REU Site: Undergraduate Robotics Research in Human-Swarm Interaction

Project Elements: *New REU Site*; Project Title: *REU Site: Undergraduate Robotics Research in Human-Swarm Interaction*; Principal Investigator: *Dr. Yu Gu*; Submitting Organization: *West Virginia University Research Cooperation*; Other Organizations Involved In the Project's Operation: *None*; Location at Which the Proposed Undergraduate Research Will Occur: *West Virginia University, Morgantown, WV, 26506*; Main Field and Sub-Fields of the Research: *Robotics, Swarm Robotics, Human-Robot Interaction*; No. of Undergraduate Participants Per Year: *8*; REU Site Type: *Summer*; No. of Weeks Per Year that the Students will Participate: *10*; Does the Project Include an International Component or an RET Component?: *No*; Name, Phone Number, and E-mail Address of Point-of-Contact for Student Applicants: *Dr. Yu Gu, (304) 293-3992, Yu.Gu@mail.wvu.edu*; REU Web Site: *To be Developed*.

Overview: A long-term goal of the proposing team is to provide opportunities to socio-economically disadvantaged students in rural Appalachia through promoting STEM education, research, and outreach. As a step towards this goal, this REU site will allow 24 undergraduate students, mainly from the Appalachian region, to perform state-of-the-art robotics research at West Virginia University (WVU). The intellectual focus of this project is to allow one human operator to effectively manage a large robot swarm for achieving desired global objectives. Tailored around a swarm system inspired by hawks' cooperative thermal soaring and foraging behaviors, three sub-projects will be conducted by undergraduate students during this project. First, a swarm testing environment with 50 custom designed robots will be developed. Second, distributed, nonhierarchical agent-level interaction rules that will allow the emergence of desirable robot swarm behaviors will be investigated. Third, novel human-swarm interaction modes for managing a large self-organized robot swarm without using a direct command and control structure between the operator and robots will be invented and experimentally demonstrated. Through these efforts, the undergraduate students will have the opportunity to work as a team in performing both fundamental research and hands-on experiments.

The educational objective of this project is to train undergraduate students into independent researchers through challenging them with real-world problems. The overall project management strategy will follow the spirit of swarm intelligence: encouraging the frequent interactions among a diverse group of less knowledgeable/experienced individuals (e.g., undergraduate researchers) to achieve something otherwise may be unachievable by the individuals (e.g. advancing the state-of-the-art in human-swarm interaction). Throughout the project, the faculty and student mentors will encourage creative thinking and frequent interactions to enhance the students' problem solving skills. This will allow them to transition from passive learners to independent thinkers of the future.

Intellectual Merit: 1. acquiring the ability for one human operator to manage a large robot swarm will significantly advance the field of robotics; 2. in this proposal, a challenging human-swarm interaction problem is broken down into several solvable steps compatible with undergraduate researcher's knowledge and capabilities; 3. a bio-inspired "quorum response" approach for self-organization enables robust and distributed social decision making; 4. the introduction of controlled distortions in the robot perception systems departs from the current robotics research and will provide unique benefits in swarm management.

Broader Impact: 1. the project will create research and learning opportunities for students from socio-economically disadvantaged areas. 2. the research experience and training provided by this project will contribute to the growth of a high-quality and diverse US scientific workforce; 3. the successful completion of the project will enable many potential robot applications such as search and rescue, environmental monitoring, and robotic mining and construction; 4. the development of an active robotics learning environment at WVU will stimulate student learning and creativity; 5. the project will promote regional outreach activities; 6. outcomes from this open-access project will be broadly disseminated to interested students and researchers from other institutions.

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1. Project Overview

1.1. Research Motivation and Challenges

Having the ability for one person to effectively manage many robots will transform the relationship between humans and robots. It will enable a vast number of new concepts, designs, and applications that are not currently possible. For example, a swarm of climbing robots could prune trees into artistic shapes; corals may be coordinated by swimming robots to collectively build under-ocean structures; and emergency alerts and escape routes could be displayed in the sky with the aggregation of hundreds of drones. There are several *research challenges* associated with achieving these capabilities, which will fuel innovations during this project:

1. It is no longer feasible for the human operator to pay individual attention to each robot in a swarm. *Questions*: *how to divide up the decision load among the human operator, the self-organized swarm, and individual robots?*
2. It is no longer feasible to program each robot individually for performing different tasks. *Questions: how to design the robots before knowing their specific roles? How to allocate tasks among robots without the need for hard coding or a centralized authority?*
3. There is no guarantee that the emergent group behaviors, as results of bottom-up interactions among a large number of autonomous robots, will be desirable. *Question: What modes of influence can be exerted by the human operator to achieve high-level objectives while maintaining the robustness of the bottom-up swarm behaviors?*

1.2. Objective of the REU Site

The proposed REU site will support a group of talented undergraduate students to find innovative answers to these research questions, build hardware testbeds, and perform robot swarm experiments and demonstrations. Eight undergraduate students, to be recruited mainly from rural Appalachia, will join West Virginia University (WVU) each year for ten summer weeks to work on this project. They will be trained and mentored by three faculty members and work alongside a group of talented graduate students. Through this effort, we are expecting to meet the following key objectives during the three-year project period:

Intellectual Focus: allow one human operator to effectively manage a large robot swarm for achieving desired global objectives.

Educational Objective: train undergraduate students to become independent researchers through challenging them with real-world problems.

The successful completion of this project will contribute to our *long-term goal* of serving social-economically disadvantaged students in rural Appalachia in STEM education, research, and outreach.

1.3. Targeted Student Participants

The proposed REU site will target non-WVU undergraduate students majoring in STEM disciplines from non-Ph.D. granting intuitions that are regionally close to WVU for participation. Almost all these colleges and universities are in the economically-disadvantaged Appalachian region, where many students are first generation college students, have received few guidance in their career path, and have few opportunities to join research projects. Part of the motivation for targeting these institutions is to establish a sustaining network of schools to support our growing graduate program in robotics. This effort will not only enlarge our application pool, but will also provide inspirations and opportunities for Appalachia students to continue their advanced education. To prepare for this project, in the summer of 2018, through internal WVU support, we conducted a pilot program with positions for non-WVU students, which allowed us to approach several regional non-Ph.D. granting institutions including Community Colleges (CC) and

Primarily Undergraduate Institutions (PUIs) (e.g., Bluefield Community College, Fairmont State University, Washington and Jefferson College, California University of PA, and Penn State Berks). This allowed us to begin to establish a set of regional recruiting contacts in the area of robotics and to open dialogues with these institutions regarding our plans to propose an NSF REU site.

