Efficient Distributed Controller for Wandering Robot Formations using Local Sensing and Limited Range Communications

E.M. Saad, M.H. Awadalla, A. M. Hamdy and H. I. Ali

Abstract— This paper focuses on the development of wandering robot formations and shows the cooperation and coordination among the robot teammates to maintain the achieved formation regardless the complexity of the environment. To address these issues, this paper proposes a new behavior based robot architecture. This architecture is based on a novel technique for location determination using local sensing. The proposed architecture is implemented using the well known robot simulator Webots. Experiments for many difficult tasks such as the passage through narrow corridors, obstacle avoidance, swerving with large angles, and switching between different formations have been conducted. These Experiments prove the efficiency of the proposed controller. The obtained results show that the constructed formations are more stable and accurate even in cluttered and uncluttered environments.

Keywords— Local sensing, Multi-robot coordination, Robot formations.

I. INTRODUCTION

This paper addresses the problem of achieving a global behavior by a group of mobile robots. This problem has become of paramount interest nowadays as a result of its various important applications. Mobile sensing networks, cooperative transportation and mine field exploration are some examples of tasks which can be assigned to a robot group. Robot formations comprise an essential part for most of these applications. The paperaim is to concentrate on developing an intelligent controller for robots having very simple design so that they could exhibit a complex global behavior. The robots are aimed to organize themselves to take different geometric formations. Also, they should be capable of dealing with difficult situations which they may face in their environment. The robot team should be able to avoid obstacles, pass through narrow corridors (in fish or bird swarm fashion), swerve in large angles and switch between different formations. Exhibiting all these capabilities using very simple hardware is really a well respected challenge.

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The rest of the paper is organized as follows. Section 2 gives a review of related work. Section 3 illustrates the hardware platform for the robots. Section 4 presents the proposed intelligent controller. Section 5 describes the experimental work. Section 6 gives a discussion and the conclusions.

II. RELATED WORK

Various approaches have been proposed for the problem of emerging a global behavior for a group of robots [1-3]. In [4], a group of simulated robots are used to perform some robot formations such as circles and simple polygons. In this work, robots have a global knowledge about the other robots' positions. Each robot orients itself to the furthest and nearest robot. In [5], a group of mobile robot motion was also considered. They used the matrix formation performing a right turn as an example. In [6], a formation is defined by a so-called virtual structure (VS). The algorithm assumed that all robots have a global knowledge; it iteratively fit the VS to the current robot positions, displaced the VS in some desired direction, and updated the robots' positions. [7-8] face parts of the controller needed for robot formations, their work depend on vision and complicated manipulations. The work in [9] tried to find a general algorithm for robot formations using local sensing. Their approach was based on gaining other robots information via a camera mounted on each robot. The algorithm depended on constructing an ordered robots chain using their ID's. Then using simple rules, each robot could compute the distance and angle to be maintained with a friend robot. Using a camera as a local sensor complicated the controller which may be simplified if any other simpler hardware could be used. The work in [10] used the so-called local template by which robots gradually construct the desired formation. It verified the proposed approach for chain formation only. The main point achieved was the usage of simple hardware for gaining information.

Although the above mentioned approaches gave a better performance, however, some of them implied complex sensing mechanisms. Others only provided a few number of robot formations.

The paper work proposes a simple vision approach based on infra-red transmitters and receivers by which the distance and the angle of neighboring robots can be measured. It enables each robot to see all other nearby robots (although each robot transmits data using unique frequency). The controllers are designed such that each robot starts to follow the first observed teammate. This mechanism enables the robots to construct the robot chain rapidly from any randomly oriented team state, in a predefined area. Then, each robot can compute the friend angle and distance, despite of the fact that the chain is not ordered, in order to construct the desired formation.

III. Hardware Platform

The hardware platform is divided into four parts. The first one contains the collision avoidance sensors. The second part comprises the infrared eyes used for supporting the proposed vision mechanism. The third one is the transceiver whereas the fourth part includes the differential wheels and the robot body.

Collision avoidance is based on four infra-red distance sensors arranged on the robot front half, as shown in Fig. 1. The two side sensors help in avoiding side obstacles and wall corners as will be illustrated in the following sections.

The proposed infrared eyes mechanism is used for measuring the distance and angle of an infrared transmitter relative to a robot. The idea is based on measuring the signal strength of the transmitter signal by two infrared receivers fixed on the robot front half as shown in Fig. 2. By knowing the distance between the receivers, both distance and angle of the transmitter can be determined. The equations that calculate the distance and angle will be proved later. The transceiver is an omni-directional infra-red one. Each robot has a transceiver with unique transmission frequency and limited communication range of 0.25 meter.

The transmitter is used for sending self-identification information as well as some useful information to other robots. This is achieved by repeating the information received by each robot through its transmitter. By repeating the data received by the omni-directional receiver, the data can be exchanged between robots even if they are not within the communication range of each other.

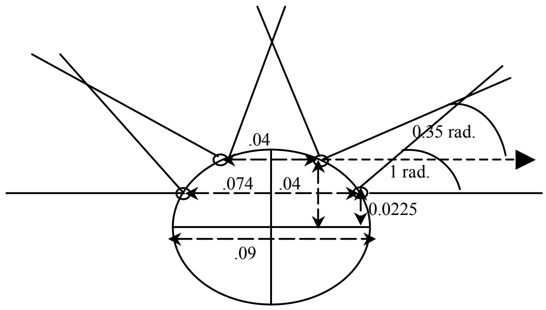

Fig. 1. Collision avoidance sensors arrangement (all units in meters).

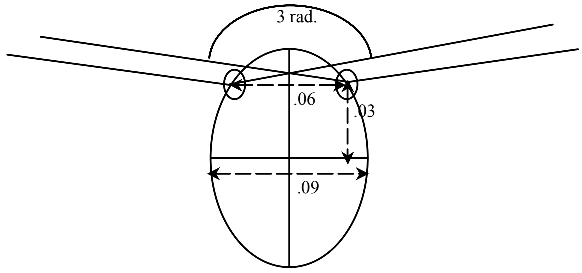

Fig. 2. The infrared eye mechanism (all units in meters).

