Swarm Collaboration of Multiple Robots

[1]Muhammad Taqi Naveed, [2]Hassam Hassan
Department of Electrical Engineering
Institute of Space Technology
[1]Taqi9932@gmail.com
[2]Hassam_hassan@outlook.com

***Abstract* – In this paper we have tackled the implementation and working of multi-agent systems or simply swarm systems. Different types of systems are present in the hybrid approach to implement coordinated behavior in organisms. We selected the Swarm Intelligence system due to its efficiency, ingenuity and its ability to be scalable, flexible and robust, for our research of collaborative behavior of the three robots. To implement the SI systems three robots were used for this purpose. These robots were tested at the labs under various conditions to verify whether they can fulfill they requirement or not. The robots were designed and implemented in such a way that they maintain a line following sequence and triangle formation only through the use of intercommunication via wireless communication protocol. The results indicated that the robot that employ the swarm technology has the ability to not only surpass the other systems but also become a vital force in the future technology. This work highlights the further need of research in this area and how it can benefit other fields of interests.**

***Index Terms* – Swarm Collaboration, Multi-agent system, Formation maintenance, Swarms, Swarm collaboration**

I. Introduction

Multi-agent system, swarm systems, are based on the swarm principle. Nature has always been a prime inspiration for scientists to develop new technology. Through observation we are able to simplify and solve relatively difficult problems and thus improving the understanding of complex problems.[1]

From nature we take the example of coordinated behavior like that of flock of birds, school of fish, herds of animal etc. The animals work together in the form of a group to hunt or to avoid predators. This also helps these animals by increasing the probability in locating more food for the herd.

This is all done through the collaborative nature of these animals. Humans also working, in either firms and corporation, work by collaborating with each other and thus increasing the overall productivity .These are all the example of collaborative behavior of multi agent system that work together to achieve a common task.[2] [1].

Biologists have been working on understanding about how the animals interact with each other in a swarm. The main understanding of the biologists is that the swarm systems is a result of intercommunication among the individual components of the system.

Through the overlay of the important information these systems transmit important data to each other thus increasing the information of overall system.[1]

Engineers, Mathematicians and biologists are trying to employ the swarm collaborative system in their studies. Engineers are trying to build robots that have the capability to work by inter collaboration of the individual components in the system. By collaboration the overall performance of the system increases and system achieves a relatively new state of stability and durability.

In recent years the engineers have started working on the applications such as formation making of multiple robots and achieving a task by collaboration of these multi agent systems. Through these techniques many new perspective such as nano scale robots and aerial maneuverability can now be achieved which was though impossible before.[3]

A. *Motivation for Multi gent systems:*

For multi-robot system three characteristics: Scalability, Robustness and flexibility are eminent without these characteristics the purpose of swarm robotics is failed to be taken into account.[2][4].

Robustness can be defined as the ability of the system to withstand harsh conditions or the degree of how much a system can withstand failures and still work[5].Multi agent system following and working under the principle of "Social Insects" are highly robust. This is due to the property of swarm that even if an individual element fail other systems are present to replace it. This technique causes an enormous increase in the adaptivity of machine or system under harsh conditions.[3]

Scalability is organizing and collaborating the small or large number of individuals that constitute the multi agent system. Larger the number of individual small robots greater the scalability and robustness of the system thus increasing the performance of the system[6].

Flexibility is the ability of the multi agent system to adapt itself and change it characteristics to its respective environment without effecting the performance of the system. These systems have the property to organize and arrange themselves according to the problem they face. If a new problem occurs these systems changes their respective abilities to cater for problem under consideration.[5]

B. *Research Parameters:*

In this paper we have taken the multi agent system as a course of our research and working on its application in the field of robotics. Multi agent systems are flexible and durable than single systems. Therefore in our research we used the swarm collaboration for multiple robots. [6]

Our research comprise of multi agent systems that exhibit swarm collaboration through the prospect of formation making. The robots make the use of inter communication protocol and perform the task specified to them through the preprogrammed system.

