Swarm Test Arena for Resilient Systems: an experimental setup to study and test bio-inspired algorithms

Ms. Rasika Ravindra Kale, Embry-Riddle Aeronautical University

I am currently pursuing M.S. Systems Engineering and have graduated with B.E. in Mechanical engineering from University of Pune, India and M.S. in Aerospace Engineering from Embry-Riddle Aeronautical University, Daytona Beach FL. My research with BID4R lab at Embry-Riddle Aeronautical University involves creating a robotic swarm platform with an initial goal of creating a proof-of-concept test arena for biologically inspired resilient systems. The future goals include scaling the swarm to aerial and space vehicles, creating scientific collaboration projects and providing STEM outreach to new generation of engineering students. My personal goal is to apply systems engineering principles to space applications and space debris removal.

Bryan Watson, Embry-Riddle Aeronautical University - Daytona Beach

Bryan Watson, PE earned his Ph.D. at the Georgia Institute of Technology and his B.S. in Systems Engineering at the United States Naval Academy in 2009. After graduating, Bryan joined the nuclear Navy, serving as a submarine officer onboard the U.S.S Louisville and at the Naval Prototype Training Unit from 2009-2017. Significant milestones include earning the Master Training Specialist Certification (the military's highest instructor accreditation), Nuclear Professional Engineer Certification, two Naval Achievement Medals, the Military Outstanding Volunteer Service Medal, and a Naval Commendation Medal for his work troubleshooting and repairing the Moored Training Ship 635's reactor and electrical distribution faults. Following his transition from active duty, Bryan earned his PhD as a member of both the Computation and Advancement of Sustainable Systems Lab, where he developed a new method for distributed system demand estimation, and at the Sustainable Design and Manufacturing lab, where his work focused on increasing System of System resilience. Bryan's work has been published in the Journal of Industrial Ecology, Journal of Mechanical Design, and IEEE's Systems Journal.

At Embry-Riddle, Bryan's current work is focused on investigating the use of biologically inspired design to increase the resilience of modern system. The goal of their work is more reliable services to users, increased user safety, and increased sustainability for connected manufacturing, energy, and infrastructure systems.

James E Hand, Embry-Riddle Aeronautical University - Daytona Beach

James Hand received his B.S. in Computer Science from the University of Arkansas, Fayetteville, Arkansas in 2020. While there he worked on several projects, including the university's NASA Lunabotics competition team. Following this he received his M.S. in Unmanned and Autonomous Systems Engineering at Embry-Riddle Aeronautical University (ERAU), Daytona Beach, Florida in 2022, with a thesis focused on soft robotics in underwater environments. As part of this degree, he was recognized with the Outstanding Master's Student award in 2021. Currently he is a doctoral candidate in Electrical Engineering and Computer Science at ERAU. His studies include work on understanding the complex behaviors in insects that create emergent colony security in the face of infections, and how those behaviors can be used to improve Multi-Agent System security to faulted agents. Additionally, he is a 2024 DoD SMART Fellowship scholar.

Matthew Scheinblum-Brewer, Embry-Riddle Aeronautical University - Daytona Beach

Swarm Test Arena for Resilient Systems: An experimental setup to study and test bio-inspired algorithms

Abstract

The use of swarm robots to develop, test, and analyze innovative algorithms has been increasing in academic settings. Current swarms vary in capabilities such as motion, sensing, computational power, and manipulation, tailored to specific algorithm requirements. We introduce the Swarm Test Arena for Resilient Systems (STARS), comprising of a fixed testbed with computer vision data collection and a swarm of semi-autonomous rovers. This setup is ideal for our work implementing biologically inspired algorithms and studying robotic interactions akin to a biological colony, enhancing our understanding of complex systems and system resilience. Unique in design and size, STARS is on track to become one of the largest wheeled swarms created by students, serving as a valuable educational tool for integrating software and hardware in engineering systems. It offers students opportunities to explore electronics, software, algorithm design, and hardware implementations, fostering research, multidisciplinary engineering, STEM outreach, and scalable applications for aerial and space vehicles. This article outlines the methodology employed in developing the STARS and details the insights gained, aiming to inspire further advancements in swarm robot development.

