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Robotics Research

The 18th International Symposium ISRR

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Editors

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Foreword

At the dawn of the century's third decade, robotics is reaching an elevated level of maturity and continues to benefit from the advances and innovations in its enabling technologies. These all are contributing to an unprecedented effort to bringing robots to human environment in hospitals, homes, factories, and schools; in the field for robots fighting fires, making goods and products, picking fruits and watering the farmland, and saving time and lives. Robots today hold the promise for making a considerable impact on a wide range of real-world applications from industrial manufacturing to healthcare, transportation, and exploration of the deep space and sea. Tomorrow, robots will become pervasive and touch upon many aspects of modern life.

The *Springer Tracts in Advanced Robotics (STAR)* was launched in 2002 with the goal of bringing to the research community the latest advances in the robotics field based on their significance and quality. During the latest 15 years, the STAR series has featured publication of both monographs and edited collections. Among the latter, the proceedings of thematic symposia devoted to excellence in robotics research, such as ISRR, ISER, FSR, and WAFR, have been regularly included in STAR.

The expansion of our field as well as the emergence of new research areas has motivated us to enlarge the pool of proceedings in the STAR series in the past few years. This has ultimately led to launching a sister series in parallel to STAR. The *Springer Proceedings in Advanced Robotics (SPAR)* is dedicated to the timely dissemination of the latest research results presented in selected symposia and workshops.

This volume of the SPAR series brings the proceedings of the 18th edition of the International Symposium of Robotics Research (ISRR). This symposium took place in Puerto Varas, Chile from December 11th to December 14th, 2017. The seven-part volume edited by Nancy M. Amato, Greg Hager, Shawna Thomas, and Miguel Torres-Torriti is a collection of a broad range of topics in robotics ranging from control to human–robot interaction, from mobility to manipulation, from perception to planning, along with Blue Sky articles describing new early-stage ideas that inspired discussion and debate. The content of these contributions provides a wide coverage of the current state of robotics research: the advances and challenges in its theoretical foundation and technology basis, and the developments in its traditional and new emerging areas of applications. The diversity, novelty, and span of the work unfolding in these areas reveal the field's increased pace of development and expanded scope.

From its beautiful venue to its excellent program, the 13th edition of ISRR culminates with this important reference on the current developments and new directions in the field of robotics—a true tribute to its contributors and organizers!

Naples, Italy
Stanford, CA, USA
July 2019

Bruno Siciliano
Oussama Khatib
SPAR Editors

Preface

The 2017 International Symposium on Robotics Research (ISRR) took place in beautiful Puerto Varas, Chile from December 11–14, 2017. Consistent with the history of ISRR, our goal was to design a meeting in an out-of-the-ordinary setting which would be a forum for debate and discussion with an emphasis on future visions for robotics research.

In a change from the past, the program featured papers of two different formats: full-length papers of up to sixteen pages reporting on recent results, and a new Blue Sky format that were six pages in length. The latter were introduced to describe new early-stage ideas that would inspire discussion and debate. A prize for the best paper was supported by the CRA Computing Community Consortium. The final program featured 53 full-length papers organized into ten sessions, and 16 blue sky papers organized into three sessions. As is usual for ISRR, all papers were presented in a single-track format to enhance interaction, debate, and discussion. The papers were presented in panel format, with each panel including a short introduction, three 15-minute oral presentations, 3-minute spotlight talks for authors presenting posters, and a substantial discussion period including authors from all papers in the session.

In addition, the program featured four invited talks by leading researchers in the field. These included a perspective on manipulation by Matthew Mason, a perspective on interaction and medical robotics by Marcia O'Malley, a perspective on biomechanics in the light of robotics computation by Yoshihiko Nakamura, and a perspective on service robotics by Henrik Christensen. The program also included an industry panel which discussed current and future trends for robotics from the industry perspective. We also organized a doctoral consortium for students from around the world with support from the National Science Foundation and several companies.