When recruiting for this proposed project, we will expand our list of target CCs and PUIs by leveraging the network established by WVU Office of Undergraduate Research, which has an extensive track record of recruiting for multiple WVU REU sites. Our application will specifically encourage students from underrepresented groups (e.g., females, minorities, and first generation college students) to apply to the program. We envision ideal candidates for the program to be rising juniors, although outstanding rising sophomores and seniors will also be accepted into the program.

1.4. Organizational Structure

The proposed REU site will be organized by three faculty members and a graduate student, with the support of the WVU Office of Undergraduate Research and the Statler College of Engineering and Mineral resources. Dr. Yu Gu will serve as the project PI and the REU site director. He will be responsible for the overall project management, recruiting, training material development, and reporting. He will also mentor undergraduate researchers in areas of autonomous robot systems design and human-robot interaction. Dr. Powsiri Klinkhachorn (Klink) will provide mentorship in areas of robot instrumentation, programing, and system integration. Dr. Jason Gross will provide mentorship in areas of state estimation and system modeling/simulation. A dedicated graduate research assistant will work full time during the summers on the project. The student will assist the PI by helping the REU participants to orient and settle down at WVU, coordinating weekly research efforts and team building activities, and serving as an on-site day-to-day and emergency contact person. Ryan Sigler, coordinator of enrollment management for the Statler College will provide support on student recruitment and logistics. Many (over 10) graduate students in the PI and mentors' labs will provide additional training and advising supports to REU participants on a volunteering basis. These students have already been mentoring over a dozen WVU undergraduate researchers and have both the experience and the passion to help their junior peers.

1.5. Timetable

An estimated timetable for the first project year (2019) of the REU site is provided in Table 1.

Year 1	Proposed Activities
February	Develop project website, online application, and training materials. Advertise the REU site. Visit several target universities
Mid-March	Deadline for REU applications
Late-March	Review of applications and make REU offers
Early April	Finalize eight REU participants, receive information (e.g., travel, research preference), send training material including an information package with online resources
May 20 – July 26	10-week summer research program
May 20 – May 22	Three-day intensive training and team building activity and incoming questionnaires
June 21	Mid-summer oral presentation and intermediate questionnaires
July 25	Research poster presentation and outgoing questionnaires
July 26	Open house demonstration to invited K-12 students
Aug. 2019 – July 2022	REU participants can access robotics testing environment remotely and contribute to additional development and testing. They can also interact on a discussion board and provide advice/mentorship to REU students in later years
Jan 2019	Former REU participants contacted via tracking questionnaire for updated information on career path

Table 1: Timeline for the proposed Year 1 project activities. The timeline for subsequent years will be similar.

With the help of the WVU Office of Undergraduate Research, the timetable for several current and proposed REU sites will be synchronized to better perform recruiting, training, demonstration, data collection, and reporting activities.

1.6. Participating Organization's Commitment to the REU Activity

WVU is the flagship public land-grant institution in the Established Program to Stimulate Competitive Research (EPSCoR) state of West Virginia. WVU is also a R1 (Highest Research Activity) University as classified by the Carnegie Foundation. WVU has a dedicated Office of Undergraduate Research, led by an experienced NSF REU site director, Dr. Richards-Babb. The Office of Undergraduate Research will aid the PI in REU site administrative tasks of program advertisement and recruitment, collection and collation of applications, and tracking of participants. In addition, the office organizes educational programming (e.g., workshops, scientific tours, culminating poster symposium) to directors of summer undergraduate research programs across the WVU campus. Dr. Richards-Babb, with over a decade of experience in successfully running REU sites, also provided mentorships to the PI in help preparing this proposal.

The WVU Statler College is highly committed to the growth of both the robotics area and the undergraduate research program within the college. The college recently supported major growths in robotics personnel and research facilities. To prepare the development of this REU proposal, the college also funded four summer undergraduate researchers in summer 2018. As mentioned earlier, two of these students were recruited from outside of WVU for the PI to gain experience on handling the logistics associated with leading an REU site. With three additional students funded by WVU Office of Undergraduate Research, six students funded by different projects, and a volunteer, the PI Gu and mentor Gross involved 14 undergraduate students in their research labs during summer 2018 (Fig. 1). These students made significant contributions to robot development, programing, testing, outreach, as well as the development of a robot swarm testing environment in support of this proposed project.

Fig.1. A subset of 14 undergraduate students worked in PI Gu and mentor Gross's research labs during Summer 2018. These students were supported by WVU internal funding and externally funded projects. Two students were recruited from outside of WVU.

2. Nature of Student Activities

2.1. Biological Inspiration

Nature watchers have long been fascinated by the swarming behaviors of insects, birds, fish, quadrupeds, and humans. In most cases, the group behavior is collectively shaped by individual decisions (Conradt & Roper, 2005; Sumpter et. al., 2008; Vicsek & Zafeiris 2012). The decisions made by one agent are, however, not always independent from the decisions made by the others. For example, real fish were reported to follow a similar looking robotic fish in Marras and Porfiri's (2012) experiments. Similar conforming behaviors were also reported in human groups (Asch, 1956). In one of the experiments (Dyer, 2008), a small percentage of informed individuals were able to lead a large group to a certain destination without them knowing it.

A key mechanism for enabling conformity in animal groups is called "*quorum response"* (Conradt & Roper, 2005). Many animals were shown to exhibit a highly nonlinear response function to their neighbor's decisions (Seeley et al., 2006; Ward et al., 2008; Sumpte & Pratt, 2009): they often ignore the behavior of a single neighbor, but get strongly influenced as more (i.e., a quorum) neighbors committed to the same decision.

2.2. Human-Swarm Interaction

The main difference between human control of a robot swarm and a traditional multi-robot system is that the swarm should be (at least partially) considered as a coherent entity instead of multiple individuals (Kolling et al., 2016). In general, existing swarm control approaches can be categorized as following: 1. global adjustment of the swarm behavior through either switching to a new set of agent-level algorithms (Kolling et al., 2013) or adjusting the control parameters (Hexmoor et al., 2005); 2. use stigmatic or physicomimetics approaches that involves changing the physical or virtual environments (Leonard & Fiorelli, 2001; Walter et al., 2006; Kira & Potter, 2009; Kolling et al., 2012; Spears & Spears, 2012); and 3. indirect swarm control through controlling or influencing a sub-set of the swarm members (Couzin et al., 2005; Goodrich et al., 2011; 2012; Walker et al., 2014).

