Mini FRED and Mother FRED, a Light Seeking Robotic Swarm

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***Abstract*— The FRED swarm is comprised of five heterogeneous multi sensory robots capable of a small suite of behaviors, designed in the vain of the Pfeifer and Bongard Intelligent and Collective Systems Design Properties and Principles. Two robot types were constructed: mini-FRED and mother-FRED. Four mini-FRED robots, and one mother-FRED were used in five trial runs of five minutes, each. However, it would be possible to change the swarm size without loss of generality with respect to overall swarm behavior. Mini-FRED is a simple robot utilizing two sensors and two actuators attached directly to the NXT mindstorms brick unit that doubles as the robot chassis. Mini-FRED was designed for exploring behavior in search of an energy source (e.g. light), with basic obstacle avoidance mechanisms guided by light and touch sensors placed at the robots front. This robot then communicates its findings to any and all nearby robots through projected sound via speaker port. Mother-FRED is a more complex robot utilizing three spatially distributed microphones and one rotating sonar "head" used for obstacle avoidance. Mother-FRED does not have light sensing capability, but instead listens for directionality of high-volume, high-pitch tones in search of the sub-swarm of mini-FRED robots. Clustering of the swarm at or near the primary light source in the environment was seen in all five trial runs. Emergent behavior was observed in both robots, as well as the collective swarm. Mini-FRED exhibited excellent obstacle avoidance through light-sensing alone, and rarely needed its degenerate touch sensing capabilities. Emergence was especially apparent in the mother robot who showed wall-following, and spatial centering behavior not designed for in the robot's construction and programming. The swarm showed light following and clustering behavior as expected, but also exhibited exploratory behavior when the cluster became large enough for the mini-FRED robots to touch one another, sending one or more robots in search of an alternative light source.**

I. INTRODUCTION

Swarm robotics provide an interesting and dynamic platform by which to study both robotic, neural, and animal behavior and cognition. Multi-robot systems employ varying combinations of homogeneous or heterogeneous independent robots. Swarm robotics are especially useful for studying complex emergent behaviors that are based in simplistic behaviors and neural processes. Pfeifer and Bongard explain that "A [...] motivation for studying collective phenomena is that because individuals can interact in groups, they can do things that individual agents cannot do on their own. For example, ants can find the shortest path to a food source by depositing pheromones as they search for food and return from the food source, as well as following the pheromone trail with the highest concentration. This mechanism is extremely simple, but it only works if there are many ants. If the shortest path to the food source had to be found by a single ant, this would require considerable cognitive abilities (e.g., memory and comparing distances) and exploratory activity on the part of the individual, capacities beyond a single agent [1]." The FRED swarm follows in this vain and was designed using some of the very simple rules outlined by Braitenberg vehicles [2] (attraction to light), as well as some simple behaviors seen in nature, specifically that of honey bees [4]. There are two type of agents in the robotic swarm: four "mini-FRED" agents and one "mother-FRED" agent. Mini-FRED agents search for light in a similar way that FRED did [3]. The main goal of these robots was to search for "food" while avoiding environmental obstacles. We replicate scavenging behavior through light-seeking behavior. The purpose of light-seeking behavior is one of survival, in that solar powered robots could hunt for its own light and therefore power, a highly desirable trait [5]. In contrast, mother-FRED is completely blind to light but is provided with three microphones that provide directionality of high-volume, high-pitch tones in search of the sub-swarm of mini-FRED robots.

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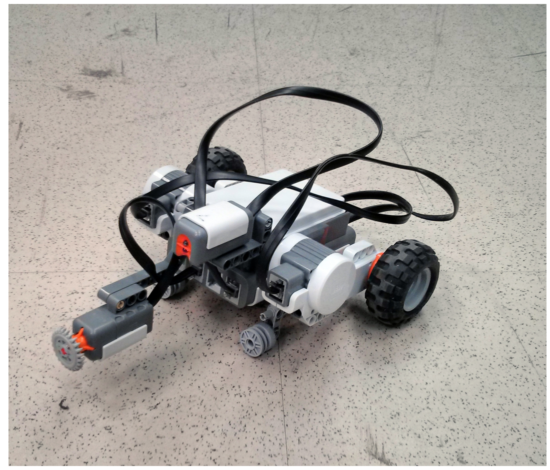

Fig. 1. Mini-FRED in the MAE biorobotics laboratory.