At first we have studied the various other research done by previous researchers on the specified area. Through research we were able to find that there has been a limited research at application level of swarm robotics. Swarm robotics is still an emerging and there has been a very limited research on the side of formative collaboration of multi agents we have taken this under consideration for our research and tend to improve this so that future research can benefit from this.

This paper is based on actual factual experiment performed on the robots in the laboratory at the Institute of Space Technology. The results gained are through experiments performed on the hardware and software both. Our research paper comprise the area of swarm intelligence based on the working of collaboration of multiple robotic systems [7].

Swarm robotics is a very far and wide area of research, we have narrowed down our research to the area of formation making and collaboration of the swarm systems. We have employed the autonomous robots that can carry out their decisions based on the information gathered through their systematic intelligence.

The computation intelligence[8] is inspired through studying nature and the approach it takes to solve the complex problems. It is comprised of: Artificial Neural Networks that mimic human brain and follows a computational mechanism similar to the activity of neurons in the brain, Evolutionary Computing that follows the population evolution. It is actually following the Darwin evolutionary theory that is solving computation based problems through the use of evolutionary programs that changes and reprograms itself based on the problems that it currently faces. Then we have Fuzzy Systems that " approximate human reasoning using imprecise or, fuzzy, linguistic terms".[6] The fuzzy logic actually means the logic that comprise in the domain of human understanding we have fuzzy logic stated as reasoning based on approximation rather than fixed and exact values. Lastly we have Swarm Intelligence that is based on the behavior of social insects and their inter collaboration to work together to achieve the common goal. Our current research works on the SI behavior of the systems and working on the collaborative behavior of robots to achieve this task.[9]

C. Research Sections:

The research is done by studying and implementing the swarm logic on three robots. The robots were carefully selected through various testings in the labs at the Institute of Space Technology Islamabad. For ease of use the programming device used was Arduino due to its high memory and processing power.

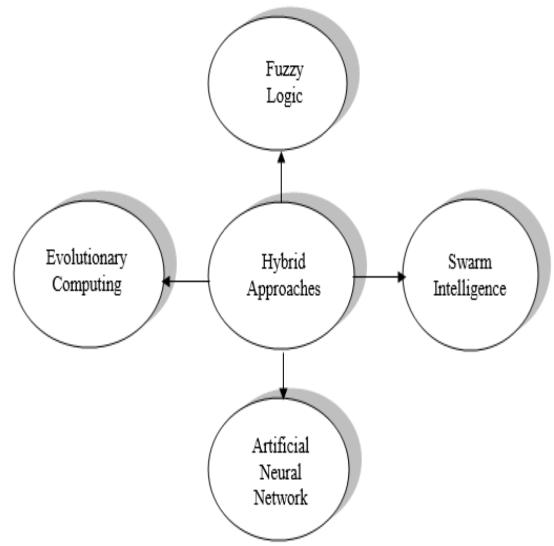


Figure 1: Computational intelligence paradigms

The research paper comprise the introduction first summarizing the swarm logic and its importance giving a brief overview of the swarm robotics and its advantages of other fields. Then the research methodology is presented that explains how the swarm collaboration was achieved in the robots through the use of various experimentations and testing.

Swarm collaboration is achieved using a master slave concept[10] in the current research instead of independent behaviour of the robots. Through the use of master slave concept we were able to ascertain the swarm principle using minimal resources. Through using this concept we verified that instead of a master robot we can replace it with a ground station or other form of system that can work the same as the master system in the swarm collaboration.

Various parameters are discussed in each section of the robotic accessory employed and its use in the robotic behaviour. [11] Different parameters are studied and included in the paper. Various formation techniques are described in the methodology and employed on the robots.

After the methodology the results are presented for the paper that include the various paradigms and conditions corresponding to the behaviour of the robots. The results are then tested with hypothetical computer simulated model and studied the differences with actual and theoretical results. Through them we were able to ascertain and verify the use of swarm robotic system in the current industry. It was to be kept under consideration that the sensing system of robots must have minimal interference from the external stimuli thus the robot can work efficiently under harsh conditions.

Finally conclusions are drawn from the acquired results that wether this method is applicable or not and can this method be used in the industry. Through the results however we were safely able to conclude that swarm robotics is a very diverse and greatly applicable field in the modern technological era and with a few leap of faith swarm technology can easily surpass other fields in mere decade.