Despite many different ideas, the research field of human-swarm interaction is still in its infancy with most studies focused on simplistic tasks. The greatest challenge originates from a *paradox*: the robustness of a swarm comes from its open-ended, distributed, and bottom-up interactions. Human control, representing goal-driven influences from a single point, is not quite compatible with the idea of the swarm intelligence. To tackle this challenge, we will highlight the benefits of using *physicomimetics* and *distorted perception* in swarm management, which will allow the swarm to meet global objectives without sacrificing its robustness acquired through bottom-up interactions.

2.3. Technical Approach

2.3.1. Case Study: Hawk's Dilemma

To put the proposed ideas into a context, a case study is first introduced, which is inspired by the swarming behavior of hawks. Many hawk species use thermal soaring (Henderson, 2008) to boost their endurance while searching for prey or migrating (e.g., broad-winged hawks in Fig. 2). They often face a dilemma: the chances of finding thermal updrafts increase with a coordinated effort; however, the chances of finding food decrease with more hawks crowded in the same airspace. Globally, the

Fig.2. A kettle of hawks. Photo: Eric Masterson

hawks exhibit complex swarming behaviors with frequent switching of tasks (e.g. between soaring and exploring). At a micro level, each individual makes decisions to maximize its own benefits.

In this project, the hawks' swarming behaviors will be reproduced with a set of physical simulations using a large number of ground robots. Additionally, a human operator will manage the swarm for meeting high-level mission objectives, such as providing surveillance in regions of interests. Specifically, the simulation will involve up to 50 identical micro robots on a tabletop platform, as illustrated in Fig. 3.

During experiments, each robot will simulate simplified behaviors of a hawk. The robot will make its own individual decisions based on measured/estimated local parameters (e.g., robot pose and local flow direction, as visualized with a contour map in Fig. 3) and will be able to exchange information with neighboring robots within a certain distance range. The energy state (including internal battery energy, kinetic energy, and potential energy) of a robot will be simulated instead of representing the true robot battery use. The robot energy level would be decreased due to actuations and time elapses and would be increased due to (simulated) atmospheric energy harvesting and (simulated) food consumption. Whenever a robot's simulated energy state dropped below a preset threshold, the vehicle is considered inactive and will be automatically removed from the tabletop with a cable driven parallel robot. Therefore, the total number of robots in the experiment will be decreasing over time. Each robot's goal is to stay alive by actively harvesting atmospheric energy and finding food.

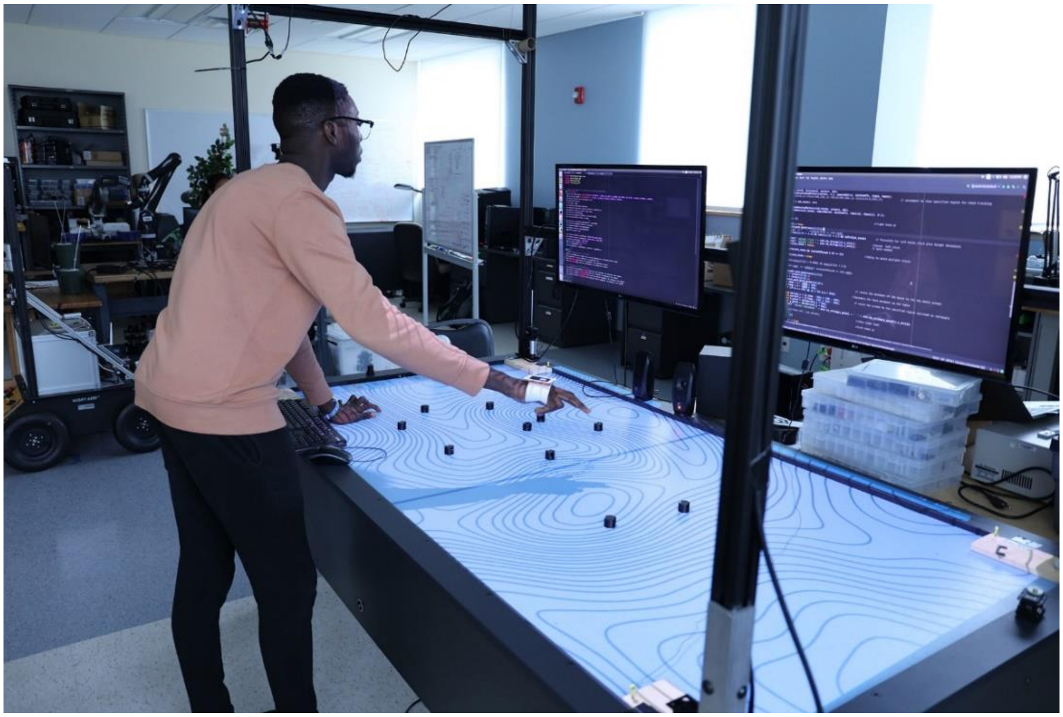

Fig.3. An illustration of an envisioned human-swarm interaction test scenario. The test structure was developed by an undergraduate researcher Conner Castle during summer 2017. Conner is currently a graduate student in the PI's lab. The student in the photo is Kiki Yaw Sarpong, who is an undergraduate student from California University of Pennsylvania. Kiki was supported by WVU internal funds to develop a hand pose recognition software to interact with the robots on the table. The black cylinders on the tabletop are 3D printed shells for the swarm robots, which will be fully developed during the REU project. The motion of these robots will be captured by an overhead camera, a capability developed by another undergraduate researcher Jared Beard during summer 2018. The projected contour on the tabletop represents the thermal activities. A small cable driven parallel robot is under development and will help deploy and retrieve swarm robots.

The operator will rely on the robots to provide in-situ measurements (e.g., checking for objects of interest or chemical leaks) in the workspace, with different and time varying priorities for different areas.

Instead of providing direct control commands to each robot, which would overwhelm a person's cognitive bandwidth, the operator will try to influence the robot swarm's overall behavior. This requires balancing the robot's needs (so that they will not all quickly die off) and the operator's high-level objectives.

Building around this overall concept, the proposed REU project will be broken down into three sub-projects: 1. experimental system development; 2. enable a self-organized robot swarm; 3. perform human-swarm interaction, where each sub-project will be conducted by several undergraduate students.