Keywords

Robotic swarm, biologically inspired resilient systems, experimental platform, multi-disciplinary engineering, systems engineering STEM outreach

1 Introduction

The characteristics of biologically inspired swarm algorithms are derived from natural phenomena such as complex collective interactions between ants, bees, birds, fish etc. [1, 2, 3] These algorithms have provided innovative methodologies to solve problems pertaining to complex systems in the real world that require a high level of computation. Yuce B. et al. [4] utilized the concept of foraging behavior honeybees to propose a new Adaptive Neighborhood Site change and Site Abandonment (ANSSA)-based optimization algorithm and tested it with multiple benchmark functions. E. Sahin [5] presents a definition of swarm robotics inspired by biological systems such as aggregation of amoeba into slime mode, information exchange in bacteria. Bodi, M. et al. [6] proposed BEECLUST, an algorithm that uses the aggregation behavior of honeybees and controls the autonomous underwater swarm. Sutantyo, D. et al. [7] investigated the application of an anti-phase synchronization algorithm that is inspired by the calling pattern of frogs to allocate communication slots to solve interference problems of underwater swarms. Watson B. C., et al. [3] created a conceptual model of an ant colony and the strategies that it employs to restrict the propagation of fungal infection that prevents the collapse of colony. Yong, L. et al. [8] applies the memory processing technique of ant colony to intrusion detection. All these examples include modeling multi-agent systems that address the cooperative interactions of agents within the system and their ability to make autonomous decisions to accomplish the allocated tasks. [9, 10, 11, 12] The applicability of this research spans a large number of systems including surveillance UAV formations, consensus of the data acquired by the agents in a satellite swarm, optimal path planning of vehicles and many more. [1, 13]. For these algorithms to be useful, however, they must be validated – either by simulation or with physical test beds.

Simulation is one of the primary tools by which engineers verify and validate systems [14]. It is through simulation that design choices are tested and it allows rapid prototyping of research ideas. Typically, this is through the lens of complex computer simulations that try to approximate physical environments. To accommodate the complexities of a wide range of multi-agent systems, various simulation platforms are utilized such as, JADE, VOLTRON, MASON, GAMA etc. [15]. However, physical experiments are equally as important, for both validation as well as education. For example, wind tunnels can be simulated using computation fluid dynamics software, but using a physical wind tunnel to test designs can provide more accurate data. In addition to being more accurate in real world conditions these physical simulators have been shown to be more likely to inspire interest for students in a given subject [16]. Thus, while computer simulations are an important part of data gathering in engineering, physical simulators and experiments provide unique insights into real world operating conditions.

Robot swarms are the most suitable test platforms for multi-agent systems since they are defined by Arnold, R. et al [17]. as “a group of three or more robots that perform tasks cooperatively while receiving limited or no control from human operators.” They can provide an environment to adopt the “theory to prototype” approach before applying novel collective algorithms to industrial projects [12]. Rubenstein, M. et al [18] developed a swarm of thousand small Kilobots and implemented “collective algorithm” to validate self-assembly characteristics of a multi-agent system in which the swarm can regain the 2D shape after external disturbances are applied. This displays the ability of agents to locally communicate and cooperate. One of the most well-known examples of a similar swarm can be seen in Georgia Institute of Technology’s Robotarium Project. Robotarium is a freely accessible swarm robotics platform meant to provide researchers with access to real robotics hardware from anywhere in the world [19]. Currently the Robotarium swarm consists of up to twenty robots and is focused on research data collection, though computer simulations of the system are publicly available which could possibly be used for educational purposes. MilyBots is a platform of eight highly sophisticated and customized wheeled rovers powered by geared motors with a unique ability to incorporate Visual Programming Language for creating dynamic choreographies for swarm testing along with the collective swarm algorithms [20]. One of the applications of this swarm is testing the game play e.g., soccer. STARS is uniquely positioned between these two types of swarm platforms such that it can provide a validation platform for testing novel algorithms inspired by complex systems as well as a learning environment in an academic setting to support STEM education.

The purpose of this article is to introduce to the Engineering Education Community the STARS platform. Our approach to real-world testing focuses on a swarm of wheeled rovers with low computational complexity, readily available low-cost components, ease of programming, efficient data communication and wireless charging capability. This article proceeds as follows: first, we describe the motivation for STARS, followed by the conceptual design and an example experimental setup. Next, the way STARS has enabled educational outcomes is described. The article closes with a description of future work and lessons learned from the development of this platform.

2 Motivation for STARS

The STARS platform provides a 2D analogy for many types of systems. The disadvantages of not having a fully 3D capable system can be minimized when the proper considerations are made. In fact, the use of a ground-based system can even be considered, in some situations, to be a benefit when considering the requirements for operating an aerial or water-based swarm, due to the safety and operational requirements inherent in those systems.

When abstracted away the individual robots in this swarm can represent a wide variety of specialized real-world systems. For example, due to the two wheeled design of the robots, they are capable of on the spot turning, which can mimic changes in direction and velocity for land, air, sea, and space, with only minor differences to the real-world result. Additionally, STARS is meant as a prototyping and testing tool for complex algorithms designed in simulation. Specifically, STARS acts as a middle ground between computer simulation and production implementation on costly real-world systems. It is not meant to account for every aspect of every possible system or environment, but in its current configuration it does provide an extremely useful analog to many of them. For our work, we focus on the use of algorithms to increase system resilience.