There has been some major work done in the field of swarm robotics. Some work that we would like to mention here are the works of *Erol S¸AH˙IN* in the[7], [12] that really helped us in our research concerning the collaborative behaviour of swarm. Another work that we would like to point out is the application of swarm robotics in the field of military done by the LUMS university[4]. These are some of the works that we have studied and used in our current research paper to help us in our current area of research as swarm robotics is a field of limited research currently.

II. Research Methodology

A. *Research and Collaborative Behavior*

In our current research we used the 3 robots for swarm metal detection. The robots were carefully selected by continuous testing in labs at Institute of Space Technology Islamabad.

To verify the swarm behavior and swarm logic we made the robots make triangle formation and attain this formation throughout a series of obstacles. This has been done previously therefore we were able to get help through [10]. Further we made a robot master and made it a line following robot. The rest of the 2 robots were devoid of line following capabilities and only through intercommunication and transfer of information these robots were able to keep the formation. Verifying the use of swarm logic in this discipline.[13]

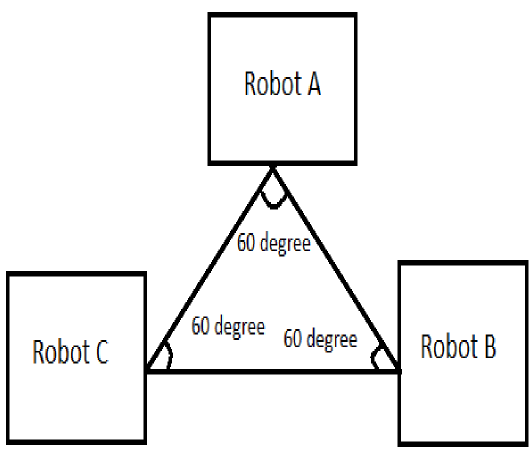


Figure 2: Triangle Formation of Robots

The three robots keep an equilateral triangle formed throughout the whole experiment even upon change in position or disturbance of one robot, the robots rearrange themselves in this formation keeping a distance of 5 meter among themselves and keeping a steady angle of 60 degree. [11]

The main objective was to keep the formation throughout the obstacle course. The running course was designed so that robots have to face the difficulty of maintain this formation and through the use of algorithm and smart programming this was achieved

Similarly for the formation of line following we used the line following protocol in the master robot and the slave robots were devoid of this facility. They had to maintain and follow the master robot purely through the use of inter communication and nothing else.[14] Again the robots were run through an obstacle course based on the line following mechanism and checked whether these robots tend to follow the implied swarm principle or not.

The slave robots must keep a distance of 5 between itself and master robot at all times and must maintain this distance throughout the scenario.[15]

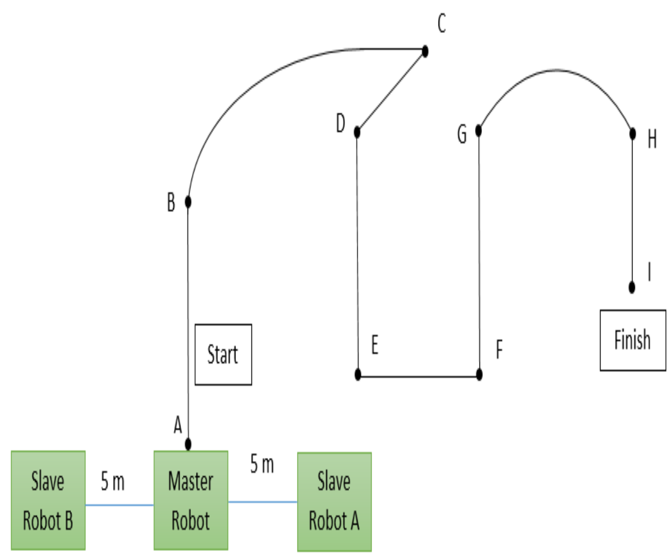


Figure 3: Initial test course for line following and triangle formation systems

Final obstacle course used was based on the design used by National Robotics competition at the 2010 National Robotics competition. This is a simple and easy to use design and we employed this design for our final testing of the robots.

