Title

Untethered Swarm Robots with Independent Crawling and Rolling Motions

Authors
Yue, W
Zhou, X
Sui, F
et al.

Publication Date
2023

UNTETHERED SWARM ROBOTS WITH INDEPENDENT CRAWLING AND ROLLING MOTIONS

Wei Yue[1,†], *Xinyu zhou*[2,†], *Fanping Sui*[1,†], *Mingzheng Duan*[1], *and Liwei Lin*[1]
[1]Department of Mechanical Engineering, University of California, Berkeley, USA
[2]Peking University, China
[†]Wei Yue, Xinyu Zhou and Fanping Sui contributed equally to this work.

ABSTRACT

We have demonstrated mm-scale untethered robots using a single axis magnetic field control to have swarm operations and independent crawling and rolling motions. There are three distinctive accomplishments as compared with the state-of-art: 1) working prototypes in the mm-scale with a moving speed of ~50 body size/s under the crawling mode operation; (2) an ultra-high moving speed of ~277 body size/s under the rolling mode operation; and 3) demonstrations of several complex swarming behaviors including chain-shape formation, crawling, and separation As such, the proposed operation schemes provides a new class of strategies to control mm-scale swarm robots for potential environmental and medical applications, such as minimally invasive surgeries.

KEYWORDS

Swarm robot, magnetic actuation, independent controllability, crawling, rolling.

INTRODUCTION

Swarm robots may autonomously organize themselves into a highly functional units to accomplish tasks beyond the capabilities of individual robots. Currently, artificial swarm robots can be categorized into two types: the dilute swarms and the dense swarms [1]. For the dilute swarms, robots can steer clear of collisions and maintain an optimal distance from each other for coordinated movements. They are best suited for exploration tasks such as patrolling in open water [2] and collective constructions [3]. For the dense swarms, robots need to remain in physical contact with one another to effectively exchange interactions. The close proximity between robots enables the system to generate large mechanical forces for applications such as drug delivery [4] and load carrying operations [5].

Natural swarm operations may transform from a dense to a dilute formation and vice versa. For instance, large groups of bacteria can assemble into a dense swarm to generate turbulent flows and facilitate the mixing of nutrients [6]. Alternatively, they could be separated from swarms to explore surroundings individually through the running and tumbling motions. The flexibility between dense and dilute swarms is crucial in medical applications such as minimally invasive surgery [7], where robots must form a dense swarm formation to navigate throught narrow channels within the human body and transform into a dilute swarm formation to perform individual tasks. However, current state-of-art mm-scale robots fall short of practical usage requirements for swarms. Prior works have shown small-scale robots can be functional well under physically constrained spaces, but they lack the strength to carry out individual tasks independently [8]. Demos of swarm robots with independent actions are successful but these robots are too large for use in the human body [9]. Here, we propose and demonstrate untethered mm-scale swarm robots to perform various operations in the forms of dense swarms as well as independent crawling and rolling actions in the

