide feedback in cases of occlusions, gradually morphing when the robot solves the issue. Sonification is today exploited in different branches of research. Its application to swarm robotics is promising yet to be fully explored.

6. An example

In our research, we started from the simple definitions of state superposition, probability amplitude to get an outcome, and destructive measurement to sketch some applications for robotic swarms. In particular, we defined a circuit modeling pairwise interactions between robots, where the behavior of the i-th robot at time $t + 1$ is influenced by the results previously obtained by the j-th robot at time t. The swarm behavior emerges from these autonomous pairwise interactions. In [15], we also defined a block matrix representing the swarm information from the point of view of robots. Diagonal blocks contain information about each single robot, and off-diagonal blocks contain the pairwise information exchange. Our block matrix characterizes a robotic swarm. Comparing different swarms means comparing different matrices. To this aim, we presented a formalism based on category theory, allowing comparisons of swarms at the "same level" (e.g., swarms of the same number of simple flying robots and of simple swimming ones) and at "different levels" (e.g., swarms of different degrees of complexity and adaptability to different environments).

In another study [27], we added sonification to get auditory feedback of quantum-driven robots during their motion, without any pre-composed musical material (except a library of single pitches). We connect all the presented elements, that is, quantum + swarm + sound. We first start with the definition of a mission, and how the basics of quantum computing can enter it. We focus on a search-and-rescue mission, with multiple robots searching for a target. The closer the robot to the target, the higher the level of 'success.' We can model the 'closeness' via a probability amplitude to get 'success.' In this way, we can immediately introduce the concept of quantum superposition: a robot that has no clues on the target is in a balanced superposition of 'success' and 'failure.' The robot can get information on target proximity through its sensory detection: infrared light, laser, visible light information, sonar feedback, and so on, according to the nature of the target, the physics of the scenario, and the characteristics of the robot. For the sake of simplicity, we consider, as a measure of the robot's successfulness, the Euclidean distance from the target. We can extend the quantum analogy to the notion of position, as we call it "reward."

In fact, we can define probability amplitudes to be in a corner of the 2D (or 3D) space. For the sake of simplicity, we now consider as 'positions' the peaks of the quantum wavefunctions. We can thus build a logic gate working this way: in a pairwise interaction, robot 1 communicates to robot 2, telling where it is (probability amplitudes for the position) and what it found (the reward). If the position of robot 1 is well-defined (a position more likely to be centered on 1 or 0, rather than on an equal superposition of them) and it is successful (reward more toward 1, success), then robot 2 follows robot 1. Otherwise, robot 2 explored other portions of space. Which ones? Having more than two robots with pairwise interactions, each robot can shape its decisions by evaluating the feedback of its peers. Or, we can have a computational center that receives the feedback for each robot, and, according to the output of the quantum circuit for decision-making, tells each robot where to go. We take the collection of the reached spatial points

