Framework for Present Swarm Robotic Systems and New Implementations to Increase Scalability

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Abstract: Existing Swarm Robotics systems are focused on robustness, flexibility, and scalability. However, amongst the three features, scalability in many systems isn't addressed sufficiently. This paper makes a case for scalability by focusing on the important aspects of acquiring positions of the robots and handling communication between robots. After researching and comparing several existing Swarm Robot systems, a new system named Swarmesh, which uses infrared for positioning and WiFi-Mesh for communication, was proposed. Further development is discussed to address optimizations to the system.

Keywords: **Swarm Robotics, Infrared Location, Mesh Communication, Scalability**

1. INTRODUCTION

1.1. Background of Swarm Robotics

In recent years, "Swarm Robotics" [1] has emerged as a study of a complex system of simple yet interconnected robotic agents. Together, agents communicate to solve a bigger universal task through nothing more than their sensory input and without any connection to an external centralized database. By coordinating "large groups of relatively simple robots"[2], this field of research explores how communication within large groups of identical counterparts transforms simple instructions into complex behaviors. Swarm Robotics increases the success rate of designated tasks, especially those that are hard for one robot to solve alone. An example of a real-life Swarm Robotic application is using a swarm of robots to do search and rescue after natural disasters [3]. However, there are many more optimizations and crossovers in fields ranging from "mechanical autonomy, data mining, drug, and blockchains" [4]. Swarm Robotics systems have many advantages over other systems, given that they typically have very simple components. "Thus, the robotic units could be, in principle, modularized, mass-produced, and could be interchangeable and maybe disposable…" because it focuses on robustness, flexibility, and scalability [5][6]. Among the three features of Swarm Robotics, this paper mainly focuses on scalability.

1.2. Significance and Issues of Scalability

Scalability here not only refers to the number of robots in the system relative to the space it takes up in an environment (also referred to as swarm density) but also handling adding, and dropping robots from the swarm system [7]. Adding more robots to the system will bring many benefits, such as increasing the system's computation power and sensing ability in an area of operation. This feature is crucial to adapting the robots for different tasks. For example, when the system needs to move heavy objects from point to point, more robots will be needed. With scalability, the system is also fluid enough that the number of robots can be reduced when the environment becomes smaller. It is easy to adapt a quick surplus or subtraction to the swarm's population. In this aspect, Swarm Robotic architecture makes its characteristic of scalability extremely important towards further development of better robotic systems. As of now, due to problems such as cost restraints, lack of technical know-how, as well as the hardware limitations of robots when communicating with each other, many Swarm Robotics systems lack scalability.

1.3. Potential Solution to Increase Scalability

The scalability of a Swarm Robotics system can be improved by the aggregates that improve swarm density. In this sense, swarm density changes by using different methods of communication and positioning. Improving the methods for the Swarm Robots to acquire global information (emphasis on communication), as well as lowering the buildup of inaccuracies each robot makes relative to its position within the Swarm (emphasis on positioning) can increase scalability.

2. REVIEW OF EXISTING WORK

Many universities and institutes have built Swarm Robotics systems. The notable ones include Kilobot from Harvard University[8], R-one from Rice University[9] and Jasmine from the University of Stuttgart[10].

A breakdown of each of these systems is as follows, with a summary and synopsis on implementations that compare their pre-existing communication and positioning methods to a new outlook of scalability in the upcoming sections:

Table 1 Existing Systems [11] -

Name	Communication + Positioning	Positioning Description	Dimension/ Diameter (cm)
Kilobot	Infrared	Infrared	3.3
Jasmine	Infrared	Infrared	3
R-one	Radio, Infrared	Infrared	10

All of the three systems use infrared (IR) for positioning and communication, however, the ways they utilize IR are very different. For Kilobot, each robot only has one IR transmitter and one IR receiver. The IR transmitter emits IR light on a white surface, so the robots nearby can use the IR receiver to know the distance between the robots and perform simple communication [8]. The way R-one and Jasmine use IR is similar. Both systems have IR transmitters and IR emitters around the robots so that they can know the distance between each of the neighboring robots [9][10]. However, to simulate real animals that work in swarms, Jasmine also uses IR for robot-to-robot communication. Contrarily, R-one adds radio to each robot to increase their power, therefore enable them to broadcast messages to the whole swarm system[9].