The moving mechanism is based on differential wheels that give a simple way to move forward and backward as well as spinning and movement in an arc. The robot main body is a cylinder of 0.09 meter diameter and 0.08 meter height.

The whole robot is implemented on Webots 5.1.9 simulator. Fig. 3 is a plan view for the robot showing the vision mechanism, the omni directional transceiver. All parts shown are infra-red transducers. Additionally, light system is installed to indicate the behaviors of the robot during simulation. This is an easy way to facilitate detecting errors of the proposed controller. There is an avoidance LED that indicates the direction from which the robot senses an obstacle. There is another LED that identifies the robot to be followed by emitting a distinct color for each robot. Finally, a formation LED indicates that the robot will cooperate with its teammates to construct the formation.

Fig. 4 shows the avoidance hardware which is based on four infra-red distance sensors located on the front half of the robot body. Fig. 5 shows the whole robot designed on the Webots simulator. The yellow bar shown in the figure is a controlled pen used to mark the robot tracks on the plan, if needed. This pen is of great importance in measuring the swerving angle exhibited by any robot.

Till now, a good idea about the proposed robot hardware is given. In the following section, the proposed intelligent robot controller for robot formations will be illustrated.

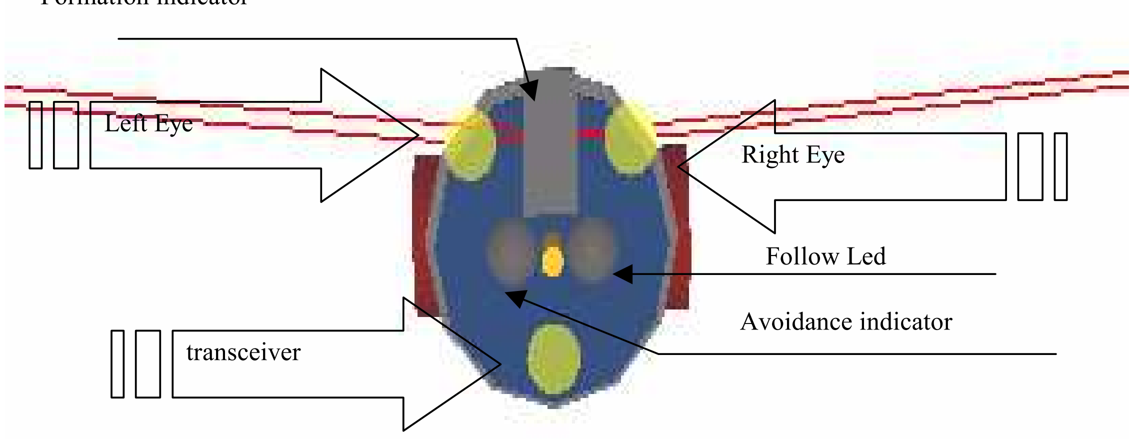

Fig. 3. A plan view showing the vision. mechanism

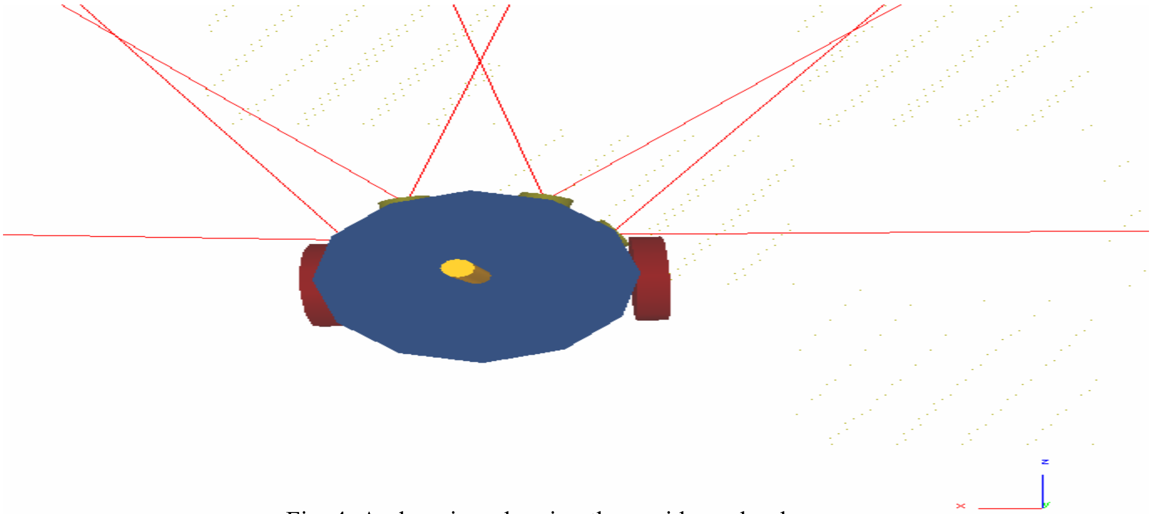

Fig. 4. A plan view showing the avoidance hardware.

