Introduction to the Special Section on Resilience in Networked Robotic Systems

THIS Special Section of the IEEE TRANSACTIONS IN ROBOTICS is devoted to the topic of *resilience in networked robotic systems*. This collection of articles aims to provide a deeper understanding of resilience as it pertains to multirobot systems, and to disseminate the current advances in designing and operating networked robotic systems. We understand *resilience* to be a characteristic that enables a multirobot system to withstand or overcome unexpected adverse conditions or shocks, and unknown, unmodeled disturbances. It refers to the contingent nature of the robots' behaviors that is aimed at preserving their functionality or minimizing the time periods during which their functionality is compromised.

The 17 articles in this section explore new algorithmic and mathematical foundations toward resilience. Jointly, they cover problems within perception, planning, and control. Individually, they focus on tackling specific types of stressors, including adversarial attacks, unmodeled noise, communication disruptions, and failure of resources and robot capabilities. As a guide to this Special Section, we have organized the papers into four groups:

1) articles that propose methods to deal with adversarial attacks;
2) articles that focus on methods that exploit structural changes and other multirobot coordination mechanisms;
3) articles that focus on issues due to communication network disruptions; and
4) articles that address policy synthesis and dynamic controller tuning.

RESILIENCE TO ADVERSARIAL ATTACKS

In [A1], Mallmann-Trenn *et al.* develop a method that uses a robot's neighborhood to find and eliminate adversarial robots in the presence of a Sybil attack. In [A2], Banik and Bopardikar consider a path-planning problem on a graph wherein a defender seeks to find an optimal path from a source to a destination vertex in the presence of an attacker. They model the problem as a zero-sum multistage game and characterize the Nash equilibria. In [A3], Usevitch and Panagou present a method that propagates vector messages from a set of leaders to all followers within the network in the presence of faulty or adversarially behaving robots that provide misinformation. In [A4], Santilli *et al.* develop a local interaction protocol that drives a set of robots toward a region delimited by the positions of another set of robots, namely the leaders, in the presence of adversarial robots in the network.

Three articles focus on the consensus problem. In [A5], Yemini *et al.* develop a mathematical framework to characterize convergence when additional information on trust can be leveraged. They show that convergence is possible even when adversarial agents constitute more than half of the network. In [A6], Bonczek *et al.* consider stealthy cyberattacks that exhibit nonrandom behavior within the multirobot system. They propose a runtime monitoring framework that considers the signed residual and triggers an alarm when an attack is detected. Finally, in [A7], Yu *et al.* show how consensus can be achieved in the presence of adversaries, even when communication topologies are time-varying.

RESILIENCE BY EXPLOITING STRUCTURAL CHANGES AND OTHER COORDINATION MECHANISMS

In [A8], Ramachandran *et al.* address resource failures and provide a method that optimally reconfigures the communication network so that the robots affected by the failure can continue their tasks. In [A9], Seraj *et al.* propose a collaborative planning and control algorithm that allows robots to perform different tasks according to their respective capabilities. In a similar vein, in [A10], Notomista *et al.* develop an optimization framework that represents heterogeneous robot capabilities and that is able to accommodate for situations where environmental conditions make certain features unsuitable to support a capability. Lastly, in [A11], Roehr presents an organization model that allows exploitation of redundancies when optimizing a multirobot system's probability of survival with respect to a desired mission.

RESILIENCE TO COMMUNICATION NETWORK DISRUPTIONS

In [A12], Chang *et al.* use a covariance intersection method for localization, rendering the communication update explicit and ensuring estimation consistency at the same time. Their experiments show how to deal with varying communications connectivity, including entirely or partially blocked interrobot communication. In [A13], Yang *et al.* consider a multiuser remotely operated mutirobot system. They consider issues arising due to time-varying delays in communications. They propose a control strategy that robustly synchronizes the system, enabling users to teleguide the robots and to feel the actions of the other users, despite the time-delayed communications.

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Resilience by Policy Synthesis and Controller Tuning

In [A14], Baxevani *et al.* consider the leader decapitation problem, and they provide a machine-learning-based approach that endows agents with a cascade of independent learning modules that enable them to discover their role in the overall system coordinating strategy, in order to restore operation normalcy after disruption. In [A15], Schlotfeldt *et al.* consider sensor failures and propose an online trajectory-planning method that plans attack-robust control inputs over a look-ahead planning horizon. In [A16], Street *et al.* present a multirobot planning framework that utilizes learned probabilistic models of how congestion affects navigation duration. The method solves a sequence of time-varying Markov automata, where transition probabilities and rates are obtained from a probabilistic reservation table. Lastly, in [A17], Antonante *et al.* introduce two unifying formulations for outlier-robust estimation, and they provide minimally tuned algorithms that dynamically decide how to separate inliers from outliers.