System resilience is a key consideration reflected in most systems, such as modeling coastal infrastructure after root systems to better withstand environmental challenges or utilizing algorithms inspired by mountain gazelle behavior to enhance the reliability of power control system operations [21, 22, 23]. The STARS platform has the capability to test various biologically inspired algorithms aimed at improving system resilience. This characteristic makes STARS a unique educational platform for the student researchers in the field of systems engineering and young students interested in pursuing a career in engineering.

The need for human resources in the industry with STEM education and practical experience has exponentially increased over the past few decades. Multiple studies have explored the scope and benefits of incorporating interactions with robotic platforms as a part of the K-12 curriculum [24, 25, 26, 27]. Jdeed M. et al. [28] conducted a study where a swarm robotic platform Spiderino was utilized in classroom training format for K-12 education. It displayed enhanced interest and appreciation expressed by the students towards application-based learning in STEM. Wilson S. et al. [29] developed a modular multi-robot platform with detachable gripper modules that are affordable and made available to the students to explore robotics and learn programming. Many other multi-robot platforms are developed that can offer varying levels of complexity and modularity suitable for use to promote hands-on approach in STEM education [29]. A prominent goal of STARS is to provide an environment for applying systems engineering principles with a multidisciplinary approach to utilize the swarm test platform. As the focus of this platform, a complex system's behavior is tested and analyzed, which opens more avenues for student researchers to explore and build multi-agent system models using bio-inspired algorithms [30]. Hence, STARS contributes to creating awareness about the application of systems engineering in multiple fields such as environmental science, communication architecture, economy, optimal path planning for autonomous vehicles etc. It encourages a collaborative and multidisciplinary research environment.

This swarm system was designed, developed, verified, and run by a multidisciplinary team. The team is comprised of several students from varying educational backgrounds and levels, from undergraduates to master's students, and doctoral candidates. Due to the nature of the system and building STARS from the ground up, expertise was required in a wide range of areas, including electrical circuit design, 3D component design and fabrication, computer vision, test arena design and fabrication, and many more. The multidisciplinary engineering approach and the significance of this platform as an educational tool are explained in the following sections.

3 Conceptual Design of the Test Platform

The test platform serves as a proof-of-concept for bio-inspired algorithms designed to improve the resilience of multi-agent systems. It also creates an avenue for verification and testing of mathematical models and simulations of these systems. To achieve this objective a swarm of rovers was created, representing a colony of biological entities. To facilitate the observation and analysis of swarm operation, a confined arena and overhead computer vision system was employed. The technical requirements for the rovers were identified to imitate the behavioral qualities of biological entities that are often the source of algorithm inspiration, with an objective of achieving suitably low operational and computational cost. The rovers are equipped with the capabilities of vision, motion, data processing, wireless data communication, autonomous operational lifespan management with off-the-shelf and low-cost components. An autonomous wireless charging algorithm was also designed to support long operational lifespan (169 minutes) of the swarm during the experiments and to satisfy the requirements of minimizing human intervention.

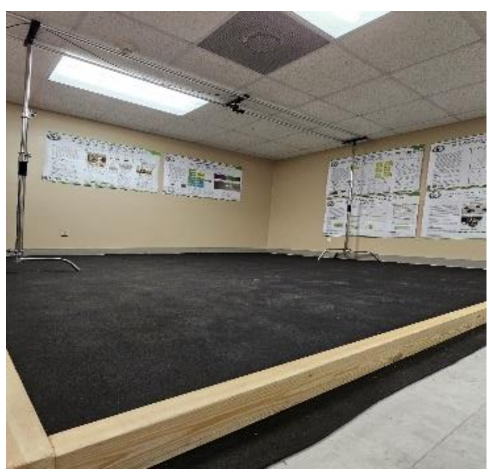

Fig.1 Swarm test arena with overhead cameras for computer vision (STARS)

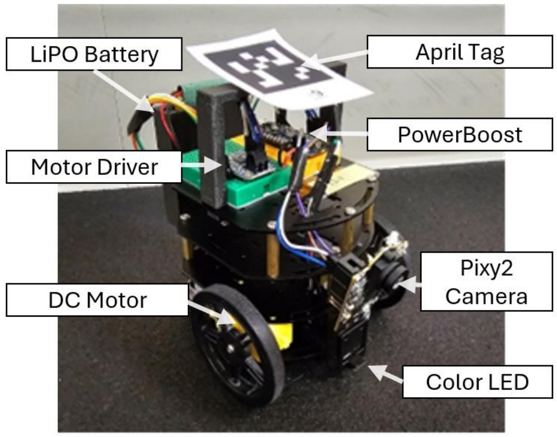

Fig.2 The Rover with labeled Components of Interest

The platform enables the swarm to display behavioral qualities of a biological colony with tracking of interactions, identification of mates, and storage of unique identifiers such as interaction profiles. During the experiment, the swarm can enter multiple operational modes namely initialization, default range of motions, agent detection and battery management. These modes can support the testing of algorithms created to improve a complex system's response to external disturbances or threats and analyze their scope. The analysis of possible threats identified from the observation of experiments provides opportunities to increase the threat management potential of the swarm, making it more resilient and in turn meeting a prominent goal of this platform.

