2019 19th International Conference on Advanced Robotics (ICAR)
Belo Horizonte, Brasil, December 02-06, 2019

Adaptable Platform for Interactive Swarm Robotics (APIS): A Human-Swarm Interaction Research Testbed

Neel Dhanaraj[2*†] Nathan Hewitt[3*] Casey Edmonds-Estes[4] Rachel Jarman[5] Jeongwoo Seo[6] Henry Gunner[7] Alexandra Hatfield[8] Tucker Johnson[1] Lunet Yifru[1] Julietta Maffeo[9] Guilherme Pereira[1] Jason Gross[1] Yu Gu[1]

Abstract— **This paper describes the Adaptable Platform for Interactive Swarm robotics (APIS) — a testbed designed to accelerate development in human-swarm interaction (HSI) research. Specifically, this paper presents the design of a swarm robot platform composed of fifty low cost robots coupled with a testing field and a software architecture that allows for modular and versatile development of swarm algorithms. The motivation behind developing this platform is that the emergence of a swarm's collective behavior can be difficult to predict and control. However, human-swarm interaction can measurably increase a swarm's performance as the human operator may have intuition or knowledge unavailable to the swarm. The development of APIS allows researchers to focus on HSI research, without being constrained to a fixed ruleset or interface. A short survey is presented that offers a taxonomy of swarm platforms and provides conclusions that contextualize the development of APIS. Next, the motivations, design and functionality of the APIS testbed are described. Finally, the operation and potential of the platform are demonstrated through two experimental evaluations.**

I. INTRODUCTION

Over the last few decades, swarm robotics has emerged as a research field in addressing the requirements of large-scale, distributed robotics applications. Swarm intelligence is a result of low-level interactions between multiple robots as well as the environment. This emergent behavior can allow a swarm to address problems with robustness and flexibility that is not achievable by a single robot or multiple robots under centralized control. However, the swarm's behaviour is difficult to predict and manage [1]. The addition of a human operator can measurably increase a swarm's performance as the operator may have a higher level of intelligence or intuition unavailable to the swarm [2]. Many approaches to human-swarm interaction (HSI) have been developed [1], yet HSI is far from being a solved problem, or even a well-defined field. More intuitive methods to control swarms of unspecified sizes, while accounting for a human operator's cognitive bandwidth, must be developed. This is slowed by the barrier for entry to development of an HSI system; although the robotic swarm research community has experienced a recent boom in the development of low-cost systems [3], [4], no existing system addresses all the considerations to provide a testbench for HSI research.

In our opinion, an ideal HSI platform should be: (1) low-cost and low-maintenance, to allow for ease of manufacturing and operation; (2) physically embodied, to account for real-world constraints; (3) capable of running agents of various complexities with user-defined rulesets so that HSI with various algorithms may be tested; (4) versatile in its presentation of information to explore these effects on operator cognition; and (5) capable of accepting many types of input devices to allow exploration of HSI either based on or augmented by methods such as gesture control, gaze tracking, and voice commands. Developing such a platform would allow researchers to focus on the field of HSI without being constrained to a particular ruleset or interface.

Fig. 1. Full system testing field of APIS with a human operator modifying the simulated environment using the overhead projector.

The primary contribution of this paper is to present the design, development, and operation of a swarm robot platform that allows future HSI research on arbitrary sets of swarm algorithms and robot conditions. Our specific contributions are:

- A brief survey of relevant approaches to swarm robotic platform design, which explores the flexibility offered by different high-level system designs;
- The design of Adaptable Platform for Interactive Swarm robotics (APIS) shown in Figure 1, a robot swarm built on low-cost and commercial-off-the-shelf hardware components;
- A flexible software architecture that allows for easy

This work was supported in part by the National Science Foundation Research Experience for Undergraduates Program, Award #1851815, and West Virginia University Statler College.

† Corresponding author.

*Lead Authors: ndhanaraj@wpi.edu; nhewitt@uncc.edu

[1] West Virginia University. [2] Worcester Polytechnic Institute. [3] University of North Carolina Charlotte. [4] Bowdoin College. [5] Loyola University Maryland. [6] Vanderbilt University. [7] Centre College. [8] Concord University. [9] California University of Pennsylvania.

978-1-7281-2467-4/19/$31.00 ©2019 IEEE

modifications to inputs, outputs, information transparency, communication, and agency of individual robots.

To best illustrate our design decisions, this paper will first present a brief survey of existing swarm platforms in Section II. This will be followed by an in-depth explanation of the design choices in the overarching APIS system, hardware, and software in Section III. Next, Section IV will present and discuss the results of a set of preliminary demonstrations of this platform. Finally, Section V will present the conclusion and future steps for the APIS system development.