II. AGENTS

There are two type of agents in the robotic swarm: four "mini-FRED" type of agents and one "mother-FRED" type of agent. Mini-FRED agents search for light in a similar way that FRED did [3]. In contrast, mother-FRED is completely blind to light but is provided with three microphones that provide directionality of high-volume, high-pitch tones in

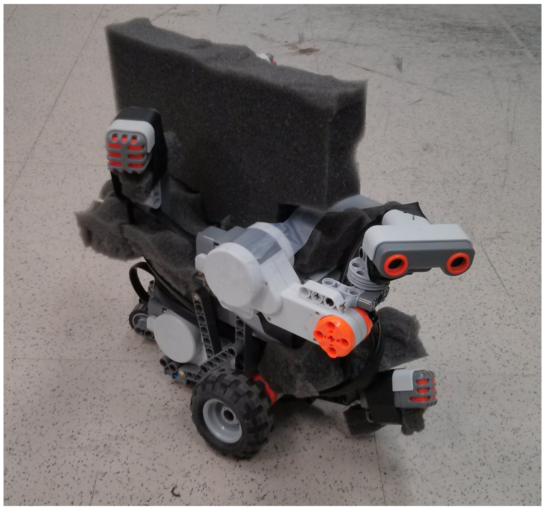

Fig. 2. Mother-FRED in the MAE biorobotics laboratory.

search of the sub-swarm of mini-FRED robots. Details about the construction of the two type of agents follow up in Sections II-A and II-B.

A. Mini-FRED Construction

Mini-FREDs are very simplistic consisting of only two motors and two sensors: a sonar sensor and a contact sensor. Both sensors and actuators were attached directly to the inverted NXT brick for ease of construction, where the NXT brick served as a chassis. The two motors are located on the sides and allow for driving and steering, the sensors are placed facing forward and serve as an obstacle avoidance and light seeking tool. A picture of a mini-FRED can be seen in Figure 1.

B. Mother-FRED Construction

Mother-FRED is a more complex robot with two motors and four different sensors: three microphones and a sonar. The layout of the motors is similar to mini-FRED. The three microphones are located on top of the robot and facing different directions (left, right and forward). Mother-FRED will use the microphones to detect where sound is coming from. The sonar sensor is mounted on a rotating head in a simplified version of the rotating head that FRED had [3]. The microphones allow for sound detection while the sonar is used for obstacle avoidance. Foam was placed at the microphone mounting points to avoid any rattle of the plastic LEGO pieces that may introduce noise to the microphones. Separating barriers of foam were placed between the microphones and neighboring motors. A large dividing foam wall was placed between the left and right microphones to shield each microphone from contralateral audio that would de-weight the directional bias necessary for the robot's navigation. A picture of mother-FRED can be seen in Figure 2.

C. Mother-FRED build process

The build process for the mother robot was not straightforward. Both morphology and neural processing were iterative processes. The Lego NXT Mindstorms kit is supplied with a microphone sensor that measures decibel magnitude only. However, it was immediately apparent that this was not the case as decibel magnitude should scale linearly with distance. Instead a clear exponential trend was seen (see figure 6). We attempted correction via linear transform. By taking readings at various distances and creating a linear multiplier, we were able to account for variation in microphone sensitivity.

Another major problem was the inconsistency/noise in the microphones. Our next attempt at microphone value correction was to filter the microphones. We implemented a second order low-pass Butterworth filter with a time constant of four seconds. Although this helped, a DC offset was clearly biasing the microphones.

A calibration procedure was implemented where the robot would take five seconds of readings before beginning the exploration process. During this time a mean value was calculated for each microphone and subtracted from the time-locked microphone signal as a DC offset.

Despite these advancements, it was clear that the microphones were still not performing optimally, and struggled to discern directionality. We therefore resorted to morphological alterations. Foam was placed at the microphone mounting points to avoid any rattle of the plastic LEGO pieces that may introduce noise to the microphones. Separating barriers of foam were placed between the microphones and neighboring motors. A large dividing foam wall was placed between the left and right microphones to shield each microphone from contralateral audio that would de-weight the directional bias necessary for the robots navigation.

Due to the changes made during this process, the Butterworth filter order and time constant were altered at each step. The final filter was a third-order low-pass Butterworth filter with a time constant of two seconds. However, despite linear transformation, DC offset correction, low-pass filtering, and various morphological changes, the microphones simply could not discern directionality to an acceptable level.

Ultimately, it was clear that in order to obtain clean readings, the motors on the robot would need to cease completely. This led to the need for discrete motions of the mother-FRED robot. In the final version of the robot, the linear transformation, DC offset correction, and morphological additions were maintained. The filter, however, was now unnecessary since a continuous motion was no longer maintained. A flowchart outlining the mother robots behavior is outlined in figure 4.

III. PFEIFER AND BONGARD DESIGN PRINCIPLES FOR INTELLIGENT AGENTS

This project involved the construction, programming, and testing of a cognitive robotic swarm that follows the Pfeifer and Bongard principles of design and collective robotics [1].