4 Example Experimental Setup and Technical Specifications

The test platform as described in the previous section is utilized to conduct testing of biologically inspired algorithms using interactive swarm operations. Each aspect of the setup is explained in this section in relation to a biological colony.

- **Test arena**
  A confined space of 12 feet by 12 feet is created to conduct swarm experiments using wooden plank boundaries with mat flooring (Fig 1). The arena contains two overhead camera stands that are used to mount the cameras for computer vision analysis. Charging stations used for wireless charging of rovers are positioned along the sides of the arena.

- **Rover chassis**
  The rover's body is constructed using anodized aluminum frames, DC motors, wheels and mounting hardware [31]. This provides a three-layered structure that fits within an envelope of length of 3.9 inches, width of 4.4 inches, and height of 2.6 inches. The attachments created for the external sensors and the LiPo battery are 3D printed.

- **Battery power**
  A LiPo battery, with a standard voltage rating of 3.7V, is incorporated in each rover to

supply power for operation, computation, and communication (Fig 3). The battery is rechargeable and has a 3000 mAh capacity which is suitable for long durations of experiment as mentioned in the previous section. Each rover will detect battery level throughout the operational lifespan and trigger charging mode of operation as programmed via Arduino. Battery power is distributed as per the varying demands of the Arduino NANO 33 IoT, a DRV8833 motor controller, and a Pixy2 camera via the PowerBoost 1000 Charging board. The wireless charging capability is implemented using a Qi wireless transmitter attached to an external power outlet and a Qi wireless receiver attached to the rover via the PowerBoost 1000 Charging board. This is analogous to biological entities replenishing and distributing the energy, as required by the tasks to be performed.

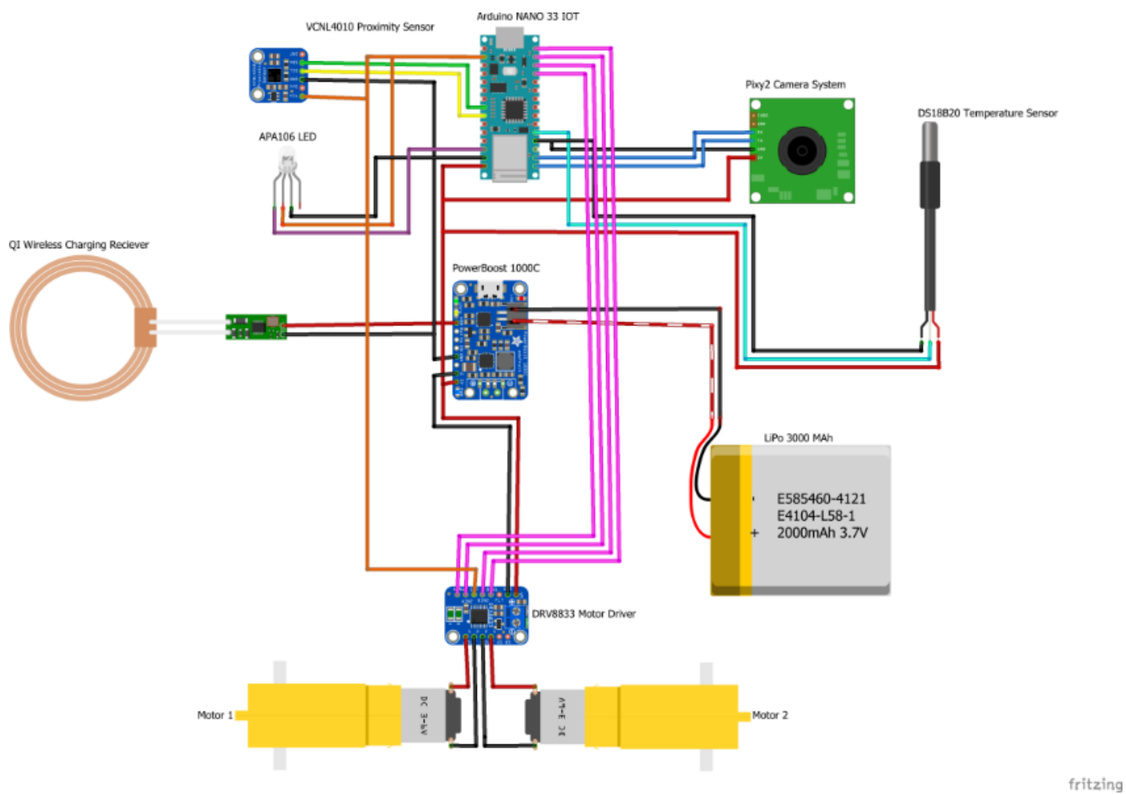

Fig. 3 Electrical Circuit Diagram for the Rover

- **Sensors**
  Pixy2 cameras are utilized for onboard detection of colors and light [32]. The Arduino is programmed to implement actions corresponding to specific colors identified by the camera. The cameras provide open-source software and compatibility with multiple user interface connections including SPI, I2C, UART, and USB [32].