The criteria of distance and angle achieved through the use of two techniques:

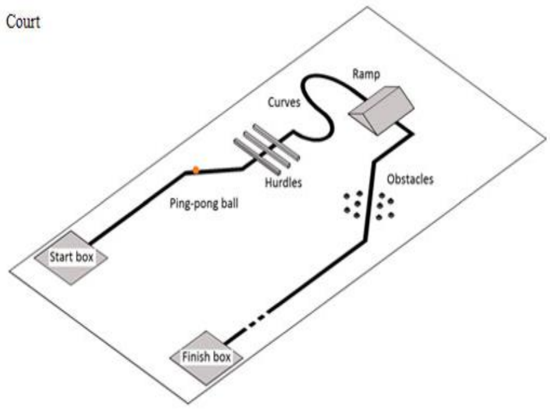


Figure 4: Obstacle Course used for final testing[16]

(i) Distance Measurement:

Distance measurement was achieved using the Ultrasonic sensors. In the triangle formation the master robot has the ultrasonic sensors at 3 positions. Through the use of IET algorithm used by the Tatsuya Kato*, Keigo Watanabe and Shoichi Maeyama in [10] we were able to make the triangle formation and achieve this

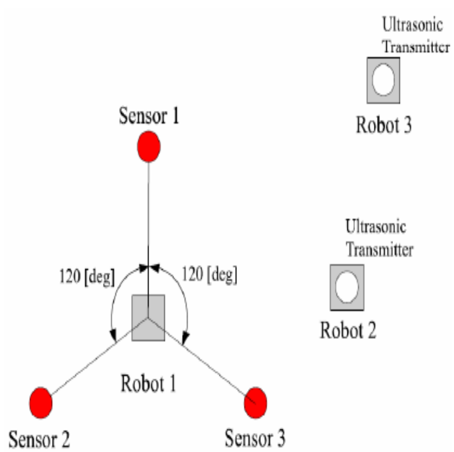


Figure 5:Position of sensors[10]

Now this method has been briefly explained in the [10]. However we also employed the use of IMU for the calculation of the positing of the respective robots.

In the case of Line following technique we installed the algorithm that all four sides of the robot have the ultrasonic sensors. Through this the master robot has a clear field of view of its sides. Using the IR pair we were able to ascertain the difference between the master and slave pair of robots.

If the robots go out of the position they were calibrated in such a way that the master robot stops until the out of place slave robot attains the desired position vice versa.[17]

The angle is kept at 60 degree as all the sides of an equilateral triangle are same therefore this angle was easy to maintain if the distance was maintained. The distance maintaining was however quite challenging and catering for external stimuli was the major task.

(ii) Angle Measurement:

The angle measurement was done using the magnetometer and digital compass in both line following and triangle formation robots. In line following case when the robot took the turn the magnetometer measures the angle and transmits the angle change to the slave robot. The slave robot follow this action of the master robot and make the respective turn when necessary thus keeping up with the master robot in keeping the formation and distance throughout the course.

The formula for angle calculation is

$$\Theta = tan^{1} y/x$$

This is only true when the compass is on flat surface however in case of tilted surface we have

$$X_h = X * cos\ (alpha) + Y*sin\ (gamma) *sin\ (alpha) – Z *cos* (gamma) *sin\ (alpha)$$

And

$$Y_h = Y*cos\ (gamma) -Z*sin\ (gamma)$$

Through the use of above mentioned formula we were able to calculate the X and Y thus calculating the angle for the tilted surfaces.

(iii) Communication Protocol:

Communication between the master and slave robots was done using the RF transceiver pairs. They are cheap and have the capability to transmit to communicate over large distance using less power.

The master robot transmits continuously its current location and its angle so that if the slave robots are out of sync it can make the proper adjustment and make the robots stay on the course of its movement. The transmission protocol has to be very fast for it to work otherwise this will fail under the conditioning of fast feedback response systems.[18]

B. Procedure:

The motors in the robots have been calibrated using the Pulse width modulation so that there are no shocks occur upon the turning of the robots. This is done in all master and slaves as it is a basic mechanism that need to be installed. The narrow pulses are given in case of turning and wide pulses are given on the straight line movement.[19]

The robot follows the line or keeps up the triangle formation throughout the obstacle and then transmits its location and data to the slave robots. The slave robots follow the master robot and are devoid of all sensors except the communication protocol and IR transmitting end.