A. Three-Constituents

The first of the Three-Constituents principles is the definition of the ecological niche or task environment. The FRED swarm was designed to operate in an environment of varying light. The optimal environment may include several discrete light sources of high intensity. Furthermore, we make the assumptions that the niche has obstacles of varying shapes and sizes, and that the ground is relatively even and flat. The swarm was designed with a classroom or lab setting in mind. This defines the specific niche.

The second of the three constituents is the definition of desired behaviors. The FRED swarm was designed to be a collective set of heterogeneous embodied agents that interact with the laboratory environment in specific manners. Firstly, the mini-FRED's (see Figure 1) behavior was to mimic that of basic animalistic behavior defined as the continuous search for an energy source in the form of light. These robots avoid potentially dangerous situations through general obstacle avoidance through use of the light sensor (see Section V). In case of an actual collision, a degenerate system was in place to sense the contact and turn the robot in a new direction. The larger mother robot (see Figure 2) acted similar to the manner of a "queen bee". The mother robot would have little sensing ability, and no ability to sense light. In order to find light itself, this robot was designed to communicate with the smaller mini robots through the use of microphones and speakers. The intended behavior of the mother robot was to search out the mini robot that was indicating that it had found the highest amount of light. Ultimately, the mother robot's behavior would prove to be more complex (see Section V-B).

Finally, the design of the agent was to be considered. The first challenge for the mini-FRED was to provide directionality without the addition of multiple sensors of a single type. In order to achieve this, the mini robots would turn their entire body left and right, taking multiple readings in the process. This allowed directionality in their logic leading to the behavior outlined in Section V. In contrast, mother-FRED was constructed with a rotating "head" that would allow the sonar sensor to survey an area, taking multiple readings. For more information about these robots' construction, see sections II-B and II-A.

B. Complete Agent

The second of the Pfeifer and Bongard [1] principles emphasizes that the agent be designed as a complete agent with subsystems interacting in tandem in the real world. For the purposes of this design principle, we must both consider individual robots as well as the swarm, which can also be thought of as a complete agent.

The mini robots have two basic sub-systems in their light seeking and obstacle avoidance. This robot demonstrates the convolution of these two sub-systems wherein one without the other would be useless. Light seeking behavior would be difficult if the robot was unable to navigate its environment through obstacle avoidance. Likewise, without light seeking behavior, the robot would be static and any obstacle avoidance would be unnecessary. The mother robot follows the same logic through sound exploration and obstacle avoidance via sonar rather than touch sensing.

Perhaps the most prominent example of design as a complete agent is the swarm as a whole. The end goal was to bring the swarm into a collective group or "cluster" near a light source. Importantly, the cluster must include the mother robot. In order to reach this goal, the entire swarm was required. Without the multiple mini robots seeking out a light source, the mother robot would be completely unable to do so alone as it is not equipped with light sensing capability. As we can see, the swarm was designed as a complete agent.

C. Cheap Design

The principle of cheap design, states that the agent should benefit from the characteristics of the interaction with the environment in a way that results in a simple, easy or "cheap" design of the agent. The mini robots exploited this design principle to a great degree. The mini robots are incredibly simple in that they utilize only two motors, and two sensors, one of which is a degenerate system. It is therefore possible for these robots to run even when missing a sensor. During trial runs, we even observed a motor detach, and the robot continued to function to an acceptable degree! These robots exploit the smooth nature of the floor in the lab setting to allow use of just two motors, crudely attached directly to the NXT brick which also serves as the chassis (see more in section II-A). They also exploit the shadowy nature of the lab environment to utilize the light sensor as both a light-seeking device and obstacle avoidance device through the assumption that shadowy areas are more likely to be obstacles.

The swarm utilizes cheap design in a few ways. First, the environment used in the test setup had a single light source. This was very helpful in self-organization (see section **??**). The environment was also dimmed with the exception of this light source.

D. Redundancy

Redundancy was a design principle used throughout both the individual robots as well as the swarm as a whole. The mini robots used both a light sensor as well as a degenerate touch sensor for obstacle avoidance. Furthermore, the robots were even capable of gross movement when one of the two actuators (motors) were disconnected or severed.

The mother robot utilized three microphones placed in various orientations, as described in section II-B. In order for directionality to be preserved, only two of the three microphones were needed. Should one microphone become disconnected, the mother would continue to function, although it would likely converge at a slower rate.

The swarm utilized redundancy through sheer numbers. In total, the swarm was comprised of five robots including four mini robots that performed constant light exploration. The mother robot could respond to as little as a single robot. Therefore, it is entirely possible for up to three mini robots to fail before the swarm system would cease to function.

E. Sensory-Motor Coordination

"The principle of sensory-motor coordination states that through sensory-motor coordination, structured sensory stimulation is induced [1]." Sensory-motor coordination is evident in both robots as well as the swarm. The mini robots utilize a motor task that involves sweeping left and right while taking corresponding sensor values at the various angles. It then utilizes the sensor values to make an informed decision about directionality in its next movement. Similarly, the mother robot takes simultaneous readings from a multi-sensor array to make its decision. The mother robot also utilizes a sweeping sonar head similar to that in [3] that sweeps its surroundings for impending contact.