  The APA106 color changing LEDs with dimming capabilities are utilized to display the colors for default and color matching modes of operation. The Pixy2 cameras detect the colors, and the Arduino produces a corresponding programmed response by manipulating the RGB value of LEDs for the rovers. This translates to the unique identifier profile displayed by entities in a colony and how it evolves with the interactions within the colony.

The VCNL4010 proximity sensor is employed to achieve distance-based collision avoidance (within 200 mm) for interactions within the swarm and with the boundary of the arena. This ensures safety of rovers during swarm experimentation [33].

- **Motion**
  Two DC motors independently connected to two wheels of the rover provide the translational motion with support from a plastic caster ball which provides rotational motion [31]. The speed and distance to be travelled based on the scenarios of experiments is controlled via Arduino instructions. This allows the agents to move in a 2-D plane.

- **Computation and data processing**
  An Arduino Nano 33 IoT is used to control the rovers for all the operational scenarios defined in the previous section [34]. This board utilizes a Cortex M0+ SAMD21G18A 48MHz processor, in addition to having Wi-Fi and Bluetooth modules, and a 6 axis IMU. It connects motion, vision, and wireless communication over Wi-Fi to implement programmed swarm interactions. The signals from overhead cameras generated by capturing the rover specific April Tags, which are similar to QR codes, are transmitted over Wi-Fi and processed by the Arduino to locate and orient the rovers for battery management scenarios. The colors emitted by LEDs and detected by Pixy2 cameras are processed to match and update the color representation of individual pheromones in the detection and matching scenarios. The motion of rovers is governed by the Arduino for each of the scenarios by sending programmed signals to stop, start, move forward, move backward, and rotate through DC motors, and the DRV8833 motor controller board. The Arduino board provides low computational power which translates to decision-making capabilities suitable for biological entities.

- **Example Swarm Operation**
  When the experiment is initialized, the rovers possess 100% battery power and are situated at random initial positions inside the test arena. The swarm initiates the motion sequence and emits red and blue flashing colors using LEDs. The flashing indicates that a rover is ready to pair with another member of the swarm. The swarm moves to the next mode of operation in which the rovers begin a search algorithm using camera to detect the flashing colors displayed by other rovers. If a color match is found between two rovers, the rovers turn the LEDs green before sharing their individual unique RGB identifier. Both rovers will observe the other's identifier and update their personal RGB identifier based off their partner.

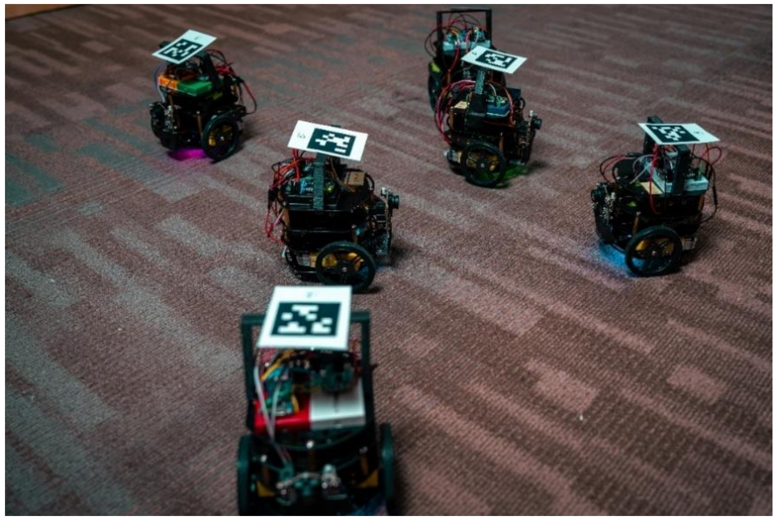

Fig.4 The Operational Swarm with Rover Interactions

5 The STARS Platform as an Educational Tool

The STARS platform is primarily utilized by researchers who are involved in building biologically inspired algorithms by testing these algorithms with the swarm. Additionally, researchers have used the swarm in research focused on understanding the impact educational experience has on observations of physical systems. Finally, the STARS platform can be used with external groups of students pursuing K-12 education as an example application of robotics and systems engineering.

