Integration of communication constraints into physiocomimetic swarms via placement of location based virtual particles

2011

Joshua J. Haley
University of Central Florida

INTEGRATION OF COMMUNICATION CONSTRAINTS INTO PHYSIOCOMIMETIC SWARMS VIA PLACEMENT OF LOCATION BASED VIRTUAL PARTICLES

by

JOSHUA J HALEY

A thesis submitted in fulfillment of the requirements for the
Honors in the Major Program in Computer Engineering
in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, FL

Spring 2011

Thesis Chair: Dr. R. Paul Wiegand

Abstract

This thesis describes a change to the Physiocomimetics Robotic Swarm Control framework that implements communication constraints into swarm behavior. These constraints are necessary to successfully implement theoretical applications in the real world. We describe the basic background of swarm robotics, the Physiocomimetics framework and methods that have attempted to implement communications constraints into robotic swarms. The Framework is changed by the inclusion of different virtual particles at a global and local scale that only cause a force on swarm elements if those elements are disconnected from a swarm network. The global particles introduced are a point of known connectivity and a global centroid of the swarm. The local particles introduced are the point of last connectivity and a local centroid. These particles are tested in various simulations and the results are discussed. The global particles are very effective at insuring the communication constraints of the swarm, but the local particles only have partial success. Additionally, some observations are made about swarm formations and the effect of the communication range used during swarm formation.

Dedication

For my family who loves and supports me,

And encourages me to fulfill my potential.

Acknowledgements

I would like to acknowledge and thank all of the faculty members whom have helped me with this thesis.

My Thesis Chair Dr. Paul Wiegand for helping me find a topic that interests me and for guiding my research

My Thesis committee Member's Dr. Sumit Jha and Dr. Zuhair Nashed for taking the time and having the patience to work with me.

And Dr. Avelino Gonzalez for helping me decide to write an HIM Thesis.

Table of Contents

Table of Functions & Figures

Chapter 1: Introduction and Background

1.1 Introduction to Swarm Robotics

A quick note on nomenclature: In this paper swarm element, node, agent or robot all refer to the same concept. We will try to consistently use swarm element, but when analyzing another author's research we will use their terminology. Additionally, the "swarm" refers to the collection of all elements and the "swarm control system" refers to the local interaction rules implemented.

Swarm intelligence is a system that seeks to create emergent intelligent behavior via large number of locally interacting elements. It is characterized by decentralized self-organizing systems that and gains its name from the swarming behavior of social insects such as ants and bees. The term was introduced by Beni and Wang [1] where they created a swarm system that was inspired by biological cellular systems. Since then a number of swarm paradigms have been created inspired from many natural things including ant colonies, bird flocking, bacterial growth and fish schooling. [2] Not all naturally inspired swarms are biological in nature; the Physiocomimetics swarm control framework described in following sections is inspired by Newtonian Physics.

Swarm Robotics is the application of these swarm principles to robotics systems and swarm-robotics.org a collaborative academic site defines it as "the study of how large number of relatively simple physically embodied agents can be designed such that a desired collective behavior emerges from the local interactions among agents and between the agents and the environment.” [3] In the context of swarm robotics, the individual robots are considered unintelligent agents only capable of local behavior and the whole swarm itself as the intelligence entity that exhibits the complex behavior.

There are a few principal motivations for Swarm Robotics both in application and economics. Swarm systems exhibit an extreme robustness owing to the existence of some many similar elements. This redundancy and decentralized control stops the loss of any single node from causing catastrophic failure. [4] The simplicity of each element makes each agent simpler to build and less prone to failure and provides economic incentive. Swarm systems are attractive to robotics because of the highly simplistic and modular nature of a swarm that translates to mass-produciblility, disposability, and interchangeability of individual robots which until swarms were highly specialized to a single task. [5] Proper swarm paradigms are also extremely flexible and allow for a large number of problems to be solved by changing certain parameters in the system. [4] Finally, Swarm systems are designed with extremely scalable in mind. Robotic swarm systems are often demonstrated with a smaller number of elements because of cost, but the control paradigms themselves allow for a large margin of group sizes.

Now what are the criteria for a robotic system to be considered a swarm? Sahin [4] defined the criteria as follows:

- The system must be composed of autonomous robots. The agents in the swarm need to have a physical embodiment with actuation capabilities and not require centralized control.
- The system should be relevant for the coordination of a large number of robots. Although tests are done with fewer robots because of cost, the swarm control system should be capable of controlling at least 10 robots.
- The system should be composed of only a few homogenous groups of robots. An ideal swarm might have all robots being identical, but specialization is sometimes necessary when you have multiple objectives that the swarm must complete. A system is not considered a swarm if all elements are different and follow different local interaction rules.
- The system robots should all be relatively simple. That is to say, a single robot shouldn't be capable of achieving your swarm objective on its own. The coordination of robots should be either essential or improve the performance of achieving the objective.
- The robots should have local sensing and communication abilities. The robots in a swarm are controlled by local interactions thus local sensing and communications are all that are necessary. Additionally, the use of global communication can prevent scalability of the swarm and create a single point of failure. It is this criterion that is the focus of this thesis.

The applications of a Swarm Robotics are vast. A small sampling of logical applications of Swarm Robotics is given by Sahin. [4] Tasks that involve covering a region such as monitoring and surveillance are a prominent application owing to a robotic swarm's ability to self-form and adjust themselves to monitor particular areas. Tasks that are too dangerous benefit from the individual elements in a swarm being disposable. In a task such as minefield clearing, an individual robot may be expensive to build or replace. Robotic swarms also contain the ability to work faster or slower just by adjusting the number of elements in the swarm. In the above minefield example we could more quickly clear the minefield by employing more robotic agents, whereas the single robot solution cannot easily scale to work faster. Finally, tasks that require redundancy in order to properly be completed. These tasks benefit from a robotic swarm's large amount of similar nodes and self-correcting nature.

It is important to note the criteria and applications presented thus far are theoretical. There has not yet been a swarm that perfectly implements the criteria or else the entire field would have no room for advancement. We instead will try to further a particular swarm paradigm toward completion of the above criteria by enhancing its characteristics. In this thesis, we worked with the Physiocomimetics swarm control framework which has been shown to have a diverse group of applications.

