

# Undergraduate Research Academy (URA)

## Cover Sheet

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BY NOON, WEDNESDAY, MARCH 30, 2005  
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STUDENT Ross Mead MENTOR Dr. Jerry Weinberg & Dr. William White

PROJECT TITLE Algorithms for Control and Interaction of Large Formations of Robots

**ABSTRACT:** The abstract is a brief, comprehensive summary of the content of the proposal in about 150 words *in plain language*. Reviewers receive their first impression from this abstract. The information needs to be concise, well-organized, self contained, and understandable to persons outside your academic discipline.

In April 2000, representatives from NSF and NASA met to discuss harvesting solar power in space to help meet our future energy needs. One solution that received considerable attention was the use of robots to form a solar reflector. Imagine the space shuttle releasing thousands of robots, each with a reflector attached. How can these robots organize to form a large parabolic structure? Once organized, how can this *formation* be effectively controlled? The approach of this project is to treat the formation as a lattice of computational units, or cells. Each cell is in one of a given set of states governed by a set of rules. A command would be sent to a small number of robots; the formation would then transform as the other robots react to changes in their neighbors. A graphical user interface would provide visualization of the formation and update the status of each robot. The research of this type of user interface for interacting with a large group of robots has been largely unexplored.

*Upon submitting this proposal, I verify that this writing is my own and pledge to fulfill all of the expectations of the Undergraduate Research Academy to the best of my abilities. I understand that failure to do so may result in return of fellowship money to the University and forfeiture of academic credit and honors recognition.*

*Ross A. Mead*

Signature of the Student

*this student during this project. I verify that this student is capable of undertaking this proposed project.*

*Jerry B. Weinberg*

*Jill W. Wolf*

Signature of the Faculty Mentor

*This project is within the mission and scope of this department, and the department fully supports the faculty mentor and student during this venture.*

*Barry M. Wayne*

Signature of the Department Chairperson

*I testify that all necessary research protocols (human, animal, toxic waste) have been fulfilled, and I support this proposed faculty-student scholarly activity as within the mission of the College/School.*

*Paul G. Asakura*

Signature of the Dean of the College/School

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## I. Introduction and Significance

In April 2000, the National Science Foundation and the National Aeronautics and Space Administration held a joint workshop on autonomous construction and manufacturing for electrical power systems in space. In this workshop, participants explored harvesting solar power in space to help the world meet its future energy needs. This concept of Space Solar Power (SSP) involved placing a large solar collector panel or reflector panel in space and focusing a concentrated beam of solar energy on a panel on Earth that would be diverted to an energy plant [Illustrations, Figure 1]. The workshop resulted in a series of challenges that researchers would need to address, most significantly, the difficulties and high-cost of transporting the components necessary for constructing a large solar reflector that is potentially numerous kilometers in size, as well as the construction of the reflector itself.

One solution that received considerable attention was the use of robots to construct such a large structure. The workshop report articulated one version of this solution in which the solar reflector is composed of a formation of robotic units:

“[The reflector is] actually created by having a swarm of coordinated independent semi-intelligent objects [(i.e., robots)] acting in concert. A solar reflector might be created in this way by having thousands of small free-flyers, each with a piece of mirror attached to themselves, fly into and then maintain a parabolic formation. One advantage of this strategy is that if the system is ever damaged, the swarm could reconfigure to eliminate the damaged elements but still maintain whatever level of uniformity might be required.”  
[1]

This poses some interesting research questions. For example, once deployed, how does this large collection of robots communicate and coordinate their activities to form an organized parabolic structure resembling a reflector? How do the robots know when and where to move to maintain their position within the formation? And how can one operator or a small group of operators communicate with thousands of robots to effectively change the formation as needed?

These questions have yet to be successfully addressed. Research in creating and maintaining organized formations of robots is a relatively new area of investigation, and implementation and testing has only been applied in simulation or on small groups of robots. Modern algorithms can be adapted based on already existing robot control strategies for purposes of group behavior and interaction,

generating a new technique for multi-robot coordination. Once implemented, a means for controlling and interacting with the robot formation is crucial. However, an interface between humans and large formations of robots remains largely unexplored.