The final program provided some interesting perspectives on the topics and themes that are receiving the highest interest in the field. Planning was the topic which had the most submissions; it was allocated three sessions in the final program. The topics discussed ranged from motion planning for hopping rovers to trajectory optimization with contacts to planning for muscle-actuated bodies. It also included discussions on planning for soft robots, multi-robot coordination, and improved methods for mapping and motion planning.

Learning and perception were also popular topics, with two sessions devoted to each. In learning, topics ranged from adaptive policy transfer for stochastic dynamical systems to topometric localization and reinforcement learning for visual–inertial calibration. The perception session addressed a wide range of topics including exploration and mapping, perception for grasping, object pose estimation, and sparse point registration.

Three topics were addressed with a single session: human–robot interaction, manipulation, and control. Human–robot interaction addressed topics such as viewing navigation as a cooperative activity, learning groundings for natural language interaction, and communicating robot arm motion intent with head-mounted displays. Manipulation included presentations on sampling-based planning of in-hand manipulation, a deterministic sampling-based verification algorithm for path non-existence, and trajectory planning and stabilization for pushing. Control presentations included multi-objective optimal control with temporal logic models, reactive control of transitional legged robot maneuvers, and control of quadrotors using the Hopf fibration.

As noted above, the program included the three blue sky sessions. The first session focused on cognitive topics—how to align values between a human and a robot, a computational theory of pain, an axiomatic theory of risk, human-assisted robot control, and human interaction challenges for autonomous agents in the wild. The second panel discussed planning and learning, touching on task representations for coupling perception to action in dynamic scenes, data-driven motion synthesis, self-directed lifelong learning for robot vision, deep multimodal learning, and Bayesian active learning for adaptive motion planning. The final session included several papers on multi-robot systems—covering the value of diversity in robot teams, controlling microrobot swarms using rotating magnetic dipole fields, and large sensors with adaptive shape using micro-aerial vehicles. The session also included a paper on smart materials for robotics and the economics of cloud-based robot motion planning.

The final awards for the blue sky papers were as follows:

First Place: Materials that Make Robots Smart by Nikolaus Correll and Christoffer Heckman, University of Colorado Boulder
Second Place: Pragmatic-Pedagogic Value Alignment by Jaime F. Fisac, Monica Gates, Jessica Hamrick, Chang Liu, Dylan Hadfield-Menell, Malayandi Palaniappan, Dhruv Malik, Shankar Sastry, Tom Griffiths, and Anca Dragan, University of California Berkeley
Third Place: DART: Diversity-enhanced Autonomy in Robot Teams by Nora Ayanian, University of Southern California Autonomous Agents in the Wild: Human Interaction Challenges by Laura Major and Caroline E Harriott, Draper Labs

After the symposium, a one-day workshop was organized in Santiago on the campus of the Pontificia Universidad Católica de Chile for all researchers, graduate, and undergraduate students of the local universities. The day was divided into four blocks of talks by leading experts and two blocks of spotlight presentations made on recent developments followed by interactive sessions. The first block of talks covered topics related to human–robot collaboration and interaction including the talks on interaction control by Sami Haddadin, engagement of patients in therapy with wearable technologies by Marcie O'Malley, a comparative overview of robot and human manipulation by Matthew Mason, and a look at the evolution and ongoing developments on human–robot collaboration by Oussama Khatib. The second group of talks revolved around robot design and application challenges with a presentation on unified digital human and humanoid motion synthesis for product design and evaluation, ongoing humanoid and aerial robot development and applications by Masayuki Inaba, and recent developments and trends in agricultural robotics by George Kantor. The third group of talks focused on perception and sensing topics. It included a talk by Gregory Hager on teaching robots using computer vision techniques, a presentation on face recognition in challenging low-quality images by Domingo Mery, and a talk on recent advances in random finite sets applied to robotic navigation and tracking by Martin Adams. The fourth block of talks was concerned with dynamics and planning. The talks covered topics on non-Cartesian task representation in dynamic environments by Darius Burschka, motion planning for many arms and objects by Kostas Bekris, mobile manipulator challenges in agriculture and mining by Miguel Torres and applications of sampling-based motion planning by Nancy Amato. The spotlights covered topics ranging from medical applications and learning to manipulation and control. With a participation of more than 100 undergraduate students from the different local universities, and 20% of the talks given by the Chilean researchers, the workshop was an intense day that covered current challenges and a diversity of existing ideas.