1.2 What is Physiocomimetics?

Physiocomimetics is an Artificial Physics (AP) based swarm control framework first introduced by Spears et al [6] that models robots as particles in a molecular dynamics simulation. It is inspired by natural physics where small interactions form vastly complex system behavior. [7] The authors of Physiocomimetics follow the design philosophy that "that AP be as distributed as possible and … we require as little information as possible." [6, p.139] Using this design philosophy each element of the swarm is only affected by local interaction and lacks a central control system. This lack of central control makes the swarm self-organizing, fault-tolerant, and able to self-repair. [7] By abstracting individual swarm elements to particles, the size of the actual agent does not matter and can vary greatly in size and application. For Nano-bots, microsatellites, or micro-UAV's the computational power available might be quite primitive, so Spears et al needed to make the system computationally efficient with simple rules.[6] To accomplish this goal, they made the physics system a Newtonian Particle simulation where each element maps to a particle controlled by $\mathbf{F}=m\mathbf{a}$ equations.

Newtonian equations are continuous and kinematics requires the use of calculus to describe behavior of a particle, so for Physiocomimetic some simplifying changes will be made. Each particle is modeled using a discrete time approximation where at a time state t the ith particle has a speed v and position x. Now at each time step Δt the these values change according to the laws of kinematics with $\Delta x = v$, $\Delta v = F\Delta t/m$, $v = c_f(v + \Delta v)$ where m is the mass of the ith particle, F the sum of all forces acting on a particle because of other particles, and c_f a coefficient of friction that allows for controlling system stability. [6][7] Additionally, we can constrain some of the particle behavior by defining upper limits on particle velocity, particle acceleration, particle rotational velocity and maximum force that allows for robot constraints to be accounted for at swarm design. [8] The force between two particles in the Physiocomimetics simulation is given below in Function 1.1, where E is the effective range of the force.

Function 1.1

A Physiocomimetics Force Equation

$$F_{ij} = \begin{cases} -G\frac{(m_i m_j)^a}{r_{ij}^d} & \text{if } r_{ij} \in [0, R) \\ G\frac{(m_i m_j)^a}{r_{ij}^d} & \text{if } r_{ij} \in [R, E] \\ 0 & \text{otherwise} \end{cases}$$

Taken without permission from [8]

This leaves us a number of parameters that need to be chosen, namely m and c_f for each particle, and G, R, a, d, for every particle pair. Although this is an exponential particle space, methods to find these parameters for a number of applications have been found via Evolutionary Searches and graph theory approaches. [9] We can also place virtual particles that represent some goal location or other objective that is not instantiated as a robot in the swarm. This is often done in order to achieve some objective or implement restrictions in swarm behavior. It is important to realize, that though the forces involved are all fictitious and the product of simulations, the robotic elements in the swarm behave as if they were real.

1.3 Why Physiocomimetics?

The radius needs to be determined for Function 1.1 to work properly. This may either be done via computationally expensive computer vision solutions, or if a communication link was guaranteed we could just communicate coordinates gathered from a GPS like system. There also exist potential applications such as surveillance or distributed communication networks that require an Ad-hoc network of communications ensuring a connection between every node.

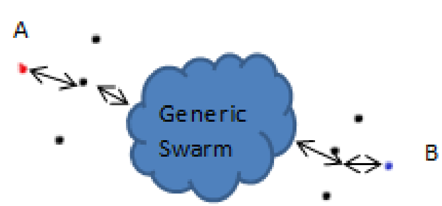
Physiocomimetics is computationally more efficient than similar Artificial Physics swarms that create potential fields and resolve them to forces at runtime requiring some integration such as [10]. [6] Physiocomimetics has also been shown to have a number of working applications such as robotic formations, chemical plume tracing, object protection and boundary patrol. [6][11][12] It is because of the proven applications, scalability and the simplicity and efficiency of design that we will be Physiocomimetics as our swarm in which we implement communications considerations.

Chapter 2: State of the Art Review

Communications in Swarm Robotics control systems have often been left by researchers as an implementation issue and not considered vital to system design. This attitude has made the amount of research into the area sparse, incomplete or just unmentioned in most Swarm Robotics research. Although this may be true in some systems, for applications where swarm communications the desired objective or the objective depends on the existence of a communication network it is absolutely critical that we have a constraint in place that makes sure that all swarm elements can communicate with each other. Such behavior can make the existing swarm control systems less costly to implement, and create new applications of existing systems. The principal idea of what we are trying to accomplish is given by Figure 2.1, for all element pairs A & B in the swarm; we want to ensure that a communication link exists between them.

Figure 2.1

Elements in Communication example



No one has yet tried to implement these communication considerations into a Physiocomimetics swarm, so we will have to look to other similar systems to see what has already been done in the field.

Benavidez et al [13] designed a hybrid mesh/hierarchal network topology to distributed commands to heterogeneous robotic swarms. In their network topology a “master” swarm agent distributes commands to the “slave” agents which are only capable of forwarding the commands. [13] The problem with this system is that it breaks the swarm paradigm. By issuing commands to individual robots the system is no longer a swarm but rather just an elaborate central control system. There is no robustness because the loss of one of these master nodes destroys all communications. The system does not define a way for a “slave” agent to propagate back information either which makes it unsuitable for all information gathering or communication applications. Additionally, a lack of proper testing procedure and poor explanation of the tests the authors did perform make it difficult to determine whether the system truly works as they claim. These weaknesses make the system unsuitable for our purposes, but provide a list of behaviors to avoid in our communications system design.

Garagic [14] designed a swarm control system where each element is modeled with a functional differential equation that takes communication constraints into account. [14] The system essentially created attractive and repulsive forces on each robot that could be incorporated into Physiocomimetics as an additional force on each particle. The metric of interest in the paper is communication delay, where under some delay threshold a formation could be created. The problem with the author's method is that it created an under damped control system that lead to oscillating motion of the swarm agents. [14] Additionally, no results or actual control system was given because of the projects proprietary nature thus there is no way to know whether the control system works at all. However, for all the faults of the control system a communication based force is similar to what we have done to modify Physiocomimetics with the same goal.

The idea of creating a force based on communication strength is a common requiring idea. Dunbar and Esposito [15] presented a system where an agent is modeled as a particle in a scalar field. The field is similar to a gravitational potential field, but instead relies on communication strength rather than mass to create the fictitious forces. Their system works by defining a piece-wise potential function (see function 2.1) that works to keep robots from colliding with each other, but making it so far away robots come closer into communications range. [15] We can see from function 2.1 that even though the authors have shown that their system works, it is computationally inefficient and requires the use of numerically solving differential equations.