The student researchers responsible for building the platform have considered the following aspects during the design, development, and testing stages of the STARS platform lifecycle:

- The software demands based on the simulation of the bio-inspired algorithm.
- The hardware demands to accommodate the identified software specifications.
- The hardware demands to build the test arena.
- The cost and availability of all components of the platform.
- The timeframe of designing and building the platform.
- The timeframe of conducting swarm experiments.
- The qualities of biological system under consideration, that the swarm must mimic.
- The swarm parameters chosen to test the complex systems.

In this process, the students can study the principles of complex systems and system resilience [35]. They can learn to choose and assemble the software and hardware components that are specific to the required swarm operations and learn to update those components based on experimental findings. The platform allows them to collaborate and integrate the mechanical, electrical, and software systems to build the platform and achieve a common goal with swarm experiments. This also allows the students to advance systems engineering research by exploring the real-world applications of innovative biologically inspired algorithms, create system simulations, and test the system's capabilities and limitations with the swarm.

Moreover, STARS promotes multidisciplinary engineering from two different perspectives:

- Consideration of the constraints on mechanical, electrical, and software systems to work towards achieving one goal of testing the innovative algorithms based on natural phenomena.

- The applications of single systems engineering aspect such as biologically inspired complex systems to multiple real-world scenarios including air traffic management [28], optimal resource allocation for wildfire management [36], communication and control for satellite swarms/formations [13].

The researchers who contributed to building this platform and who formally participated in the swarm experiments are students from multiple educational backgrounds including cybersecurity, electrical engineering, computer science, software engineering, aerospace engineering, spaceflight operations, aeronautical sciences, and mechanical engineering. This not only provides multiple outlooks when developing this system but also multiple approaches to detect vulnerabilities of that system when implemented using the swarm experiments.

For example, as a part of a STEM outreach initiative, STARS collaborated with a group of undergraduate students pursuing electrical engineering at XXX University to design, build, and test the wireless charging stations for the swarm. This process not only required the students to study the electrical and mechanical systems of the rover but also encouraged them to research the operational requirements of a swarm as a multi-agent system. Additionally, STARS has been designed to allow groups of K-12 students to visit the platform and observe the swarm when it is operational. This allows them to form an understanding of topics including engineering systems, systems integration, scientific research, biologically inspired systems, algorithm development, electrical systems, and swarm robotics. This creates an excellent opportunity to generate interest in systems and multidisciplinary engineering and higher STEM education [28].

6 Conclusion

Swarm test arena for resilient systems (STARS) is a platform that allows for the testing and verification of biologically inspired algorithms. At present the swarm is capable of imitating a biological colony through rovers with integrated electro-mechanical systems programmed via Arduino. The swarm can identify and confirm the mates from its own colony. The swarm has low computational capabilities as suitable for social biological components like ants. This platform presents learning and research opportunities pertaining to systems and multidisciplinary engineering and contributes to the STEM outreach by encouraging young students to pursue research in engineering. The scope of this platform can be expanded to accommodate a greater variety of biologically inspired algorithms and hence test a variety of applications to the real-world complex systems. The future work includes upgrading the rovers with PCBs, testing a multitude of biologically inspired algorithms and the resulting swarm interactions.

Finally, we present a list of lessons learned from student researchers in the field of systems engineering, responsible for STARS development:

- Create well-documented and detailed requirements definition for the platform in the conceptual design phase. This entails defining the functions, attributes, performance metrics and safety critical parameters of the platform including the rovers, the test arena and the computer vision system. A clear idea of the platform ensures that the specifications of hardware and software components are compatible with the overall operational needs of the system, clarifies the desired characteristics of the system and mitigates the risk of exceeding the budget.
- The power distribution on the rover is highly sensitive to the connector type, gauge, and current specifications of the connecting wires. Even a small deviation of these parameters can affect the power input and functionality of other components.
- The motion of rovers with motor-driven wheels is highly sensitive to the weight distribution of components on the rover, even for small platforms. This is especially useful to consider when assembling external mounts on to the rover's chassis.
- Develop a sequential protocol for testing the rover components followed by a comprehensive evaluation of the rover's overall functionality before deploying the algorithm intended for the experimentation. This step identifies the smallest of issues at the component level which reduces the probability of system failure.
- Ensure that the cameras on the rover are calibrated and adjusted to detect the intended LED emissions under changed light conditions in the test arena. The light exposure and the location of the camera on rovers are critical to facilitate the rover interactions using color detection and matching algorithms.
- Create a work breakdown and schedule for the tasks that must be completed for the development of the platform and towards the intended experiment. This is especially important for multidisciplinary collaborative projects such as this where students from different research backgrounds are responsible for completing parts of the platform. In an academic setting, it will facilitate the timely validation of the novel bio-inspired algorithm and enable the utilization of experimental data to advance and publish the research.
- If attempting to construct a large swarm with off-the-shelf parts, ensure sufficient inventory exists of all parts needed prior to beginning purchases.