In closing, we would like to acknowledge the help and support of everyone who contributed to the organization of ISRR. We would like to especially acknowledge our sponsors which included: Siemens, Honda Research Institute, Franka Emika, Automatica, Godelius, the National Science Foundation, the Computing Community Consortium, and the International Federation of Robotics Research.

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Contents

Blue Sky Ideas

Controlling Homogeneous Microrobot Swarms In Vivo Using Rotating Magnetic Dipole Fields

Jake J. Abbott and Henry C. Fu

Biomedical "microrobots", which are typically conceived as simple microstructures with no actual computational intelligence on board, can be functionalized to perform targeted therapy in the body such as chemotherapy or hyperthermia [10, 14]. The majority of the work on biomedical microrobots has focused on magnetic swimmers and screws that use a chiral structure (e.g., a helix) to convert magnetic torque generated by a rotating magnetic field into forward propulsion, although we have shown that achiral structures can also be propelled in the same fashion [3]. This method of propulsion compares favorably to other methods of magnetic propulsion [1].

Biomedical applications will likely require the control of a large number of microrobots (i.e., a swarm) to accomplish a therapeutic task. However, this is difficult for two reasons. First, the entire swarm will be subject to some globally applied magnetic field, and the distances between individual microrobots will be small compared to their distances from the field-generation source, resulting in them experiencing very similar magnetic fields to each other. Second, for clinical use it may be unrealistic to assume that each microrobot can be individually localized; rather, a medical image will show a swarm of microrobots as a blob in the image [13].

To date, research on the control of multiple magnetic microrobots has either considered a small set that are individually localized [5, 6], or a swarm that is controlled as an aggregate unit with no ability to differentiate microrobots [13], or a swarm in which microrobot heterogeneity is required for differentiation [2, 15]. No prior work

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has proposed a solution for the comprehensive control of a swarm of batch-fabricated homogeneous microrobots, a likely scenario for practical realization.

In this paper, we propose two ways to think about controlling a swarm of homogeneous microrobots in vivo. We can treat the swarm as an object to be manipulated, and perform basic manipulation primitives on the swarm such as "move the aggregate swarm to a new location," "spread out the swarm," "gather the swarm together," or "split the swarm into smaller swarms and move them to separate locations." Alternatively, we can directly control the concentration field of the microrobots throughout a volume of interest. We will describe how the unique properties of rotating magnetic dipole fields can be utilized to make both of these strategies possible.

Our group has put significant effort into characterizing and utilizing magnetic dipole fields due to their numerous desirable properties, first and foremost being that they have a simple analytic representation that lends itself to analysis and real-time computation. Dipole fields are generated by spherical permanent magnets,[1] and the fields generated by certain other permanent-magnet geometries[2] and specialized electromagnetic sources[3] can be accurately approximated by the dipole model at clinically realistic distances. It is easy to conceive of a clinical scenario in which the patient is surrounded by one or more relatively small dipole sources in close proximity to the location of interest, as opposed to designing a large one-size-fits-all system into which the patient is placed (which is typical in prior work).