Function 2.1

Dunbar and Esposito, 2005 Potential Field Equation

$$\phi_{\text{range}}(d(x,y)) = \begin{cases} \phi_{\text{Marr}}(d(x,y)) & d(x,y) < d_s \\ 0 & d_s \leq d(x,y) \leq d_c \\ \phi_{\text{sp}}(d(x,y)) & d_c < d(x,y) \end{cases} .$$

$$\phi_{\text{sp}}(d(x,y)) = kd(x,y)^2,$$

$$\phi_{\text{Marr}}(d(x,y)) = \frac{C}{2\pi\sigma}(h - \frac{d(x,y)^2}{\sigma^2})\exp\left(\frac{-d(x,y)^2}{2\sigma^2}\right)$$

Taken without permission from [15]

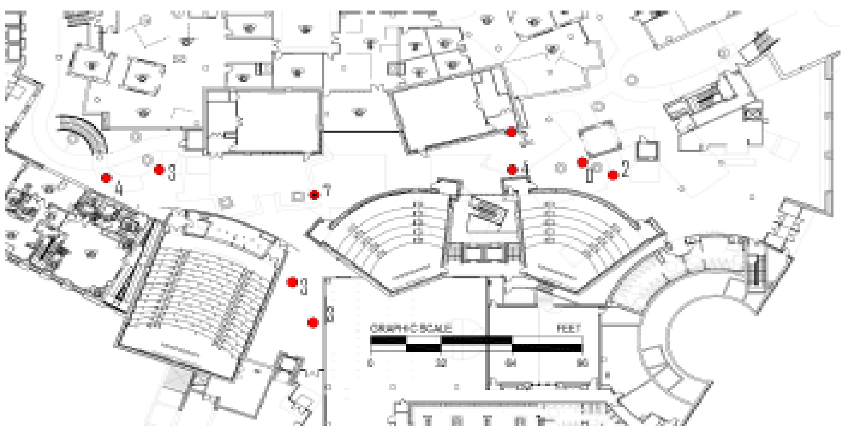
The system also promotes forming swarm clusters of disconnected elements to some minimum number before performing a target behavior with the goal of creating redundant communication links. The system does not take into account procedure for node loss, just disconnection. The authors successfully implemented communications constraints into their swarm. However, their system requires the use of global knowledge which is counter to the swarm paradigm and the authors own stated objective to “be completely decentralized with no leaders or followers, each robot is an autonomous unit.” [15, p. 402] Each robotic agent in the swarm is not capable of acting on its own if it’s provided with global knowledge every time a change in the system occurs. The strengths of the authors’ approach were the ability to reconnect disconnected nodes to the swarm’s distributed network, and communications redundancy which were taken into account in our communications constraint design.

Another AP based approach is Radio Frequency directed Virtual Force (RFVF) where uses locally gathered RF signal measurements to create virtual forces. [16] This is essentially very similar to Physiocomimetics with the exception that signal strength rather than Euclidean distance is a controlling metric of the virtual force. The authors’ objective is to create a self-forming distributed Ad-hoc network that maximizes coverage by spreading out to the maximum possible connected distance. This is one of the applications we want to create for Physiocomimetics, but we do not want to constrain our system to only this application as the authors have. In their paper, Guan et al incorporates location state saving in order to combat connectivity loss by allowing for backtracking to a previous connection location. This will increase robustness by preventing the fragmentation of the swarm caused by nodes wandering out of contact, but it does not take into account the possibility of node loss where backtracking will not reconnect a disconnected node. Additionally, storing previous states of the elements location can be costly or impossible in swarms where the individual agents are quite small. The authors have shown that their system is relatively fault tolerant when random nodes are removed from the system and that the system then self corrects, but their assertion that "RFVF ultimately unifies the framework of self-configuration, self-healing, self-optimization" is too optimistic. If it were true, the field of swarm robotics would be completely solved.

Perhaps the best presented research on Swarm Robotics control systems based on communications considerations is [17] where researchers from MIT created an Ad-hoc wireless network that required no global knowledge to function. Each robot in their system had a Wireless Access Point which connected with each other Wireless Access Point to form a wireless mesh topology. In the authors system, all the robots started at a central drop point where they were all connected by single link connections. The swarm designers define two parameters m, the minimum number of allowed connections, and M the maximum number of allowed connections. Until the robot met the above constraints, the robot would then move randomly away from the other robots in effect spreading out the wireless coverage. The authors proved that the system should eventually converge on a stable solution if one exists. That is to say, a solution requiring three nodes to be connected cannot exist in a system with only two robots.

The authors conducted several simulations with 30 robots with a wireless range of 10 meters in a field of 10,000 square meters. The simulation never reaches the optimal coverage area, but yields an average coverage area of 64% and provides self-repair and redundancy. The redundancy and coverage area was shown to be adjustable by adjusting the maximum and minimum parameters. To show the real world validity of their control system the authors created 9 custom built robots that were deployed into a distributed wireless network on the first floor of the MIT Stata Center (see Figure 2.2 below). The system provided 500 square meters of wireless coverage and only took 35 minutes to converge.

Figure 2.2
MIT Stata Center



Taken without permission from [17]

The system used by Correll et al [17] works well, and if a control method besides random movement is used it could speed up convergence time. We believe that using the number of connections rather than analyzing each connection's wireless strength as is computationally efficient. Additionally making the swarm control system agnostic to the particular communications protocol being used makes it so the same procedure can be used with a multitude of sources from the small wireless network presented in the paper, to large networks such as cellular or satellite communications.

We can see that research has been done in the area of distributed communications considerations and constraints in swarm robotics, but the topic is far from solved. Additionally, even though no one has researched the topic in the context of Physiocomimetics, AP approaches have been taken using forces based on signal strength that contain elements that can be incorporated into Physiocomimetics. Some of the authors' approaches violate the principles of the swarm paradigm and thus are unacceptable for creating a better swarm. In the coming chapters we will attempt to take the best ideas from the above research and implement several unique original ideas to implement communication considerations and constraints into the Physiocomimetics framework.