3. METHODS

3.1.1 Positionings

The positioning system has a direct impact on the scalability of the Swarm Robotics system. The research of Han Wu, et al. points out that "Precise localization" is the key to achieving "coordination and control of swarm robots" [12]. Without a precise, immediate positioning system when scaling up the Swarm Robot entity, the system would have difficulties discovering neighboring robots. This results in unexpected collisions between each unit, compromising the completion of tasks, thus reducing the scalability of the system.

The existing Swarm Robot platforms' positioning systems lack an ideal positioning system because it is not completely reliable. Kilobot [8], despite being able to measure the distance between robots based on the intensity of IR radiation, still is incomplete in perceiving the environment. When one robot receives radiation, it cannot determine the orientation of the robot emitting radiation. Such imprecise positioning greatly reduces the scalability of the system when adding or dropping robots from the system, since the extra examination on the exact position of its neighboring robot required will undermine the immediacy. Meanwhile, Jasmine is only capable of perceiving its surrounding environment, such as detecting obstacles [10]. The inability to measure robot-to-robot distance makes the Jasmine swarm unable to accomplish numerous swarm behaviors, such as following or patrolling. Given these systems' problems, new positioning systems must prioritize both distancing and perceiving more accurately to help with scalability.

3.1.2 Positioning Implementation: Infrared

The positioning system of the system built (hereafter named Swarmesh) uses eight F5 of 5mm IR emitters and eight IR receivers. Different from Jasmine [9] (Fig. 1) whose IR receivers face out and collect IR signals directly, the IR receivers of the Swarmesh system face up and receive the reflection of the IR signal from a 3D-printed cone. The design has two components, the receiver plate and the emitter cone, each holding eight receivers and eight emitters (Fig. 2). The emitter cone and the receiver plate form a 45-degree angle. The eight receivers are arranged in a circle, pointing vertically upwards; the eight emitters are placed horizontally outwards from the emitter cone.

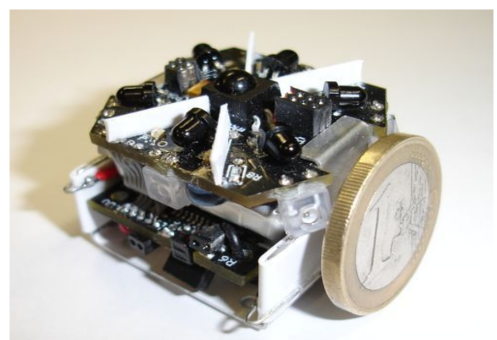


Fig. 1 Photography showing the positioning IR emitters and receiver on Jasmine [10].

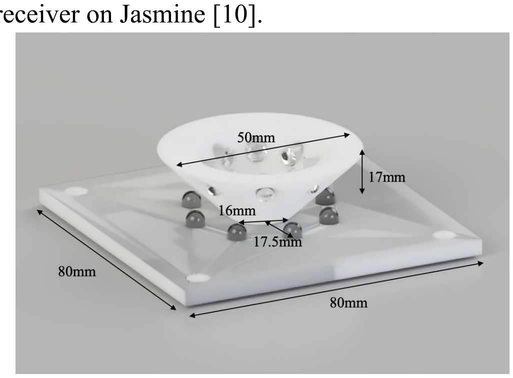


Fig. 2 Swarmesh mechanical drawing showing the dimensions of the assembled plate and cone.

The circuit of the emitters and receivers are implemented on an independent PCB (Printed Circuit Board) attached to the receiver plate, as shown in Fig. 3. The main control board of the unit connects to the PCB via a 10 pin connector cable, which powers the circuit with 3.3V voltage, controls the IR emitter and reads the data from the IR receivers. An 8:1 multiplexer model CD4051 on the main PCB samples the analog input from the receivers before passing the readings into the microprocessor's Analog to Digital Converter module. The distance between the robots is inversely correlated to the analog readings from the IR receivers. The estimations of the distance between robots are derived from multiple quantitative experiments.