The need for algorithms for the control and interaction of robotic formations extends beyond that of SSP. For example, a large line formation could be implemented for the efficient planting and maintaining of uniform rows of crops. Additional applications include the autonomous navigation of various types of motor vehicles, ranging from ground-based vehicles, such as cars, to aircraft or watercraft. Recent applications for highway traffic control and safety are also being explored [2; Illustrations, Figure 2].

## II. Context, Background, and Literature Review

This approach to the autonomous control of creating and maintaining multi-robot formations is similar to work done in coordinating formations of Earth-bound, mobile robots [3, 4]. This work has been inspired by biological or organizational systems, such as geese flying in formation. In Fredslund *et al.* [3], mobile robots are assigned a particular formation to follow, like a line, a V-shape, or a diamond [Illustrations, Figure 3]. Each robot is assigned a position in the formation and an identification number that is transmitted, allowing each robot to find its neighbors. A robot leader is designated that transmits the specified formation. Using a combination of laser sensors, color tracking, and robot intercommunication, each robot is able to identify its neighbor and adjust its orientation appropriately. In this way, the robot group is able to maintain a stable formation.

A variety of work has also been done to apply reactive type control structures to create emergent group behaviors from individual behaviors. Seminal work by C. Reynolds [5] shows how individuals can exhibit emergent aggregate behavior similar to flocking birds. In this work, simulated birds alter their movement in three-dimensional space based on the direction, pitch, yaw, velocity, and distance of their neighbors. Flocking algorithms have been used for both physical and simulated robots [6]. A digital hormone model, inspired by biological cell interaction, has also been proposed for robotic organization [7]. However, these apply more to swarms as opposed to formations. For our purposes, a *swarm* is

defined as a massive collection that moves with no group organization, much like a swarm of bees or a flock of birds [Illustrations, Figure 4]. While a *formation* is similar, the distinction is made in that it maintains a global structure, much like a flock of geese or a marching band [Illustrations, Figures 5 & 6]. Robot formations have been applied to other applications such as automated traffic cones [2], while swarm behavior control has been applied to urban search-and-rescue robotics [8].

The challenges for applying a robot formation approach to SSP include generalizing the formation process, increasing the size of the robot formation, and formation management. The current work on mobile robot formations requires that individual units have some sense of where they belong in the formation, most notably who their neighbors are supposed to be. One of the goals of this project is to generalize the need for this information or at least create it more dynamically as the swarm becomes a formation and as the formation adjusts its pattern. Previous work on maintaining formation has been applied on up to a half-dozen robots. However, to better demonstrate group behavior on a larger scale, the number of mobile agents must be increased.

In multi-robot management, little work has been done in terms of a human-robot interface for formations. Skubic *et al.* [9] implemented an impressive sketch-based interface via Personal Digital Assistant and global communication to control a small team of mobile robots already in formation [Illustrations, Figure 7]. This proves to be inadequate for SSP, and thus an original interface must be designed and created for the control of large robotic formations.

### **III. Goals/Objectives**

For a formation of robots numbering in the thousands, such as the 33,000 robots that Landis [10] projected would be needed for SSP, direct control through a remote operation interface, in which an operator or a small group of operators must take control of each individual robot, is impractical. Rather, the robot formation will require some level of autonomous control. Computationally, the simplest robot control strategy is behavior-based, or reactive, control. The reactive control strategy closely couples sensor input to actions [11]. It relies solely on communication with local robot neighbors, and hence has

the advantage of eliminating the need for each robot to maintain information about the global or overall structure of the entire formation.