A magnetic dipole moment $\boldsymbol{m}$ generates a field $\boldsymbol{h}$ at each point $\boldsymbol{p}$ (with respect to the dipole), which is described by the point-dipole equation:

$$\boldsymbol{h} = \frac{1}{4\pi \|\boldsymbol{p}\|^3} \left[3\hat{\boldsymbol{p}}\hat{\boldsymbol{p}}^T - I \right] \boldsymbol{m} = \frac{1}{4\pi \|\boldsymbol{p}\|^3} H\boldsymbol{m} \tag{1}$$

We see that the magnetic field is nonlinear with respect to position, with a strength that decays rapidly from the source as $\sim\|\boldsymbol{p}\|^{-3}$, but the field is linear with respect to the dipole itself. We can use H to capture the shape of the dipole field, which is invariant to distance from the source.[4]

We showed in [8] that if a dipole moment is rotated about, and orthogonal to, some axis $\hat{\boldsymbol{\omega}}_m$, then the field at any given point in space will rotate about, and orthogonal to, some axis $\hat{\boldsymbol{\omega}}_h$, with the same period. The inverse problem was also solved (i.e., How should we rotate the dipole to achieve some desired $\hat{\boldsymbol{\omega}}_h$ at some desired location?):

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[1] We have developed a spherical-permanent-magnet robotic end-effector capable of continuous singularity-free rotation of the spherical magnet about any axis [17].

[2] We show in [11] that the fields of cubic and certain cylindrical permanent magnets—which are easy to fabricate (and purchase in variety of sizes), fixture, and manipulate—are accurately approximated by the dipole model not far outside of their minimum bounding sphere.

[3] We developed an electromagnetic source called the Omnimagnet, comprising three mutually orthogonal coils with a common soft-magnetic spherical core, all in a cubic package [12]. The Omnimagnet was optimized such that its field is accurately approximated by the dipole model just outside of its minimum bounding sphere.

[4] We use the "hat" notation to describe unit-normalized vectors (e.g., $\hat{\boldsymbol{p}} \equiv \boldsymbol{p}/\|\boldsymbol{p}\|$), as well as pointing-direction vectors that are inherently unit length (e.g., $\hat{\boldsymbol{\omega}}$).

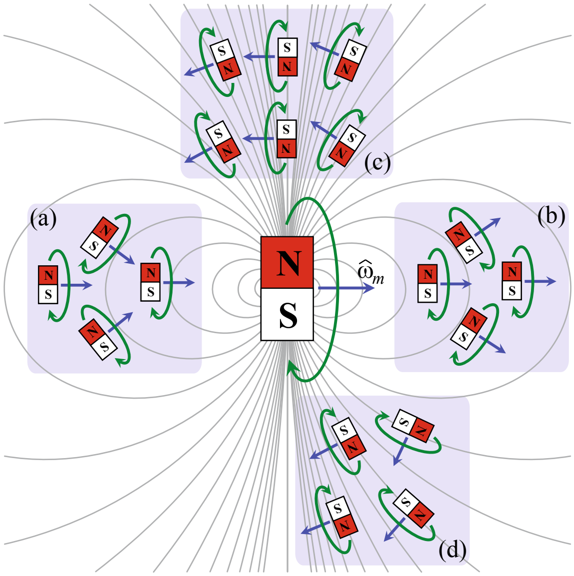

Fig. 1 A magnetic dipole moment $\boldsymbol{m}$, with instantaneous field lines shown, is rotated about axis $\hat{\boldsymbol{\omega}}_m$, with swarms of microrobots shown at different locations. The microrobots are shown simply as rotating magnets without any chiral structure, with their respective $\hat{\boldsymbol{\omega}}_h$ vectors shown. At locations along the axis of $\hat{\boldsymbol{\omega}}_m$, swarms are driven straight while either **a** gathering or **b** spreading the swarm. At a location that is orthogonal to $\hat{\boldsymbol{\omega}}_m$ such as (**c**), the swarm does not gather/spread, but it is steered. At general locations, such as shown in (**d**), the swarm will experience both gathering/spreading and steering

$$\hat{\boldsymbol{\omega}}_h = \widehat{H^{-1}\hat{\boldsymbol{\omega}}_m} \quad \Longleftrightarrow \quad \hat{\boldsymbol{\omega}}_m = \widehat{H\hat{\boldsymbol{\omega}}_h} \tag{2}$$

where $H^{-1} = (H - I)/2$ is always well conditioned. The body of a microrobot located at $\boldsymbol{p}$ will tend to align with $\hat{\boldsymbol{\omega}}_h$ as its magnetic element synchronously rotates with $\boldsymbol{h}$, and $\hat{\boldsymbol{\omega}}_h$ will become the microrobot's "forward" direction.