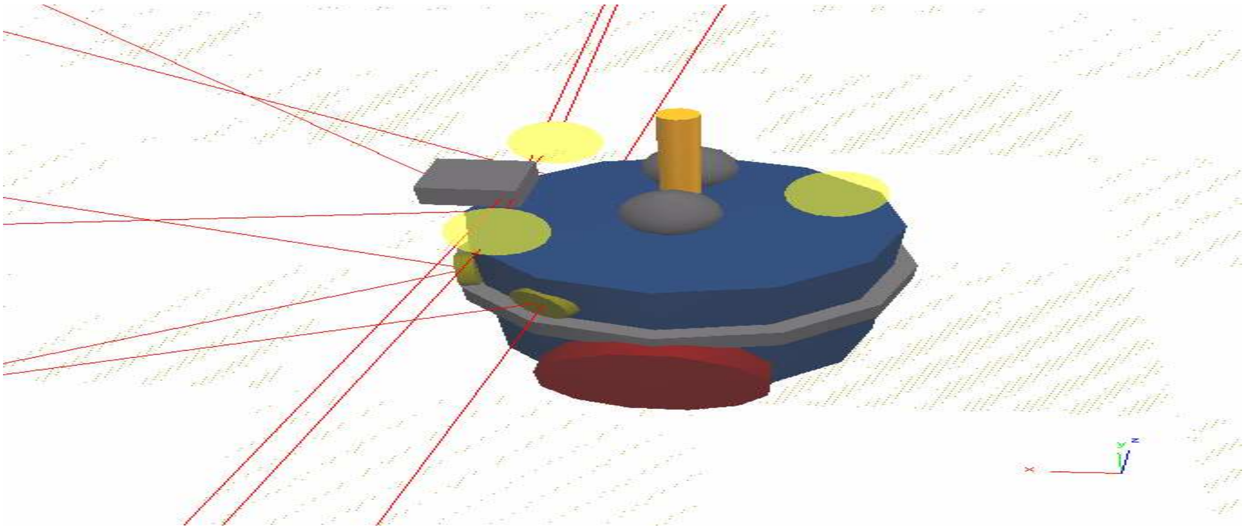

Fig. 5. The whole robot.

IV. The Proposed System

The proposed intelligent controller is based on Subsumption architecture [8-9]. Fig. 6 shows the robot behaviors. All robots initially exhibit avoid and follow behaviors. By this way, they avoid collision with obstacles and construct a chain by following the first observed robot. Each follower will stop following if the leader is followed by another robot so that a chain can be constructed correctly. Each robot sends the number of robots leading it to its follower so that the final robot joining the chain could recognize chain completion. When the chain completes, the robot at the chain tail sends a chain completion message to its leader which in turn forwards the message to its leader and so on. Finally, the chain leader receives this message and recognizes the chain completion. The chain leader starts exhibiting a “move in circle” behavior, after chain completion, till the capture of the robot at the chain tail. Other robots merely continue following.

When the chain leader captures the robot at the chain tail, the robot team actually succeeds in constructing a circle formation having a radius determined by the chain leader. The circle formation is a good starting point for many symmetric formations like diamonds, wedges, polygons… etc. So the chain leader sends a message to its follower to start initiating the desired formation. This message is obviously forwarded to all robots as previously described. Each robot starts computing the formation parameters locally. These parameters are the distance and the angle to be maintained with its robot team-mate to collectively construct the desired formation. Some robots need to exchange their leaders by their followers. The leader is then informed that the robot team is ready by forwarding a ready message from each robot to the leader. At this point, the leader starts wandering so that the following robots could adjust the distance and the angle with their respective leaders. These different behaviors are illustrated in details in the following subsections.

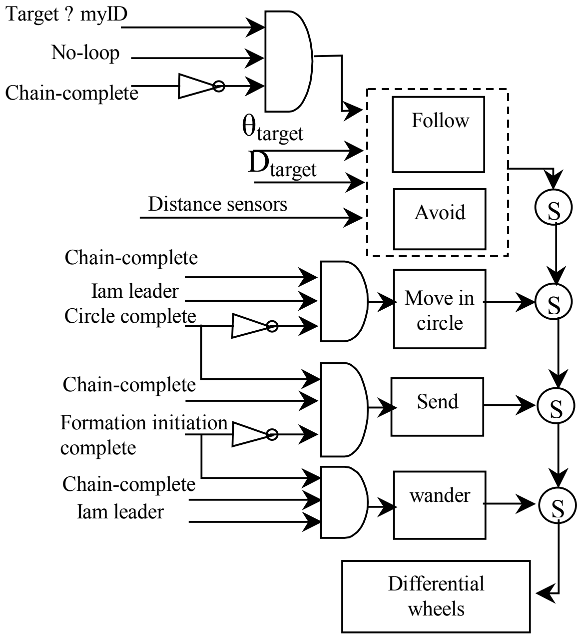

Fig. 4. The proposed robot behaviors and their interaction.

A. The Follow Behavior

The follow behavior is based mainly on measuring the distance to a target robot and the angle of the target robot with respect to the observing robot heading. Then through translational and rotational motions, a desired distance and angle are maintained. Measuring the distance and angle of the target robot is based on the infrared eye mechanism previously proposed. The idea of this mechanism is to measure the signal strength of a single infrared transmitter with two infrared sensors. By knowing the distance between them, one can accurately calculate the distance to the transmitter. Furthermore, the angle of the target robot with respect to observing robot heading can be computed as well. Fig. 7 illustrates a simplified graph by which the calculations will be demonstrated. The received signal strength is inversely proportional to squared distance from the receiver to the transmitter.

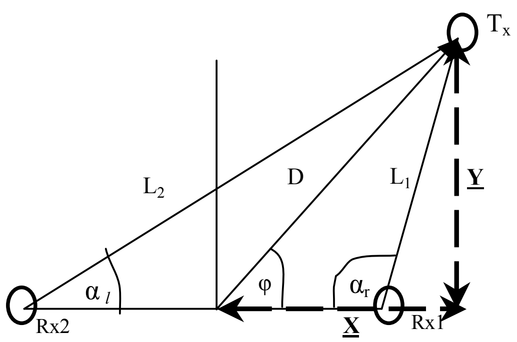

Fig. 7. Calculating the distance and angle of a friend robot.

$$L = (1 / signal\_strength)^{0.5} \quad (1)$$
$$\cos \alpha_r = (L2^2 - (l^2 + L1^2)) / (-2lL1) \quad (2)$$
$$X = l/2 - L1 * \cos \alpha_r \quad (3)$$
$$Y = L1 * (1 - \cos 2 \alpha r)^{0.5} \quad (4)$$
$$\Phi = \tan^{-1} (Y / X) \quad (5)$$
$$D = (X2 + Y2)^{0.5} \quad (6)$$

It is clear from the Eqs. (1-6) that after calculating the distances L1, L2, using Eq. (1), and by knowing the distance between the two receivers l, all what is needed can be calculated. As it is shown in Fig. 7, Φ is the target angle with respect to robot heading and D is the distance between the target and the point midway the two receivers of the observing robot. Fig. 8 describes the algorithm proposed for following a robot by maintaining a desired target angle with respect to the follower heading. It also maintains a desired distance between the target and the follower. The proposed approach gives a good performance in case of small number of robots. However, when the number of robots increases, some problems will arise.