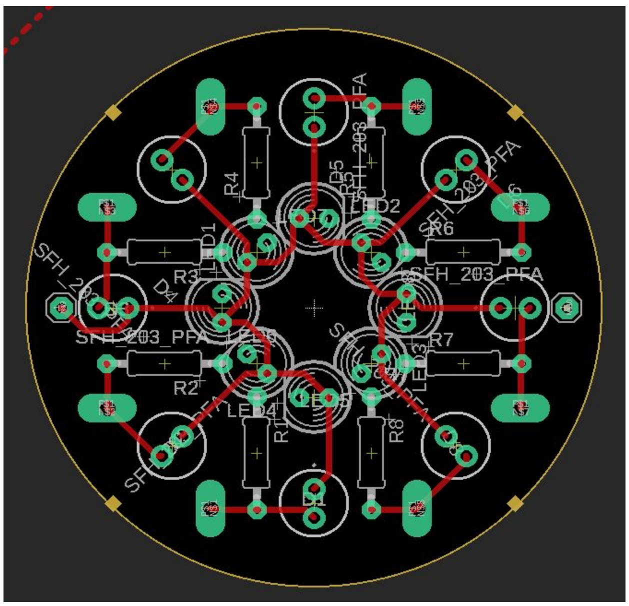


Fig. 3 PCB design for the positioning mechanism.

3.2.1 Communication

Many methods have been researched to handle communication tasks between robots, such as observing the interactions between the robots and the world, observing the behavior of other robots or using an explicit communication system [13]. Among these methods, explicit communication systems have the best performance when handling communication tasks. However, the stability of the system becomes crucial when applying it in multi-robot systems [13]. Two common methods in current existing systems are infrared (IR) and radiofrequency (RF). Examples of systems that use IR to communicate are Kilobot [8] and Jasmine [10]. In both systems, IR signals are encoded with messages but have limitations. Each robot needs to be in direct sight of another robot to communicate with each other. Another example is the system implemented by R-one, which uses radio waves as the communication method but it also has limitations [9]. Such limitations include having to create ways to handle message collisions between two robots when the communication channel is occupied. Another limitation lies in the valid communication range of the robots. It is limited by the signal coverage range of the communication module on the robots, which also causes difficulties to cooperate with all the robots in the system. Per definition, the scalability of the system is equivalent to its ability in adding and dropping individual robots from the system. Even for traditional WiFi communication, there exist certain limitations. With WiFi, getting information about every robot is easy, but the number of robots within the system depends on the router. The WiFi-based system has a central router that receives information from different robots and distributes them to the target robots. This causes problems when the system begins to grow because the number of devices that can connect to one access point is usually limited. Besides, it also faces the problem of the limited operating range. Robots must operate in the area where they can receive the signal from the WiFi device, which is another form of limitation.

3.2.2 Communication Implementation: Wifi-Mesh

Considering all the aspects above, a WiFi-based mesh system was designed to handle the communication tasks for the swarm system. The mesh network is implemented based on ESP-Mesh [14]. Instead of traditional star-shape network structure, the Wifi-Mesh network uses a tree-shape topology. Every robot can act as either the root, the intermediate node or the leaf node. Root nodes and intermediate nodes will store all the Media Access Control (MAC) addresses of the robots within the tree network. This structure makes adding robots to the system easy. Each robot will automatically connect with its closest neighbor and become its child node. Then, all robots existing robots in the network will update their address table. When a robot tries to communicate with another robot, it will first search whether the target robot is in its address table. If not found, it will continue searching for its parent's address table until it reaches the root. Design-wise, the number of robots in the system could be unlimited, providing the system with great scalability.

Furthermore, the mesh system has the additional advantage of being stable, given the way that the system manages network connections. The mesh network constantly monitors whether there are new robots activating their mesh communication function. It then assigns parent nodes with strong signal strength to this robot and adds it to the system. When mechanical or software errors occur to one robot, it will disconnect itself from the system. Its parent nodes will also pop its MAC address from their address table.