2.3.2. Sub-Project 1: Experimental System Development

As shown in Fig. 3 earlier, a table-top robot swarm testing environment is being developed in the PI's lab, mostly by undergraduate researchers. The current capabilities include robot motion estimation using images provided by an overhead camera, projection of virtual environment and other information on the robot workspace, and human hand gesture estimation for interacting with the robots. A cable driven parallel robot will be used for automatically deploy/arrange/remove robots and other objects in the robot workspace. This parallel robot is currently being developed to be able to visit different parts of the volume above the tabletop.

During the first sub-project, the swarm testing environment will be further developed to meet the project research needs. First, 50 modular robots, evolved from the design of the open source Zooids swarm robot (Le Goc et al., 2016) will be developed. These robots will be slightly enlarged compared to the original design. Each robot will have an LED array on its top surface to display a unique pattern for the overhead camera to identify and to estimate the robot motion. It will also have a top facing photodiode to sense light intensity. A few moving laser dots will be projected onto the table surface to simulate preys. When a robot senses a laser dot with its photodiode, it would receive a boost in its simulated energy level (i.e., considered as food consumption) and the laser dot will then be turned off.

The robots will communicate with a nearby computing cluster available in the lab through a local Wi-Fi network. The cluster with 80 CPU cores will perform simulations of the test environment, simulate communications among neighboring robots, perform independent decision making for each robot, and provide a user interface for human-swarm interaction.

The atmospheric simulation will be based on the thermal model described by Allen (2005), which will be pre-computed and loaded during the robot experiments. Each robots will then generate simulated air data measurements and perform local wind field state estimation with a nonlinear Kalman filter based on our previous work (Rhudy et al., 2014, 2017). A planning algorithm (Chakrabarty & Langelaan, 2011) will then be developed to guide the motion of each robot to harvest thermal energy.

A web site will be created to allow users to access and design experiments on the swarm test setup remotely. This would allow past REU participants and other interested students and researchers from different intuitions to participate in this research remotely.

To summarize, the following five research tasks will be performed for this sub-project:

Task #1.1: custom micro robot development (mechanical, electrical, and firmware) and the production of 50 robots. Student involvement: Year 1, two students for development, all eight students for construction. Faculty mentor: Klink.

Task #1.2: robot test platform improvement (robot tracking, data communication, develop laser pointers for prey simulation). Student involvement: Year 1, two students. Faculty mentor: Gu.

Task #1.3: simulation of atmospheric conditions and estimation of robot energy level. Student involvement: Year 1, two students. Faculty mentor: Gross.

Task #1.4: perform motion planning and obstacle avoidance for individual robots. Student involvement: Year 1, one student, Year 2, one student. Faculty mentor: Gu.

Task #1.5: allow internet remote access of the swarm testing environment. Student involvement: Year 1, one student. Faculty mentor: Klink.

By the end of this sub-project, the swarm testing environment will be fully established. The robots will be able to perform simulated energy harvesting in the workspace although only limited interactions among the robots will be exhibited. Through these activities, undergraduate researchers will apply knowledge they learned in classes, such as mechanical design, electronics, data acquisition, communication, modeling/simulation, planning and control, and then integrate them in a complex physical robot system. They will also learn how to make engineering tradeoffs during the design process, the challenges of working with a real multi-agent system, and the importance of working effectively in an interdisciplinary team.

2.3.3. Sub-Project 2: Self-Organized Robot Swarm

For each robot, its most important task is to make right decisions quickly in order to maximize its "*lifetime utility*". This includes: 1. avoid collisions with other robots, obstacles, and the boundary; 2. manage its energy state to stay aloft longer; 3. balance the time spent between exploring and soaring; and 4. engage in mutually beneficial social interactions with the peers. This leads to the *objective* of Sub-Project 2, which is to find distributed, nonhierarchical agent-level interaction rules that allow the emergence of hawk-swarm-like behaviors.

To enable efficient robot exploration of the workspace, a contained gas model (Payton et al., 2001; Cheng et al., 2005) using a combination of repulsive and attractive forces among local agents will allow robots to disperse within the search region and to deal with a decreasing number of robots over time. The design of the robot controller will start from the three classic Boids (Reynolds, 1987) rules: separation, alignment, and cohesion. In addition, virtual repulsive forces will be generated by the boundary to keep the robots inside the specified areas.

To accurately estimate the location of a thermal center, it would be beneficial to share the measurements among several local robots. With measurements from more robots covering an extended area, the best thermal updraft candidate could be identified. The estimation performance could be further improved when at least a subset of participating robots are moving in a coordinated fashion in a favorable geometry that maximize observability of the estimation. The question is whether these increasingly sophisticated behaviors could be realized without a central coordinator? In other words, can sub-teams of robots spontaneously form (and dissolve) and make sound decisions using only local information exchange and interactions?

Inspired by the way that a swarm of bees collectively find and decide on a new home location, a "*quorum response*" approach (Seeley et al., 2006; Sumpter & Pratt, 2009) will be used to enable the self-organized thermal sensing and soaring behaviors. In the proposed method, each robot constantly performs an evaluation of the local 3D wind field (Rhudy et al., 2014, 2017). If the robot is in a downdraft, its utility function would be penalized for staying at that location. If an updraft is detected, the robot further estimates the thermal strength and its center location based on its onboard sensors and data provided by its neighbors (i.e., using a locally centralized approach). An upper bound, similar to the Dunbar's number (Dunbar, 2010) in concept, will be put on the maximum number of neighbors that a robot could interact with for keeping the computational load compatible with local resources. If a robot believes that it found a thermal updraft and has an estimate of its strength and center location, it starts broadcasting this finding to the neighbors (i.e. "*recruiting*"). A neighbor, if it also has its own estimate using data provided by a different set of robots (due to spatial differences), would compare the two estimates. If the estimates agree within a reasonable degree, the two robots forms an "*alliance*". Each vehicle in the alliance starts circling its own estimated thermal center with a radius that is a function of the thermal strength and individual preferences. The distances between robots are also regulated by the attractive and repulsive forces generated using the gas expansion model as was discussed earlier.

Once an alliance is formed, group size and consensus is then calculated (Xiao et al., 2007). Each vehicle in the alliance continues to recruit additional agents through sharing the group consensus with them. This creates a *positive feedback* to allow a self-organized group to grow continuously. The positive feedback needs to be dampened with *negative feedbacks*, so that false beliefs would not be sustained over time. There are two mechanisms for providing this effect. First, each robot independently evaluates the situation at all time; if its estimate deviates from the group consensus to a certain degree and for an extended period of time, it would unsubscribe from the alliance. Second, the relative weights of the members in computing group consensus reduce over the time, giving new members more chances to express their opinions in the system.