II. A BRIEF SURVEY OF EXISTING SWARM SYSTEMS

Several platforms have been developed to address the different needs of swarm robotics research. This section surveys existing swarm platform designs and presents their motivations, strengths, and limitations. We characterize these platforms as one of the following: simulator, decentralized hardware, or simulated decentralized hardware swarm platforms. We further discuss human machine interaction (HMI) and HSI research and relate ideas derived from our characterization of swarm platforms to these research fields. From this discussion we draw conclusions about relevant features of an HSI testbench.

It is important to first recognize heterogeneous and modular self-reconfigurable swarm research as distinct subcategories because of their contributions to swarm research. Modular self-assembly and self-reconfigurable swarm platforms examine ways that agents can organize themselves into a pattern or structure to better address a range of environments [5], [6], [7], [8], [9], [10]. Research in heterogeneous swarm platforms is motivated by the idea that homogeneous platforms do not address the complexity of hardware required in real-world applications [11]. These platforms are not discussed in depth in this survey because the respective research questions that they address are out of scope of this swarm robot platform taxonomy.

A. Swarm Simulation

Simulating robotic swarms allows for a variety of swarm experiments in a controlled environment at a lower cost than hardware platforms. This allows for a low barrier of entry for experiments, which can enable researchers to observe the behavior of large and complex swarms in controlled environments. Simulation also offers the ability to run faster than real-time, providing insight to long-term swarm behaviors and supporting evolutionary or reinforcement learning robotics research. However, it is difficult for a simulation to accurately model a robot's hardware and the physical interactions between robots. The inaccurate modeling of communication and sensing, as well as movement and collisions in the environment, can lead to differences when comparing the simulation to the hardware experiments. One swarm simulation platform is ARGoS, a multi-robot simulator designed for complex swarm experiments that involve many types of robots. This simulator focuses on being both efficient in computation for many robots and flexible in customizing the simulation [12]. This is accomplished through its modular architecture, which allows wide modification of the simulation and implementation of new features. With 10,000 robots, ARGoS was able to simulate 2D interactions 40% faster than real-time and 3D dynamics in near real-time. Simulators such as Webots, Gazebo and others [13], [14], [15], [16], [17] have also been used to simulate robot swarm applications.

B. Decentralized Hardware Platforms

The disparities between simulation and hardware are addressed through decentralized hardware swarm platforms. In this paper, we define *decentralized hardware* swarm robotic platforms as hardware focused swarm platforms where the agents have sensing capabilities that are used to make decisions. These platforms are fully decentralized, with no central computer facilitating communication, meaning that each robot is limited by its sensing abilities and overall hardware limitations. Many platforms have been developed in this fashion such as Jasmine, Kilobot, S-bot, and others [3], [4], [18], [19], [20], [21], [22], [23]. Characterizing the ability of these robots as a spectrum that ranges from simple agents to complex agents is useful because it describes the kind of swarm algorithms these platforms can address. For example, the aggregation problem [1] can be characterized as a swarm behavior that emerges from simple agents which only need to perceive where other local robots are. In contrast, swarm algorithms implemented to solve more intricate problems, such as search and rescue, require more complex agents. Such agents are characterized by a greater individual perception of the environment and sophisticated decision-making abilities. It is difficult to create a metric for this spectrum of swarm platforms because establishing whether the robots are simple or complex agents is inherently subjective. It is useful, however, to define and give examples of the extremes of such a spectrum.

We define *simple agents* to be robots with limited sensing and perception abilities along with simple rules for decision making. For example, the Kilobot is a low-cost, scalable swarm platform made up of simple agents [3]. This platform was designed to make testing swarm algorithms on many robots easily accessible to researchers. The Kilobot's design was primarily motivated by allowing scalability; as a result, Kilobot has comparatively limited hardware. The robots have only basic locomotion supplied by vibration motors and simple sensing of IR signals, allowing the cost to be as low as $14 per robot. This platform has demonstrated decentralized self-assembly behavior where a 1,024 Kilobot swarm can assemble into user-defined 2D shapes. The principle benefit of a simple agent swarm platform, such as the Kilobot, is that it allows researchers to test on large swarms.