4. TEST SETUP & RESULTS

4.1 Infrared and Testing

During the pilot tests, the voltage reaches its peak at around 3000mV, when the distance is at 10 cm. With distances greater than 30 cm, the voltage is around 200mV. Considering the influence of ambient light (mostly sunlight), which makes the readings rise, the upper bound of detection is set at 30 cm. Thus, the distance in the full-scale tests ranges from 10 to 30 cm. The full-scale tests were implemented with two robots, where one robot receives the IR signal and the other robot emits IR signal (Fig. 4). The test was performed on a test board designed for the task. The robot receiving IR signal is fixed at the center of the bottom line, while another robot that is not shown emits IR signal at different locations on the test bench specially designed to collect the data points (Fig. 5). This test collects the voltage readings from the robot emitting IR signals. Voltage signals were measured every increment of 5-degree angles starting from the 90-degree line to the 67.5-degree line on the protractor. This measurement was repeated with varying length, measured at intervals shown by the figure, from lines labeled 11 to 20 (Fig. 5). During the tests, one emitter on the emitting robot always points at the center of the receiving robot's receiving cone. The voltage of receivers one to five was recorded (receiver six to eight were not recorded as it was found in pilot tests that the cone blocks the IR signal from emitting the receivers at its back). The voltage data is mapped to the distance and angle.

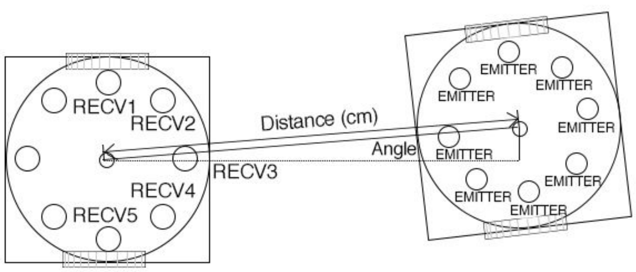


Fig. 4 Diagram of positioning test.

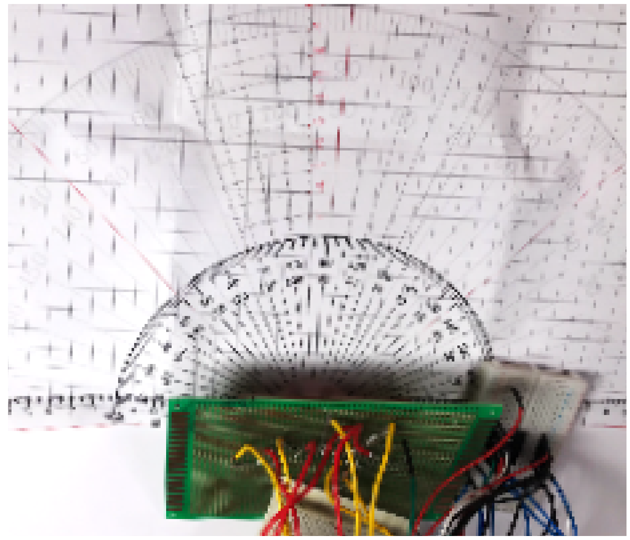
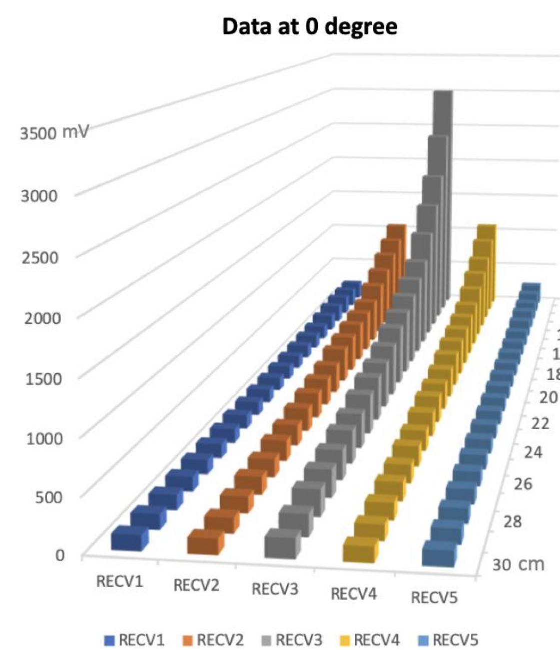


Fig. 5 Bottom view of IR positioning plate and IR cone in the testing bench, driven by an auxiliary circuit to collect the information of the data points.