The swarm can be thought of as its own agent utilizing sensory-motor coordination in its unidirectional communication scheme as outlined in section V, where the mother's motor movements are ultimately a result of the mini robots' sensor readings.

F. Ecological Balance

"The principle of ecological balance has two parts. The first states that given a certain task environment, there has to be a match between the complexities of the agent's sensory, motor, and neural systems. The second aspect is closely related to the first; it states there is a certain balance or task distribution between morphology, materials, control, and environment [1]." This principle can be seen in both robots.

The construction or morphology of the mini robot (section II-A) is simple in nature for both sensory and motor systems. This is evident in that there are both two sensors and two actuators. In keeping, the neural system of this robot is also simple. The designed behavior and neural system of this robot is discussed section V-A and illustrated in Figure 3.

The construction of the mother robot (section II-B) was also simple in nature, although somewhat more complex than the mini-FRED robot. The mother robot consisted of three microphones, one sonar sensor, and three actuators: two for drive, and one to rotate the sonar head. Although, at first glance, it appears there are more sensors than actuators, we might argue that three of the sensors (microphones) serve a single purpose together, and thus the sensor/actuator balance is maintained. Mounting these various sensors presented a morphological challenge, and thus the mother-FRED robot was also more complex, morphologically speaking. These complexities were balanced by the neural systems in place to process the data. Due to the inconsistency between the microphone readings, and non-linearity of the microphones themselves, filtering their values to obtain meaningful data was a difficult endeavor. The mother-FRED robot's neural processing is further outlined in Figure 4.

G. Parallel, Loosely Coupled Processes

"The principle of parallel, loosely coupled processes states that intelligence is emerged from a large number of parallel processes that are often coordinated through embodiment, in particular via the embodied interaction with the environment [1]." The mini robot utilized two basic parallel processes. Firstly, its life purpose is to seek out light, and thus its first process is to do just that (see Figure 3). However, a second process is monitoring the touch sensor, ready to override the light seeking process at any time. The processes of the mother robot operate in a similar manner where the light seeking and touch sensor override processes can be replaced by pitch seeking and directional sonar sensing, respectively.

The swarm also exhibits parallel processes, where the mini robots are primarily searching for light, and the mother robot is primarily searching for the largest cluster and tones. Through embodiment and swarm interaction, this leads to the emergence of clustering behavior in the higher-light areas of the area.

H. Value

The eighth principle refers to a value system that determines which things are "good" or "bad" for the agent. The FRED swarm collectively seeks for new sources of light while avoiding obstacles. Thus, the swarm's value system is based primarily on light, and secondarily on the clustering of robots.

Light was chosen as a value object due to its natural correlation to food in the animal kingdom. Where animals seek out food for sustenance, a swarm of robots might seek out light as a potential energy source. Light-seeking behavior may prove highly useful in solar powered robotics, theoretically allowing a continuous lifespan without need for intermittent charging, creating a "self-sufficient" swarm [5].

Clustering was chosen as a value object in order to mimic behavior seen in bees and many other animals. Clustering in the wild is commonly seen for various reasons including defense or "strength in numbers", as well as complex social systems. Bees form large hives, where a queen bee is necessary for reproduction, but cannot easily travel. Therefore, a heterogeneous swarm of bees emerge to take on various roles for the hive including, but not limited to habitat exploration. When a potential new habitat is found, the bee communicates this to the hive, and the hive makes a collective decision. In this paradigm, the mother robot could be considered analogous to the queen be or the swarm itself. The mini robots would then be analogous to the worker bee who is exploring for pollination or new habitats [4].

IV. PFEIFER AND BONGARD DESIGN PRINCIPLES FOR COLLECTIVE SYSTEMS

Several different examples of embodied collective intelligence are outlined in [1]. These example vary greatly in scope, purpose, interaction, and complexity. It is clear that the collective intelligence (e.g. swarm robotics) is not "unified or clearly delineated subject matter [1]." However, it is important to summarize the essential principles observed in the creation of collectively intelligent systems and agents. The FRED swarm was designed in with these principles in mind, as they are outlined below.

A. Level of Abstraction

"The term collective intelligence applies not only to groups of individuals, but equally to any kind of assembly of similar agents, such as groups of cells, or groups of modules in robotic systems. Whenever talking about collective intelligence we must clearly identify the scale or level of abstraction at which we are investigating our agents [1]." In the case of the FRED swarm, the level of abstraction is rather simple. We leave the discussion of the individual subsystems within robots to the construction sections II-A and II-B. For the purposes of the collective intelligence discussed here, the individual robots define the level of abstraction. Two types of robots exist: mini-FRED and mother-FRED. Five robots exist in total: four mini-FREDs and one mother-FRED. These five robots will collectively be referred to as the "swarm".