Multiple alliances with competing ideas could form and co-exist in a local area. However, once a critical number (i.e. a quorum) is reached in one particular group, all the robots in other neighboring groups may abandon their original opinions and join the largest group. This process could be achieved using a nonlinear response curve in a way that a robot values the opinion of a larger group's consensus much greater than from a smaller group (Sumpter & Pratt, 2009).

There are several advantages of this proposed approach. First, there is no leader in the group, so no robot is forced to obey other's orders. Instead, each agent has its own (but not entirely independent) judgment of the situation and makes decisions to take care of its self-interest. Second, each robot only has access to local information, but the group decision happens on a larger spatial scale, with the involvement of many agents, and utilizes each robot's collected information. Moreover, this is a distributed approach that is fully scalable. Finally, the quorum response approach allows an easy tradeoff between the decision time and accuracy through changing the quorum value and/or the response curve (Sumpter & Pratt, 2009). Each of these advantages were demonstrated in the bee and ant swarms' home searching behaviors and will be shown on a robot swarm system in this project.

To summarize, the following three research tasks will be performed for the second sub-project:

Task #2.1: robot agent-level rules design for explorations. Student involvement: Year 2, two students. Faculty mentor: Gross.
Task #2.2: enable self-organized cooperative soaring groups. Student involvement: Year 2, three students, Year 3, one student. Faculty mentor: Gu.
Task #2.3: large-scale cooperative swarm experiments. Student involvement: Year 2, two students, Year 3, one student. Faculty mentor: Klink.

By the end of this sub-project, the robot swarming behavior will be demonstrated with the tabletop robot test environment. Through these activities, undergraduate researchers will be able to innovate in swarm robot programing, gain fundamental insights of the relationship between agent-level rules and the emerged global behavior, and test their ideas in a sophisticated physical multi-robot environment. The outcome of this research will be reported first in a conference paper and later in a journal publication.

2.3.4. Sub-Project 3: Human-Swarm Interaction

The self-organized swarm behaviors are not always going to be aligned with human operator's mission objectives under dynamically changing situations. This is where human judgments can come into play. The operator's roles here are multiple: 1. define and change the boundary of the robot operating region; 2. change search priorities for different parts of the region; 3. deal with a decreasing number of robots (and lowered energy level) in the swarm. The ***objective*** of this sub-project is therefore to find novel human-swarm interaction modes for managing a large self-organized swarm without using a direct command and control structure between the human operator and robots.

Each piece of information sent by the human operator will be broadcast to all agents. In other words, the swarm will be viewed by the operator as a single entity; e.g., like a plume of visible gas with each robot as a gas particle. To properly contain the gas, a "*balloon*" could be used. The air inside of a balloon is not necessarily uniform as self-organized behaviors such as convection (or in this case, group soaring) could take place. Connecting the balloon analogy to the control objectives of the project, several physicomimetic based human-swarm interaction methods can be designed. First, defining the boundary of the search region is now becoming the simulation of a 2D balloon with a special shape. The boundary will be broadcast to all robots so it can be factored in each robot's decisions. Second, the shifting and changing of the boundary shape is similar to morphing and moving the balloon. This involves a continuous broadcasting of slowly and smoothly evolving shapes and center locations of the boundary to the robots. Finally, dealing with a decreasing number of robots is analogous to the shrinking of the balloon, and/or the decease of air density inside of the balloon. This can be achieved by broadcasting a smaller surveillance area over time and through the dispersion behavior of robots.

A second group of human-swarm interaction tools are based on the adjustment of global parameters that affect agent-level rules. This can be imagined as changing the gas particle behavior by warming-up or cooling-down the balloon. Global parameter adjustments can be made by influencing the priority between exploring and soaring. This can be achieved by changing the incentive associated with the food searching behavior used in each robot's utility function.

The final human-swarm interaction objective is to set search priorities for different regions of the workspace. This can be accomplished with two potential approaches. The first one is for the human operator to broadcast a priority map, which sets incentives for the robots to prefer the search of certain areas. The second approach is subtler. It takes inspiration from the "*space-time warping*" near objects of large masses (e.g. stars). The goal here is to *distort* an agent's perception system so that its (seemingly independent) decision is manipulated to meet other objectives without the agent consciously knowing them. For example, the distance estimates between agents can be distorted with a "*warping function*", as if there were objects of large masses placed at points of interests determined by the operator. The locations and masses of these virtual objects will be broadcast to all robots through the communication network. In this way, all robots still believe that they uniformly filled up the space in the area despite the fact that an uneven distribution is created in the system. The main advantage of this second approach is that it allows achieving globally-specified goals without sacrificing the robustness and flexibility of the emergent behaviors.

The proposed human-swarm system architecture is summarized in Fig. 4. Each robot has an independent decision making mechanism based on utility evaluation, but the information provided by the perception system could be distorted. The swarming behaviors are enabled by the low-level interaction rules (i.e., for exploration) and the bio-inspired "*quorum response*" mechanism (i.e., for cooperative soaring). The human operator interacts with the swarm through an interactive user interface. The operator has multiple ways of influencing the swarm behavior, for example: the boundary of the search region can be modified or shifted in a way similar to moving gas particles inside of a balloon; the robots' priority between exploring and soaring can be influenced through global adjustment of the incentives; and the regions of priority will receive special attention by the robots with distorted senses of distance. The operator will directly monitor the robot behaviors on the table-top and perform intuitive interactions with the swarm system through a mixed reality setup (e.g. changing the boundaries and priority regions directly with their hands through hand motion capture and overhead projection).

To develop these approaches, the following four research tasks will be performed during the third sub-project:

Task #3.1: develop an interactive mixed-reality user interface. Student involvement: Year 2, one students, Year 3, one student. Faculty mentor: Klink.

Task #3.2: influence the boundary of the swarm. Student involvement: Year 3, two students. Faculty mentor: Gross.

Task #3.3: adjust the tradeoff between exploring and soaring. Student involvement: Year 3, one student. Faculty mentor: Gross.

Task #3.4: Influence the swarm to explore dynamic regions of interest. Student involvement: Year 3, three students. Faculty mentor: Gu.