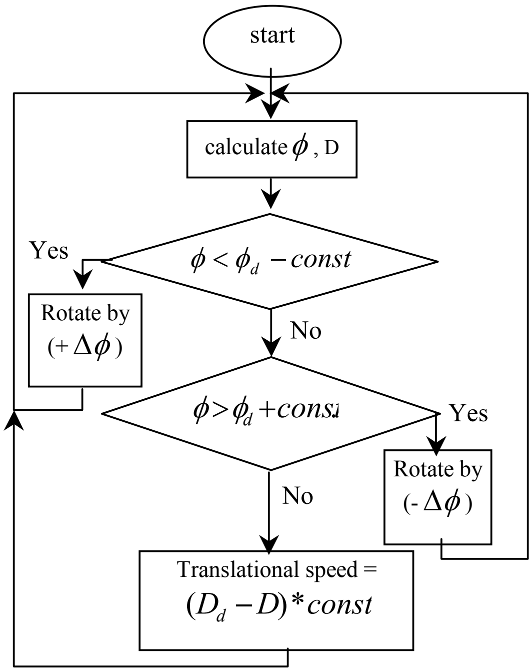

Fig. 8. Follow behavior.

The first problem is the interference that will occur at the observing robot receivers. A solution to this problem is to give each robot a unique transmission frequency. On the other hand, the observing robot can switch among the frequencies of the neighboring robots.

The second problem occurs when two robots try to follow the same leader. To solve this problem, the leader resends the follower ID. So all other robots will stop following that leader if they do not receive their ID's, as a consequence for their request.

Adapting The Follow Behavior

After the formation is constructed, many problems arise when the robots exhibit the follow behavior such as:

- Formation damage during swerving
- Formation damage when it passes through a narrow corridor

A modification to the follow behavior is introduced. The idea becomes more intelligible if we look to the robots constituting the formation as a single large entity. In this way, a solution to the previously stated problems can be achieved by allowing the individual robots to adapt their follow angle with respect to its surrounding obstacles. So the formation as a whole could shrink if surrounded by side obstacles. Also, it could expand again when the surrounding environment is free of obstacles. The obtained results show that the modification of the follow behavior has a good impact on the formation wandering.

To get the follow behavior modified, a new follow angle φ_f as a function of φ_D and the robot distance sensors readings is calculated. Eq. (7) illustrates the calculation of φ_f in case of following a leader on the right hand side.

$$\varphi_f = \varphi_D - (FLSR * k_1 + LSSR * k_2) \quad (7)$$

where,
FLSR = front left sensor reading
LSSR = left side sensor readings
k_1,k_2 are constants that could be determined empirically

Equation (8) illustrates the calculation of φ_f in case of following a leader on the left hand side.

$$\varphi_f = \varphi_D - (FRSR*k_1 + RSSR*k_2) \quad (8)$$

where,
FRSR = front right sensor reading
RSSR = right side sensor readings
k_1,k_2 are constants that could be determined empirically

B. Avoidance Behavior

For the proposed system, the sensors are distance sensors and the behavior is cowardice. The sensors are arranged as shown in Fig. 1. The relation that connects the sensors to the motors is written below:

Right speed = -FLSR / k_3 - LSSR / k_4 + speed
Left speed = -FRSR / k_3 - RSSR / k_4 + speed

A. Where,
FLSR = front left sensor reading
LSSR = left side sensor readings
FRSR = front right sensor reading
RSSR = right side sensor readings
k_3,k_4 are constants that could be determined empirically

If no sensors' readings are present then the equations give the speed that causes a forward translation with slight curvature. The front distance sensors' readings cause the robot to turn opposite to the direction of the nearest obstacle.

C. Move in Circle Behavior

This behavior needs the calculation of two parameters, the circle radius and the differential wheels' speeds. The arc radius is calculated by knowing the number of robots and the desired distance between them. Fig. 9 is an illustrative example for four robots. The same idea can also be used for n robots. As shown, the radius of the circle can be computed from:

$$\theta = 2\pi / n \quad (9)$$

$$r = \frac{D_d}{2 * \sin(\theta / 2)} \quad (10)$$

The differential wheels robot can move in an arc. As shown in Fig. 10, if the angular speeds of the wheels are ω_1, ω_2 respectively, then after time t, l_1,l_2 can be computed as:

$$l_1 = r_w * \omega_1 * t = r_c * \alpha \quad (11)$$

$$l_2 = r_w * \omega_2 * t = (r_c + ws) * \alpha \quad (12)$$

Where,
r_w = wheel radius,
ws = wheels' separation

From Eqs. (11,12) we can deduce that:

$$r_c = (\omega_1 . ws) / (\omega_1 - \omega_2) \quad (13)$$

As expected, if $\omega_1 = \omega_2$, r_c tends to infinity and the robot moves in a straight line. But if $\omega_1 > \omega_2$ the robot moves in an arc with radius r_c.

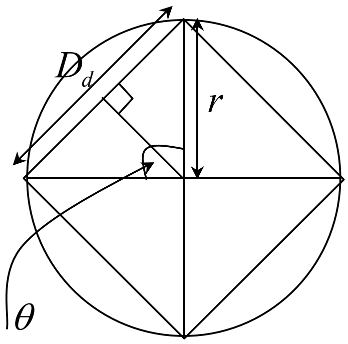

Fig. 9. Computing the radius of four robots circle.