This article contained three contributions: first it presented the STARS platform to the academic community. Secondly, it provides insight and motivation for future academic swarms. Third, we provide lessons learned during the engineering process. While our future work will focus on using STARS to investigate biologically inspired algorithms, we hope this article will inspire additional engineering departments to invest in these types of platforms for both education and research.

Acknowledgements

The authors gratefully acknowledge the support of XXX University's College of XXX XXX Program.

References

1 Duan, H., Huo M., and Fan, Y, "From animal collective behaviors to swarm robotic sooperation," National Science Review, 2023, pg 10.

2 Dorigo M. and Di Caro G., "Ant Colony Optimization: A New Meta-Heuristic", Proceedings of the 1999 Congress on Evolutionary Computation; Washington, DC, USA. 6–9 July 1999.

3 Watson, B.C. and McNeill, C., "Using an Agent-Based Model to Explore the Effectiveness of Strategies Used by Ants to Mitigate the Spread of the Fungus *Ophiocordyceps camponoti-rufipedis"*, Journal of Insect Behavior*,* **37**, 181–199 (2024). https://doi.org/10.1007/s10905-024-09860-z

4 Yuce B., Packianather M. S., Mastrocinque E., Pham D. T. and Lambiase A., "Honey Bees Inspired Optimization Method: The Bees Algorithm. Insects", 2013 Nov 6;4(4):646-62. doi: 10.3390/insects4040646. PMID: 26462528; PMCID: PMC4553508.

5 E. Şahin, "Swarm Robotics: From Sources of Inspiration to Domains of Application," in Swarm Robotics, E. Şahin and W.M. Spears, Eds. SR 2004, Lecture Notes in Computer Science, vol. 3342, Springer, Berlin, Heidelberg, 2005, pp. 10-20. [Online]. Available: https://doi.org/10.1007/978-3-540-30552-1_2

6 Bodi, M., Möslinger, C., Thenius, R. and Schmickl,, T.m "BEECLUST used for exploration tasks in Autonomous Underwater Vehicles", IFAC-PapersOnLine, Elsevier, 2015, vol. 48 no. 1 p. 819 – 824, ISSN 2405-8963, https://doi.org/10.1016/j.ifacol.2015.05.133

7 Sutantyo, D. and Levi, P., "A bio-inspired TDMA scheduling algorithm for underwater robotic swarms," *2013 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, Shenzhen, China, 2013, pp. 1107-1112, doi: 10.1109/ROBIO.2013.6739612.

8 Yong, L. and Sunjun L., "Intrusion detection system based on ant colony memory principle," International Conference on Apperceiving Computing and Intelligence Analysis, Chengdu, 2009, pp. 153-157, doi: 10.1109/ICACIA.2009.5361130.

9 Falco, M. and Robiolo, G., "A systematic literature review in Multi-Agent Systems: Patterns and Trends" 2019 XLV Latin American Computing Conference (CLEI), Panama, Panama, 2019, pp. 1-10, doi: 10.1109/CLEI47609.2019.235098.

10 Han, S., Zhang, Q., Yao, Y., Jin, W., Xu, Z., and He, C. "Llm multi-agent systems: Challenges and open problems", 2024. URL https://arxiv.org/abs/2402.03578..

11 A. Dorri, S. S. Kanhere and R. Jurdak, "Multi-Agent Systems: A Survey," in IEEE Access, vol. 6, pp. 28573-28593, 2018, doi: 10.1109/ACCESS.2018.283122811

12 Schranz M, Umlauft M, Sende M and Elmenreich W., "Swarm Robotic Behaviors and Current Applications.", Front Robot AI, 2020 Apr 2;7:36. doi: 10.3389/frobt.2020.00036. PMID: 33501204; PMCID: PMC7805972.

13 Moric, I., "Capabilities of Commercial Satellite Earth Observation Systems and Applications for Nuclear Verification and Monitoring", Science and Global Security, 2022, vol. 30 no. 1 p. 22–49, https://doi.org/10.1080/08929882.2022.2063334

14 Xiang, X., Kennedy, R., Madey, G. and Cabaniss, S., "Verification and Validation of Agent-based Scientific Simulation Models", Agent-Directed Simulation Conference, 2005.

15 Xie, J. and Liu, C., "Multi-agent systems and their applications", Journal of International Council on Electrical Engineering, 2017, pg. 188-197. 10.1080/22348972.2017.1348890

16 Krüger, J., Höffler, T., Wahl, M., Knickmeier, K. and Parchmann, I., "Two comparative studies of computer simulations and experiments as learning tools in school and out-of-school education", Instructional Science, 2022, 50. 1-29. 10.1007/s11251-021-09566-1.