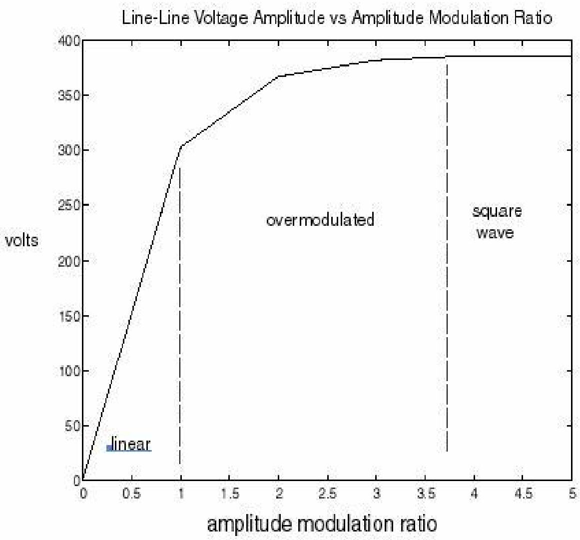


Figure 6: Pulse width modulation wave form

Upon the running of the robot they exhibit the swarm behavior by the use of intercommunication protocol. The robots were programmed so that if any robot goes out of place in the formation the system stops and calibrates itself first then keep the process going on. [20] However this is done only in the beginner stages of communication protocol and not done on the scale of large number of robots.

As the number of robots increases in a swarm the redundancy increases and it becomes much more difficult to calibrate the robots therefore this is done on small scale currently and at later stages this will be research will be done to maintain the pentagonal and hexagonal formations on the obstacle course.[21]

The robots are calibrated at high pressure and temperature testing labs so that we are able to use the swarm systems at places where human beings are unable to perform such as nuclear spillages and at high temperature areas.[22] Due to presence of limited budget we were unable to use the high quality IC's and Boards for our research and have to do with the medium quality instruments to gain data and get research values for the current scenario. [23]

Data gained through these experiments was tested many times and it was verified that for certain conditions this data is applicable for large scale networks too.

C. Programming and Algorithm development:

For the robots we used Arduino boards as the base of our programming and data handling. Arduino boards are fast and much more precise than the normal boards and due to the fast computation and ease of use these boards are used quite a lot in the projects.

Arduino built in libraries and programming was used for this research however a whole new algorithm and program was developed to gain appropriate feedback and calibration of the systems.[24] Using the Proteus software the circuits were tested before hand before implementing on the system under consideration. Matlab simulations were performed to check the stability and working of the system.

III. RESULTS

The results obtained were quite similar to the computer simulation performed.

A. Line Following Technique:

In the line following collaboration we gained the results with an error of 3%. The robots were able to successfully follow the Master robot pattern with a delay of 2 seconds when no obstacle was placed. [25] However in the presence of obstacle the slave robots lagged behind the master robots with a delay of 10 seconds however it was catered through the use of programming and improving the algorithm. This delay was reduced to 5 seconds.

(i)Phase Calculation:

Main problem occurred during the turning of the master robot and the follow up of the slave robot. Master robot was not measuring the angle precisely using the magnetometer so to overcome this problem we employed the IMU and digital compass.

Sr. No	Theoretical phase	Actual phase using magnetometer	Difference in the phase
01	0^o	9.68^o	9.68^o
02	45^o	53^o	8^o
03	90^o	107^o	17^o
04	180^o	196^o	16^o
05	360^o	373^0	13^o

Table 1: Phase calculation for Line following System using magnetometer

The error was caused due the interference of the electromagnetic waves that caused distortion in the magnetometer [26]. This distortion caused error in the measurement which in turn made variation in the movement of the slave robots.