By the end of this sub-project, effective human influence of the robot swarm behavior will be demonstrated. Through these activities, undergraduate researchers will explore innovative ways of interacting with a collectively emergent system behavior without direct controlling individual building blocks of the swarm. They will also gain first-hand knowledge of the nonlinearity and robustness of robot swarm behaviors through observations and interactions during experiments. The outcome of this research will be reported first in a conference paper and later in a journal publication.

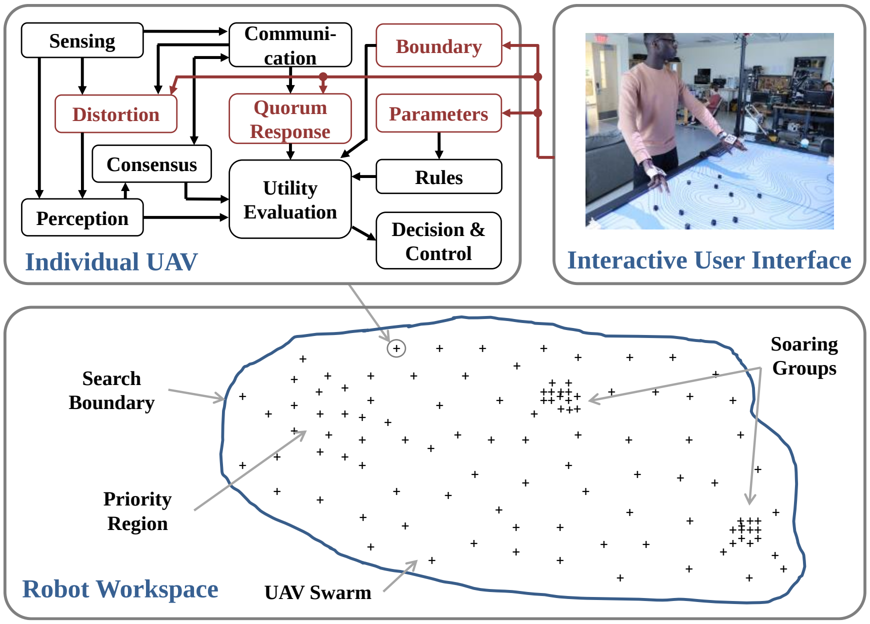

Fig.4. Proposed human-swarm interaction system architecture.

2.4. The PI's Philosophy on Working with Undergraduate Students in Robotics Research

Based on the PI's past observations the main barriers that prevent many undergraduate students to engage in productive robotics research are the following:

1. The need to work with physical systems. Most students have received little training on how to work with hardware. The students who have excelled in this area often had related hobbies or extra-curricular experiences. Many students find hands-on tasks hard and have difficulty connecting them to the knowledge that they learned in classes.
2. The need to have a systems-level view when working in a collaborative multi-disciplinary environment. It is often easy for a student to claim that "*this is not my problem*", while most problems in robotics actually require teamwork to solve.

The PI's main approach to solve both problems is "*Learning by Doing*". This means significant student contact time with physical systems and frequent interactions among team members of different backgrounds. The PI also like to formulate engineering problems as *challenges* that are slightly beyond the student's knowledge and perceived capabilities. By giving students ownership of these challenges, and through careful guidance, we help them to become independent learners and thinkers. With this active learning approach (Bonwell & Eison 1991; Bean, 2011), students' creativities are stimulated and they become more confident, comfortable, and competent in solving complex robotics problems.

2.5. Undergraduate Research Training and Mentoring

The proposed human-swarm interaction research presents a perfect opportunity to stimulate undergraduate research in the senses that 1. the research tasks are all within reach of students' knowledge and capabilities; 2. the project requires multidisciplinary collaboration and teamwork; and 3. the testing of the human-robot interaction will expose students to the real challenges of dealing with physical systems.

To help preparing students to take on these challenges, a multi-layered mentoring approach will be implemented. Before students arrive at WVU, virtual tours (through a telepresence robot) and a series of webinars will be presented by the faculty mentors to provide students with the foundational knowledge in robotics. In parallel, reading materials will be provided to students and a series of small quizzes will be designed to gauge the students' knowledge in robotics, research interests, and their strengths and weaknesses. This information will be used in finding a match between students and different research topics/tasks. For the 2nd and 3rd year REU participants, remote demonstration of the robot experiments will also be performed. Discussion with REU participants from previous years will be encouraged to help pass along important project knowledge.

During the first three days of the REU summer program, students will go through a series of intensive training offered by both the WVU Office of Undergraduate Research and the research mentors. The training topics will include lab safety, research methodology, research ethics, human-subject protection, graduate fellowship opportunities, and robotics research topics that were not easily communicated during the pre-REU webinar training. Each student will then be assigned with an initial task, a faculty mentor, and a graduate student mentor. The communications between the students and faculty mentors will stay open through daily briefing, weekly reporting, and dedicated office hours. Weekly meetings will be held to track research progress and plan for future activities. During each of these meetings, a graduate student will serve as a guest lecturer, presenting a relevant robotics topic that she/he is working on. A formal mid-summer presentation will be organized with all REU participants, faculty mentors, graduate students, and other WVU undergraduate researchers. Each undergraduate student will be required to give a 20 minute research talk, followed by a short Q&A period. Towards the end of the REU program, students will participate in the university-wide undergraduate research poster presentation, organized by WVU Office of Undergraduate Research. The PI will also orgnize an open house to invited K-12 students (many from local robotics teams and students participating in engineering camps at WVU) to showcase the outcome of the REU research.

The overall project management strategy will follow the spirit of swarm intelligence: encouraging the frequent interactions among a diverse group of less knowledgeable/experienced individuals (e.g., undergraduate researchers) to achieve something otherwise may be unachievable by the individuals (e.g. advancing the state-of-the-art in human-swarm interaction). Instead of spoon-feeding the students or providing rigid guidelines of what they need to do, the mentors will encourage self-learning and creative thinking to enhance the student's problem solving skills. Within this framework, frequent brainstorming sessions will be held and the developed project approaches will be constantly questioned. Students will be encouraged to venture into other tasks and directions, and each team member's responsibility will be earned, instead of given. The students will be encouraged to try risky approaches and the failures will be supported and carefully analyzed. This open-mind and open-interaction approach has been proven to be highly successful in the PI's previous projects, and have helped many undergraduate students to transition from passive learners to independent thinkers.