17 Arnold, R., Carey, K., Abruzzo, B. and Korpela, C., "What is A Robot Swarm: A Definition for Swarming Robotics", IEEE 10th Annual Ubiquitous Computing, Electronics & Mobile Communication Conference (UEMCON), 2019, 0074-0081. 10.1109/UEMCON47517.2019.8993024.

18 Rubenstein, M., Cornejo, A., and Nagpal, R, "Programmable self-assembly in a thousand-robot swarm", Science, vol. 345 no. 6198 p. 795–799*,* doi:10.1126/science.1254295

19 Wilson, S. et al., "The Robotarium: Globally Impactful Opportunities, Challenges, and Lessons Learned in Remote-Access, Distributed Control of Multirobot Systems," in IEEE Control Systems Magazine, vol. 40, no. 1, pp. 26-44, Feb. 2020.

20 Vega L., Buscaron, C., Schwartz, E. M. and Arroyo, A. A., "MILyBots: Design and development of swarm robots", Machine Intelligence Laboratory, University of Florida, 2008

21 Madni, A & Jackson, S., "Towards a Conceptual Framework for Resilience Engineering", Systems Journal, IEEE, 2009 3. 181 - 191. 10.1109/JSYST.2009.2017397.

22 E. Stachew, T. Houette, and P. Gruber, "Root Systems Research for Bioinspired Resilient Design: A Concept Framework for Foundation and Coastal Engineering," Frontiers in Robotics and AI, vol. 8, Apr. 2021, doi: https://doi.org/10.3389/frobt.2021.548444.

23 M. E. C. Bento, “Design of a Wide-Area Power System Stabilizer resilient to permanent communication failures using bio-inspired algorithms,” Results in Control and Optimization, vol. 12, p. 100258, Jun. 2023, doi: https://doi.org/10.1016/j.rico.2023.100258.

24 M. E. Karim, S. Lemaignan and F. Mondada, "A review: Can robots reshape K-12 STEM education?" 2015 IEEE International Workshop on Advanced Robotics and its Social Impacts (ARSO), Lyon, France, 2015, pp. 1-8, doi: 10.1109/ARSO.2015.7428217.

25 Ribeiro, A., Lopes, G. (2020), “Learning robotics: a review”. Curr Robot Rep. 2020; 1: 1–11.

26 Hussain, S., Lindh, J., and Shukur, G., “The effect of lego training on pupils’ school performance in mathematics, problem solving ability and attitude: Swedish data”, Educational Technology & Society, 9(3):182–194, 2006.

27 Nataraj, C., Reddy, S., Woods, Mark, Samanta, B. and Nataraj, C. (2010), “Swarm robotics: A research project with high school students as active participants”. ASEE Annual Conference and Exposition, Conference Proceedings.

28 Jdeed, M., Schranz, M. and Elmenreich, W., “A study using the low-cost swarm robotics platform spiderino in education,” Computers in education, Elsevier, Austria, 2020, pp. 2666-5573, https://doi.org/10.1016/j.caeo.2020.100017.

29 Wilson, S. *et al*., "Pheeno, A Versatile Swarm Robotic Research and Education Platform," in IEEE Robotics and Automation Letters, vol. 1, no. 2, pp. 884-891, July 2016, doi: 10.1109/LRA.2016.2524987

30 Fraccascia, L., Giannoccaro, I., and Albino, V.. (2018), “Resilience of Complex Systems: State of the Art and Directions for Future Research. Complexity”, 2018. Article ID 3421529. 10.1155/2018/3421529.

31 Adafruit Industries. (n.d.). Mini 3-Layer Round Robot Chassis Kit - 2WD with DC Motors: ID 3244. Adafruit Industries, Unique & fun DIY electronics and kits. Retrieved from https://www.adafruit.com/product/3244

32 Pixy2 – PixyCam

33 VCNL4010 Proximity/Light sensor : ID 466 : Adafruit Industries, Unique & fun DIY electronics and kits

34 ABX00027-datasheet.pdf

35 Pallen, A. and Watson, B., “A New Multi-Agent System Consensus Algorithm Inspired by Synchronous Turtle Hatching Behavior.”, Conference on systems engineering research, 2024, https://doi.org/10.1007/978-3-031-62554-1_15.

36 Gorthey, J., Maysha, F., Watson, B., “A New Biologically Inspired Resource Allocation Algorithm for Distributed Multi-agent Systems with Limited Knowledge”, In: Salado, A., Valerdi, R., Steiner, R., Head, L. (eds) The Proceedings of the 2024 Conference on Systems Engineering Research, CSER 2024. Conference on Systems Engineering Research Series, Springer, Cham. https://doi.org/10.1007/978-3-031-62554-1_30