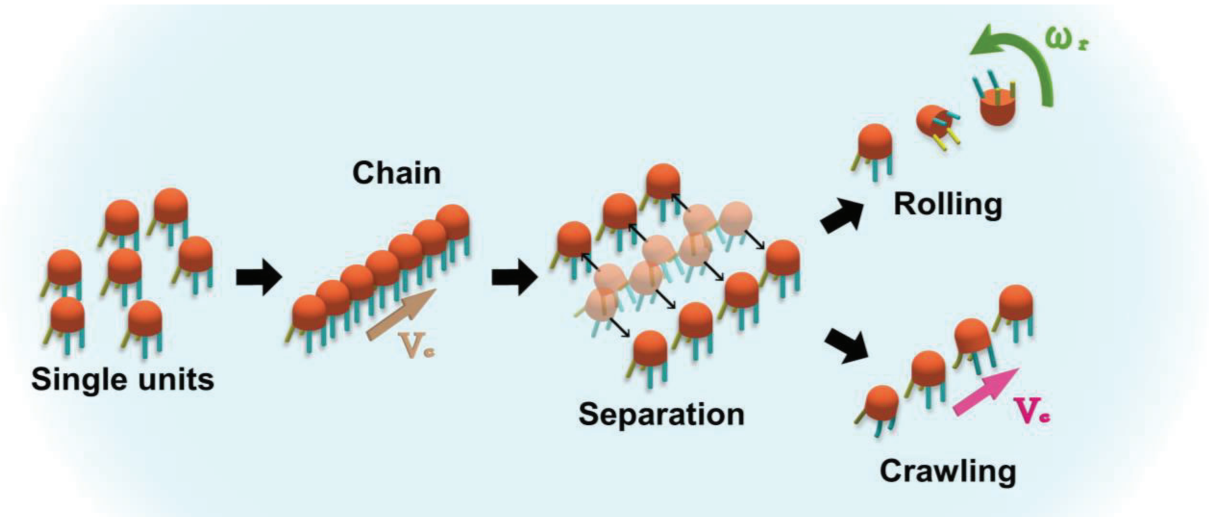

Figure 1: The mm-scale swarm robots in different motions. (left) Single units can attract each other to form a chain-line; (center-left) The chain-formation moves together under the control of the external magnetic field; (center-right) the swarm robots are separated into single units; (right) after the separation, robots can have independent rolling or crawling motions.

forms of dilute swarms. This study offers insights for the development of swarm robots to seamlessly transition between dense and dilute swarm formations.

DESIGN AND MECHANISM

In this paper, we present mm-scale untethered swarm robots that are capable of performing independent crawling and rolling motions, as well as swarm operations using a single-axis magnetic field control. **Fig. 1** provides a visual representation of the various types of motions successfully demonstrated. Firstly, multiple robots can spontaneously attract each other due to lateral attraction forces to form a chain-shape swarm. This phenomenon occurs under a weak external field. Second, this chain-shape swarm can move forward jointly as controlled by the external alternating magnetic field, via the stick-slip scheme as introduced in a prior work [10]. Third, by increasing the strength of the alternating magnetic field, the chain-shape formation is disintegrated to single robot units. Last, these single robots can have crawling or rolling motions depending on the external magnetic flux density.

Fig. 2A depicts a 3D schematic of a single robot unit, featuring a gray soft robot body that is 3D-printed using the Elastic 50A resin by a high-resolution stereolithography (SLA) Form 3 printer. The body consists of four 20-degree tilted legs and a hemispherical head to results in a good balance between the fast stick-slip actions and stable standing motions. The head has the hemispherical shape to reduce the normal interaction force between robot units for easy separations in the formation of dilute swarms. It also enhances the assembly tolerance to roll relatively with each other during the collision process to recover their stable attitudes. The holes on the robot head are designed such that when two robots are close to each other, the hole-to-hole connection has the minimum distance between the two magnets from each robot for the strong attraction force. An invisible slit-opening is located beneath the head to allow the insertion of a NdFeB magnet (N35-grade magnet with a diameter of 2 mm and length of 1 mm from Zigmyster Magnets Inc.). The flat cylindrical magnet has its magnetic direction aligned with the rotational axis of the head. In all operations in this work, the single-axis alternate magnetic field is exerted along the x-direction. **Fig. 2B** presents an optical image of the prototype robot, with a one-cent US coin. The robot unit has a radius of 1.5 mm and a height of 4.5 mm, for possible practical *in vivo* applications.

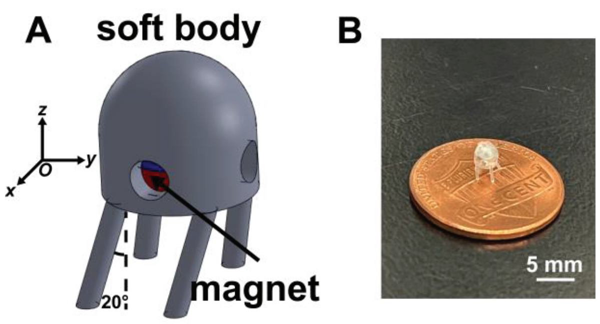

*Figure 2: **A**) the 3D schematic of the proposed mm-scale swarm robot. The 3D printed soft body is shown in the gray color, consisting of four 20-degree tilted legs and a hemispherical head. The NdFeB magnet is inserted through a slit-opening at the bottom. **B**) The digital image of a prototype robot. The radius of the robot head is 1.5 mm, and the total height is 4.5 mm.*

There are two types of robots in this work as defined by the orientation of the north-south pole of the NdFeB magnet: type A with the north pole facing downwards; and type B with the north pole facing upwards. A stable cluster of two different type robots can be assembled due to their magnetic attraction force, as depicted in the top sketch in **Fig. 3**. On the other hand, robots of the same type exert repulsive force with each other, which is also crucial for the other swarm formations. If a proper magnitude of an external alternative magnetic field is applied in the lateral direction perpendicular to both robot units as shown in the schematic of **Fig. 3**, a magnetic torque is generated in each robot with the opposite direction to result in the separation of the two robots. This requires sufficiently high magnetic flux density for the torques to overcome the original mutual lateral attraction force. If the flux density is low, robots only vibrate without separation. Experiments have demonstrated that the separation can occur with arbitrary magnetic field directions as long as the alternate magnetic field is higher than 8.7 mT, and the bottom sketch of **Fig. 3** shows one example with the robots moving to the opposite direction with respect to each other. Once robots are dispersed into single units, the robots can exhibit independent motions such as rolling and crawling by adjusting the magnetic flux density amplitude. For example, a robot can crawl forward using a stick-slip mode operation, where soft and tilted legs lift up its body on two legs of one side while the other two legs at the other side bend downwards to enable a small forward displacement. Increasing the magnetic field strength leads to faster alignment between the robot and the external field, which can cause the robot to undergo a cycle of falling down, standing upside down, falling down again, and standing up again to resemble a rolling motion.