Collectively, these articles provide key insights on the design of resilient networked robotic systems. We believe that this ensemble represents broad trends, and we hope it will further stimulate a discussion of future research directions in this field.

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Appendix
Special Section Articles

[A1] F. Mallmann-Trenn, M. Cavorsi, and S. Gil, “Crowd vetting: Rejecting adversaries via collaboration with application to multirobot flocking,” *IEEE Trans. Robot.*, vol. 38, no. 1, pp. 5–24, Feb. 2022.

[A2] S. Banik and S. D. Bopardikar, “Attack-resilient path planning using dynamic games with stopping states,” *IEEE Trans. Robot.*, vol. 38, no. 1, pp. 25–41, Feb. 2022.

[A3] J. Usevitch and D. Panagou, “Resilient trajectory propagation in multirobot networks,” *IEEE Trans. Robot.*, vol. 38, no. 1, pp. 42–56, Feb. 2022.

[A4] M. Santilli, M. Franceschelli, and A. Gasparri, “Dynamic resilient containment control in multirobot systems,” *IEEE Trans. Robot.*, vol. 38, no. 1, pp. 57–70, Feb. 2022.

[A5] M. Yemini, A. Nedic, A. J. Goldsmith, and S. Gil, “Characterizing trust and resilience in distributed consensus for cyberphysical systems,” *IEEE Trans. Robot.*, vol. 38, no. 1, pp. 71–91, Feb. 2022.

[A6] P. Bonczek, R. Peddi, S. Gao, and N. Bezzo, “Detection of non-random sign-based behavior for resilient coordination of robotic swarms,” *IEEE Trans. Robot.*, vol. 38, no. 1, pp. 92–109, Feb. 2022.

[A7] X. Yu, D. Saldaña, D. Shishika, and M. A. Hsieh, “Resilient Consensus in Robot Swarms With Periodic Motion and Intermittent Communication,” *IEEE Trans. Robot.*, vol. 38, no. 1, pp. 110–125, Feb. 2022.

[A8] R. K. Ramachandran, P. Pierpaoli, M. Egerstedt, and G. S. Sukhatme, “Resilient monitoring in heterogeneous multi-robot systems through network reconfiguration,” *IEEE Trans. Robot.*, vol. 38, no. 1, pp. 126–138, Feb. 2022.

[A9] E. Seraj, L. Chen, and M. C. Gombolay, “A hierarchical coordination framework for joint perception-action tasks in composite robot teams,” *IEEE Trans. Robot.*, vol. 38, no. 1, pp. 139–158, Feb. 2022.

[A10] G. Notomista, S. Mayya, Y. Emam, C. Kroninger, A. Bohannon, S. Hutchinson, and M. Egerstedt, “A resilient and energy-aware task allocation framework for heterogeneous multirobot systems,” *IEEE Trans. Robot.*, vol. 38, no. 1, pp. 159–179, Feb. 2022.

[A11] T. M. Roehr, “Active exploitation of redundancies in reconfigurable multirobot systems,” *IEEE Trans. Robot.*, vol. 38, no. 1, pp. 180–196, Feb. 2022.

[A12] T. -K. Chang, K. Chen, and A. Mehta, “Resilient and consistent multirobot cooperative localization with covariance intersection,” *IEEE Trans. Robot.*, vol. 38, no. 1, pp. 197–208, Feb. 2022.

[A13] Y. Yang, D. Constantinescu, and Y. Shi, “Passive multiuser teleoperation of a multirobot system with connectivity-preserving containment,” *IEEE Trans. Robot.*, vol. 38, no. 1, pp. 209–228, Feb. 2022.

[A14] K. Baxevani, A. Zehfroosh, and H. G. Tanner, “Resilient supervisory multiagent systems,” *IEEE Trans. Robot.*, vol. 38, no. 1, pp. 229–243, Feb. 2022.

[A15] B. Schlotfeldt, V. Tzoumas, and G. J. Pappas, “Resilient active information acquisition with teams of robots,” *IEEE Trans. Robot.*, vol. 38, no. 1, pp. 244–261, Feb. 2022.

[A16] C. Street, S. Pütz, M. Mühlig, N. Hawes, and B. Lacerda, “Congestion-aware policy synthesis for multirobot systems,” *IEEE Trans. Robot.*, vol. 38, no. 1, pp. 262–280, Feb. 2022.

[A17] P. Antonante, V. Tzoumas, H. Yang, and L. Carlone, “Outlier-robust estimation: Hardness, minimally tuned algorithms, and applications,” *IEEE Trans. Robot.*, vol. 38, no. 1, pp. 281–301, Feb. 2022.