B. Design for Emergence

Emergence occurs when relatively simple rules of often independently embodied agents interact with each other and their environment. These seemingly simple rules can lead to complex and interesting behavior. This was perhaps the most difficult as well as most important aspect in designing the FRED swarm. Both the mini-FRED and mother-FRED robots are simple in morphology, construction, and cognitive function. This was a purposeful design that would hopefully lead to emergence. The specifics of the designed behavior can be seen in section V-A. The subsequent emergence of interesting behavior is discussed in section V-B. The resulting behaviors were considered to be successful. In the addition or removal of robots, the end behavior (clustering and light seeking) remained relatively consistent with only the time to convergence varying. This was evidence of general scalability, a signature of "design for emergence" [1].

C. from Agent to Group

Agent design principles can also be applied to groups of agents. The FRED swarm was designed with these principles in mind. Section III, subsections III-A through III-H details the agent design principles of Pfeifer and Bongard [1] for both the individual robots as well as the collective swarm.

D. Homogeneity-Heterogeneity

Pfeifer and Bongard [1] state that "a compromise has to be found between the extreme of having only one type of general purpose module and different specialized types of modules".The FRED swarm makes use of two heterogeneous robot types: the mini-FRED and the mother-FRED. The swarm is comprised of five robots in total. Four homogeneous mini-FRED robots were used, and one mother-FRED robot was used. This is not to say that this is the only possible combination. Without loss of generality in terms of swarm behavior (section V), it would be entirely possible to include more mother-FRED robots and/or more or less mini-FRED robots. The only requirement is that the swarm has at least one robot of each type. Without one of each type, the swarm cannot exhibit any meaningful behavior. Ideally, the number of mini-FRED robots would exceed the number of mother-FRED robots in order to facilitate faster and more thorough light-seeking and exploration behavior.

V. BEHAVIOR

A. Designed behavior

The FRED swarm was designed with several behaviors in mind, that would hopefully lead to the clustering near a light sources as described in section III-H.

Mini-FRED was designed to utilize a light sensor that would serve primarily as a light-seeking sensor where sensor-motor coordination (see section III-E) would produce directionality. It was hoped that the light sensor would serve as a degenerate obstacle avoidance sensor, avoiding black objects and shadowed areas of the laboratory. Mini-FRED was also given a touch sensor for the purpose of redundancy and primary obstacle avoidance, where a collision would trigger an avoidance maneuver. Mini-FRED would relay the current ambient light value via psuedo-PWM signal through its speaker port. The percentage duration (over 1Hz cycles) and pitch of the tone emitted by the NXT brick were defined by equations (1) and (2):

$$\Delta = \alpha \times L, \tag{1}$$

$$f = \beta \times L. \tag{2}$$

Where Δ is the length of the tone expressed in seconds and f is the tone frequency in Hz. L is the reading from the light sensor which can take a value between 0 and 1023 and is unitless. Coefficients α and β have a value of 0.085 s and 5 Hz respectively.

For a flowchart outlining mini-FRED behavior, see Figure 3.

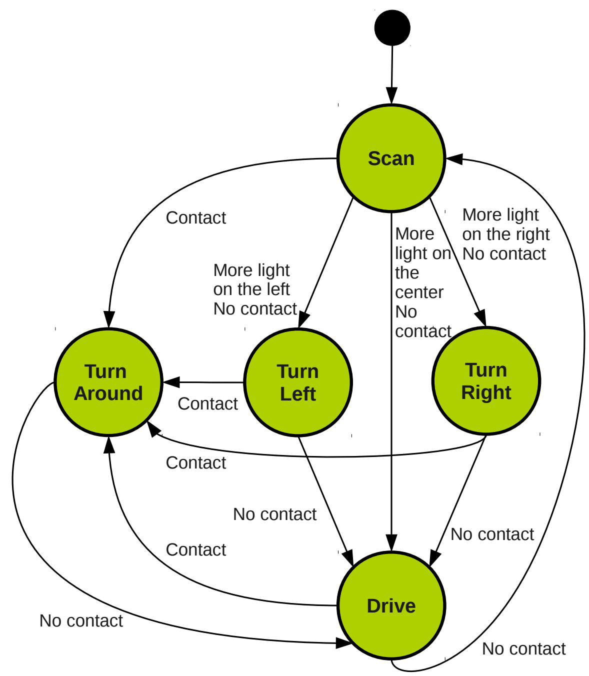

Fig. 3. Flowchart outlining mini FRED behavior depending on sensory input. Contact input overrules light input.