The slave robots due to this difference in angle did not follow the exact path as that of the master robot. This difference in phase causes a serious problem in overall movement of the robot thus causing the robot to fail at the sharp turns.[27] This is a serious problem for the system in collaborative movement.[28]

Sr. No	Theoretical phase	Actual phase using IMU	Difference in the phase
01	0^o	0.036^o	0.036
02	45^o	45.68^o	0.68^o
03	90^o	90.56^o	0.56^o
04	180^o	180.85^o	0.85^o
05	360^o	360.51^0	0.51^o

Table 2: Phase calculation for line following system using IMU

Using the IMU the phase error was reduced quite significantly causing an increase in precision.[29]. This was especially useful for the minor adjustment that were needed to be made so that the robot can work under optimum conditions.

B. Distance Calculation:

The master robot using the Wheel encoders calculated the distance it has covered taking its original position as the origin. This method was used in the research [30]. We employed the similar approach however the results were not accurate so the results could not be used in our research.

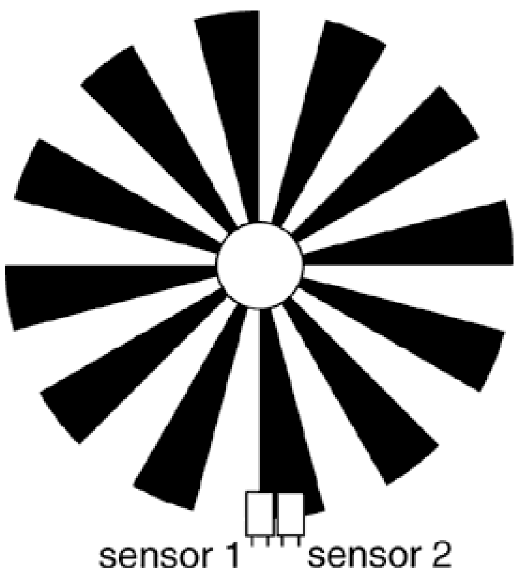


Figure 7: Wheel Encoder

The feedback control system was much more improved for the slave robots thus improving the overall system. Through the use of IMU the response time for the robots also improved thus improving the robots actuation. Using IMU we also got improved values for x and y directions.[9]

Sr. No	Actual distance calculated along x-axis	Distance measured by Encoders along x-axis	Difference in values
A-B	00m	00m	00m
B-C	10m	10.5m	0.5m
C-D	03m	3.2m	0.2m
D-E	00m	0.4m	0.4m
E-F	05m	5.6m	0.6m
F-G	00m	0.36m	0.36m
G-H	07m	6.85m	0.15m
H-I	00m	0.22m	0.22m

Table 3: Distance calculation along X-axis using Encoders for line following system

This distance was measured using the Encoders as it can be observed through the table there was a large disparity in the value thus the calculation was not made according to the requirement thus we had to utilize the IMU for calculation of x and y axis.

Sr. No	Actual distance calculated along y-axis	Distance measured by Encoders along y-axis	Difference in values
A-B	08m	8.3m	0.3m
B-C	05m	5.5m	0.5m
C-D	04m	4.3m	0.3m
D-E	08m	8.4m	0.4m
E-F	00m	00m	0.0m
F-G	08m	8.4m	0.4m
G-H	02m	2.2m	0.2m
H-I	05m	5.25m	0.25m

Table 4: Distance calculation Along Y-axis using Encoders for line following system

This problem was majorly caused due to the distortion of magnetic field due to the metallic chassis. Also the magnetometer used was of low quality therefore these problems occurred. Due to non-availability of funds we had to employ the equipment provided in the laboratory of Institute of Space Technology Islamabad.

Now we calculated distance using the IMU the following results show a marked improvement in results obtained

Sr. No	Actual distance calculated along x-axis	Distance measured by IMU along x-axis	Difference in values
A-B	00m	00m	00m
B-C	10m	10.03m	0.03m
C-D	03m	3.01m	0.01m
D-E	00m	0.02m	0.02m
E-F	05m	5.016m	0.016m
F-G	00m	0.02m	0.02m
G-H	07m	7.015m	0.015m
H-I	00m	0.012m	0.012m

Table 5: Distance calculation Along X-axis using IMU for line following system

Through the use of IMU a marked improvement was made in distance calculation along the x-axis this was done by the use of IMU that has gyros integrated with it. [31] Through this method we were able to get extremely correct and precise reading for the distance calculation along x and y axis.