Chapter 3: Problem Definition

3.1 The General Problem

The General Problem in Swarm Robotics is to create robust, scalable, self-organizing, flexible, autonomous multi-robot systems where a collective behavior emerges from local interactions between robots and their environment to solve general problems. The swarm as a whole achieves tasks that individual elements are not capable of doing on their own and was originally inspired by examples in nature such as social insects. [3]

The robustness of a swarm system is a measure of how well the swarm reacts to changing environment and the effect of individual failures on the collective behavior. A system that is highly robust should not have collective failures in response to the removal (or failure) of several elements in a large swarm. Within Swarm Robotics this robustness is created by following four principles: redundancy, decentralized coordination, simplicity of an individual element and finally distributed sensing [4]. The redundancy, decentralized coordination and simplicity of elements ensure a single point failure does not inhibit the collective behavior of the system. This is because no element is unique as a specialized robot or controlling unit in a swarm. The distributed sensing ensures that the failure or removal of several elements from a swarm does not render the swarm blind to its environment. Any expansions of Swarm Robotics paradigms should take these factors into account in its design.

In order for a swarm to exhibit scalability, the controlling paradigm needs to remain unaffected by changing numbers of elements in the swarm. [4] Any swarm paradigm needs to control an arbitrary number of elements designed into a particular swarm and coup with a changing number of elements during runtime. One of the major goals of Swarm Robotics is to have a "large number of relatively simple physically embodied agents" thus each simple element must not be overburdened in computations. [4]

Physiocomimetics has already been shown to exhibit most of the properties of a Swarm Robotic system. [6] [7] [11] We will thus be working with the Physiocomimetics platform and working to increase the robustness and flexibility of the system to better solve more problems.

3.2 The Specific Problem

The Specific Problem that we explore in this thesis is including communication considerations into the Physiocomimetic Swarm Robotics framework. The goal is to find a way to ensure that all the elements in the robotic swarm remain in communication. There are two objectives any solution to this specific problem needs to consider to ensure that the swarm elements remain in contact with one another. First, we need to ensure that the swarm in its operational behavior does not cause elements to become disconnected from its distributed communications network. Secondly, when an element is disconnected it needs a way to with high probability reconnect with the main swarm and continue to contribute to the swarm's complex behavior.

The solutions of this specific problem will make progress into the General Problem by further increasing the robustness and self-organizing capabilities of a Physiocomimetic Swarm. The first objective of the solution to the specific problem this thesis seeks to solve is important because if an element falls out of communication with the swarm, it is not contributing to the desired complex swarm behavior. Although this may not be crucial in all applications it is still a waste of resources and in communication dependent applications, such as surveillance or distributed sensor networks, it is critical for elements remain in communication for the system to function as desired. The second objective increases the robustness of the system by ensuring that if an element is disconnected from the swarm it has the capability to rejoin the swarm and contributed to the swarm again. Although these communication considerations are only implemented in a single swarm robotics paradigm, the ideas may be generalizable to robotic swarm systems in general.

3.3 Hypothesis

We hypothesize that including location based virtual particles such as local and global centroids and a point of last connectivity we can prevent elements from disconnecting from the swarm during normal swarm behavior. Additionally, we believe that by encoding the location of a home base or point of known connectivity as a virtual particle and incorporating this particle into the Physiocomimetic controlling equation we ensure disconnect elements return to the swarm.

3.4 Contributions:

- Create new applications of the Physiocomimetics framework such as autonomous self-forming communication networks.
- Increase the robustness of the Physiocomimetic framework.
- Make current proposed applications of Physiocomimetics applicable in real world environments where researchers previously have left communication details out of their research.

3.5 Attributes

This research is novel because no one has yet solved the issue of communications in general multi-agent robotic systems, and no one has approached the problem within the confines of the Physiocomimetics framework. Additionally, authors have not said exactly how they calculate distances in current Physiocomimetics applications and usually provide the element with the location of its neighbors leaving communications and sensing as a separate unsolved problem separate from the framework. We believe that leaving it as a separate control system we could cause conflicts of objectives that would stop the swarm from exhibiting desired collective behavior.

The goals of this research seek to increase the robustness and add nontrivial functionality to the Physiocomimetics framework. Any increase to robustness of a Swarm Robotics paradigm seeks to solve a part of the general problem of Swarm Robotics and thus advances the state of the art. Additionally, recall that the interactions of agents depend on the distance between them. That means that if the elements could communicate with one another, they could exchange coordinates rather than relying on expensive sensing or computer vision systems.

Some real world applications of this improved Physiocomimetic swarm include self-forming distributed communication systems such as cellular communications in a wide terrain such as the locations of current conflicts in the Middle East. We could use the system to deploy a surveillance network that does not rely on the ability of all elements to have direct contact with a central communication hub. These potential applications show the usefulness of the proposed changes to the Physiocomimetics framework.

Chapter 4: Approach

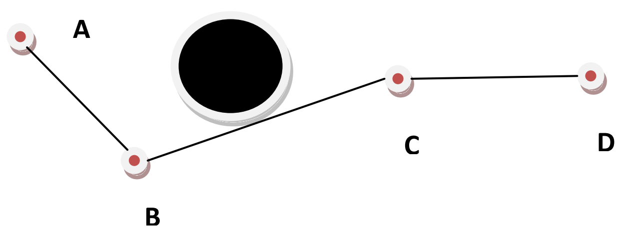
To solve our specific problem of ensuring communications in a Physiocomimetic swarm we must consider our two objectives: To prevent fragmentation of the swarm during its normal operations and to ensure that fragmented elements will reconnect with the rest of the swarm. Recall that the controlling equation of the swarm elements in its most general form is Function 4.1 and that we only consider elements within a certain predefined range when calculating this force. We must modify this equation in order to incorporate the objectives stated above and implement the hypothesis.

Function 4.1
Standard Physiocomimetics Equation

$$\mathbf{F}(t) = \Sigma \mathbf{F}_{ij}(t)$$

It is important to note that a force only exists if two elements are connected via a communications link and not obstructed. As we can see in the figure below, elements A & B are connected and thus a force between the two is calculated. However A& C are obstructed, thus A does not receive a force in response to C and vice versa. Additionally, even though no obstruction exists between swarm elements B & D, they are out of communication range and thus no connection occurs.

Figure 4.1
Obstructed and Connected Swarm Elements



To solve the first objective we implemented a rule based movement and backtracking strategy as stated in our hypothesis. The rule based movement has been implemented similarly to the method described in [17] by requiring a certain number of minimum connections to other elements, but we do not require a particular upper bound to the number of connections. In this thesis, we are only concerned with ensuring that only one connection exists to the swarm. We must first introduce a super element known as the Home Base that acts as a central routing hub that all elements must connect to. The location of this element is known to all elements and is coded before swarm deployment. While this is introducing the use of some global information into swarm behavior, it parallels greatly with real world applications. In a communication system usually there is a router of some sort between different systems (i.e. Satellite uplink) whose location is usually static. Now, while a connection to the home base exists our controlling equation will remain the same as given by [7].