If we consider a swarm of microrobots at some nominal position (e.g., the centroid of the swarm), we observe that each microrobot will be at a different $\boldsymbol{p}$ and will thus experience a different $\hat{\boldsymbol{\omega}}_h$. As shown in Fig. 1, there will be locations in the rotating dipole field in which we can conceive of basic swarm manipulation primitives, such as spreading out or gathering together while moving forward, or steering while moving forward. If the patient is surrounded by multiple sources, or a single moving source, such motions will be possible in arbitrary directions.

The phenomena that we have discussed become less pronounced as we consider locations with increasing distance from the dipole source. It is likely that we will need to utilize nonholonomic control techniques to amplify the phenomena. For example, consider the scenario depicted in Fig. 2 in which two dipole sources are on opposite sides of the swarm. By alternating between each source performing the manipulation primitive of Fig. 1b, the swarm can be made to effectively spread out in

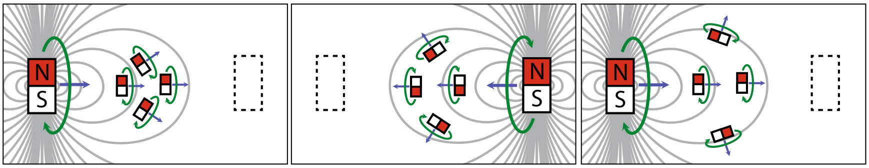

Fig. 2 As the rotating dipole source is alternated (images going from left to right), the swarm can be made to spread out without significant net motion of the centroid

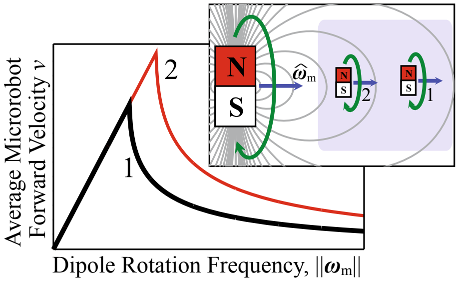

Fig. 3 In [9] we showed how the step-out regime can be exploited to differentiate *heterogeneous* microrobots in a rotating *uniform* field. The same concepts can be applied to the *homogeneous* microrobots in a *nonuniform* dipole field of interest here. Note: the step-out frequencies are not shown to scale with the microrobot locations depicted

place, without a net movement of the centroid. An analogous *gathering* of the swarm can be visualized by considering the microrobots in Fig. 1a.

Until this point, we have been assuming that all of the microrobots are rotating synchronously with the applied field. However, that need not be the case. Consider the two microrobots swimming along the $\hat{\boldsymbol{\omega}}_m$ axis in Fig. 1b. If they are both close enough to the dipole source that the magnetic field is sufficiently strong to keep them both rotating synchronously with the field, then they will move forward at the same average velocity. However, the farther microrobot will be the first to reach the "step-out" regime in which the field is too weak to generate synchronous rotation, at which point the microrobot's average forward velocity will decrease. As shown in Fig. 3, this yields a forward velocity v in the $\hat{\boldsymbol{\omega}}_h$ direction that transitions between linear and nonlinear dependence on the field rotation frequency $\|\boldsymbol{\omega}_m\|$ (in general, the forward velocity is a function of both $\|\boldsymbol{\omega}_m\|$ and $\boldsymbol{p}$). Consider the inset in Fig. 3: this phenomenon will enable the closer microrobot to catch up with the farther, effectively creating another means to gather the swarm. An analogous *spreading* of the swarm can be visualized by considering the microrobots in Fig. 1a.