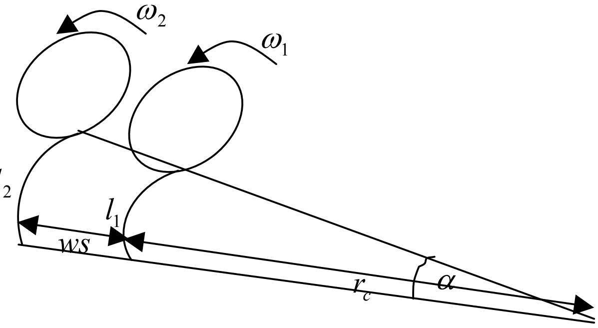

Fig. 10. Computing the arc radius of the robot path.

D. Wander Behavior

This behavior is also exhibited only by the leader. The leader starts wandering while the robots are maintaining the same formation. Parts of the formation will be damaged when the leader faces a wall or an obstacle. A solution to this problem is by sending a swerve message to followers to enforce them to swerve also. But this will help in case of smooth turns only. Another way involves changing the leadership to some other robot having no obstacles. But also this may need reconstruction for some special formations, usually the non-circular formations.

E. Send Behavior

All robots exhibit this behavior periodically to broadcast their ID's. Also when chain completes, the robot at the chain tail starts sending this information, which is then successively repeated up to the chain leader. When the leader detects circle formation completion, it sends the formation type to all other robots as well as their new ID's. The new ID's are ordered ID's. This process of renaming simplifies calculating the desired distance and angle locally. Fig. 11 gives the flowchart for these calculations, for diamond formation. After initializing the formation parameters, each robot starts sending a "formation initiation complete" message to the leader. After this the leader can wander as previously illustrated.

```
If new_ID = 1 Then
        No computation
Else if (new_ID ≤ n/4+1) Then
        θd = 45, Dd = const.
Else if (new_ID ≤ n/2+1) Then
        θd = -45, Dd = const.
Else if (new_ID ≤ n*3/4+1) Then
        θd = 45, Dd = const.
Else if (new_ID ≤ n) Then
        θd = -45, Dd = const.
```

Fig. 11. Calculating the desired angle and distance for the leader for diamond formation.

V. EXPERIMENTAL EVALUATION

A set of experiments is performed to validate our proposed system. The Webots 5.1.9 simulator is used. This is a three-dimensional simulation tool with a good graphical interface to display the simulation results. Using Webots, robots are equipped with actuators and sensors for detecting the obstacles and other robots. The behavior modules that map sensor inputs to actuator outputs can be also implemented using Webots [10].

Jakob Fredslund and Maja J. Mataric proposed formation evaluation criteria as a means of quantitatively judging the notion of being in formation [6]. They formalize this evaluation criteria checks that the robot teammates could keep the same distance between each other, during the navigation. Also it measures how the robot teammates keep their formation close to the desired formation. Using the previous evaluation criteria and some other experiments they could measure different properties and capabilities of their proposed system.

The same ideas for evaluating our proposed system are used. Our developed experiments are also used to validate the following characteristics and capabilities: stability, swerving, obstacle avoidance, and switching between formations. The proposed system is evaluated using two teams; four robots and eight robots. The large number of robots used in the second team is an indicator of a good performance even in crowded environment. In the following subsections, the results of our experiments are presented.

A. Stability

In this experiment, it is tested how the robot teammates could maintain the required formation satisfying the evaluation criteria proposed in [6]. To do this, the inter-robot distances are measured and recorded during 20 meter navigation. These inter-robot distances are measured by the robot teammates using our proposed infrared vision mechanism. Also, the corner angles of the desired formation are measured and recorded as well as the deviation of each robot about the desired formation side it participates. The corner angles are measured cooperatively by the robot teammates by exchanging the angles they measure when seeing each other. The deviation of each robot about the formation side it participates is measured locally using the proposed infrared vision mechanism readings as well as some simple trigonometric calculations.

In stability experiments, the errors in the formation parameters are measured, which are the desired inter-robot distances (dispersion), the desired formation corner angles and the straightness of the desired formation sides. These errors are recorded in tables during a 20 meter navigation each 15 msec; the simulation step. An error of 10% with respect to the desired inter-robot distance is allowed. Also, an error of 6% is allowed with respect to the shape parameters; desired formation corner angles and the straightness of the desired formation sides. Using these tables, a percentage of time information could be calculated. The stability experiment is repeated 10 times using four robots team for diamond, wedge and circle formations. The same experiment is repeated 10 times using eight robots team for the same formations.

Table 1 shows the stability results for the four robots team regarding all formations mentioned previously. Table 2 shows the stability results for the eight robots team regarding all formations mentioned previously.

Studying the results in the two tables carefully shows that the four robots team gives better results than the eight robots one. This clearly comes from the fact that the accumulation of errors will be smaller for small robot teams. But generally the performance could be considered the same in both teams. The stability is generally more than 99%. Also the dispersion and shape parameters are better for simple formations like the column and the wedge formations.

Table 1. Average of stability parameters over 10 trials using <u>four</u> robots team.

Formation	Av. D (meters)	Av. Dispersion (percent)	Av. Of errors in Shape parameters (percent)
Diamond	1.5	0.4	1.4
Wedge	1.9	0.0	1
Circle	1.55	0.4	1.4
Column	1.1	0.0	0.3

Table 2. Average of stability parameters over 10 trials using <u>eight</u> robots team.