Mother-FRED was designed to follow loud, high pitched tones. It was observed in [3] that high pitched tones led to higher dB readings in the NXT Lego Mindstorms microphones. Proximity of the mini-FRED robot also led to higher microphone readings (see Figure 6). Mother-FRED was outfitted with three microphones distributed at various angles as shown in Figure 2 and detailed in Section II-B. Based on the highest reading and its relative value to the remaining microphones, a new direction was chosen as the best approximation of the source of the noise. This behavior is defined in equation (3),

$$\gamma = \begin{cases} \phi(m_R - \frac{m_C+m_L}{2}) & : m_R > m_C, m_L \\ \frac{\phi}{2}(m_R - m_L) & : m_C > m_R > m_L \\ 0 & : m_R = m_L \\ -\frac{\phi}{2}(m_L - m_R) & : m_C > m_L > m_R \\ -\phi(m_L - \frac{m_C+m_R}{2}) & : m_L > m_C, m_R \end{cases} \qquad (3)$$

where γ is the angle turned by mother-FRED in the turning stage (see Figure 4), ϕ is a coefficient with a value of approximately 0.1 degrees and m_L, m_C, and m_R are the left, center, and right microphone readings which can take values between 0 and 1023 and are unitless.

Mother-FRED utilized a rotating sonar sensor that detected close proximity to an obstacle. If a nearby object was detected, this would override the robot's normal behavior to avoid said object. The rotation of the sonar was included for directionality purposes, where mother-FRED would turn away from the side where the object was most closely detected. The mother robot's behavior is further detailed in Figure 4.

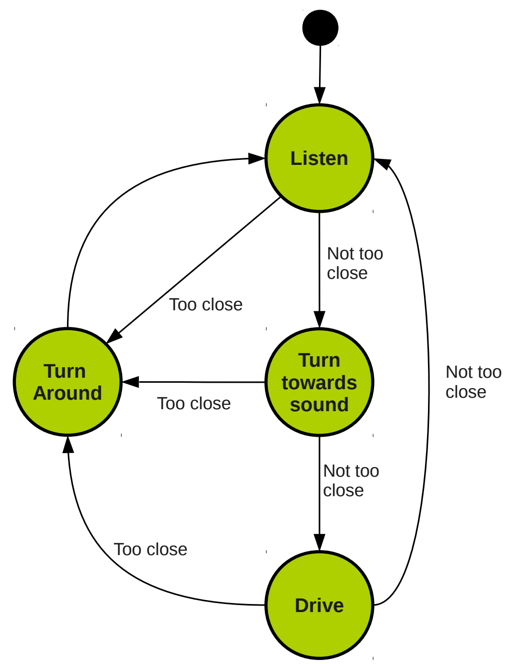

Fig. 4. Flowchart outlining mother FRED behavior depending on sensory input. Sonar input overrules microphone/sound input.

B. Emergence

Emergence was seen in several facets of robot behavior. One of the most functional emergent behaviors was that of obstacle avoidance in the mini-FRED robot. A light sensor was attached at the front of this robot for the primary purpose of light-seeking behavior. However, it was immediately apparent that mini-FRED was rarely, if ever, choosing paths that would lead to a collision with an obstacle in the room. Instead, mini-FRED would navigate obstacles, eventually converging to a light source where it would remain until it either ran into the light source itself or the object with the highest reflectivity of the light source. It was uncommon for this robot to encounter an obstacle outside of the nearby-realm of the light.

An emergent behavior of the FRED swarm stemming from the mini-FRED robot was swarm spreading. When the robots would converge to a local maximum light source, a cluster would form. This was expected behavior. Inevitably, as the cluster became larger in number and more compact in size, the mini-FRED robots would collide with one another triggering a touch sensor on one or more of the robots. When this occurred, those robots would turn in place and select a new trajectory. This led to the divergence of the cluster once it reached a "critical size". This behavior was never planned for, but shows a striking resemblance to nature. It is often seen that large hives, colonies, or even societies of humans begin to explore for new habitats once the original habitat becomes over-populated. In nature this is often the result of a depletion of resources and space, a behavior mimicked by the FRED swarm.

Another, less common emergent behavior of the FRED swarm was line following. When the divergent behavior described above happened in a semi-sequential manner, the mini-FRED robots would occasionally set off on similar paths. When this happened, a line of mini-FRED robots would form. Because of the strength in directionality of the signal, the mother-FRED robot would inevitably converge at or near the back of the line. This behavior was seen twice in the test runs, as evidenced by Figure 5.