However, to address real-world problems, it is useful to validate multi-robot solutions motivated by a collective of complex agents. We define *complex agents* in a swarm to have sophisticated sensing and decision-making, comparable to robots designed for single-robot research. As an example, the Swarm-bot is an aggregation of small robots with autonomous but limited movement and control [24]. Each S-bot is designed to be a robust, fully autonomous robot that is capable of navigation and communication. The robots have sophisticated locomotion from a combined wheel/tread differential drive and a wide array of sensing such as a camera, inertial measurement unit, and hygrometer. The complex sensor payload enables the swarm to exhibit sophisticated behavior. Results from this platform include aggregation, coordinated motion, collective and cooperative transport of an item, exploration, navigation on rough terrain, and functional self-assembling. Complex agents, such as the Swarm-bot, are beneficial because they are versatile and can test the capability of an algorithm in varied environments. The complexity of those robots, however, limits the number of agents in the collective. A swarm's behaviour may not be emergent with few agents, occasionally making the complexity a disadvantage.

The Kilobot and the Swarm-bot, respectively, are examples of simple and complex agents of decentralized hardware swarm platforms. Many other decentralized hardware platforms mentioned previously can be categorized within this spectrum of complexity. It is important to note that the hardware decisions researchers make in these systems affect the agency of the robots. These trade-offs can determine the types of experiments that a platform can conduct.

C. Simulated Decentralized Hardware Platforms

Simulated decentralized hardware swarm platforms exist as a hybrid of the simulators and hardware-decentralized platforms discussed above. We define a *simulated decentralized hardware* swarm as a platform with a centralized computer that contains information and agent-level rules for every robot, and selectively distributes knowledge of the environment to individual robots. Though this system is technically centralized, researchers can implement decentralized algorithms by simulating the robots' agent-level rules and controlling the data the robots receive.

The Robotarium swarm platform is a recent example of a simulated decentralized hardware platform [25]. The researchers behind Robotarium assert that a physical hardware multi-robot platform is integral for swarm research. Robotarium focuses on lowering the barrier of entry in swarm research by making the platform remotely accessible, and as such specifically addresses the safety aspect required to allow the user to remotely operate the platform. Robotarium's main consideration was the creation of an inexpensive, open-source robotic platform. The system allows for easy transition from simulation to hardware and includes an intuitive interface for interaction and data collection. The developer's implementation of simulation assures the safety of the robots during experimentation, addressing the cost of maintaining such a system. Experiments conducted by outside researchers prove that the platform is both easy to access and can effectively experiment with a diverse set of swarm algorithms.

The Zooids platform also implements a simulated decentralized design to enable simple control of small autonomous robots (Zooids) that can easily interact with humans as a swarm tabletop interface [26]. This requires the platform design to have independent, self-propelled units that can move as a collective, as well as react to user input. Zooids can detect when a user manipulates them through surface capacitive sensing. The software of this system takes input from the user in combination with swarm algorithm rules to plan each robot's motion in the simulation. A server then delivers these instructions to the robot. Zooids' swarm user interface acts as a tool for the user to provide input, as well as manipulate a single or a group of robots. Having a simulated decentralization platform enables flexibility in the development of human-swarm interaction algorithms on the Zooids platform. Furthermore, having multiple inputs from both the user and the swarms' own behavioral rules allows for easier coordination of the robots.

Simulating a decentralized swarm can provide the flexibility necessary for HMI and human computer interaction (HCI) research. A computer is multipurpose tool, so the human computer interface should be flexible to promote an open-ended dialogue [27], [28]. To enable a user to fully capitalize on the many uses of a computer, the HCI architecture should be both versatile and robust. Human swarm interaction research is a subset of both HCI and HMI research. Therefore, the basic principles of HMI discussed in [28] are directly transferable to HSI. Current HSI research is presented in [1], a comprehensive survey of the basic concepts, requirements past research, research gaps of HSI research. Although there are studies such as [2], [29], [30] that have examined certain human swarm control methods, the survey identifies 10 distinct HSI topics such as parameter setting, environmental control and leader influence that require significant future research to develop the growing field. By using the versatility of a simulated decentralized approach, a swarm platform can provide the capability to further research the different identified HSI topics and finally promote an open-ended dialogue between the user and swarm through the design of the swarm platform.

III. SYSTEM DESIGN OF APIS

APIS is a testbed designed to accelerate development in human-swarm interaction by offering a simulated decentralized swarm robot platform that allows for modular and versatile development of swarm algorithms. This design addresses the requirements of an ideal HSI platform identified in Section I. Like Robotarium and Zooids, which exemplify the ease and flexibility offered by using a central computer to simulate a decentralized swarm, APIS allows users to quickly prototype swarm algorithms and conduct HSI experiments with varying agent complexity. APIS implements methods for the robots to output information to the user both visually and audibly and to receive input from the user through gesture tracking, voice, and standard peripherals. In this section we outline how these high-level goals influenced our design choices and present the hardware and software architecture.

APIS consists of three main components: the swarm testing field that contains the infrastructure and test environment for the swarm, the individual robots that comprise the swarm, and the software infrastructure and simulation that facilitate the operation of the swarm.