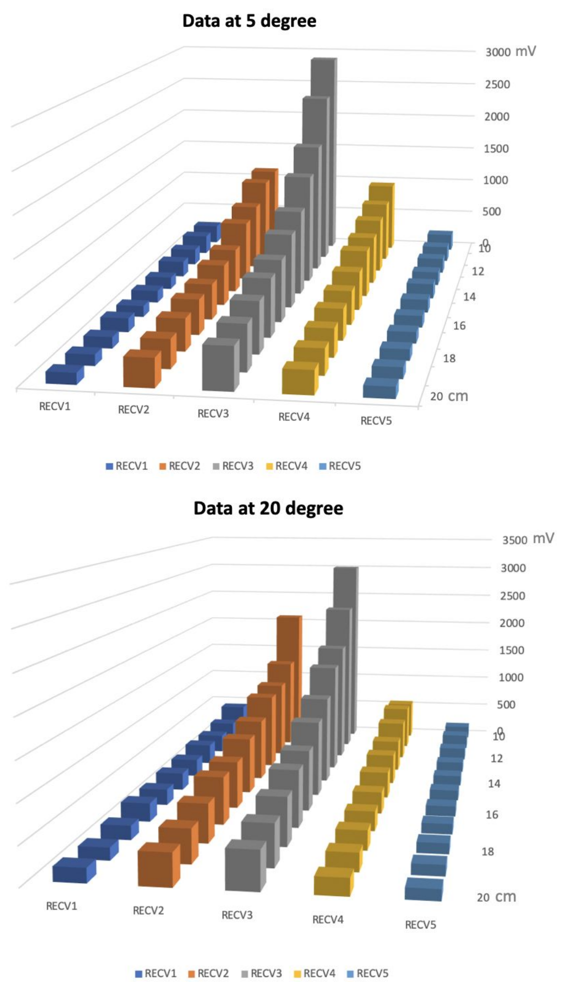


Fig. 6 to 8- Chart showing IR receivers' voltage when the emitting robot is at different positions. The angle between neighboring emitters is 45 degrees, the values in the chart is the voltage of individual emitters.

Originally, modeling emphasized on the orientation, distance and their corresponding readings of eight receivers. By inputting readings from all eight receivers, the model can output the position, namely the distance and orientation of the robot emitting the IR signal. However, during the pilot tests, this was proved to be impossible, as there are too many variables involved in positioning. But through the data, the sum of the voltage from all the receivers represented the distance in a simple but relatively accurate way. The relationship can be seen in Table 2.

Table 2 Distance and the corresponding sum of readings

sum*> 4926mV	sum ≥ 3426mV	sum ≥ 2426mV	sum ≥ 1826mV	sum ≥ 1426mV	sum ≥ 1226mV
11-12 cm	12-13 cm	14-16 cm	17-20 cm	21-25 cm	26-30 cm

* sum equals the summation of all eight readings

The orientation of the robot emitting IR is calculated using the receivers with the top three voltages. If the receiver with the greatest voltage is in the middle of two other receivers, the system will take this as a valid input. The program then regards the receiver with the greatest voltage as the central receiver and calculates the angle between this receiver and the symmetric line of the robot. Then the range of orientation is from (angle - 22.5) to (angle + 22.5).

4.2 Overall System Analysis

4.2.1 The number of receivers

The number of receivers, according to the experimental results (Fig. 9) from the Jasmine swarm [10], make up a reception area using an IR receiver that is petal-shaped. When the number of IR receivers is insufficient, this limitation leads to blind spots in the robot's detection area, thus greatly compromising the visibility of the positioning system. The ideal solution is to increase the number of receivers such that all blind spots can be covered. The amount of receivers also influences the accuracy of orientation measurement. As described above, the design measures the orientation of another robot based on the zone of the receivers with the top three readings. Thus, more receivers will increase the resolution of the orientation measurement. Notwithstanding, the limited pins number and power supply also restrict the number of receivers. On the Swarmesh, it not only covers more area by implementing eight receivers but also reduces the number of pins being used with an 8:1 multiplexer.

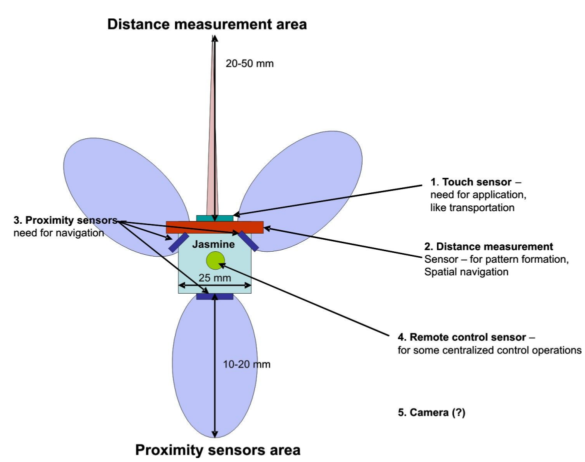


Fig. 9 Diagram of IR receivers on Jasmine (seeing from the above) [10].