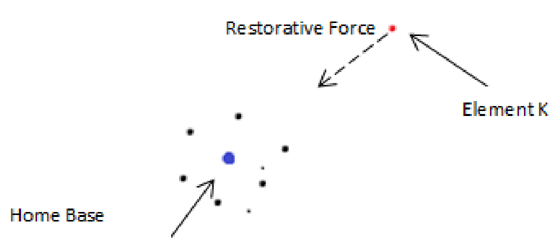
I decided to not use the Artificial Physics based approaches detailed in [15] & [14] because the first's approach required global knowledge, the latter's approach was untested and both were computationally expensive and restrictive to what communication system was used.

The question then becomes, what do we do when we are not connected to the swarm network? It is not enough to see that each swarm element is only connected to its neighbor as seen below in Figure 4.2. Similarly, we cannot merely tell the element to backtrack as its lack of connectivity may be the product of swarm element failure at which time no amount of backtracking can ensure that the element will return to the swarm network.

Figure 4.2
A Fragmented Swarm Where No Element is Disconnected

To get around these defects in behavior we will assign several virtual particles that will be explained and then tested for effectiveness. The first force applied to the disconnected elements is between each element and the home base. As we see in Figure 4.3, this will have the effect of drawing the element back into the swarm.

Figure 4.3
An Element Fragmented from the Swarm

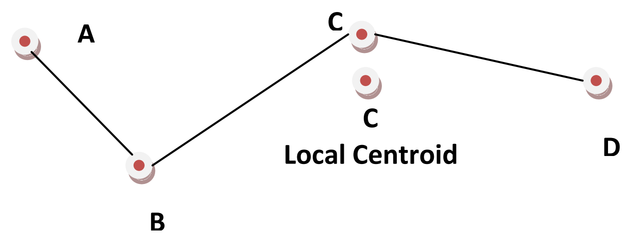


This virtual particle may not be enough to draw the element back into the swarm due to an obstruction so we will also investigate the effect of a global centroid. This centroid is essentially the weighted average of the locations of all the particles. This centroid is updated only when the element is connected with the idea that an unconnected node will not be able to effectively create a centroid without global knowledge.   This particle has the effect of drawing a swarm element toward the center of the swarm rather than the home base.

Finally, we wish to investigate several virtual particles that may help restore some connectivity without having to resort to potentially leaving the local area. These local particles are unique to each swarm element and are calculated locally by each element. Although local virtual particles do not posse the ability to restore communications after global changes such as loss of swarm elements, they do hold the potentially to quickly reconnect elements that have wandered out range. The first of such local particles is the location of last connectivity. The idea behind this virtual particle is fairly simple in that we place it in the location where the node was last considered connected.   This particle is only updated each time step if the swarm element is connected.

The second local virtual particle we will investigate is a local centroid. This is like the global centroid, with the exception that only connected elements, and the swarm element itself, will be taken into account in the centroid calculation. In Figure 4.4 below we can see that C's centroid is only dependent upon B, C, & D.

Figure 4.4
Local Centroid Example



This modification to the Physiocomimetics framework does not ensure that Element K will always reconnect under all circumstances, but as we will see it does enable a high probability of reconnection. A final pseudo-code of the modified Physiocomimetics framework is given in Function 4.3 where G is a constant parameter.

Function 4.2
Physiocomimetics Equation that Incorporates the Stated Hypothesis Functionality

If (Connected to Home Base)
    $\mathbf{F}(t) = \Sigma \mathbf{F}_{ij}(t)$
Else
    $\mathbf{F}(t) = \Sigma \mathbf{F}_{ij}(t)$
    $\mathbf{F}(t) = \mathbf{F}(t)$ + Force Due to Home Base
    $\mathbf{F}(t) = \mathbf{F}(t)$ + Force Due to Global Centroid
    $\mathbf{F}(t) = \mathbf{F}(t)$ + Force Due to Local Centroid
    $\mathbf{F}(t) = \mathbf{F}(t)$ + Force Due to Point of Last Connectivity

While these changes are theorized to work, we will test them individually in the next chapter to see which virtual particles actually have the desired effects on the swarm's behavior. It is also important to note that we will be calculating the global centroid and checking for home base connectivity using global data structures. Although this violates the principles of the swarm, it is acceptable because we are interested in the particle's effects and are not investigating these other implementation issues.

Chapter 5: Evaluation of Research

5.1 Introduction to Testing

Robots are expensive to build, so we instead simulated our swarm to test the Physiocomimetics swarm described in the last chapter.   We will be using a custom java particle simulation based up the AP C++ framework provided by Dr. Wiegand.

In order to properly test our design, we needed to define tests for the swarms connectedness, robustness, and efficiency. All tests were done on a playing field that is 2-dimensional. Additionally, all elements were given a set communication radius. In all cases, we will adjust our Physiocomimetic swarm parameters to ensure the desired behavior and then hold them constant as we adjust other test parameters. Additionally, we run all tests a number of times in order to get an average value for all performance metrics. A list of tests is given below and then a further explanation of all tests is given throughout the chapter.

- Tests 1: Effects of the New Virtual Particles in poorly connected swarms. We will randomly place particles on the playing field in such a manner where elements will randomly be connected to each other.
- Test 2: Testing Swarm Fragmentation Prevention. We will test the swarms ability to not fragment itself by setting the communication distance less than the attract repulse distance.
- Test 3: Swarm Behavior with Obstructions. We will test the swarm's behavior around a single obstacle that blocks communications.