Formation	Av. D (meters)	Av. Dispersion (percent)	Av. Of errors in Shape parameters (percent)
Diamond	3.55	0.33	1.31
Wedge	3.95	0.23	1.27
Circle	3.6	0.52	1.2
Column	1.7	1.1	1.1

B. Swerving of Formations

To validate the proposed system, get the formation wandered through its environment. In this way, the formation will be enforced to swerve with large angles near the corners of the room. As previously shown, the proposed system could face this difficult task by adapting the follow angle with the distance sensors' readings. Fig. 12 illustrates the wedge formation while swerving. The line drawn shows the swerving angle. This line is achieved by incorporating a pen to the formation leader. Fig. 13 shows the diamond formation while swerving and also the swerving angle is indicated by the drawn line. The swerving angle in both figures is around 90 degrees. In some situations, the swerving angle could be much more. This shows how the proposed system gives the robot teammates the ability to behave as one elastic entity.

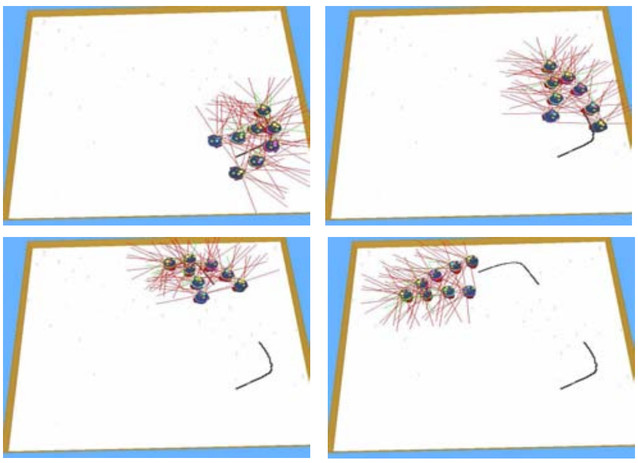

Fig. 12. Successive snapshots during wedge formation swerving.

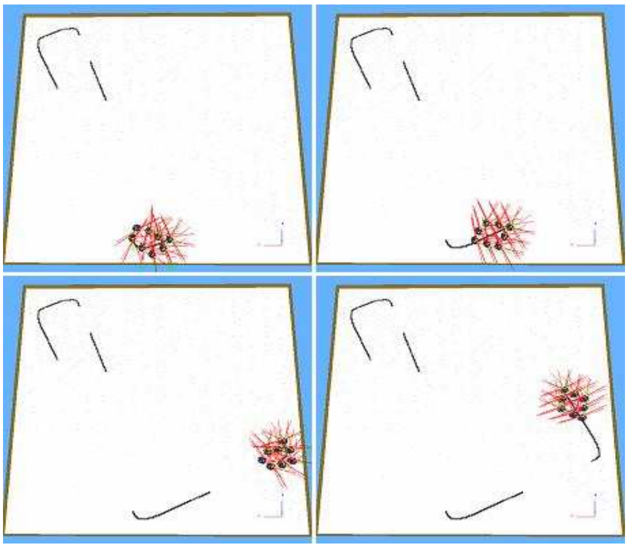

Fig. 13. Successive snapshots during Diamond formation swerving.

C. Obstacle Avoidance

In this experiment, it is tested how the robots team could avoid obstacle while maintaining their formation almost intact. The robots team is subjected to different situations. In some of them, a large cylinder in front of the robot team is put, see Fig. 14. In another one, the cylinder forms a narrow corridor with the room walls. This difficult situation could be overcome by adapting the follow angle for each robot with the distance sensors readings. As shown in Fig. 15, the formation avoids the obstacle keeping the over all formation nearly intact. Fig. 16 illustrates how the formation could shrink to pass through the narrow passage. This behavior of the robots seems to be inspired from the fish and bird swarms.

This experiment clarifies the superiority of the proposed system in avoiding obstacles and in passing through narrow corridors. The robot teammates behave in a fish or bird swarm fashion. This has been done in a distributed fashion by allowing each robot to adapt its follow angle with its distance to the surrounding obstacles.

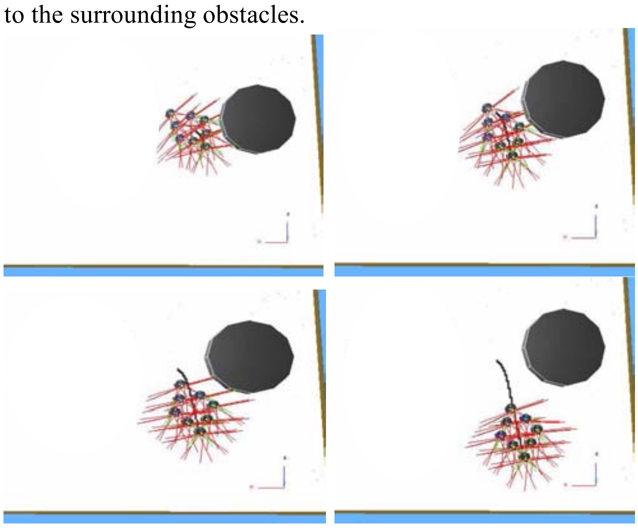

Fig. 14. Obstacle avoidance (Diamond).