The REU students will be housed in WVU dormitories. To help them quickly accustom to life at Morgantown, WV and feel welcomed by the community, they will be paired with other WVU summer undergraduate students (expected to be approximately 10 each year) and graduate students working in the PI and mentors' labs for individual help and networking. The faculty members and WVU students will take REU participants to a variety of outdoor activities such as hiking, rafting, and camping during the weekends. A graduate student funded by the REU project will serve as day-to-day information source and emergency point of contact. The REU students will also be participating in several K-12 outreach events happening each year in summer.

The faculty mentors will maintain contacts with REU participants after the program through emails and social media channels. We will work closely with the students in writing and editing technical papers until publication. We will also provide fellowship information, application advice, and career path suggestions, along with technical help on REU students' other research projects.

3. The Research Environment

3.1. Faculty Experience in Working with Undergraduate Students in Research

Dr. Gu, the PI of this proposed project, has provided mentorship to over 20 undergraduate researchers in his Interactive Robotics Laboratory (IRL). These students have played instrumental roles in robot and unmanned aircraft systems design, instrumentation, software development, and field testing. They also contributed to the publishing of two high-quality Journal papers recently. Dr. Gu has assembled in 2013 an interdisciplinary team of students, initially mostly undergraduates, to tackle the NASA Sample Return Robot (SRR) Challenge. Several undergraduate students who were conducting research at IRL had taken this opportunity to play leadership roles on the team. With their outstanding contributions, the WVU Team Mountaineers became the only one (out of over 50 teams during the five year challenge history) that had successfully completed the NASA Challenge and received $855,000 total prize. This achievement was reported by media outlets such as the Discovery Channel, ABC News, Time Warner Cable, the Associated Press, and the Air & Space Smithsonian Magazine. Most undergraduate student leaders on the team went on to graduate research with the support of several fellowships, including the NSF Graduate Research Fellowship. Using the NASA prize, Dr. Gu also initiated a $100,000 Robotics Achievement Fellowship at WVU to help recruit and support top undergraduate students interested in robotics research.

The mentor, Dr. Klink's involvement in robotics competitions as a means to teach and inspire students technology careers extends back more than a decade. Dr. Klink mentors a large number of undergraduate students participating in various robotics competitions each year and he has also mentored Morgantown's FIRST Robotics team for six years. Within these activities, students designed and constructed sophisticated robots utilizing the theory learned throughout the curriculum. Students from various engineering disciplines have had the opportunity to contribute their specialties in the design of many robots, receiving recognition for their creative robot designs and numerous awards, listed below.

- NASA/NIA RASC-AL Special Edition: Mars Ice Challenge, NASA LRC, Hampton, Va. 2018: Second Place overall award and Clearest Water award. 2017: *First Place* overall award, Most Water Collected award, and Clearest Water award.
- Mercury International Remote Robot Challenge, Oklahoma State University, Still Water, OK. 2018: Second Place overall award. 2017: Best Design award. 2016: Third Place overall. 2015: Third Place Overall.
- NASA/NIA RASC-AL Exploration Robo-Ops Student Challenge, Johnson Space Center, Texas. 2016: Second Place overall. 2015: Second Place overall. 2014: *First Place* Overall. 2013: Best Paper, Fourth Overall.
- Pacific Intl. Space Center for Exploration Systems – Intl. Mining Competition, Hawaii. 2014: *First Place*, "Best in Mining", and "Best in Operations."
- NASA Robotic Mining (Lunabotics) Competition, Kennedy Space Center, Florida. 2014: *First Place* overall (Joe Kosmo) award, First place in Mining Competition, First Place in STEM Outreach, Second place in Presentation. 2013: Second Place Overall. 2012: Third Place Overall. 2011: Second Place Overall.

The mentor, Dr. Gross's research focuses on the area of Guidance, Navigation and Control (GNC) technologies as they apply to unmanned aircraft systems, robotic systems, and space systems. In these areas, he has authored or co-authored more than 45 technical papers and has been PI or Co-PI on more than 10 externally funded research projects. He is the recipient of a NGA New Investigator Program grant, AFOSR Faculty Fellowship, WVU Big XII Faculty Fellowship, and WVU Statler College teaching and research awards. Since he started at WVU in 2014, Dr. Gross has consistently involved undergraduates in his research program including in the development of West Virginia's first CubeSat. He is currently implementing a class in which undergraduate students will design, build, and test a sounding rocket payload.

3.2. PI’ Relevant Research Projects and Facilities

The PI is also leading several large interdisciplinary research projects at WVU. This includes a USDA funded (thorough National robotics Initiative) precision robotics pollination project, a NASA funded project on improving the autonomy and surface traversability of planetary rovers in support of a future planned Mars Sample Return Mission, and a DOD funded project on cooperative exploration of underground tunnels with ground robots and unmanned aerial vehicles. A large number of graduate students and interdisciplinary collaborators are working on these projects. Exposing REU students to these high-quality and diverse projects will help them build up interest and knowledge in robotics. The different skills and talents by members of these projects will also be important resources for supporting the REU students in solving their problems at hand.

The PI manages a total over 3,000 ft^2 of lab space with state-of-the-art rapid prototyping machines (3D printers and CNC mills), robots (over 20 different ground and aerial robots), and sensors (3D Lidar, fiber optics gyro, etc.). This will provide the REU students unrestricted freedom in pursuing their creative ideas.

4. Prior NSF Support

The PI has no prior NSF support.

5. Student Recruitment and Selection

From our experience, the field of robotics is captivating to young minds. As such, recruiting in this field is primarily a task of making students aware of the opportunities and connecting to them personally. Through this REU, we will broaden the horizons of students from the poverty-stricken Appalachian region by introducing them to this rapidly growing field. In particular, we will target computer science, engineering, physics, and engineering technology majors from CC and PUI located in the Appalachian region of the eastern U.S.

To connect students to this opportunity, the PI, mentors, and selected WVU students will conduct recruitment/outreach site visits during the month of February of each project year to a set of target schools that are within short driving distance to WVU (i.e., Fairmont State, Waynesburg, Robert Morris, WV Wesleyan, Davis & Elkins, Washington & Jefferson, Bethany, Marietta, Slippery Rock, and Lock Haven etc.). We will bring our award-winning robots on these trips to perform demonstrations to interested students and faculty members. These visits will highlight the exciting robotics research that is ongoing at WVU and will feature the success stories of current and past students, mostly native to rural WV, who’ve discovered and had success in our robotics program. During this recruitment effort we will specifically encourage students from under-represented groups to apply. The recruiting/outreach trips will be supported by the WVU Statler College, which have funds already allocated for supporting this type of activity.