5.2 Test 1: Effects of the New Virtual Particles in Poorly Connected Swarms

In this test, we will simulate the effect of global swarm fragmentation by randomly placing swarm elements on an unobstructed playing field. This has the effect of testing either global swarm fragmentation due to a large amount of element loss, or random initial placement of elements such as in an aerial drop scenario. For this test we will set all our element and particle masses to 30, our home base mass to 10 and all gravitation constants to 1200. The maximum force is set to two, the maximum velocity to 20 and the maximum acceleration to 10. The effective range and the communication range are both set to 75 with an attract repulse range of 50 following the 1.5R setting given in [6] [7] [8]. The distance exponent is set to two for all swarm element interactions and one for all interactions with virtual particles. Thus our swarm element interactions are inversely proportional to the square of the distance whereas our virtual particles are inversely proportional to the distance itself. This is so local agent interactions do not prevent movement toward the virtual particles. We will individually test just the standard swarm, the swarm with Home Base enabled, and the swarm with the Global Centroid enabled. We will run each swarm with these varying virtual particles a set number of time steps 100 times to see if a stable well connected swarm configuration can be achieved. The large number of trials will lessen the effect of random chance on our results.

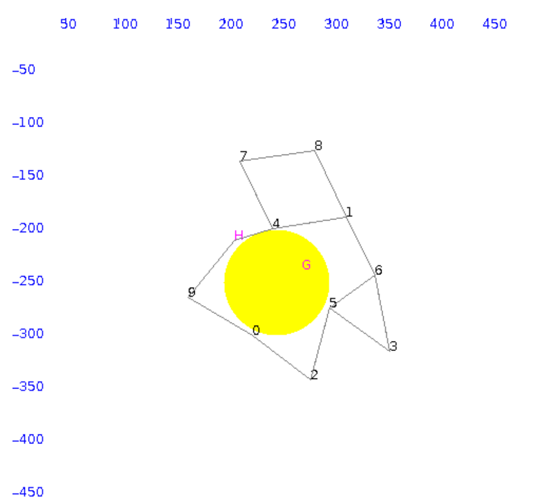
5.3 Test 2: Testing Swarm Fragmentation Prevention

In this test, we will randomly place the swarm elements close enough together to guarantee that a well-connected configuration exists. We will then increase the Attract Repulse range of the particles while leaving communication range constant with all other parameters as in the above test. To summarize the changes in parameters from the last simulation are an increased attract and repulse range of 100. This will cause the natural behavior of the system to try to push elements out of range and we can test the effect of the local virtual particles and see if they will prevent the swarm from fragmenting itself. We will test individually the particles associated with the local centroid and the point of last connectivity. Each particle type will be tested 100 times to lessen the effect of random chance. Additionally, each test will last a set number of time steps as in Test 1 and the state of the swarms global connectivity will be assessed at the end of the test.

5.4 Test 3: Swarm Behavior with Obstructions

This test is essentially a repeat of the previous two tests with an obstruction created in the center of the field as illustrated in the figure below.

Figure 5.1
Example of Swarm Obstruction



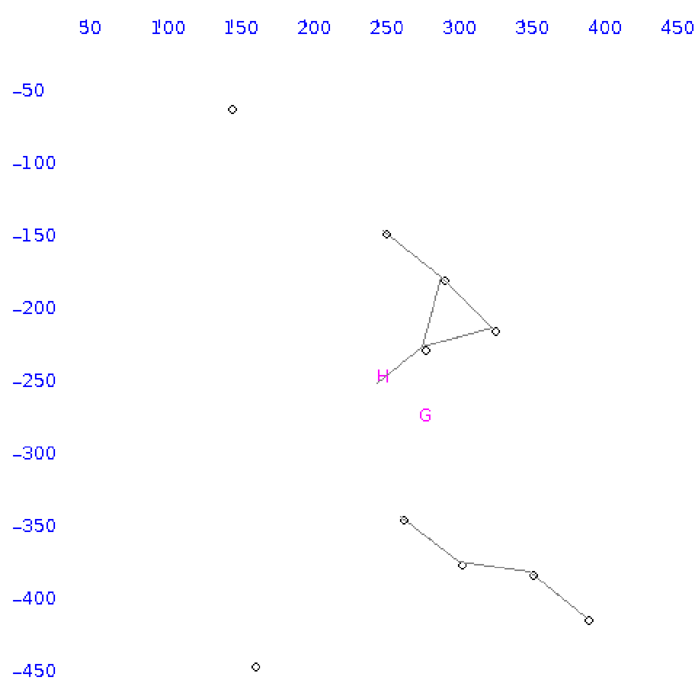
For both tests we will set our parameters as in Test 2 with an attract repulse range of 100, particle masses to 30, maximum velocity of 20, maximum force of 2 and a maximum acceleration of 10. To test the global particles effects on creating a connect swarm formation we will randomly distribute the swarm elements across the playing field and see how resilient the global particle inclusions are to the obstacle. To test the local particles that we've introduced to the swarm we will initially place the particles close enough together that they are initially well-connected. They will be tested to see that the swarm does not fragment itself just as in Test 2.

Chapter 6: Experiment Results

6.1 Test 1 Results

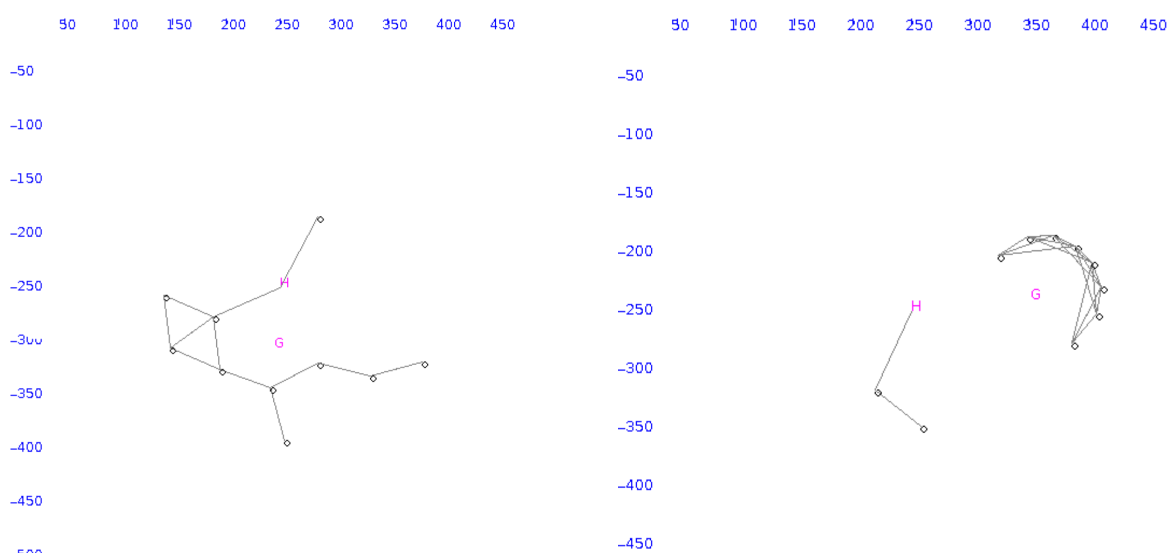
In Test 1, the statistic gathered was the percentage of cases where a well-connected swarm was created. Unsurprisingly randomly distributed swarm elements on a large playing field did not connect. They had a Global Communication Network in 0% of all the standard swarm test cases. A more representative example of the swarm configuration is given by figure 5.1, where some initial connections form small connected clusters, but the disconnected elements are unable to connect as they do not know other elements locations.