Sr. No	Actual distance calculated along y-axis	Distance measured by Encoders along y-axis	Difference in values
A-B	08m	8.013m	0.013m
B-C	05m	5.015m	0.015m
C-D	04m	4.023m	0.023m
D-E	08m	8.014m	0.014m
E-F	00m	00m	0.0m
F-G	08m	8.0134m	0.0134m
G-H	02m	2.0152m	0.0152m
H-I	05m	5.0125m	0.0125m

Table 6: Distance calculation Along Y-axis using IMU for line following system

As it is quite clear that using the IMU the along with the gyroscope and magnetometer the distance measurement technique was quite improved and there was very small error in the calibration. Thus final error was also quite small and we got a wide scope for this useful technique. [32]

(i) Triangle Formation technique:

In the triangle formation protocol the robots performed with and error of 5% relative to simulation. Throughout the obstacle course they able to maintain the triangle formation however the robots had a slow response to the external stimuli and changing the obstacle course did not cause problems in maintaining the triangle formation. [33]

In the triangle formation method the similar technique was used for measuring the distance and phase. To measure the phase first magnetometer was used however it did not give results according to required specifications.[34] To overcome that problem we had to employ the use of IMU.

Similar problem occurred for the distance measurement technique and we had to employ IMU along with gyro and magnetometer to get best values for the required experimentation and research.

(i)Phase Calculation:

Similar results were obtained in the triangle formation technique too after the use of magnetometer for phase calculation.[34]. This problem was caused due to the use of metallic chassis that was employed on the robots. To overcome that problem we had to use the IMU for the research.

Sr. No	Theoretical phase	Actual phase using magnetometer	Difference in the phase
01	0^o	5.69^o	5.69^o
02	45^o	51^o	6^o
03	90^o	100^o	10^o
04	180^o	189^o	9^o
05	360^o	374^0	14^o

Table 7: Phase calculation for Triangle Formation System using magnetometer

This problems caused the triangle formation to be broken thus master slave concept was not employed fully in this technique. The slave robots could not maintain their path along with the master robot thus maintaining the formation was impossible for these robots. To overcome this main problem we had to employ IMU in this method.[35]

This was a major problem in the system that needed to be contained otherwise the system will not function. The feedback control path of the master robot did not cater for such large overshoot values and the results were quite not up to the requirement.

The feedback control system depends upon the accuracy of the reading. If the reading are not accurate we do not get the require results and thus our experimentation fails to enhance the feedback path of the system[29]

Sr. No	Theoretical phase	Actual phase using IMU	Difference in the phase
01	0^o	0.016^o	0.016
02	45^o	45.018^o	0.018^o
03	90^o	90.015^o	0.015^o
04	180^o	180.025^o	0.025^o
05	360^o	360.035^0	0.035^o

Table 8: Phase calculation for Triangle formation system using IMU

These results show a marked improvement the phase calculation using the IMU technology that was readily available to us in the laboratory. Through the use of this technology the robots were able to follow the specified patch with little or no difficult due to the marked improvement in the feedback system of the robots.[36]

B. Distance Calculation

Similarly again we used the wheel encoders in the master robot to measure the distance travelled by the robots on the x and y plane. Similar to previous results the robots were not able to maintain the triangle formation upon the reaching of an obstacle or when they needed to gather initially.

As explained earlier this problem was caused due the inefficiency of the encoders. To overcome this hurdle IMU was employed in collaboration with the magnetometer and gyroscope. [37]

This method was used in the research [30]. We employed the similar approach however the results were not accurate so the results could not be used in our research.

Following table was made by running the robots on the Initial test course as displayed in figure 3. These test courses were carefully designed and tested to check so that the robots fulfill all the requirements that are needed of it.