The selection of applications will be mainly determined based on students’ statements on their interest and vision in robotics and any relevant extracurricular activities, faculty recommendation letters, and the evaluation of academic transcripts. No minimum Grade Point Average (GPA) will be required to apply, as the PI’s experience is that undergraduate GPA, especially in the early years, is not a strong indicator of a student’s success or passion as a researcher in specialized areas. Our online application location and timing will be coordinated with WVU Office of Undergraduate Research to maximize visibility, improve searchability, and reduce potential confusions.

The application review panel will consist of the faculty mentors, selected graduate students, and a representative from WVU Office of Undergraduate Research. Initially, a long-list of 16 students will be selected based on reviewing of application materials. A short interview with the help of a telepresence robot will be conducted with each long-listed candidate to gauge their strengths and weaknesses and their fit to the program. The pool will then be down-selected to eight to give offers, with four other students placed on the waiting list. Any available programs (e.g., internal WVU funds, other external project funding, other REUs) will also be considered to support the students on the waiting list.

6. Project Evaluation and Reporting

The PI will work closely with Dr. Richards-Babb, director of WVU Office of Undergraduate Research in performing the project evaluation. A structured approach will be used for student evaluation and data collection. It will allow us to gauge the strength/weakness of the program and to help understand the impact of the REU research on the student's learning and future career trajectory. Specifically, the students' educational background in the robotics area prior to entering the REU program and their progress in learning new robotics knowledge with the pre-REU tutorials will be evaluated with a set of quizzes. Shortly after their arrival at WVU, and upon completion of lab tours and initial trainings, incoming questionnaires will be used to gauge student expectations, research interests, and plans for future career path. Intermediate questionnaires will be given after five weeks of REU research to evaluate students' opinions on the overall quality of their REU experience, the research progress, the adequacy of resources and mentorship provided, satisfaction with the team arrangements, etc. Adjustments to the project management approaches may be made following this feedback. At the end of the ten-week program, outgoing questionnaires will be used to capture information about student research skills gained, problems solved, and improved understanding of the state-of-the-art in robotics research. The influence of this experience to the students' view of their future career plans will also be documented.

The project research progress will be evaluated based on scheduled project task completion time and milestones as summarized in Table 2. Short technical reports will be required from each REU participant on a weekly basis and will be given prompt feedback by the faculty mentors. A final report in a conference paper format will be developed collectively by all REU team members. This report will be submitted to NSF and will serve as an initial draft for publications coming out of this project.

Project Task	**Faculty Mentor**	**Student Involvement**			**Milestone**
		Year 1	**Year 2**	**Year 3**	
1.1	Klink	2	-	-	Year 1 Milestone: robot swarm testing environment fully established
1.2	Gu	2	-	-	
1.3	Gross	2	-	-	
1.4	Gu	1	-	-	
1.5	Klink	1	-	-	
2.1	Gross	-	2	-	Year 2 Milestone: robot self-organized swarming behavior demonstrated experimentally
2.2	Gu	-	3	1	
2.3	Klink	-	2	-	
3.1	Klink	-	1	1	Year 3 Milestone: effective human influence of the robot swarm behavior demonstrated
3.2	Gross	-	-	2	
3.3	Gross	-	-	1	
3.4	Gu	-	-	3	

Table 2: Project schedule and milestones.

Every January from year 2020 to 2024 (five years), all former REU participants will be contacted to assess the lasting impact of the summer research experience on the participants' career paths. The information to be gathered include expected graduation date, involvement in undergraduate research at their home intuitions, enrollment in graduate programs, change in career plans, and additional comments on the REU program.

A report capturing qualitative (e.g., student feedback) and quantitative (e.g., statistics on demography of REU applicants and participants), along with other required data and technical progress made on the project will be submitted to NSF in the annual reports.

7. Intellectual Merit

In this proposal, a challenging human-swarm interaction problem is broken down into several manageable pieces compatible to the knowledge and capability of intellectually-curious undergraduate students. Several innovations are made in solving these sub-problems. Specifically, the bio-inspired recruiting and quorum response approach for self-organization enables robust and distributed social decision making. The physicomimetics and distorted perception approaches further introduces new ways for the human operator to interact with the swarm. The testing of a large number of physical robots will improve our insights on how global swarm behaviors are emerged and influenced by external factors. Each of the proposed methods are general enough to be applied to many other applications beyond this case study. All methods are also scalable, making it possible for one human operator to manage thousands or even millions of robots in the future.

8. Broader Impacts

8.1. Impact to Education

Robotics is a great topic for attracting undergraduate students to participate in hands-on learning and creative research activities. Allowing one person to manage over 50 robots in a game-style physical experiment can spark further imaginations. This proposed REU site will broaden the participation of underrepresented students in conducting state-of-the-art robotics research. Through challenging them with a series of increasingly complex research objectives, and providing mentorships along the way, the students will develop critical thinking and problem solving skills that are essential for becoming independent researchers. The diverse topics involved in the project, ranging from robot design, wind-field estimation, system control, human-robot interaction, to bio-inspired robot interaction rules design will promote systems-level thinking and teamwork spirits among participating students.

8.2. Impact to Society

Solving the swarm management problem could have long-reaching impacts to our society. It will fundamentally change the way we think about many engineering designs and enable new opportunities for science exploration and commercialization. With a streamlined interaction between humans and swarms along with dynamic in-situ task allocation capabilities, a large group of simpler and expandable robots could be coordinated by a few remote operators to meet complex mission requirements. Such missions may include disaster response and clean up after a nuclear plant accident, robot based home delivery, and robotic construction of the future lunar bases.

8.3. Dissemination of Research Findings

The research outcomes of this project will be reported in multiple journal and conference publications, with undergraduate students as lead authors. We will also conduct the project in an open-access fashion, with complete information released through a dedicated project website, discussion group, and GitHub repository. The information to be shared includes algorithms, robot models, simulators, software, representative data sets, associated documentations, and training material. Videos of swarm and human-swarm interaction experiments will be uploaded to our YouTube channel to further increase the visibility of this project. The robot testing setup will be available through remote access so REU alumni and other interested students and researchers can be engaged in the project during regular semesters.

8.4. Involvement of Students from Historically Underrepresented Groups in STEM

The project will create research and learning opportunities for students from underrepresented groups, especially students from socio-economically disadvantaged areas. The research experience and training provided by this project will contribute to the growth of a high-quality and diverse US scientific workforce.

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