Figure 6.1
Random Placement Standard Swarm



The Swarms where a Global Centroid force was introduced in the event of disconnection fared much better with 82% of swarms being globally connected during their final configuration. However, when this global connection did not occur the swarm elements would cluster around the initial global centroid and not reconnect at all. So although this virtual particle did have some success reconnected elements, it did not work well in all cases. An Illustration of both the desired and undesired behavior exhibited by the inclusion of the global centroid is given in the figure below.

Figure 6.2
Random Placement Swarm with Global Centroid
(Desired behavior left, undesired right)



The final virtual particle introduced to the swarm in Test 1 was the home base. This home base's location was set at the center of the playing field and then manually hard coded into each swarm element. Unsurprisingly on this unobstructed playing field 100% of all test cases managed to form a well-connected swarm. While this result is impressive on an unobstructed field, it will also need testing on an obstructed field.   Although this result is thus far limited, it has shown that a communication network could be autonomously deployed in a relatively obstruction free area such as a plateau, plain or desert terrain.

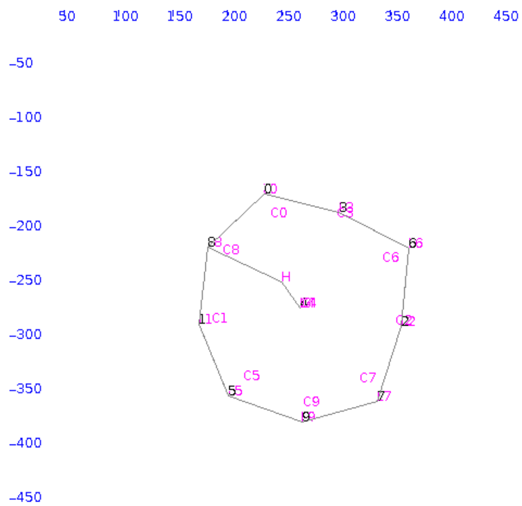
6.2 Test 2 Results

Unsurprisingly, the standard Physiocomimetic swarm merely fragmented itself in all cases; the local particles on the other hand provided some success in preventing swarm fragmentation. The effect of the virtual point of last connection caused the swarm to remain well connected in 17% of all of the trials, and the local centroid allowed the swarm to remain in constant contact 35% of the time. Combining the effects of the local particles made the swarm remain in constant communication in 27% of the test trials. While these values are disappointing, they are still better than the swarm fragmentation that occurred in every trial of the standard swarm without any virtual particles.

Two interesting observations occurred during the test trials. The first, illustrated below, is that occasionally the swarm managed to form a ring like pattern with a single element providing a connection to the home base at the center of the playing field. This pattern occurred randomly though out the trials for each virtual particle type.

Figure 6.3

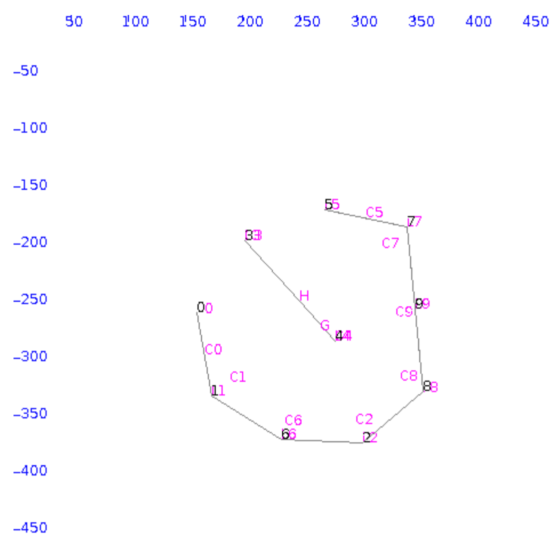
Swarm with Ring Patterns



The second observation from watching the Physiocomimetic swarm form is that its final configuration had the elements unstably jumping in and out of connection range. This instability and lack of stable configuration caused the swarm elements disconnect and reconnect continuously. Below is one such trial where swarm elements 3 and 5 were continuously flickering in and out of contact which affected the global connection of the swarm.

Figure 6.4

Swarm with Poor Connectivity



With this observation in mind, the simulation was adjusted such that for particle motion a distance of 95% of the maximum communication range was used to determine whether an element should behave normally. The actual connect status for the evaluation was still based upon the maximum communication range of the element. All simulations were rerun using this new condition ten times to determine whether the jittery solutions could be made more reliable at the cost of area covered by the swarm's global communication network. Initially this change was the only thing necessary to ensure that the swarm remained well connected without the use of any local particles, but varying the parameters showed that this is not true in all cases. After changing the parameters to a maximum velocity of 50, with maximum forces of and accelerations of 30 the swarm then fragmented itself on every trial for the standard swarm, and had a connection rate of 30%, 20%, 40% for the point of last connection, local centroid, and both virtual particles respectively. Further decreasing the effective range of communications when determining connectivity to 80% of the maximum increased these percentages to 80%, 100%, 90% indicating that preventing swarm fragmentation is best achieved by choosing the correct parameters, including the virtual particles, and at a cost of coverage, decreasing the distance that you consider two elements remain connected during the swarm formation.

6.3 Test 3 Results

The inclusion of the obstruction degraded the performance of the global particles in both cases. The swarm with the inclusion of the home base particle only yielded a well-connected formation in 83% of the trials. Similarly, the swarm with the inclusion of the global centroid particle only yielded a well-connected formation in 46% of the test trials. This is in contrast with 100% and 82% swarm connectivity for the home base and global centroid particles on the unobstructed field. This is a change of 27% for the home base particle swarm and 44% for the global centroid particle swarm indicating that while neither swarm is perfectly resilient to obstructions, the home base swarm is more so. The reason for the swarm performing poorly with the global centroid was the fact that the global centroid could be placed inside the obstruction which was an unreachable location for swarm elements.