The mother-FRED robot showed interesting behavior that emerged from the morphology of the robot. Wall following behavior was observed in many of the test runs. This was the result of the coordination of sonar-based obstacle avoidance and false microphone readings from wall-contact. As the mother robot would approach a wall at an angle, the sonar sensor would indicate to turn away from the impending collision. In doing so, the back of the robot would swing towards the wall. The wall-side microphone was located at the back of the robot and would therefore contact the wall. The movement of the wall on the microphone would lead to false large readings, and thus the mother bot would choose the next direction as toward the wall rather than away from it. As the mother turned back towards the wall, the sonar would trigger the obstacle avoidance logic, and the process would cycle. This led to wall following behavior until the behavior

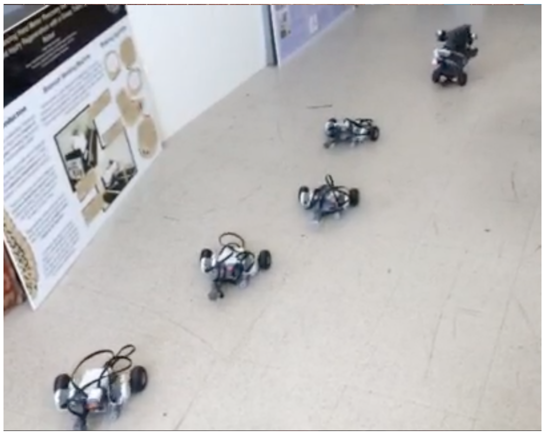

Fig. 5. Line following behavior example.

was broken by a nearby mini-FRED robot loud enough to turn the mother-FRED away from the wall.

Section V-A outlines the intended behavior of mother-FRED. It was immediately apparent that this robot's swarm interaction was not exactly as intended. Instead of converging with the largest cluster of mini-FRED robots in the highest light, the mother robot would often show indecision between the several local clusters (maxima). As such, the mother spent the majority of its time spatially distributing itself between various clusters of mini-FREDs. Only when the cluster of mini-FREDs became sufficiently large would the mother robot converge to the solution (see Section VII-C for more information about sound sensitivity).

VI. SELF-ORGANIZATION

Self-organization in the FRED swarm can be devolved into two primary methods: shared value and designed organization, outlined in sections VI-A and VI-B. Values of the FRED swarm can be seen in section III-H. Designed self-organization was realized through use of inter-robot communication achieved by auditory cues and a coding scheme defined in equations (1), (2), and (3).

A. Shared Value

Clustering of the mini-FRED robots was achieved through shared value alone. Because all mini-FRED robots utilized the same programming, it would be logical that they follow similar behavior. Their primary value was to search out ambient light in nearby areas, as defined in section III-H. In a highly controlled or simulated environment, the robots would act identically. In reality, uncontrolled variables such as sensor calibration, random noise, shadows from nearby robots, and initial conditions led to differing albeit similar behavior. Due to the shared value scheme of the mini-FRED robots, they often clustered together near a light source before diverging as described in V-B.

B. Designed Self-Organization

The designed aspect of self organization arose from communication between the mother-FRED robot and mini-FRED robots. Communication was achieved by auditory cues and a coding scheme defined in equations (1), (2), and (3). The designed organization behavior was for the mother robot to converge on clusters of mini-FRED robots that are in the highly lit areas. It would do this by listening for directionality of high-volume, high-pitch tones in search of the sub-swarm of mini-FRED robots. However, it was found that the mother exhibited indecision until the sub-swarm mini-FRED clusters reached a critical volume that would allow the full-swarm convergence, see Section VII-C for more information about sound sensitivity of mother-FRED. These behaviors are further outlined in V.

TABLE I
3 ROBOT CLUSTER TIME PERCENTAGE

	No Light	Light
No Mother	4.33%	17.33%
Mother	3.00%	35.33%

TABLE II
4 ROBOT CLUSTER TIME PERCENTAGE

	No light	Light
No mother	1.00%	7.00%
Mother	0.67%	24.67%

VII. RESULTS

A. Experimental set up

The whole swarm was placed in a controlled environment for five trial runs. Each run lasted approximately five minutes. The initial conditions of the robots were randomized to negate any initial patterning behavior. The surface of the trial run area was smooth, mimicking the behavior of SBSG 240, where the swarm was designed to operate. Due to the nature of abnormal obstacles strewn about the laboratory floor of Engineering Gateway Biorobotics lab, where the recordings took place, an area was cleared and walled in using smooth, clean walls.

B. Clustering metrics

The recordings of the 5 runs were analyzed and processed leading to the following aggregate results and Tables I, II, and III. It was found that the robots formed a cluster of 3 or more robots (regardless of the type) for 60% of the time, a 4 or 5 robot cluster 33.33% of time and a 5 robot cluster only 8.67% of the time. The 5 robot cluster was only observed in the lit region of the set up. It is also remarkable that in all three cases (3, 4, and 5 robot clusters), when the clusters exist, they are most of the time in the lit region of the set up environment and with mother-FRED being part of it. These results portray the behavior expected in Section III-H.