The testing field of APIS shown earlier in Figure 1 consists of six VICON Vero cameras, a Kinect v2, a projector overhanging a smooth 1m x 2m surface, a wireless charging station, and the system's computer. Using a lattice of IR reflective markers with over 50 unique, non-symmetrical configurations, the VICON motion capture system can identify and track the global position of all robots and other marked entities. APIS uses the VICON system positioning with simulated decentralization to allow for the absence of a localization sensors on each robot. While the VICON system is more expensive than most other options, it can be changed to an alternative system, such as OpenCV's ArUco [31]. APIS adopted the VICON primarily because it allowed for more space along the robot's top for user feedback and because of its high precision localization performance, which has sub-millimeter mean error in laboratory settings [32]. In addition to the position tracking of the VICON system, a Kinect v2 is used as a human input device to enable gesture tracking. In conjunction, the projector displays information to the user such as the simulated environment onto the physical table. Both of these tools are utilized in support of the implementation of HSI methods. Furthermore, to give APIS autonomous charging capabilities, the table is equipped with fifty wireless Qi transmitters comprising a self charging station. Each of these subsystems, except for the self charging station, communicates with the system computer. The computer is responsible for robot communication, decision making, control, and self charging, as well as simulation of test environments. This, coupled with the Kinect v2 and projector, provides a user interface for human-swarm interaction.

A. Individual Robot Hardware Design

The design of the individual robots was influenced by the following fundamental design considerations: (1) having a simplistic, compact and open-source design, (2) having a low barrier of entry to program the robots and (3) promoting an intuitive human robot interface.

The individual agents shown in Figure 1 are 2-wheel differential drive robots each with a 3D printed chassis and a commercial, off-the-shelf microcontroller, as shown in Figure 2. The robots have a cylindrical shape with a diameter of 6.9 cm and height of 8.9 cm. Each robot is equipped with two continuous rotation micro servos that are positioned non-collinearly. This placement reduces the size of the robot while still providing motion comparable to a collinear motor configuration [26]. The unique placement of the components accomplishes the requirement for compactness while providing a visually intuitive interface.

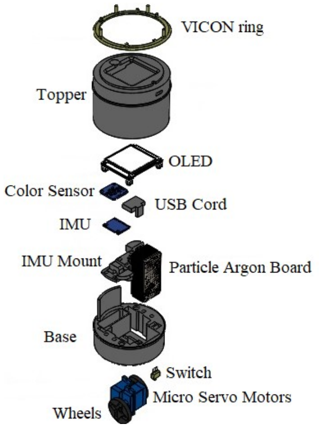

Fig. 2. Exploded view of the APIS robot's components and casing.

The APIS robot is designed to be easily programmable and modifiable to account for varying electronic configurations. Therefore, the microcontroller selected for our swarm is a Particle Argon: an open-source IoT development board for networked projects. Additionally, this IoT device gives the robot capabilities to run over-the-air (OTA) firmware updates, which facilitates robot maintenance. The Argon has built-in LiPo charging circuitry and a plethora of digital and analog IO pins for connecting peripherals such as motors, sensors, and displays. It also uses the same libraries and coding language as Arduino, which is accessible to less experienced programmers while still being advanced enough to handle complex tasks such as multithreading. The firmware implemented on the Argon board is designed to be modular, so users can choose what sensors to implement and what information the robot receives from the system computer.

Several sensors were included on each robot to serve functions that could not be addressed using VICON. The first is the inertial measurement unit (IMU), which provides information on the motion of the robots and is used to estimate robot heading angle and detect collisions. The IMU is especially vital during times of high communication latency because it gives estimated heading when there are gaps in VICON position data. The IMU was placed in the center of the robot to enhance sensor readings and collision detection. The second sensor included is a color sensor that can be used in conjunction with the downward facing projector for various experiments, such as localization using a color gradient without VICON position data.

To enable the robots to have a longer operation time and automatically recharge, the robots' design features a wireless Qi receiver module and a 3.7V LiPo battery. The battery allows for three to four hours of continuous operation. When a robot's battery drops below the specified threshold, it will move to a self charging station.

The robot's HSI interface was designed to enable the human operator to receive information from the swarm through multiple methods: a RGB LED, an OLED display and a buzzer. The RGB LED mirrors the microcontroller's onboard LED to display the system status to the user. The

OLED is a programmable display placed on top of the robot for conveying information to the human operator. The buzzer can be used to alert the user with customized tones.