In keeping with a simple reactive control strategy, the approach of this project is to treat the formation as a type of 2-dimensional cellular automata. A 2-dimensional *cellular automata* consists of a lattice of cells, each cell being in one of a given set of states. The dynamic behavior of the automata is determined by a set of rules that govern the change of state for an individual cell. The global structure of the reflector array could be viewed as a 2-dimensional lattice of robots. Each robot "cell state" would consist of its spatial orientation in 3-dimensional space with respect to some celestial body. The robot's behavior would be a set of rules for changing its state with respect to its neighbors. By designating a small percentage of robots as "seeds" or "leaders" in the formation, human intervention would change their orientation directly. This would start a type of chain reaction in the formation by each individual robot, applying behavior rules based on the change in states of its neighbors. This is analogous to seeing a crowd in a baseball stadium "doing the wave", where each individual's reaction in the crowd is based solely on the people sitting nearby. There are various neighborhoods defined for cellular automata [12], and finding the right definition of a neighborhood in the robot formation will require experimentation. In Fredslund *et al.* [3] and Wessnitzer *et al.* [13], the formations were setup so each robot only needed to identify two neighbors. In the reflector formation, the definition of a neighborhood becomes more complex. Landis [10] provides insight into potential physical configurations of individual cells [Illustrations, Figure 8], and this will be kept in mind in determining the appropriate number of neighbors.

To manage the robot formation, a graphical user interface will be developed that will provide a human operator with a visualization of the formation and information of each individual robot unit. Through the interface, the operator will be able to choose a robot that will become the "seed" to instigate a change in the formation. Changes that could be made and propagated across the cellular automata grid include heading, speed, and the specifics of the formation structure itself.

The successful completion of this project will result in a new technique for large robotic formations based on cellular automata. The project will also tread new ground in human-robot interaction

for large formations of robots controlled by one or a small group of operators. It will be implemented and tested on a modest number of physical robots, proving that the approach is viable in real space.

#### IV. Procedures and Time Line

To implement the cellular automata for robot control, the algorithms will be developed and implemented using small mobile robots called EyeBots [Illustrations, Figure 9], of which the Department of Computer Science owns eighteen. EyeBots have front and side infrared sensors that provide distance information, as well as a rotating color camera for object recognition and tracking. They also have wireless radio communication capacity for exchanging information with their neighbors.

As the algorithms and graphical user interface are being designed and implemented, a series of experiments will be conducted and evaluated based on the criteria discussed in Fredslund *et al.* [3], for reasons of comparison and analysis. These include *generality* (ability to conform to a variety of formations), *stability* (ability to maintain the formation), *robustness* (ability to respond to changes in group size), and *dynamic switching capability* (ability to respond to an operator's command for changes in its organization) [Illustrations, Figures 10 & 11].

#### Deadlines for research milestones

August 22, 2005 – October 2, 2005	Design and implement a message protocol between robots. To establish a local neighborhood in the formation, robots will need to dynamically register with their neighbors, make sure their neighbors are alive and well, and communicate their position and heading information.
October 3, 2005 – December 18, 2005	Design and implement the cellular automata control strategy. A cellular automata is controlled by a simple set of rules in each cell that respond to changes in neighboring cells. For a formation, the rules for each cell change based on the structure of the formation (e.g., a circle versus a square formation). Therefore, each cell's rules will need to be propagated throughout the formation.
December 19, 2005 – January 29, 2006	Design and implement the reactive robot control strategy for maintaining formation. Once the swarm is in formation, each robot must respond to changes in distance, heading, and speed accordingly to maintain the formation. This will require broadcast communication between neighbors and calculation of changes to motor activity.
January 30, 2006 – April 9, 2006	Design and implement a graphical user interface for human-robot interaction for formations of robots. The interface will show a visual status of the formation and the operating status of each individual robot. Through the interface, the human operator will be able to choose a new seed robot and give it instructions regarding formation changes. For experimentation purposes, the interface will also allow the operator to change the status of formation members to simulate failures or unexpected events.