A general description of the behavior of a population of microrobots can be constructed as follows. Consider a concentration (density) field of microrobots ρ at some time. Then, since at each position $\boldsymbol{p}$, microrobots move with velocity magnitude v in direction $\hat{\boldsymbol{\omega}}_h$, we can interpret $v\hat{\boldsymbol{\omega}}_h$ as the standard velocity field for microrobots used in continuum fluid mechanics [7]. Therefore, for example, by number conservation the density profile evolves in time as

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho v \hat{\boldsymbol{\omega}}_h). \tag{3}$$

This formalism can be directly related to the primitives in Fig. 1. To determine if a local population of microrobots is spreading or gathering, one would examine the rate of change in density *moving with that local population*, i.e., the material derivative of the density:

$$\frac{D\rho}{Dt} \equiv \frac{\partial \rho}{\partial t} + (v\hat{\boldsymbol{\omega}}_h \cdot \nabla)\rho = -\rho \nabla \cdot (v\hat{\boldsymbol{\omega}}_h). \tag{4}$$

A positive/negative value of $\frac{D\rho}{Dt}$ indicates an increasing/decreasing population concentration and corresponds to gathering/spreading of microrobots. Steering of microrobots is determined by the rate of change of their orientation ($\hat{\boldsymbol{\omega}}_h$) moving with the local population:

$$\frac{D\hat{\boldsymbol{\omega}}_h}{Dt} \equiv \frac{\partial \hat{\boldsymbol{\omega}}_h}{\partial t} + \left(v\hat{\boldsymbol{\omega}}_h \cdot \nabla\right)\hat{\boldsymbol{\omega}}_h. \tag{5}$$

The measures in Eqs. 4 and 5 can be combined to describe all of the scenarios depicted in Fig. 1.

Alternatively, time integration of Eq. 3 suffices to solve the forward problem of how a swarm described by an initial density ρ would behave for a given time-sequence of dipole strengths and rotation rates, which also enables motion planners that do not rely on primitives. We can conceptualize such a motion planner as follows: (1) Voxelize the given volume, with each of the voxels having a desired concentration of microrobots. From these values, compute the desired centroid and variance of the swarm. (2) Using medical images, estimate the current concentration in each voxel, as well as the current centroid and variance. (3) Construct an objective function that penalizes a combination of the errors in the quantities found in Step 2. This objective function would likely work by driving the centroid and variance of the swarm in the correct direction initially, and then fine-tuning the individual voxel concentrations. (4) For each of the dipole sources, determine the value of $\hat{\boldsymbol{\omega}}_m$ that would minimize the objective function locally. (5) From the set of $\hat{\boldsymbol{\omega}}_m$ vectors found in Step 4, choose the one that minimizes the objective function and implement it for a short period of time. (6) Go back to Step 2 and iterate until convergence.

In this paper we have described kinematic models for how rotating dipole fields can be utilized in the control of in vivo microrobot swarms. However, we did not model the transient as a microrobot aligns itself with a rapid change in $\hat{\boldsymbol{\omega}}_h$, nor did we model other magnetic and fluidic interactions that will certainly exist [4, 16, 18]. In light of this fact, the swarm-manipulation techniques that we have described should be thought of as feedforward models for the purpose of control, and as process models for the purpose of estimation, but with the knowledge that closed-loop feedback of the swarm via medical imaging will be required to ensure the swarm keeps evolving as desired. As we learn more about the unmodeled effects, it may be possible to incorporate them into improved kinematic models. Assuming microrobots are not deployed in a flowing environment (e.g., the bloodstream), we anticipate inter-microrobot magnetic interactions to be the most significant disturbance to our model. When might these magnetic interactions ruin our model of control by a dipole field? In typical cases we estimate that a microrobot's magnetic field is comparable to the external field at $\sim$2 magnetic-element lengths, i.e., for a quite dense swarm. Although even small magnetic attraction can lead to (irreversible) aggregation, for less dense swarms our methods might be used to prevent such aggregation.