B. Software Framework Design

To complement the hardware of the platform, a software architecture was developed to facilitate HSI research. The objective was to be capable of using various agents, rulesets, and input devices, focusing again on flexible usage so future effort can be focused on the behavior developed rather than the infrastructure. The diagram for the software architecture is shown in Figure 3.

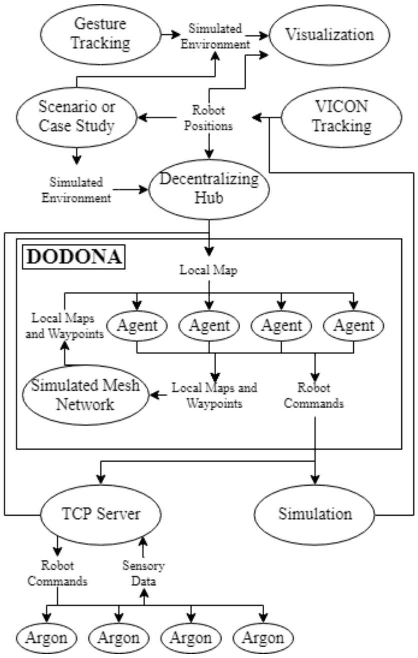

Fig. 3. Flow chart of the overarching software architecture.

A two way connection is established using a TCP server allowing communication between the robots and the central computer. Data gathered by the robots sensors, such as light and battery levels, are passed into a central information hub. The positions of the robots and objects are estimated using the VICON system. While these positions are initially in the VICON's coordinate frame, they are passed to a hub that transforms the objects relative to each robot's coordinate frame. This allows the simulation of advanced sensory capabilities, such as a LIDAR, without the need for physical sensors, and gives the ability to transition between real and simulated sensors.

The behavior for each robot is created in the Dynamically Oriented Decentralised Open-source Navigation Architecture (DODONA). For each agent, DODONA holds a model of the surrounding environment, passed to it by the central information hub, which contains methods for passing information about the environment and about each agents' goal to any other agent. Finally, DODONA contains a set of user determined rules that govern the behavior of the agents. These rules are abstracted from the rest of the software by isolating them to a piece of software (the "agent" bubbles in the diagram of Figure 3) whose only requirement is that it produce some waypoints given the local map. This allows the user to alter the rules without affecting the rest of the system.

Our simulator models real-world dynamics and includes virtual entities based on the scenario. By developing a simulation in tandem with the physical hardware, we can streamline the development of HSI by testing algorithms and decision making processes through simulation first. Additionally, multiple simple visualizations are made of the information stored by the agents and the central hub. This is shown below in Figure 4.

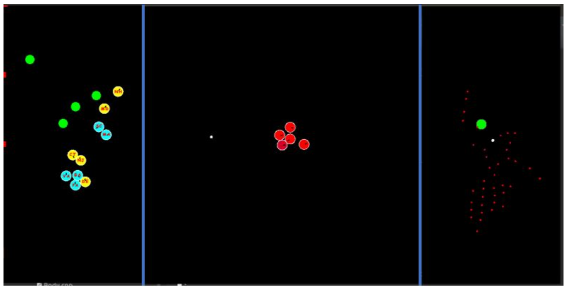

Fig. 4. Three separate visuals are created from different pieces of information stored in DODONA. From left to right, the global map, the incoming data for a single robot, and the local map for a single robot.

Additionally, the simulation makes it simple to integrate virtual objects into the environment. These objects can influence the behavior of the swarm and can be visualized by projecting them onto the table. The use of a simulated environment allows for wider variation in implementations while also streamlining creation, testing and alteration of the software. It allows the operator to modify the collective's behavior without issuing specific commands to each robot. Examples of this will be shown in our experimental evaluation section.

The versatility of the simulation layer means that our platform can support a wide variety of inputs. The current implementation of our platform utilizes a Kinect v2 coupled with gesture tracking software to enable intuitive control, as demonstrated in Section IV. Using natural human gestures reduces the level of technical knowledge needed to operate the swarm. Additionally, mouse and keyboard are available as alternative input devices.

IV. EXPERIMENTAL EVALUATION

To demonstrate the efficacy of APIS, we developed rulesets for two different case studies: (1) playing a game of air hockey with two swarm teams and (2) the exploration and investigation of points of interest. Rather than focusing on the algorithms used themselves, we showcase APIS's ability to operate under diverse rulesets and environments, alongside a preliminary implementation of human interaction.

To play a game of hockey, the robots needed to have some way of hitting the puck to the goal, while blocking the other team from doing the same. A basic physicomimetic ruleset was developed to do this. The robots were made to mutually repel each other, be attracted to designated targets, and follow vector fields. To create the desired emergent behavior, the puck was modeled as a magnet with its poles facing the goals, where each team was attracted to opposite poles. The vector field generated attracts the robots to the puck from the correct direction, while the repellent forces reduces the amount of collisions and crowding of the puck. A scenario of this case study can be seen in Figure 5.

