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Autonomous environment-adaptive microrobot swarm navigation enabled by deep learning-based real-time distribution planning

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Navigating a large swarm of micro-/nanorobots is critical for potential targeted delivery/therapy applications owing to the limited volume/function of a single microrobot, and microrobot swarms with distribution reconfigurability can adapt to environments during navigation. However, current microrobot swarms lack the intelligent behaviour to autonomously adjust their distribution and motion according to environmental change. Such autonomous navigation is challenging, and requires real-time appropriate decision-making capability of the swarm for unknown and unstructured environments. Here, to tackle this issue, we propose a framework that defines different autonomy levels for environment-adaptive microrobot swarm navigation and designs corresponding system components for each level. To realize high autonomy levels, real-time autonomous distribution planning is a key capability for the swarm, regarding which we show that deep learning is an enabling approach that allows the microrobot swarm to learn optimal distributions in extensive unstructured environmental morphologies. For real-world demonstration, we study the reconfigurable magnetic nanoparticle swarm and experimentally demonstrate autonomous swarm navigation for targeted delivery and cargo transport in environments with channels or obstacles. This work could introduce computational intelligence to micro-/nanorobot swarms, enabling them to autonomously make appropriate decisions during navigation in unstructured environments.

Swarm robotics is an important subfield of robotics[1] that seeks strategies to deploy large groups of robots that can cooperatively perform a task. To date, researchers have widely studied robot swarms at centimetre scales[2,3] and demonstrated capabilities that cannot be accomplished by individual robots, such as directional motion[4], manipulation[5] and challenging terradynamic tasks[6]. With broad application scenarios and theoretical/technical challenges, swarm robotics is receiving extensive attention[7].

In particular, swarm robotics at the micro-/nanoscale has recently become an emerging field with high impact[8–11]. As a single microrobot has a small size and volume, its capabilities may meet critical limitations, such as delivery[12,13], manipulation[14], environment cleaning[15,16] and in vivo tracking[17–19], where swarm control is the necessary technology. It is inspiring that recent technology can integrate actuators into microrobots[20], but the full integration of actuation, communication, battery and control counterparts into artificial micro-/nanorobots has not been realized, which hinders swarm navigation via individual microrobot control. As a result, swarm navigation of simple tiny agents—for example, spherical particles—actuated by external global energy fields is currently the only feasible approach. The simple microagent structure also facilitates low-cost batch fabrication and functionalization, such as drug loading[21] and therapy[22]. However, the global field actuation of thousands to millions of micro-/nanorobots, including acoustic[8,23,24], magnetic[10,25–31], electric[32] and optical [33] fields, results in a challenging underactuated swarm control problem. Such swarm control relies on the global field-induced gradients/forces[8,10,24,28,33], fluidic forces[25,27,30] or agent–agent interaction forces [29,32] to assemble and form swarm patterns. Then, the microrobot swarms can perform on-demand navigation as an entity via field regulation.

To navigate in complex and unstructured environments (for example, narrow branched channels), microrobot swarms should possess reconfigurability to adjust their distributions accordingly. Although their underactuation nature restricts the morphology changing capability, it has recently been shown that the pattern configuration can be changed by switching the mode of the global actuation field[10,24,26]. Moreover, the swarm distribution, for example, swarm shape and orientation, can also be tuned by field parameter control[10,24,26,29,34]. Such reconfigurable microrobot swarms have high adaptability to working environments, emerging as active matter with physical intelligence[35]. However, to date, these adaptations rely on manual inputs of the operator, who observes the swarm/environment and controls the field parameters. Hence, current microrobot swarms lack the intelligent behaviour to autonomously make decisions (that is, computational intelligence) when interacting with working environments. In fact, to manoeuvre the reconfigurable swarms well, human operators need extensive training to understand the swarm mechanisms and characteristics. As microrobot swarms may consist of thousands, even millions of basic elements that are loosely interacting, inappropriate manual control actions could break the stability of the swarm pattern or cause obstacle collisions that make the navigation fail. In addition, it is overwhelming to simultaneously plan and control multiple swarm parameters (for example, swarm shape, orientation and motion). Therefore, autonomy and thus computational intelligence is critical for microrobot swarms, to enable them to autonomously make timely and optimal

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