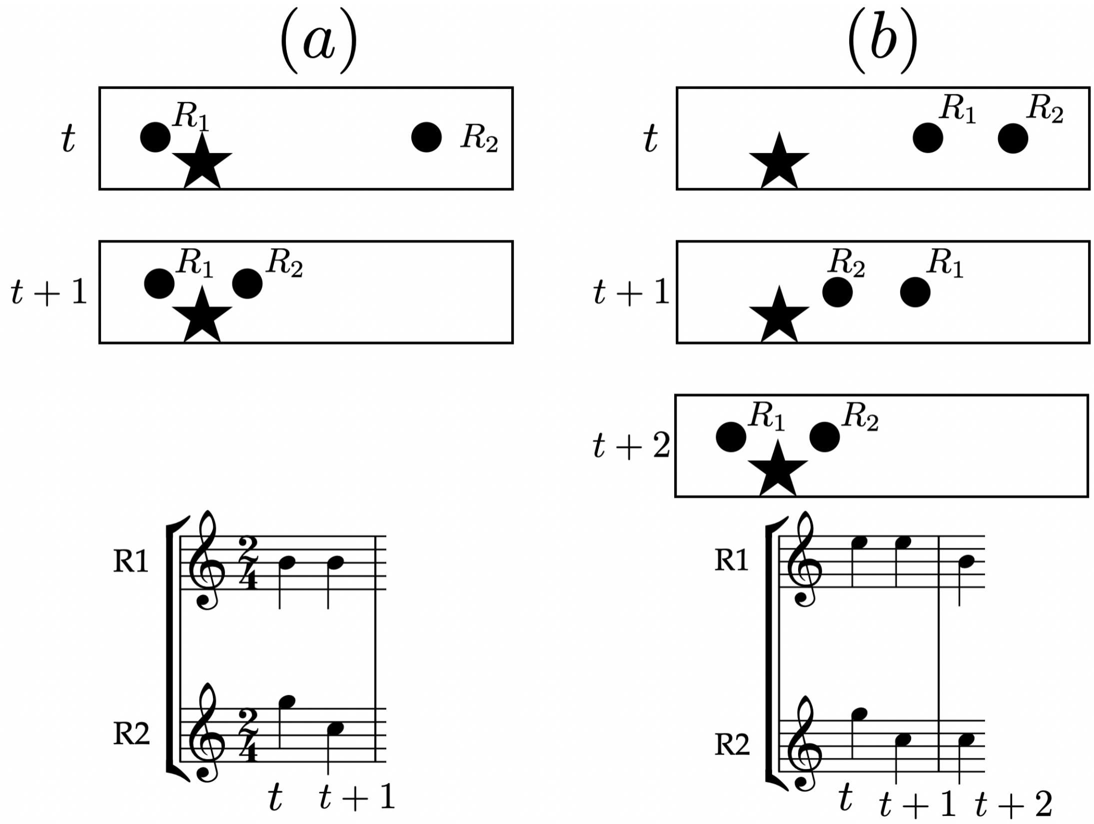

Figure 1: R_1, R_2 are two robots. The star indicates the target. The visual indication of position is actually the peak of the probability wavefunction. To each position there corresponds a musical note. R_1 searches and sends information to R_2. Case (a): if it is successful (probability amplitude of success higher than 0.5) and the position is well-defined (probability amplitude of one extreme of the line higher than 0.5) at t, then R_2 reaches it at t_1. Case (b): if it is not successful, R_2 searches elsewhere at $t + 1$, and, in case of success, R_1 reaches it at $t + 2$.

and we map them into sound. Thus, at each time point, we obtain a chord, where the position of each robot corresponds to a note. The complete simulation is thus transformed into a chorus of robots. Figure 1 illustrates the core idea two robots approximately moving along a line and their bichords.

We consider the mapping of robotics positions to pitches at each time point, eventually using different timbres to distinguish between each robotic element. We discretize pitches using the Western tuning systems, to easily represent classic scores. The superposition of notes produced by each robot at each time point constitutes a chord. Observing the robots for four-time points, we get a harmonic sequence of five chords. A different swarm behavior corresponds to a different harmonic sequence. The closer the robots, the closer the pitches, and we obtain a harmonic cluster. If the robots are approaching, their pitches are getting closer. If the robots are all moving in the same direction in a parallel way, then also the voice leading will be parallel. If the robots have to find a target and their sound corresponds to the (sonified) position of the target, then the mission is successful. If the robots converge on the wrong point, they will lead to another pitch. Finally, we obtain a sequence of chords that is the sonification of the robotic-swarm movement. Video examples and more technical details can be found in [27].

7. Conclusions and perspectives

Here, we summarized the Whats, Whys, and Hows of swarm robotics, quantum computing, and the two research fields mixed. Amongst the reasons to undertake such an endeavor, we may consider the swarm as a classic field [28]. Then, we can discretize the formalism treating the swarm as a quantum field, toward a future *Quantum Swarm Theory*, inspired by quantum fields in advanced quantum mechanics. Another reason is a renewed approach to quantum cognition through the lens of the swarm. We may try to model a cognitive complex unit through its decomposition into multiple sub-entities. The brain can be thought of as a collection of interacting neurons, where each ‘neuron’ is a robotic unit. In this sense, in the future we may exploit the quantum machinery to shape and support complex operations behind swarm interaction, such as deep learning.

The connection between the biological world, quantum computing, and robotic models [29] is yet to be explored. From quantum improvements for path planning, [22, 30], to quantum-based decision-making systems, to sonification strategies allowing quick comparisons, we can focus on technical efficiency-related studies and conceptual advancements. The quantum challenge for robotics and artificial intelligence [31] is just started. Stay tuned!

References

[1] J. Preskill, Quantum computing 40 years later, in: A. Hey (Ed.), Feynman Lectures on Computation, 2nd ed., Taylor & Francis Group, Abingdon, UK, 2021.
[2] J. Stolze, D. Suter, Quantum Computing: A Short Course from Theory to Experiment, Wiley, Weinheim, Germany, 2004.
[3] P. Benioff, Quantum robots and environments, Physical Review A 58 (1998) 893.
[4] H. Hamann, Swarm Robotics: A Formal Approach, Springer, Cham, 2018.
[5] M. Schranz, M. Umlauft, M. Sende, W. Elmenreich, Swarm Robotic Behaviors and Current Applications, Frontiers in Robotics and AI 7 (2020).
[6] R. Eberhart, Y. Shi, J. Kennedy, Swarm Intelligence, The Morgan Kaufmann Series in Artificial Intelligence, Morgan Kaufman, Burlington, MA, USA, 2001.
[7] F. Zambonelli, N. Bicocchi, G. Cabri, L. Leonardi, 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, 2011.
[8] C. H. Hemelrijk, H. Hildenbrandt, Schools of fish and flocks of birds: Their shape and internal structure by self-organization, Interface Focus 2 (2012) 726–737.
[9] K. Zhu, M. Jiang, Quantum Artificial Fish Swarm Algorithm, in: Proceedings of the 8th World Congress on Intelligent Control and Automation, 2010.
[10] S. Berman, Q. Lindsey, M. S. Sakar, V. Kumar, S. C. Pratt, Experimental Study and

Modeling of Group Retrieval in Ants as an Approach to Collective Transport in Swarm Robotic Systems, Proceedings of the IEEE 99 (2011) 1470–1481.