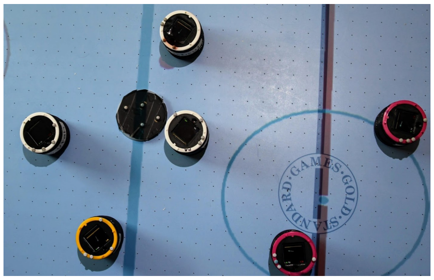

Fig. 5. 3 vs 3 Hockey Game. Robots chase the puck (middle left) to push it towards a goal.

This case study serves as a simple example of what the simulated decentralized approach can accomplish. Although the robots were not estimating positional sensor data, we were able to simulate the existence of a mapping sensor successfully. The case study also demonstrates the usefulness of the simulation as a debugging tool for algorithms before application to a physical system.

Next, a different case study was used: searching for and investigating points of interest with a swarm. There was a specific biological behavior we wanted to use for this case study, drawn from the swarming behavior of hawks. Various hawk species use thermal updrafts to prolong their soaring while searching for food. On an individual level, they have a dilemma between either seeking an updraft with other hawks to conserve energy or exploring elsewhere to increase their chances of finding food [33]. This results in complex emergent behavior within the swarm of hawks.

A biomimetic ruleset was developed with the aforementioned hawk behavior as inspiration. A gradient was generated to simulate the existence of areas with thermal updraft, while points of interest were randomly generated on the map. The robots were given a virtual energy level, which decreased at varying rates depending on the gradient value and increased when reaching a point of interest (i.e., a food source). With the goal of the robots being to maintain and improve their energy levels, we created rules to explore unseen areas of the map, visit food nodes, and travel to higher areas of the contour. Human interaction was implemented by raising/lowering areas of the gradient, which effectively lets the user direct the robots to search an area of the map more thoroughly.

This was accomplished using a Kinect v2 depth camera to recognize the gestures of a user. In our scenario, a user points at an area on the contour map, and closes their hand to select that location. They can then raise or lower their hand to increase or decrease the map's values at that point. Because the robots' rulesets are dependent on the contour map, this approach allows the user to indirectly influence an arbitrary number of agents, regardless of their count, thus lessening required cognitive bandwidth for control of the swarm. Because this occurs in real-time, the robots' resulting behavior is directly observable and completes a feedback loop with the operator. Although rudimentary, this demonstrates the ability of the APIS system to incorporate new input devices, opening possibilities to further HSI experimentation. An example of robots reacting to a placed contour feature can be seen in Figure 6.

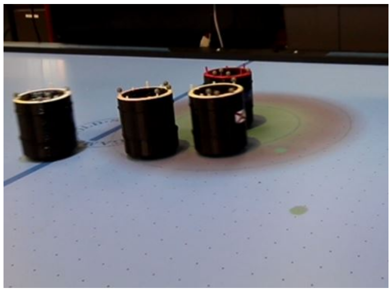

Fig. 6. Robots discovering a virtual thermal updraft represented by the gradient contour and using it to find points of interest more efficiently.

With this case study, we were able to further validate the capabilities of APIS. By using peripheral input, a preliminary case of human-swarm interaction was tested. As the primary contribution of this work is the APIS system itself, these studies are limited in their scope. While simple, these studies demonstrate the system's capability to incorporate user input with the swarm in real-time with relative ease, fulfilling the design tenants proposed by this paper.

V. CONCLUSION AND FUTURE WORK

In this paper, we presented the design of the Adaptable Platform for Interactive Swarm Robotics (APIS), a swarm robotics platform that addresses the barriers to research in human swarm interaction. APIS is an HSI testbed made up of 50 low-cost homogeneous robots that was designed and built by a team of 12 undergraduate students in 10 weeks with commercial off-the-shelf hardware. Sensors and human feedback devices are incorporated into the testing field and the robots to facilitate effective human-swarm interactions. Furthermore, the DODONA software architecture allows for flexible software modifications to the platform as well as easy addition of inputs and outputs. The paper presents a short survey of other swarm robotics platform that provides a taxonomy of swarm platforms. This allows us to present an argument that a simulated decentralized hardware approach gives APIS the versatility needed for researchers to quickly prototype new algorithms and focus on developing results related to HSI research. The developed platform was verified by testing two case studies with different implemented rule sets.