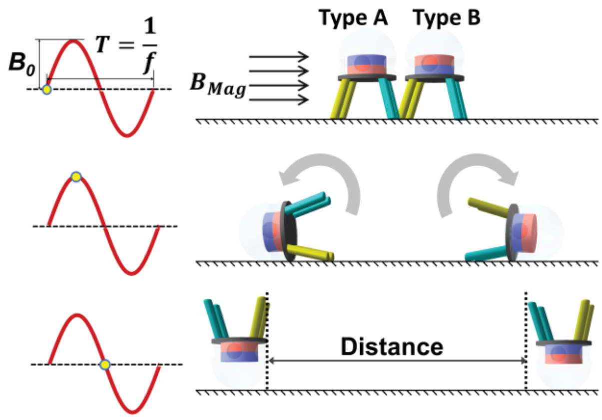

Figure 3: Separation and rolling operation mechanisms. Adjacent robots attract to each other due to opposite magnetic north and south poles. An externally applied lateral alternating magnetic field as shown induces rotations in opposite directions to separate two robots.

RESULTS AND DISCUSSION

The moving velocity of the robot under different magnetic flux densities has been measured with a constant driving frequency of 80 Hz via digital image processing using a high-speed camera as shown in **Fig. 4**. In general, the motion is divided into three distinct phases: crawling, falling, and rolling. When the magnetic flux density is less than 0.39 mT, the robot crawls steadily and its velocity increases monotonically with respect to the magnetic flux density. Specifically, it is found that between 0.18 mT and 0.29 mT, the velocity increases from 2.09 mm/s to 5.7 mm/s as the reinforcement of leg bending action. Between 0.29 mT and 0.39 mT, the velocity sharply increases from 5.7 mm/s to 53.4 mm/s due to excessive leg bending action to cause the robot being propelled into air for the high moving velocity. This jumping mechanism significantly enhances the stick-slip motion for high velocity. Between 0.39 mT and 2.47 mT, the robot is unable to move forward and falls down on the ground. The high magnetic torque prevents the robot from returning to a standing position and results in the falling position. The external magnetic field's direction is parallel to the robot's polar direction in this position such that there is no magnetic torque to reset its upward posture. However, if the magnetic flux density exceeds 2.47 mT, the robot's motion behavior changes dramatically. When the unit falls, an angular velocity due to the inertia effect helps the extra rolling motion. A sufficiently strong magnetic field can help completing a full rolling cycle otherwise the robot remains in the falling position. The threshold is observed at 2.47 mT for the prototype robot when it reaches the upside-down attitude with a velocity close to zero. Under an applied magnetic field of 2.47 mT and above, the robot is found to roll at a nearly constant linear velocity of approximately 830 mm/s, which corresponds to 80 rotations per second and the driving frequency is also 80 Hz. This moving velocity is exceptionally high at 277 body lengths per second.

Fig. 5A illustrates the swarm operations of three single robots to form a 3-unit chain-shape due to the magnetic attraction force. Type A robot is placed at the middle and type B robots are placed at the two ends. There are lateral attraction forces between the middle unit and the robots at the two sides for a balanced system. If robots at the two sides are released by the tweezers, the attraction forces will pull them toward the middle robot to form the chain shape. In this example, the initial distance between the units is about 6 mm before they are self-assembled due to the magnetic attraction force. It is found the maximum distance for the self-assembly operation depends on the surface friction of the substrate. The relative positions of the robots are not important in this self-assembly process as the chain-shape is the stable and desirable state as explained in **Fig. 5B**. The red-color robot in the center has the opposite magnetic north-south pole direction with respect to the other two blue-color robots to induce the attraction forces and the two blue-color robots have a repulsive force to each other. For the blue-color robot at position O_2, both the blue-color robot at position O_3 and the red-color robot at position O_1 induce magnetic forces in different directions as shown. The x-directional component of the forces causes the robot to move towards the right, leading to the formation of the chain shape in **Fig. 5C**. The y-directional component is also crucial because the swarm operation can only be stable if it is an attraction.