[11] W. M. Shen, P. Will, A. Galstyan, C. M. Chuong, Hormone-Inspired Self-Organization and Distributed Control of Robotic Swarms, Autonomous Robots 17 (2020) 93–105.

[12] C. Noirot, J. P. E. C. Darlington, Termite nests: Architecture, regulation and defence, in: T. Abe, D. E. Bignell, M. Higashi (Eds.), Termites: Evolution, Sociality, Symbioses, Ecology, Springer Netherlands, Dordrecht, 2000, pp. 121–139.

[13] I. Slakov, C. Carrillo-Zapata, D. Jansson, H. Kaandorps, J. Sharpe, Morphogenesis in robot swarms, Science Robotics 3 (2018).

[14] X. Dong, M. Sitti, Controlling two-dimensional collective formation and cooperative behavior of magnetic microrobot swarms, The International Journal of Robotic Research 39 (2020) eabe4385.

[15] M. Mannone, V. Seidita, A. Chella, Categories, Quantum Computing, and Swarm Robotics: A Case Study, Mathematics 10 (2022) 372.

[16] G. Liu, W. Chen, H. Chen, X. Jiahui, A quantum particle swarm optimization algorithm with teamwork evolutionary strategy, Mathematical Problems in Engineering 19 (2019) 1805198.

[17] D. Dong, C. Chen, C. Zhang, C. Chen, Quantum robot: structure, algorithms and applications, Robotica 4 (2006) 513–521.

[18] L. Lamata, M. Quadrelli, C. de Silva, P. Kumar, G. Kanter, M. Ghazinejad, F. Khoshnoud, Quantum Mechatronics, Electronics 10 (2021) 2483.

[19] P. Atchade-Adelomou, P. Alonso-Linaje, J. Albo-Canals, D. Casado-Fauli, qRobot: A Quantum Computing Approach in Mobile Robot Order Picking and Batching Problem Solver Optimization, Algorithms 14 (2021). URL: https://www.mdpi.com/1999-4893/14/7/194.

[20] A. Koukam, A. Abbas-Turki, V. Hilaire, Y. Ruichek, Towards a Quantum Modeling Approach to Reactive Agents, in: 2021 IEEE International Conference on Quantum Computing and Engineering (QCE), 2021.

[21] M. Alvarez-Alvarado, F. Alban-Chacón, E. Lamilla-Rubio, C. Rodríguez-Gallegos, W. Velásquez, Three novel quantum-inspired swarm optimization algorithms using different bounded potential fields, Nature Scientific Reports 11 (2021) 11655.

[22] A. Chella, S. Gaglio, G. Pilato, F. Vella, S. Zammuto, A quantum planner for robot motion, Mathematics 10 (2022) 2475.

[23] T. Blackwell, Swarm music: improvised music with multi-swarms, in: Proc. AISBSymposium in Artificial Intelligence and Creativity Arts Science, 2003, pp. 41–49.

[24] J. McLurkin, Stupid robot tricks: A behavior-based distributed algorithm library forprogramming swarms of robots (Master's Thesis), 2004.

[25] J. McLurkin, The Swarm Orchestra: Temporal Synchronization and Spatial Division of Labor for Large Swarms of Autonomous Robots, https://groups.csail.mit.edu/mac/projects/amorphous/6.978/final-papers/jamesm-final.pdf, 2022.

[26] F. Santos, Musical abstractions for multi-robot coordination (2016). URL: https://smartech.gatech.edu/handle/1853/55049.

[27] M. Mannone, V. Seidita, A. Chella, Quantum RoboSound: Auditory Feedback of a Quantum-Driven Robotic Swarm, in: RO-MAN 2022 Proceedings, IEEE, Naples, Italy, 2022, pp.

287–292.

[28] V. Edwards, P. deZonia, M. A. Hsieh, J. Hindes, I. Triandaf, I. B. Schartz, Delay induced swarm pattern bifurcations in mixed reality experiments, Chaos 30 (2020) 073126.

[29] P. S. Emani, J. Warrell, A. Anticevic, et al., Quantum computing at the frontiers of biological sciences, Nature Methods 18 (2021) 701–709.

[30] Z. Li, W. Liu, G. Li-E, L. Li, Path Planning Method for AUV Docking Based on Adaptive Quantum-Behaved Particle Swarm Optimization, IEEE Access Multidisciplinary 7 (2019) 78665–78674.

[31] A. Wichert, Principles of Quantum Artificial Intelligence, World Scientific, Singapore, 2020.