## V. References

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- [8] S. Tejada, A. Cristina, P. Goodwyne, E. Normand, R. O'Hara, & S. Tarapore (2003) "Virtual Synergy: A Human-Robot Interface for Urban Search and Rescue". In the Proceedings of the AAAI 2003 Robot Competition, Acapulco, Mexico.
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- [13] J. Wessnitzer, A. Adamatzky, & C. Melhuish (2001) "Towards self-organising robot formations : a decentralised approach", Proceedings of the European Conference on Artificial Life.
- [14] J. Fredslund, M. J Mataric (2002) "A General Algorithm for Robot Formations Using Local Sensing and Minimal Communication", IEEE Proceedings on Robotics and Automation, 18(5).

## VI. Budget Justification

Total Contractual Services Cost	\$200
Total Commodities Cost	\$200
Total Travel Costs	\$400
<b>Total Request</b>	<b>\$800</b>

### Contractual Services

The EyeBots used for the implementation and testing of the algorithms described generally cost \$2,750 apiece [<https://www.zagrosrobotics.com/>]. However, this expense is avoided with the cooperation

and generosity of the Department of Computer Science, which will be providing use of all 18 of them. A C-compiler will also be provided with the EyeBots to allow each robot to be programmed.

Powerful tools are necessary for creating the controls needed for effectively interacting with and manipulating the robot formation. [<http://www.journeyed.com/>] offers a 1-year student license for Discreet's 3ds Max 7 for \$180 (plus \$10 shipping and handling), which provides all of the functionality needed. This application is incredibly powerful, and will enable great flexibility and ease in control design and implementation. OpenGL is a graphics language that extends the capabilities of the standard-C programming language, and is available free to the public. This will be helpful in manipulating objects created in 3ds Max, and will be particularly helpful for algorithm simulation purposes. Microsoft Visual Studio .NET is provided free of charge by the Department of Computer Science to students within the major, and will be the backbone of the interface. The .NET framework will be utilized for interactions between different programming languages and objects, providing an easy means to communicate valuable robot and world information, both physically and in simulation. It will also be helpful in defining manipulation parameters and limitations of control objects, and more importantly, the effect of those controls on the robot formation itself.

### **Commodities**

Dry-erase boards marked with an x-y coordinate system will be used for visual reference and observation of robots on a 2-dimensional plane. Initial tests will be done on one or two boards, while later tests may involve numerous boards (potentially eight) for large scale experimentation. These boards can be found at local hardware stores for \$12 apiece. A box of dry-erase markers costs \$4. PVC pipe can be purchased for approximately \$0.30 per foot, and will be used to construct physical barriers (walls), as well as provide a means for robots to reference and verify their position and orientation based on external landmarks. A package of colored construction paper costs around \$1, and may also provide a means of referencing and landmarking using the EyeBot color camera.

Additionally, various materials are also necessary in preparation for the URA Student Symposium poster session. These include multiple sheets of poster board and a package of markers, each

costing \$4 a piece. Videocassettes will also be required for presenting different robot grouping scenarios. VHS tapes cost \$3 apiece.

**Travel**

Registration for attending the American Association for Artificial Intelligence (AAAI) Robot Competition and Exhibition costs \$250. A block of rooms has been reserved for conference participants at a reduced rate of approximately \$115 per night. Additional student funding for presenting at the conference is available from AAAI, the Undergraduate Research Academy, and the Department of Computer Science. Securing these funds will aid in travel and registration costs, but, any remaining funds will be paid at the expense of the researcher.

**VII. Illustrations**

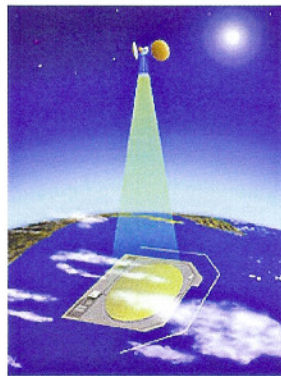


Figure 1: Example of Space Solar Power.