References

1. Abbott, J.J., Peyer, K.E., Cosentino Lagomarsino, M., Zhang, L., Dong, L., Kaliakatsos, I.K., Nelson, B.J.: How should microrobots swim? Int. J. Robot. Res. **28**(11–12), 3663–3667 (2009)
2. Cheang, U.K., Lee, K., Julius, A.A., Kim, M.J.: Multiple-robot drug delivery strategy through coordinated teams of microswimmers. Appl. Phys. Lett. **105**(8), 083705 (2014)
3. Cheang, U.K., Meshkati, F., Kim, D., Kim, M.J., Fu, H.C.: Minimal geometric requirements for micropropulsion via magnetic rotation. Phys. Rev. E **90**, 033007 (2014)
4. Cheang, U.K., Meshkati, F., Kim, H., Lee, K., Fu, H.C., Kim, M.J.: Versatile microrobotics using simple modular subunits. Sci. Rep. **6**, 30472 (2016)
5. Chowdhury, S., Jing, W., Cappelleri, D.J.: Controlling multiple microrobots: recent progress and future challenges. J. Micro-Bio Robot. **10**(1–4), 1–11 (2015)
6. Diller, E., Giltinan, J., Sitti, M.: Independent control of multiple magnetic microrobots in three dimensions. Int. J. Robot. Res. **32**(5), 614–631 (2013)
7. Kunda, P., Cohen, I., Dowling, D.: Fluid Mechanics, 6th edn. Academic Press, New York (2015)
8. Mahoney, A.W., Abbott, J.J.: Generating rotating magnetic fields with a single permanent magnet for propulsion of untethered magnetic devices in a lumen. IEEE Trans. Robot. **30**(2), 411–420 (2014)
9. Mahoney, A.W., Nelson, N.D., Peyer, K.E., Nelson, B.J., Abbott, J.J.: Behavior of rotating magnetic microrobots above the step-out frequency with application to control of multi-microrobot systems. Appl. Phys. Lett. **104**(14), 144101 (2014)
10. Nelson, B.J., Kaliakatsos, I.K., Abbott, J.J.: Microrobots for minimally invasive medicine. Ann. Rev. Biomed. Eng. **12**, 55–85 (2010)
11. Petruska, A.J., Abbott, J.J.: Optimal permanent-magnet geometries for dipole field approximation. IEEE Trans. Magn. **2**, 811–819 (2013)
12. Petruska, A.J., Abbott, J.J.: Omnimagnet: an omnidirectional electromagnet for controlled dipole-field generation. IEEE Trans. Magn. **50**(7), 8400810 (2014)
13. Servant, A., Qiu, F., Mazza, M., Kostarelos, K., Nelson, B.J.: Controlled in vivo swimming of a swarm of bacteria-like microrobotic flagella. Adv. Mater. **27**(19), 2981–2988 (2015)
14. Sitti, M., Ceylan, H., Hu, W., Giltinan, J., Turan, M., Yim, S., Diller, E.: Biomedical applications of untethered mobile milli/microrobots. Proc. IEEE **103**(2), 205–224 (2015)
15. Tottori, S., Sugita, N., Kometani, R., Ishihara, S., Mitsuishi, M.: Selective control method for multiple magnetic helical microrobots. J. Micro-Nano Mechatronics **6**(3–4), 89–95 (2011)
16. Tottori, S., Zhang, L., Peyer, K.E., Nelson, B.J.: Assembly, disassembly, and anomalous propulsion of microscopic helices. Nano Lett. **13**(9), 4263–4268 (2013)
17. Wright, S.E., Mahoney, A.W., Popek, K.M., Abbott, J.J.: The spherical-actuator-magnet manipulator: a permanent-magnet robotic end-effector. IEEE Trans. Robot. **33**(5), 1013–1024 (2017)
18. Yu, J., Xu, T., Lu, Z., Vong, C.I., Zhang, L.: On-demand disassembly of paramagnetic nanoparticle chains for microrobotic cargo delivery. IEEE Trans. Robot. **99**, 1–13 (2017)