To investigate the capabilities of the swarm robots as a single unit to navigate in complex environments, a path in a specially designed structure featuring a narrow channel and an open space is depicted in **Fig. 6**. This setup emulates the possible operation in the minimally invasive surgery to access a large space from a narrow passage, such as in the stomach through a medical tube structure. Initially, the three robots are joined together to form a 3-by-1 chain-shape structure similar to that in **Fig. 5A** and travel through a narrow channel together toward the open space (**A1-A3**) in about 1 second under the external magnetic field of 1.6 mT. This magnetic flux density is too strong for single units but appropriate for the chain assembly because the mutual attraction forces prevent the units from falling down. Subsequently, the direction of the external magnetic field is rotated continuously by 180 deg in the horizontal plane in order to direct the chain-shape structure to make a U-turn (**A4-A5**) and crawls backwards by fixing the external magnetic field direction at the end of the operation (**A6**) in about 0.9 second. After 1.9 seconds into the operation, the magnetic field strength is abruptly increased to have the

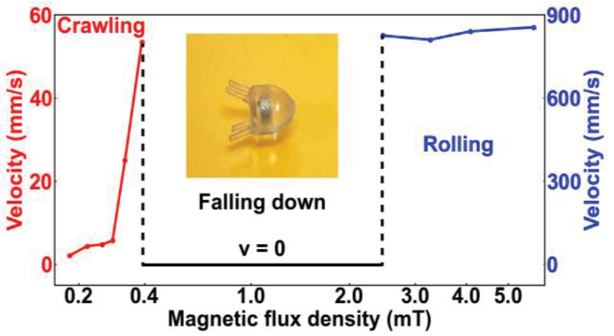

Figure 4: Velocity vs. magnetic flux density of a prototype robot under an alternating magnetic field with the driving frequency of 80 Hz. As the magnetic flux density increases, the motions of the robot have three different phases: the crawling phase, the falling down phase and the rolling phase.

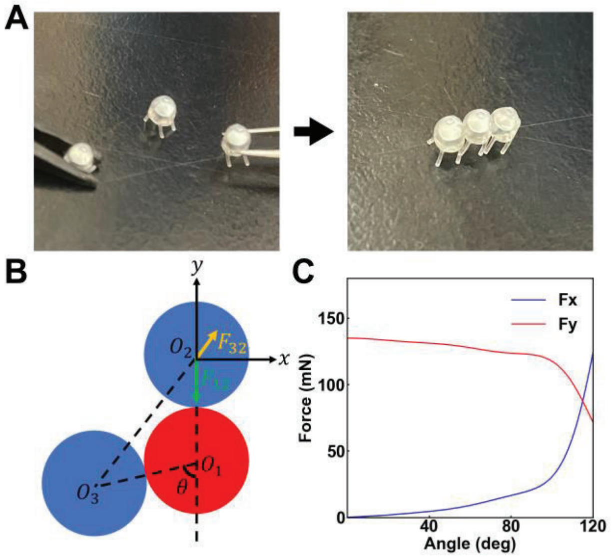

*Figure 5: **A**) Three swarming robots are self-assembled due to the magnetic attraction force. **B**) The mechanism to form this unique stable chain-shape formation. **C**) Simulation results of force imposed by other robots projected in the x- and y- directions.*

magnetic flux density at 14.3 mT, which starts the chain separation process into single units in just 83 milliseconds (**A7**). Afterwards, individual robots continue their rolling motions towards different locations for possible different functions (**A8**). This test demonstrates the swarm functions of various kinds, including the assembly, moving together as a unified structure, separation, and moving individually as single units of the prototype mm-scale robots. This could have potential applications in minimally invasive surgeries when robots are to be guided to a specific region and then separated to perform distinct tasks.

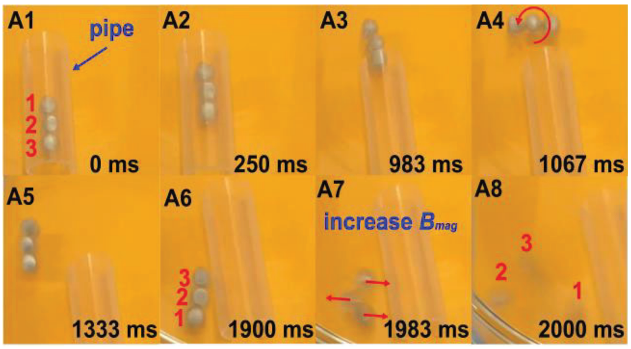

Figure 6: Optical images showing the formations of swarm robots to accomplish three different tasks under the externally applied magnetic fields, including A1-A3) crawling together in a chain-shape through a pipe in about 1 second; A4-A6) moving together in the open space and making a U-turn to crawl backwards in the form of a chain-shape in about 0.9 second; and A7-A8) separating under an increased magnetic field and rolling separately to different directions in about 0.1 second.