4.2.2 The Number/Opening Angle of Emitters

To ensure one robot is discoverable by other robots, the IR radiation emitted needs to be as strong as possible. But as Fig. 10 shows IR emitters also have the petal-shape radiant area, which will also result in blind spots in its radiation area. Simply increase the number of emitters will also result in too much power in-take. Another solution is to implement wide-angle IR emitters, which could easily cover a wider range without too many of them. However, such emitters often sacrifice the distance of radiation for the opening angle. Therefore, the system used eight F5 emitters (non-wide-angle emitter), which has the biggest opening angle and will not take too much power.

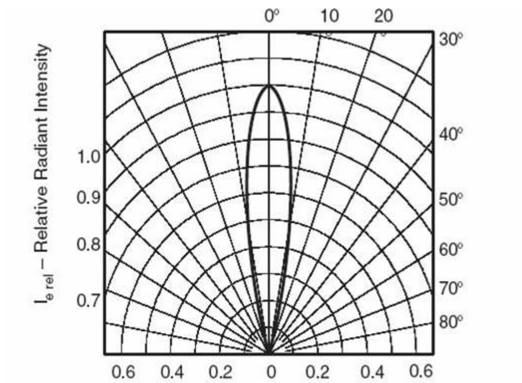


Fig. 10 Diagram of IR emitters on Jasmine [10].

4.2.3 Direct/Indirect IR radiation

As discussed in the first point, a limited amount of IR receivers result in the robot having blind spots within a detected range. In addition to increasing the number of receivers, another solution is to increase the design of the positioning mechanism. On Swarm Robots such as Jasmine [10], blind spots will occur because both the receivers and emitters face outwards. In the Swarmesh design, the radiation shoots on the cone, which then reflects and diffuses IR radiation, thus enabling more receivers to receive the IR signal. According to Fig. 11, when the emitter is shooting at the middle of two receivers (the orientation of the other robot is at 22.5 degrees) from 200 mm away, the receivers are still capable of receiving the IR signal.

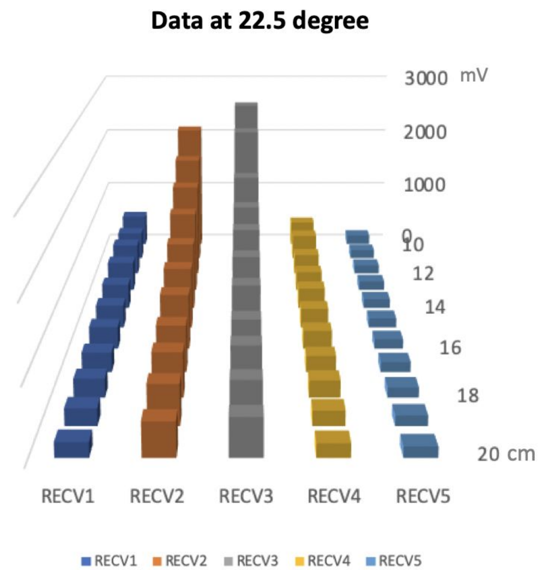


Fig. 11 Readings of the emitter shoot in the middle of two receivers.

5. DISCUSSION & FUTURE WORK

This paper has explored ways to improve the system's scalability. The main focuses were on the inter-communications between robots and the relative positioning approach. The proposed methods provide relatively low cost, yet stable performance. Since the system requires no extra hardware, the test space of the robots can be simplified.

5.1 Size & Mechanical Design

Swarmesh's current design is 80 mm x 80 mm. Compared to other robots like Jasmine, which are only 25 mm wide, Swarmesh is larger in size [10]. This means that certain robot behavior tests are more complicated because the area must suit the experiment needs. Further work can be done to design each unit to be smaller, and with an optimal design, allow robots to be more easily assembled and their batteries replaced.

5.2 IR environmental disturbances

The current design utilizes continuous IR signals to measure the distance between units. This technique requires filtering and a controlled environment, as IR emissions from each mobile unit can be influenced by any change of ambient light. Testing Swarmesh in an environment with daylight compromises the IR signal to some extent. The design of Swarmesh includes, within the electrical circuit, a possibility to pulse the signal emitted by each unit to filter environmental noise. However, further software development must be done to discover better solutions towards this aspect of the present design.