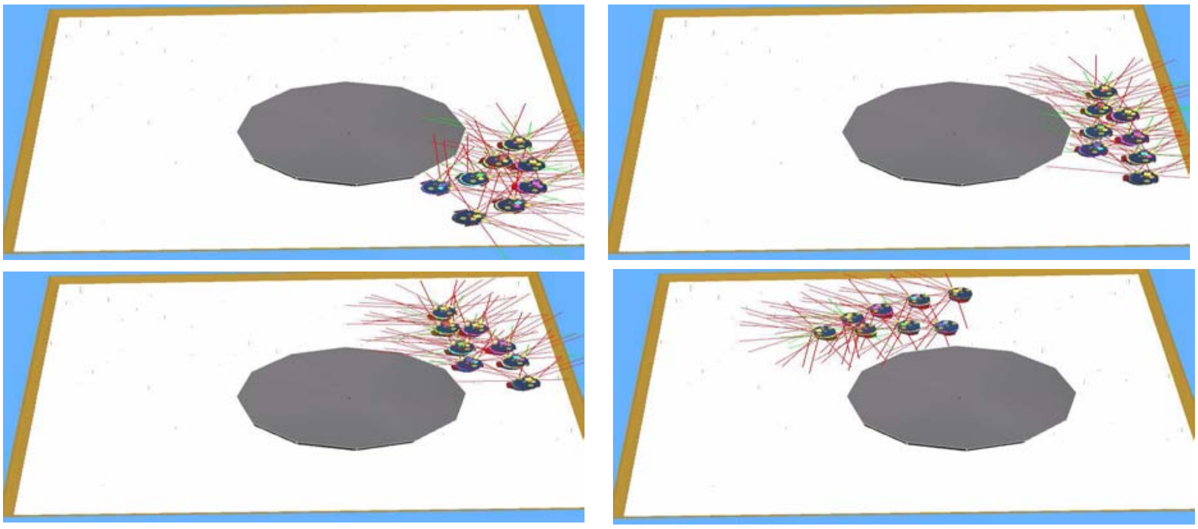

Fig. 15. Formation shrinks during the passage through narrow corridors (wedge).

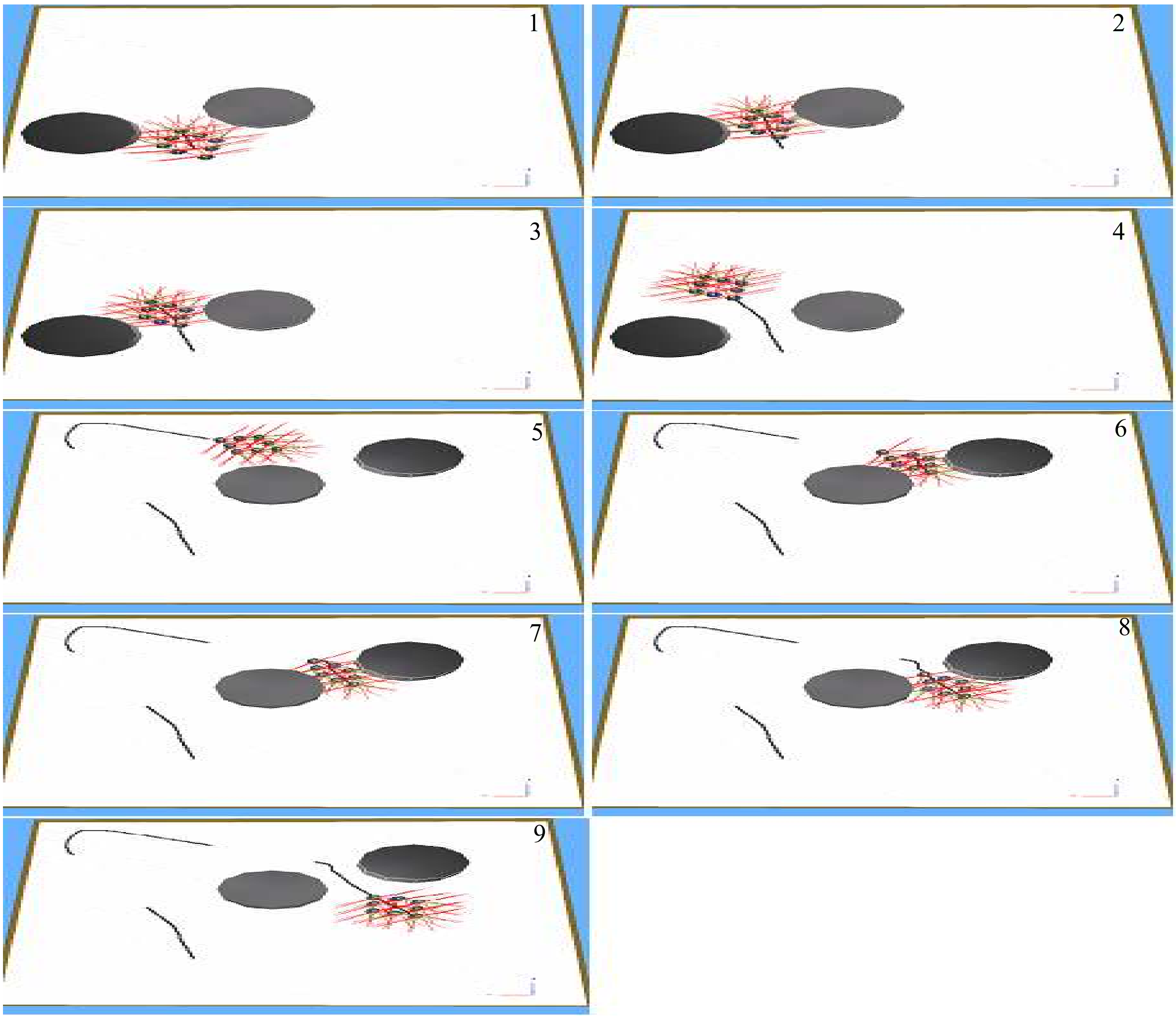

Fig. 16. Diamond formation passing through two successive narrow corridors.

D. Switching

In this experiment, the ability of the robot team to switch between different formations is tested. The idea for switching between circle, diamond, and wedge formation is very simple; just changing the follow angle with your leader. On the other hand, changing to column formation needs exchanging the leaders themselves. So, less than half of the robots need to exchange their leaders by their followers. Finally, they start following using a follow angle of zero degrees.

Fig. 17 shows how the robots could switch from wedge formation to diamond, circle and finally to column formations. From this figure and by knowing that the room is 4*4 meters, it is noted that the robot team could switch between these four different formations in less than 3 meters long.