Sr. No	Actual distance calculated along x-axis	Distance measured by Encoders along x-axis	Difference in values
A-B	00m	00m	00m
B-C	10m	10.25m	0.25m
C-D	03m	3.32m	0.32m
D-E	00m	0.14m	0.14m
E-F	05m	5.36m	0.36m
F-G	00m	0.46m	0.46m
G-H	07m	7.26m	0.26m
H-I	00m	0.12m	0.12m

Table 9: Distance calculation along X-axis using Encoders for triangle formation system

As with the previous system the encoders did not give the specified results for the triangle formation system

Through the use of collaborative behavior the robots were able to maintain a triangle formation throughout the course even at the face of a hurdle the robots maintained their position throughout.

IV. Conclusion

In this paper we were able to provide a detailed overview of swarm systems and the increased efficiency of swarm systems over the other types of local hybrid systems. Swarm robotics is an interesting alternative to single type of robotic functions due to its robustness, scalability and flexibility.

Even though swarm systems are decentralized, we employed the master slave concept for the ease of use in the current swarm system. Through the use of various formation making and maintaining the formations through the collaboration we were able to verify the swarm principle in the robotics and its vast applications in the industry.[38]

Communication was done by the use of the use of the RF transceivers and distance measurement was achieved using the Ultrasonic and IR sensors. Programming was done on the Arduino board and algorithm was developed in the Arduino script. Computer simulations were performed in the MATLAB and Circuits were made in the Proteus software.

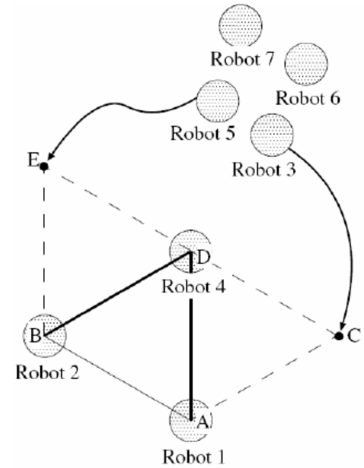
Advantages of swarm robotics are vast. Tasks that cannot be performed by single robots can easily be performed by many small individual robots, increased speed, decentralized, low cost and ease of design are some of the few of the advantages of swarm systems.

As still and emerging field in the engineering[24] swarm robotics shows a huge promise in tackling problems that single robot unit have failed to do so far thus not only decreasing the budget cost but also increasing the efficiency of overall systems.[39]

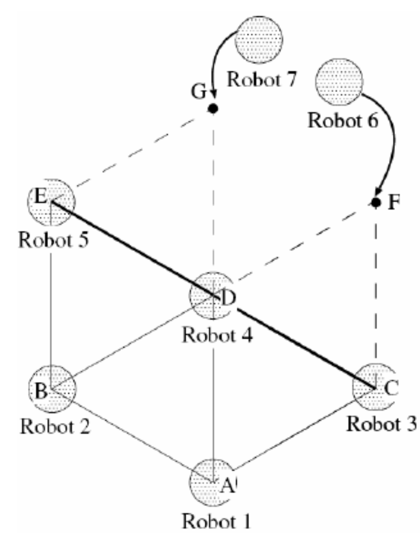
V. Further Work

In further work we will try to employ the formation making and handling without the use of master slave concept. This will concrete the basis for the decentralized and autonomous systems.

Hexagonal formation by the IET, (a) Triangle ABD was formed and point of C and E were fixed (b) Point of F and G were fixed (c) Complete forming hexagon [10]



(a)



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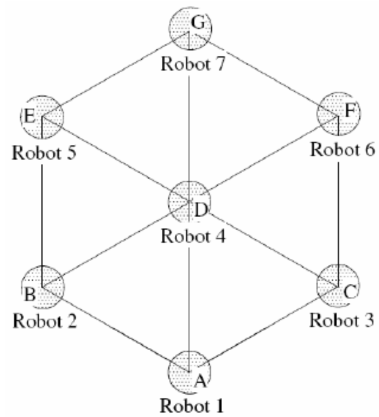

(c)

Furthermore we will increase the number of individual robots to large number of 20 to 30 instead of using 3 robots and try to form much more formations such as pentagon, or octagon etc. This will further enhance the understanding of the collaborative behavior and understanding of the swarm systems.[40]

Using the IET method we can increase the number of robots in the formation and can make further formations using this collaborative technique.

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