5.3 Infrared Angling Problem

Each Swarmesh robot unit faces the possibility of not having any of their 8 receivers pointing towards the center of another unit. Hence, robot communication is at risk of occasionally having a relatively weak signal. The scenario is represented in Fig. 12 is one of the most extreme cases, where direct IR reception is at the weakest signal. In these cases, the IR signal read is almost undetectable and will be calculated as "undetected," despite the close proximity. The impact of these situations must be analyzed with more experiments to evaluate if they could inhibit the entire Swarmesh's sensing ability significantly.

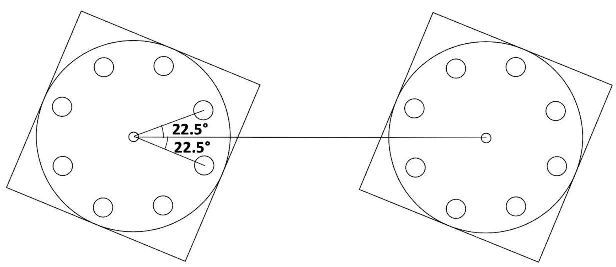


Fig. 12 The case where direct IR reception does not exist when the line connects centers of two Swarmesh both happen to bisect the 45° angle created by two IR receivers.

5.4 Mesh Communication

Swarmesh robots communicate by utilizing WiFi technology as a Mesh. This greatly improves the scalability of the robot system but presents some limitations. A limitation of WiFi mesh is the topology of the system. Since the mesh network has a tree shape structure, every data package that goes from one of the tree branches to another branch needs to go through the root. According to the document of ESP-Mesh [14], handling requests from child nodes requires each parent node to allocate space for its children's data packages. Before the child nodes send the data packages, they need to send a request to their parent node. The child nodes send the data packages only after getting confirmation from the parent node [14]. This procedure makes communication slower as more robots are introduced to the system. Therefore, a remedy to the communication problem is to use small data packages of 256 bytes per package for the instructions. This design theoretically works for over a thousand units simultaneously, but further testing is needed to confirm the scalability of the system.

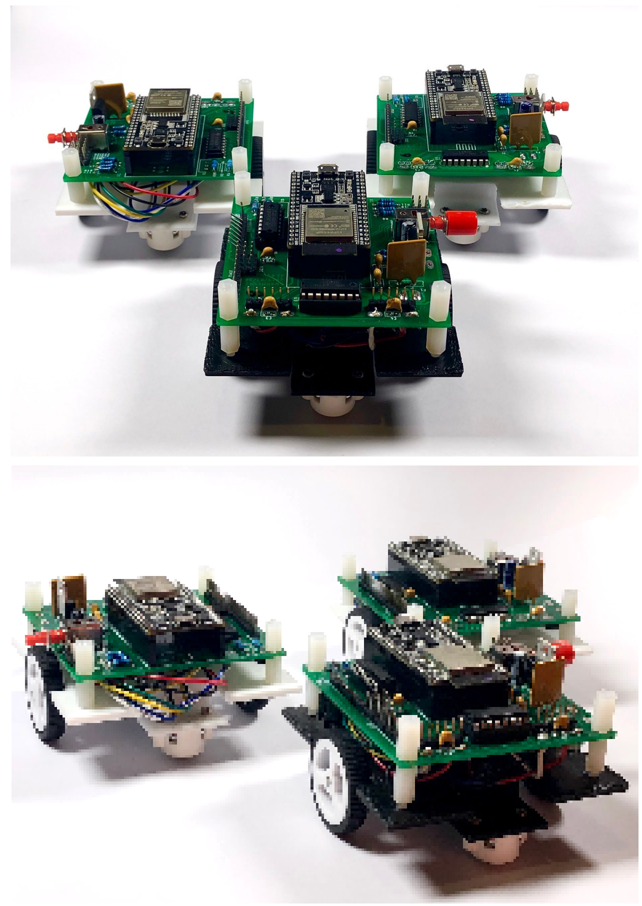


Fig. 13 - 14 The current system with mobility system, main PCB and ESP32 microprocessor implemented

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