Future steps should be taken to increase the ability of the testing field and to automate the platform's maintenance. It is important to fully realize the potential ways a human can interact with a swarm and incorporate the necessary hardware and software architecture to facilitate such research. This can be accomplished by further developing the hawk-inspired HSI target-searching algorithm and by initiating research in other HSI case studies. The APIS platform is an open source platform and the full documentation, CAD, and code is available under the BSD 3-Clause License. Both this paper and the documentation details the design of APIS; it is our hope this will promote further research and development into human-swarm interaction. Documentation, code, and CAD, are available at http://bit.ly/2Zu0xOf. Videos of case studies and HSI experiments are available at http://bit.ly/2ypgdXj.

ACKNOWLEDGMENT

We would like to acknowledge Henry Vos, Alexandra Collins, Benjamin Buzzo, and Derek Ross for their significant contributions in developing the APIS platform.

REFERENCES

[1] A. Kolling, P. Walker, N. Chakraborty, K. Sycara, and M. Lewis, "Human interaction with robot swarms: A survey," *IEEE Transactions on Human-Machine Systems*, vol. 46, no. 1, pp. 9–26, feb 2016.

[2] S. Bashyal and G. K. Venayagamoorthy, "Human swarm interaction for radiation source search and localization," in *2008 IEEE Swarm Intelligence Symposium*. IEEE, sep 2008.

[3] M. Rubenstein, C. Ahler, and R. Nagpal, "Kilobot: A low cost scalable robot system for collective behaviors," in *2012 IEEE International Conference on Robotics and Automation*. IEEE, may 2012.

[4] F. Mondada, M. Bonani, X. Raemy, J. Pugh, C. Cianci, A. Klaptocz, S. Magnenat, J.-C. Zufferey, D. Floreano, and A. Martinoli, "The e-puck, a robot designed for education in engineering," *Proceedingsofthe9thConferenceonAutonomousRobotSystemsandCompetitions*, vol. 1, no. 1, pp. 59–65, 2009. [Online]. Available: http://infoscience.epfl.ch/record/135236

[5] A. zgr, S. Lemaignan, W. Johal, M. Beltran, M. Briod, L. Pereyre, F. Mondada, and P. Dillenbourg, "Cellulo," in *Proceedings of the 2017 ACM/IEEE International Conference on Human-Robot Interaction - HRI*. ACM Press, 2017.

[6] H. Kurokawa, A. Kamimura, S. Murata, E. Yoshida, K. Tomita, and S. Kokaji, "M-TRAN II: Metamorphosis from a four-legged walker to a caterpillar," in *Proceedings 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2003) (Cat. No.03CH37453)*. IEEE, 2003.

[7] H. Wei, Y. Chen, J. Tan, and T. Wang, "Sambot: A self-assembly modular robot system," *IEEE/ASME Transactions on Mechatronics*, vol. 16, no. 4, pp. 745–757, aug 2011.

[8] B. Salemi, M. Moll, and W. min Shen, "SUPERBOT: A deployable, multi-functional, and modular self-reconfigurable robotic system," in *2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, oct 2006.

[9] J. Liedke, R. Matthias, L. Winkler, and H. Worn, "The collective self-reconfigurable modular organism (CoSMO)," in *2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*. IEEE, jul 2013.

[10] K. Kotay and D. Rus, "Locomotion versatility through self-reconfiguration," *Robotics and Autonomous Systems*, vol. 26, no. 2-3, pp. 217–232, feb 1999.

[11] M. Dorigo, D. Floreano, L. M. Gambardella, F. Mondada, S. Nolfi, T. Baaboura, M. Birattari, M. Bonani, M. Brambilla, A. Brutschy, D. Burnier, A. Campo, A. L. Christensen, A. Decugniere, G. D. Caro, F. Ducatelle, E. Ferrante, A. Forster, J. M. Gonzales, J. Guzzi, V. Longchamp, S. Magnenat, N. Mathews, M. M. de Oca, R. Grady, C. Pinciroli, G. Pini, P. Retornaz, J. Roberts, V. Sperati, T. Stirling, A. Stranieri, T. Stutzle, V. Trianni, E. Tuci, A. E. Turgut, and F. Vaussard, "Swarmanoid: A novel concept for the study of heterogeneous robotic swarms," *IEEE Robotics & Automation Magazine*, vol. 20, no. 4, pp. 60–71, dec 2013.

[12] C. Pinciroli, V. Trianni, R. O'Grady, G. Pini, A. Brutschy, M. Brambilla, N. Mathews, E. Ferrante, G. D. Caro, F. Ducatelle, M. Birattari, L. M. Gambardella, and M. Dorigo, "ARGoS: a modular, parallel, multi-engine simulator for multi-robot systems," *Swarm Intelligence*, vol. 6, no. 4, pp. 271–295, nov 2012.