When testing the swarm fragmentation and the local particles, just decreasing the effective communication range to 95% of the maximum was enough to prevent the swarm from ever fragmenting. However, when the communication range was left at maximum, we yielded well connected swarms in 2% of the trials of the point of last connection swarm, 16% of the local centroid swarm, and 2% of the trials with all local particles.

Chapter 7: Conclusions and Further Research

7.1 Conclusions

From the research trials done on the Physiocomimetic swarm we can determine the effectiveness of our proposed virtual particles on swarm communication. The home base particle worked perfectly in all test cases on an unobstructed playing field, but had some degradation on an obstructed playing field. The global centroid had a lesser affect still increased the rate at which well-connected swarm formations occurred, but was also more affected by the inclusion of an obstacle than the home base. It was demonstrated that to keep a swarm from fragmenting itself it was acceptable to decrease the effective communication range used during the determination of element movement. This amount that the connection range needs to be decreased is based on the parameters and at the cost of the range of the swarm's coverage. If this is unacceptable, the local particles were able to increase the number of trials in which the swarm remained well connected from 0% to 17% for the swarm with the point of last connection, 35% for the swarm with the local centroid and 27% for the swarm that included both. Given a well-connected swarm that is expanding near an obstruction, we could prevent the swarm from fragmenting by merely decreasing the effective communication range used when determining swarm movement. This was at a cost of swarm coverage size thus we also tested the local particles with the full communication range and yielded very poor connection rates. This indicates that the best policy is to include a home base or point of known connectivity, and limit the connection range used when determining element movement. If this is unacceptable a local centroid can be included to increase the probability that a well-connected formation will occur, but it cannot be guaranteed. The global centroid showed no advantage over the home base.

7.2 Future Research

The results presented above show that it is possible in some conditions to ensure communications in the swarm. In unfavorable conditions we still can increase the probability that the well-connected swarm will exist, but more research needs to be done to guarantee that swarm remains in full connection. It was observed during the local particle tests that the elements oscillated between well connection and disconnection and this effect should be studied further.

Additionally, there are many implementation problems that were not considered as they were beyond the scope of my research. The global centroid calculation was done via global knowledge as was determining whether the swarm was well connected by use of the Floyd-Warshall algorithm both of which violate the principles of the swarm network. These issues could be addressed by the design of a routing and distributed computing system that allows for a mostly accurate calculation of these factors, and if this problem has not been solved presents and interesting research problem.

References

[1] Beni, G., Wang, J. Swarm Intelligence in Cellular Robotic Systems, Proceed. NATO Advanced Workshop on Robots and Biological Systems, Tuscany, Italy, June 26–30 (1989)

[2] “Swarm Intelligence. “Wikipedia. Wikimedia Foundation, 23 Nov 2010. Web. 27 Nov 2010. <http://en.wikipedia.org/wiki/Swarm_intelligence>

[3] "Swarm Robotics." www.swarm-robotics.org.N.p., 20 08 2010. Web. 21 Nov 2010. <http://www.swarm-robotics.org/index.php/Main_Page>.

[4] Sahin, E., "Swarm Robotics: From Sources of Inspiration to Domains of Application", SAB 2004 International Workshop, July, 2004, Santa Monica, pp. 10-20

[5] Gerardo Beni, "From Swarm Intelligence to Swarm Robotics", SAB 2004 International Workshop, July, 2004, Santa Monica, pp. 84-97

[6] Spears W., Spears, D., Hamann, J., Heil, R., “Distributed, Physics-Based Control of Swarms of Vehicles”. Autonomous Robots 17 [2004a] 137-162

[7] Spears, W., Spears, D., Rodney, H., Keer, W., Hettiarachchi, S., "An Overview of Physiocomimetics", SAB 2004b International Workshop, July, 2004, Santa Monica, pp. 84-97

[8] Ellis, C. and Wiegand, R. P. “Actuation Constraints and Artificial Physics Control. “In Proceedings of the Tenth International Conference on Parallel Problem Solving from Nature.2008 pp. 389–398.

[9] Wiegand, R. P., Potter, M. A., Don, A. Sofge, D., and Spears, W., “A Generalized Graph-Based Method for Engineering Swarm Solutions to Multiagent Problems.” In Proceedings of the Ninth International Conference on Parallel Problem Solving from Nature. 2006 Pages 741–750.

[10] Kraus, S., Shehory, O., and Yadgar, O. 1999. Emergent cooperative goal-satisfaction in large-scale automated-agent systems. Artificial Intelligence, 110:1–55.

[11] Spears, W., Heil, R., Zarzhitsky, D., “Artificial Physics for Mobile Robot Formations.” IEEE Conference on Systems, Man and Cybernetics. 2005 pp. 2287-2292

[12] Frey, C., Zarzhitsky, D., Spears, W.M., Spears, D.F., Karlsson, C., Ramos, B., Hamann, J.C.; Widder, E.A., "A Physiocomimetics control framework for swarms of Autonomous Surface Vehicles," OCEANS 2008 2008

[13] Benavidez, P.; Nagothu, K.; Ray, A.K.; Shaneyfelt, T.; Kota, S.; Behera, L.; Jamshidi, M.; , "Multi-domain robotic swarm communication system", IEEE International Conference on System of Systems Engineering, 2008. SoSE '08. 2008 pp.1-6

[14] Garagic, D., "On delay-dependent stability of a swarm of networked autonomous vehicles under communication constraints," Swarm Intelligence Symposium, 2005. SIS 2005. Proceedings 2005 IEEE, 2005, pp. 289- 293

[15] Dunbar, T.W.; Esposito, J.M., "Artificial potential field controllers for robust communications in a network of swarm robots," System Theory, 2005. SSST '05. Proceedings of the Thirty-Seventh Southeastern Symposium on, 2005 pp. 401- 405

[16] Guan, K.; Imbrenda, D.; Ghanadan, R.; Hsu, J.;, "Distributed sensing and communications in tactical robotic networks," Military Communications Conference, 2008. MILCOM 2008.IEEE, 2008 pp.1-7

[17] Correll, N.; Bachrach, J.; Vickery, D.; Rus, D.;, "Ad-hoc wireless network coverage with networked robots that cannot localize," IEEE International Conference on Robotics and Automation, 2009. ICRA '09, 2009, pp.3878-3885