DART: Diversity-Enhanced Autonomy in Robot Teams

Nora Ayanian

1 Introduction

The field of multi-robot systems (MRS) is growing at a rapid pace. Research in MRS spans many different areas, including automated delivery [1–3], surveillance [4], and disaster response [5, 6]. There have also been many successful demonstrations of increasing numbers of robots [7–12]. MRS have also been successfully deployed in the field including in warehousing [13], manufacturing [14], and entertainment [15]. While these outcomes show the promise of MRS, the environments in which MRS have been successful are highly controlled, and some are highly instrumented, enabling precise tuning of controllers and nearly perfect knowledge of environmental conditions.

Many environments where MRS could be beneficial are not highly controlled or equipped with the extensive infrastructure often necessary to coordinate large teams of robots with state-of-the-art algorithms. For example, containing wildfires, searching collapsed buildings, patrolling borders, monitoring infrastructure, and containing oil spills all occur in highly dynamic and unique environments (no two collapsed buildings are the same), with high uncertainty and little control over other non-robot agents in the environment. One of the most desirable benefits of MRS is *robustness*, wherein robots can compensate for loss of capabilities by relying on other robots in the team. However, the uncertainty of many real-world environments renders current algorithms, even those designed for robustness, ineffectual. *The reason for this is not due to limitations in robot hardware, but in how multi-robot problems are solved.* Many controllers are so specialized and optimized for specific capabilities and conditions that they cannot cope with uncertainty. Thus, the true benefits of robustness in teams of robots have yet to be achieved.

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2 Motivation

In disaster response alone, the potential impact of autonomous MRS is substantial: 60,000 people die each year in natural disasters [16]. The company DJI announced that *one* properly equipped drone can find a missing person more than *five times faster* than traditional search methods [17]. This makes robots an ideal tool for disaster response.

However, most robots used in search and rescue today are teleoperated [18], requiring trained operators which may not be nearby. Disaster response that is autonomous, without the need for an expert operator, can reduce response time and save more lives, especially when a trained operator may be hours away.

The potential applications of autonomous MRS go well beyond disaster response, including military, agriculture, transportation, manufacturing, and fulfillment applications. However, current solutions for MRS have not successfully transitioned from controlled environments such as laboratories or warehouse facilities to the inherently high uncertainty in these complex environments. Without infrastructure that provides communication and localization, and without knowledge of or control over the environment, current state-of-the-art methods fail.

While the field of MRS has advanced significantly, the same problem-solving paradigm has remained. First, the problem is defined. Next, complexity is reduced by making several assumptions to simplify the problem, such as terrain and communication range. Finally, an optimal solution to that specific problem is designed and applied to all the robots in the team. This paradigm (Fig. 1a) limits the capability of MRS to cope with real-world environments. The solutions are brittle, as the assumptions made are easily invalidated and the optimized controller is not designed for real environments. In the best case, the controller is able to overcome these challenges, but it is not a good solution to the problem. In the worst case, the controller cannot cope, causing mission failure, loss of high-value assets, and casualties; after all, if the same failed controller is applied to all robots, all of them will fail.

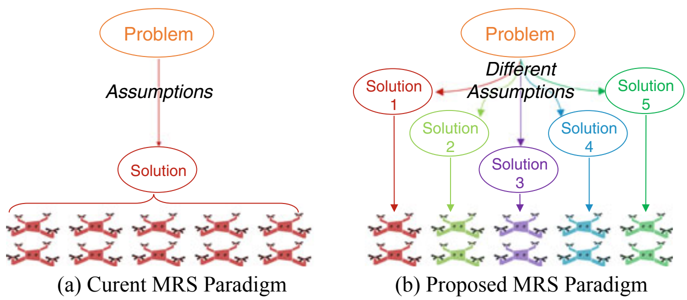

Fig. 1 **a** The current MRS problem-solving paradigm is linear, applying the same solution to all robots. **b** The proposed novel paradigm takes advantage of diversity in controllers to handle various scenarios