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Effects of Population Density on the Emergence of Circle Formation in Multiple Robots System with a Local Vision

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Abstract

This paper deals with the effects of robot population density on the emergence of circle formation in multiple robots system. Individual robot has a specific range of signal communication to detect other robots. According to the information about the location of one or two robots detected by the signal communication within the range, the robot takes an action such as proceeding forward or turning left/right at each time step. Implementing this action selection algorithm to each of the robots, we carry out the computer simulation of global behaviors in the multiple robots system, and we find that there exists a certain condition under which the circle formation emerges in the multiple robots system. To investigate the effects of the robot population involved and the size of the simulation area on the characteristics of the circle formation, the computer simulation was made and it clarified that the emergence of the circle formation in the multiple robots system is strongly influenced by the robot population density rather than to the robot population and the simulation area size.

1. Introduction

When a number of robots equipped with local communication ability interacts each other physically and informationally, it is expected that a new competence may emerge within the multiple robots. This situation is generally called as "emergence of group intelligence". The concept may be used in realizing a cooperative behavior in multiple robots system, where the robots are equipped with simple mechanical function and action principles.

Extending the above general idea to a specific area of robotics; i.e., colony-formation or group morphology formation in multiple robots system, there have recently been several research works on the group morphology formation. C. Reynolds proposed the "Boids" theory in his paper [1], which can describe the herds' behavior vividly. N. Sannomiya et al. presented a "fish behavior model" [2] that can describe mathematically the various kinds of fish school behavior such as stable group-morphology formation. With regard to a geometric pattern formation in multiple robots system, K. Sugihara and I. Suzuki proposed the distributed type of the algorithm by which many robots can gather onto a specific formation e.g. a line segment, a circle formation, and a polygonal formation. I. Suzuki and M. Yamashita proved the mathematical or algorithmic theorem about the possibility to obtain the common x-y coordinate system with respect to each of the robots involved. From different view of the robotic system morphology formation, S. Murata and his colleagues have developed a "Self-Assembling Machine" [6] that can be re-configurable according to the environment condition for each robotic module.

In the research works on the group morphology formation or school behavior in multiple robots system, it is generally supposed that a robot has simple mechanical function and a reflex intelligence. The main reason for this is that most of the multiple robots system is considered to be applied to the field of micro-robots. We follow the above viewpoint, and accordingly we have built-up a robot model with the mechanical function such as locomotion, touch sensor and local vision. The robot action is determined by the two factors, i.e., collision avoidance and turning according to the locating of other robots around itself observed by the local vision. Then we may expect that the robots may create a certain geometrical formation through such dynamic interactions occurring in the robotic system, or in other words a group morphology formation. We have already shown the simulation results of such circle formation in the previous paper [7], in which a simple algorithm of action selection was employed by taking into account of the interactions among the robots. The study has made clear the characteristics of such circle formation emergence. For instance, the robotic behavior of a circle formation in the specific robot population is strongly related to the parameters of a robot function, i.e., vision angle and turning angle. Considering the application of this kind of the robotic circle formation to the morpho-genesis of the robotic body, we imagine that such circle formation may advance to a formation of large-scale structure by dynamic interactions among the generated robotic circles in a similar way that cells organize tissues. For practical use, the circle formation by multiple robots system may have a potential application to perimeter security forces monitoring the invaders. From this kind of discussion, we think it is significant to study the condition of a large-scale circle formation in the large number of multiple robots system and find critical parameters. We thus carry out a series of computer simulations to investigate the critical condition for such robotic circle formation with focussing on the population of robots and a robot-working area size. The simulating study shows that the circle formation emergence prefers a certain population density of robots involved rather than a robot population and the working area size.