[13] N. Koenig and A. Howard, "Design and use paradigms for gazebo, an open-source multi-robot simulator," in *2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)(IEEE Cat. No. 04CH37566)*, vol. 3. IEEE, 2004, pp. 2149–2154.

[14] E. Rohmer, S. P. Singh, and M. Freese, "V-rep: A versatile and scalable robot simulation framework," in *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2013, pp. 1321–1326.

[15] O. Michel, "Webots: Symbiosis between virtual and real mobile robots," in *International Conference on Virtual Worlds*. Springer, 1998, pp. 254–263.

[16] S. Carpin, M. Lewis, J. Wang, S. Balakirsky, and C. Scrapper, "Usarsim: a robot simulator for research and education," in *Proceedings 2007 IEEE International Conference on Robotics and Automation*. IEEE, 2007, pp. 1400–1405.

[17] R. Vaughan, "Massively multi-robot simulation in stage," *Swarm intelligence*, vol. 2, no. 2-4, pp. 189–208, 2008.

[18] J. Haverinen, M. Parpala, and J. Roning, "A miniature mobile robot with a color stereo camera system for swarm robotics research," in *Proceedings of the 2005 IEEE International Conference on Robotics and Automation*. IEEE, 2005.

[19] F. Arvin, K. Samsudin, and A. R. Ramli, "Development of a miniature robot for swarm robotic application," *International Journal of Computer and Electrical Engineering*, pp. 436–422, 2009.

[20] F. Arvin, J. C. Murray, L. Shi, C. Zhang, and S. Yue, "Development of an autonomous micro robot for swarm robotics," in *2014 IEEE International Conference on Mechatronics and Automation*. IEEE, aug 2014.

[21] A. Turgut, F. Gke, H. elikkanat, L. Bayindir, and E. Sahin, "Kobot: A mobile robot designed specifically for swarm robotics research," Middle East Technical University, Tech. Rep., 01 2007.

[22] M. Dorigo, "SWARM-BOT: an experiment in swarm robotics," in *Proceedings 2005 IEEE Swarm Intelligence Symposium, 2005. SIS 2005*. IEEE, 2005.

[23] G. Caprari, P. Balmer, R. Piguet, and R. Siegwart, "The autonomous micro robot ”alice”: a platform for scientific and commercial applications," in *MHA Proceedings of the 1998 International Symposium on Micromechatronics and Human Science. - Creation of New Industry - (Cat. No.98TH8388)*. IEEE, 1998.

[24] M. Dorigo, E. Tuci, R. Groß, V. Trianni, T. H. Labella, S. Nouyan, C. Ampatzis, J.-L. Deneubourg, G. Baldassarre, S. Nolfi, F. Mondada, D. Floreano, and L. M. Gambardella, "The SWARM-BOTS project," in *Swarm Robotics*. Springer Berlin Heidelberg, 2005, pp. 31–44.

[25] D. Pickem, P. Glotfelter, L. Wang, M. Mote, A. Ames, E. Feron, and M. Egerstedt, "The robotarium: A remotely accessible swarm robotics research testbed," in *2017 IEEE International Conference on Robotics and Automation (ICRA)*, May 2017, pp. 1699–1706.

[26] M. L. Goc, L. H. Kim, A. Parsaei, J.-D. Fekete, P. Dragicevic, and S. Follmer, "Zooids," in *Proceedings of the 29th Annual Symposium on User Interface Software and Technology - UIST*. ACM Press, 2016.

[27] P. Dourish, *Where the action is: the foundations of embodied interaction*. MIT press, 2004.

[28] L. A. Suchman, *Plans and situated actions: The problem of human-machine communication*. Cambridge university press, 1987.

[29] Z. Kira and M. A. Potter, "Exerting human control over decentralized robot swarms," in *2009 4th International Conference on Autonomous Robots and Agents*. IEEE, 2009, pp. 566–571.

[30] A. Kolling, K. Sycara, S. Nunnally, and M. Lewis, "Human-swarm interaction: An experimental study of two types of interaction with foraging swarms," *Journal of Human-Robot Interaction*, vol. 2, no. 2, pp. 103–129, 2013.

[31] R. Munoz-Salinas, "Aruco: a minimal library for augmented reality applications based on opencv," *Universidad de Córdoba*, 2012.

[32] P. Merriaux, Y. Dupuis, R. Boutteau, P. Vasseur, and X. Savatier, "A study of vicon system positioning performance," *Sensors*, vol. 17, pp. 12–15, 07 2017.

[33] C. L. Henderson, *Birds in flight: the art and science of how birds fly*. Voyageur Press (MN), 2008.