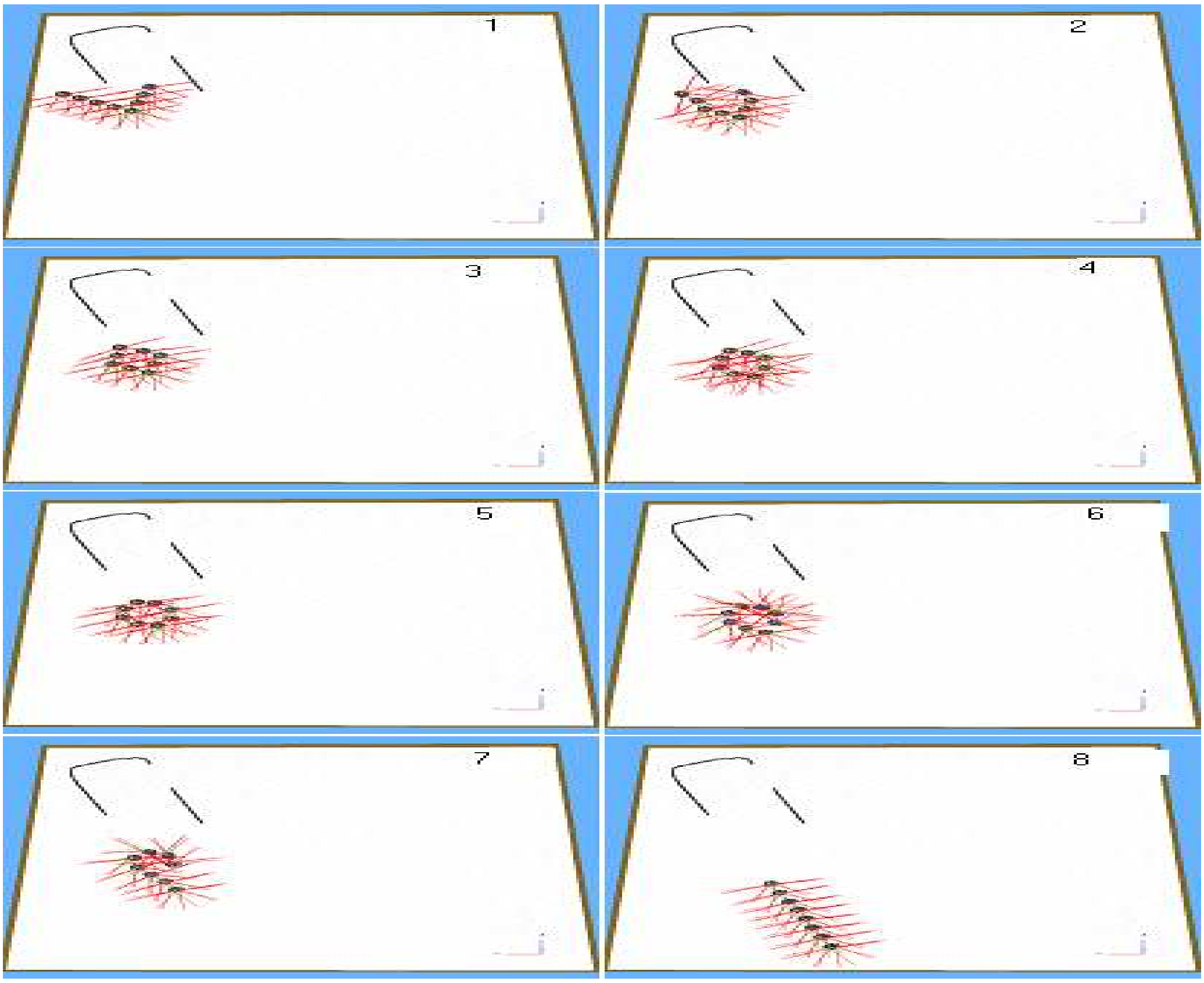

Fig. 17 Switching among different geometrical formations

VI. CONCLUSIONS

The paper concludes that the robots are capable of exhibiting a global behavior namely constructing geometrical formations using any number of robots. A new mechanism for vision is also introduced and implemented. This mechanism is implemented via simple hardware which results in simpler controller design. Using such simple hardware is an objective in itself. The importance of this appears clearly if this is compared with the work in [6], which depends mainly on a camera. Using a camera not only means a more complicated hardware than this work, but also implies a much more complicated controller, i.e. large efforts and labor work to design the system as a whole.

Even though there is no specific leader for the robot teammates and all robots have limited communication range, the proposed approach gives better improvements in the whole system performance. The robot teammates start from random positions, ordering, and orientations. They only get nearly close to each other to speed up constructing their first chain. Most of the previous work assumes initial ordering and at most random headings (not positions). The limited communication range is a must to approximate more practical cases. The work in [6-7] assumes that there is a global communication channel with unlimited range. So our approach seems to be more practical.

The proposed algorithm is implemented using the well-known simulator “Webots”, which offers greater flexibility in robot hardware design. Sensors can be simulated as close as possible to practical counterparts. Motors mechanical systems and environmental effects can be simulated with good accuracy as well. As illustrated in the conducted experiments, the robot team is capable of constructing many different geometrical formations. These formations include circle, diamond, wedge, and column geometrical formations.

The proposed system has been verified and tested against many difficult situations. The experimental evaluations explained previously show the superiority of our proposed system. The evaluation experiments use a performance metrics proposed in [6]. The results are almost the same and sometimes are better than those obtained in [6]. It should be noted that, the use of limited communication range, much simpler hardware, and more restricted conditions during the experiments is established in our work. The stability experiments show excellent results, usually more than 99%. The robot team could swerve by large angle; more than 90 degrees, keeping the whole formation intact. This point gives our system its superiority with respect to all previous works. The ability of the proposed system in avoiding obstacles is also tested and verified. The robot team could pass through narrow corridors formed by the obstacles in a fish, swarm fashion. This shows how the robot teammates could work as one large elastic entity. The ability of the robot team to switch between formations is also tested.

The robot teammates could switch between all formations; circle, diamond, wedge, and column, in less than 3 meters. This is again another point of superiority of the proposed system if compared to the previous works. For further work, the experiments will be conducted in the presence of dynamic obstacles. Finally, the proposed system needs to be implemented on real robots.

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