CONCLUSION

In this study, we present a new class of mm-scale swarm robot controls and operations by means of a single-axis external magnetic field. These robots are capable of forming a dense assembly to perform various moving functions and they can also be separated for independent crawling and rolling operations controlled by the alternating magnetic field. For example, the robot can crawl by means of the stick-slip scheme, remain stationary, or roll at an ultrafast speed of approximately 277 body lengths per second. Two types of robot units with opposite magnetic pole directions can be self-assembled together through the lateral attraction force to facilitate swarm operations. For example, three units can join together to form a chain-shape and crawl together through a narrow channel. Afterwards, a strong external magnetic field can be applied to break this chain-shape into individual robot units due to induced strong opposite magnetic torques on adjacent robots. As a demonstration example, a complex task to simulate several possible scenarios in the operation of a minimally invasive surgery is designed to demonstrate the capabilities of these swarm robots. First, individual units are assembled as the chain-shape together and the whole structure is directed to pass through a narrow channel to the open space. Next, the moving direction of the whole assembled structure is altered continuously to conduct a U-turn and to move in the backward direction. After that, a strong magnetic field is applied to separate the chain-shape robots into individual units and the rolling of individual robots toward different directions is observed. The proposed operation scheme of the swarm robot system offers a new approach to achieve flexible transitions between dense and dilute swarm formations for potential applications in medical and environmental fields.

ACKNOWLEDGEMENTS

This work is supported in part by the Berkeley Sensor and Actuator Center. The 3D-printing fabrication processes were conducted at the Jacobs Institute for Design Innovation at UC Berkeley.

REFERENCES

[1] M. Zion, J. Fersula, N. Bredeche, O. Dauchot, “Morphological computation and decentralized learning in a swarm of sterically interacting robots”, *Sci. Robot.,* vol 8, 2023.

[2] J. Gomes, M. Duarte, P. Mariano, A. L. Christensen, “cooperative coevolution of control for a real multirobot system”, in *Parallel Problem Solving from Nature–PPSN XIV: 14th International Conference*, Edinburgh, UK, 2016, pp. 591-601.

[3] J. Werfel, K. Petersen, R. Nagpal, “Designing collective behavior in a termite-inspired robot construction team”, *Science*, vol 343, pp. 754-758, 2014.

[4] A. V. Singh, M. H. D. Ansari, P. Laux, A. Luch, “Micro-nanorobots: important considerations when developing novel drug delivery platforms”, *Expert Opin. Drug Deliv.,* vol 16, 2019, pp. 1259-1275.

[5] H. Xie, M. Sun, X. Fan, Z. Lin, W. Chen, L. Wang, L. Dong, Q. He, “Reconfigurable magnetic microrobot swarm: Multimode transformation, locomotion, and manipulation”, *Sci. Robot.,* vol 4, 2019.

[6] H. Wensink, H. Henricus, S. Heidenreich, K. Drescher, R. E. Goldstein, H. Löwen, J. M. Yeomans, “Meso-scale turbulence in living fluids”, in *Proceedings of the national academy of sciences,* USA, 2012, pp. 14308-14313.

[7] M. M. al-Rifaie, A. Aber, R. Raisys, “Swarming robots and possible medical applications”, in *International Society for the Electronic Arts*, Istanbul, Turkey, 2011.

[8] Z. Li, H. Zhang, D. Wang, C. Gao, M. Sun, Z. Wu, Q. He, “Reconfigurable assembly of active liquid metal colloidal cluster”, *Angewandte Chemie International Edition*, vol 59, 2020, pp. 19884-19888.

[9] M. Rubenstein, C. Ahler, R. Nagpal, “Kilobot: A low cost scalable robot system for collective behaviors”, in *IEEE international conference on robotics and automation,* 2012, pp. 3293-3298.

[10] F. Sui, D. Wang, R. Guo, R. Xu, L. Lin, “Untethered Soft Crawling Robots Driven by Magnetic Anisotropy”, in *21st International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers)*, 2021, pp. 361-364.

CONTACT

*W. Yue; +1-510-984-8328; wei_yue@berkeley.edu
*F. Sui; +1-341-333-9262; fpsui@berkeley.edu