TABLE III
5 ROBOT CLUSTER TIME PERCENTAGE

	No light	Light
No mother	0.00%	0.00%
Mother	0.00%	8.67%

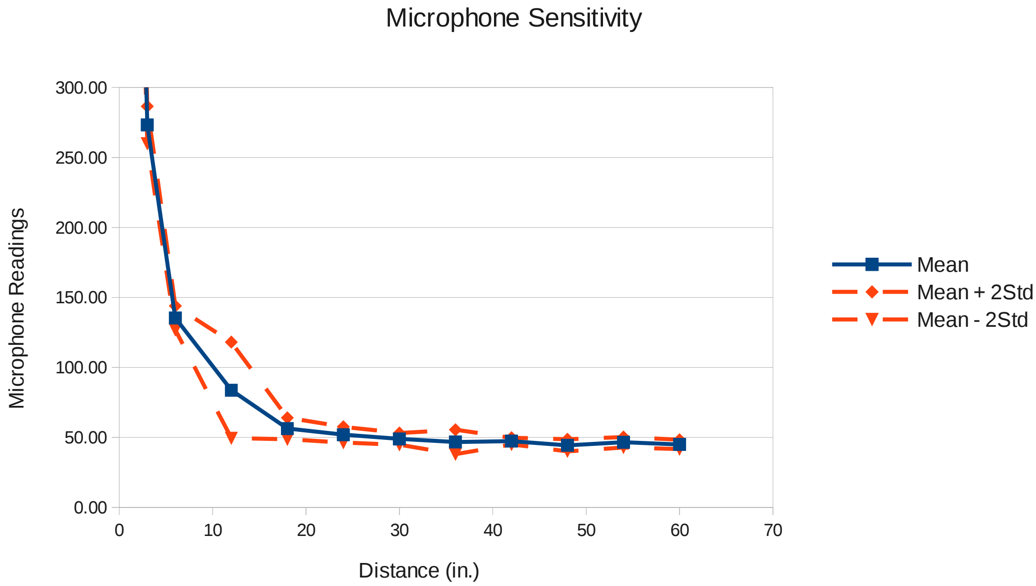

Fig. 6. Microphone value readings as a function of distance from sound source.

C. *Sensor metrics*

Microphone value readings as a function of distance from a constant sound source can be seen in Figure 6. The testing was done by approaching one of the mini-FRED robots playing a constant tone to the mother-FRED robot starting at 60 in. and with the final measurement taken with the speaker barely touching the microphone. The main conclusions from the microphone testing are: first, the readings are very nonlinear, and second, the microphones struggle to detect the mini-FRED robot at a distance larger than 20 in. Both traits can be seen in Figure 6. The consequences that stem of these two conclusions are: mother-FRED struggling to detect mini-FREDs swarms (as previously explained in Sections V-B and VI-B) and mother-FRED becoming over sensitive when too many mini-FRED robots are close or when one microphone hit the wall (as also explained in Section V-B).

Light sensors exhibited a satisfactory response and were not tested.

VIII. Conclusions

Swarm robotics provide an interesting and dynamic platform by which to study both robotic, neural, and animal behavior and cognition. Swarm robotics are especially useful for studying complex emergent behaviors that are based in simplistic behaviors and neural processes. The FRED swarm was designed using simple design principles including the Pfeifer and Bongard principles outlined in [1]. Directionality design took inspiration from Braitenberg vehicles [2] (attraction to light). The FRED swarm also borrowed some simple behaviors seen in nature, specifically that of honey bees [4]. There are two type of agents in the robotic swarm: four “mini-FRED” agents and one “mother-FRED” agent. Mini-FRED agents search for light while performing basic obstacle avoidance. In contrast, mother-FRED is completely blind to light but is provided with three microphones that provide directionality of high-volume, high-pitch tones in search of the sub-swarm of mini-FRED robots.

Clustering of the swarm at or near the primary light source in the environment was seen in all five trial runs. The robots formed a cluster of three or more robots (regardless of the type) for 60% of the time, a 4 or 5 robot cluster 33.33% of time and a 5 robot cluster only 8.67% of the time. The 5 robot cluster was only observed in the lit region of the set up. In all three cases (3, 4, and 5 robot clusters), when the clusters exist, they are most of the time in the lit region of the set up environment and include the mother-FRED robot. Emergent behavior was observed in both robots, as well as the collective swarm. Mini-FRED exhibited excellent obstacle avoidance through light-sensing alone, and rarely needed its degenerate touch sensing capabilities. Emergence was especially apparent in the mother robot who showed wall-following, and spatial centering behavior not designed for in the robot’s construction and programming. The swarm showed light following and clustering behavior as expected, but also exhibited exploratory behavior when the cluster became large enough.

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