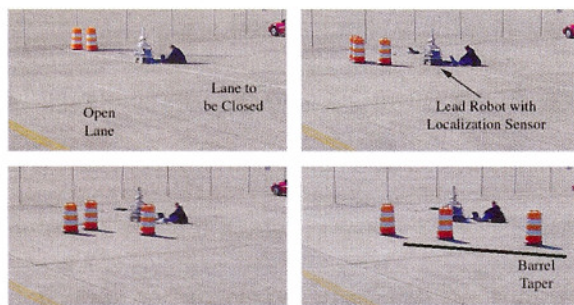


Figure 2: Robotic Highway Safety Markers. [2]

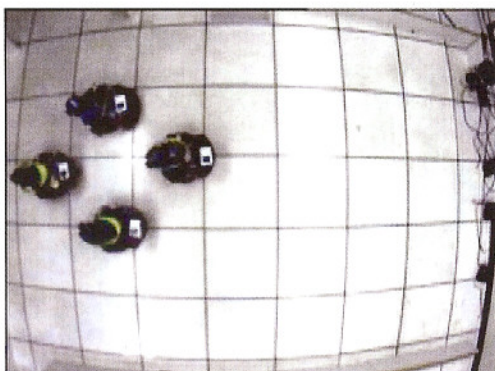


Figure 3: An overhead view of 4 mobile robots traveling in diamond formation. [3]



Figure 4: A flock of birds, demonstrating swarming behavior. Note the lack of an organized global structure.



Figure 5: A flock of geese maintaining a V-shaped formation.



Figure 6: A marching band formation, demonstrating and maintaining a well-defined group organization.



(a)

(b)

Figure 7: “Example sketches (a) Three robots in a march side by side formation (b) Robots in a follow the leader formation.” [9]

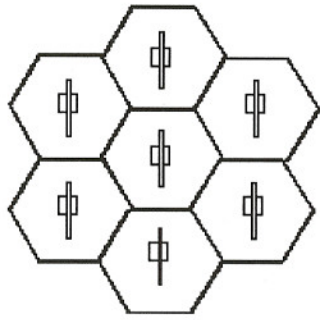


Figure 8: Demonstrates how units of robots could arrange themselves in relation to their neighbors to form a tight structure. [10]

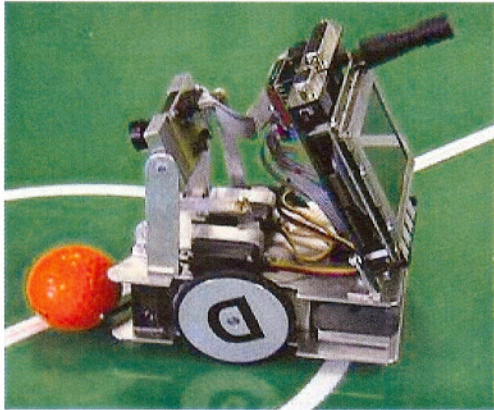


Figure 9: An EyeBot.

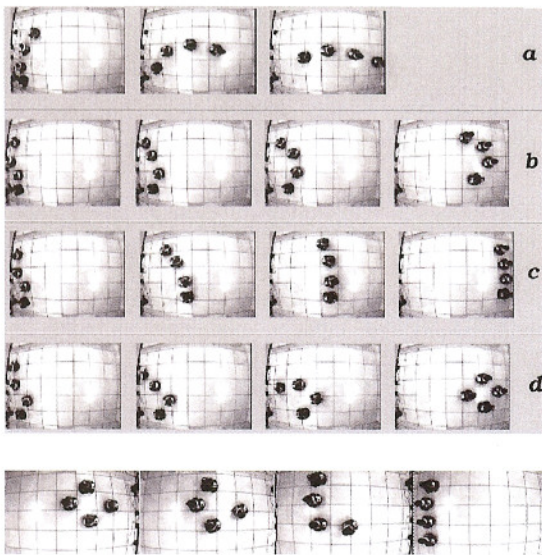


Figure 10: Demonstrates ability to create and maintain different formations (a) a line, (b) a wedge, (c) a column, and (d) a diamond. [14]

Figure 11: Robots changing formation from a diamond to a line. [3]