2. Robot Model

In this chapter we explain the important robotic parameters specifying the visual sensing function for the robot model which is used in the simulation study on the circle formation emergence. Figure 1 shows schematically the robot model equipped with two touch sensors to detect some obstacles and a local vision to detect other robots located around itself. If the robot detects some obstacles on its touch sensors, the robot acts left/right turning to avoid the obstacles. The robot has a specific range of vision R. Within the range the robot can detect other robots in the three separated areas 0, 1, and 2 as shown in Figure 1. The robot vision is symmetric with respect to its proceeding direction as shown by a dotted arrow, and the vision areas are of the front area (area 0), the left side area (area 1), and the right side area (area 2). The robot is assumed to be blind to its rear area (area 3). A single robot can detect the number of other robots located in these three areas 0, 1, and 2. More precisely speaking, the number of robots detected in each of these three areas is categorized into three levels as no robot, a single robot, and two or more robots. The other symbols in Figure 1 mean as follows: α is the turning angle of the robot for one time step, β is the half angle of the frontal view area 0; or the angle between the proceeding direction of the robot and the frontal boundary line of the area 1 or area 2 (we call this angle β as "front view angle"), γ is the angle between the proceeding direction of the robot and the rear-side boundary of the area 1 or area 2 (we call this angle γ as "side view angle").
In addition, the robot locomotion is kinematic because we think that the multiple robots system may be applied to the micro-robot area in which it is not necessary to consider the inertia effect.

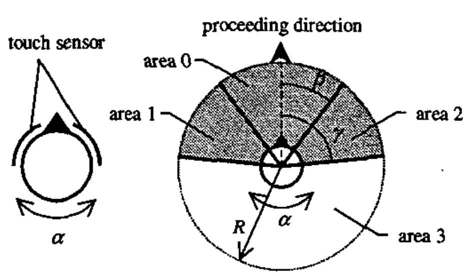


Figure 1: Robot model with local vision

3. Action Selection Rules

3.1 Basic Actions

The robot action is assumed to be undertaken in the discrete time-step process and the following three actions to be taken successively for one step. Individual robot in the multiple robots system repeat a sequence of the actions:

(i) Observe other robots within the vision range R and count the number of the observed robots.
(ii) Carry out the action already selected one step before.
(iii) Select an action for the next time step from action selection rules reflecting the situation of the environment around the robot.

The basic action of the robot is the locomotion at one time step, i.e., the robot proceeds forward or turns to left or right. The speed of the robot locomotion is set as V=15.1 [cm/s] and the turning angle for one time step is also set as α=17.6 [degree] (see 4.1).

3.2 Obstacle Avoidance

When one or two touch sensors are "on", the robot selects the action for the next time step, i.e., proceeding forward, or left/right turning. Table 1 summarizes the action selection rules for the input information from the robot touch sensors. We call the actions as obstacle avoidance. We put the first priority on the obstacle avoidance in the action selection rules.

Table 1: Action selection by touch sensor inputs

Touch Sensor Inputs	Action
None	Proceeding
Right Side	Left Turning (α [deg])
Left Side	Right Turning (α [deg])
Both Sides	Left/Right Turning* (α [deg])

(*Select the direction to turn by internal information which is memorized the last turning direction of the robot)

3.3 Following Actions

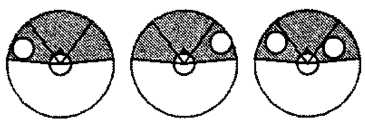
When a robot observes other robots within the before mentioned vision areas, the robot selects an action for the next time step from the number of observed robots in the vision areas. This vision is not accurate but can acquire the rough-location of other robots around itself. Figure 2 and Table 2 summarize the action selection rules which are built up according to the input information of the observed robots. A robot selects the turning by the angle α only when the robot situates in the three cases 1, 2, and 3 as shown in Figure 2. Figure 2 (a) shows the case for the robot takes left turning in which the robot observes only one robot in the area 1 and no robot in other areas. Figure 2 (b) shows the case for the robot takes right turning. Figure 2 (c) shows the case for the robot takes left or right turning, when the robot observes respectively only one robot in each of the areas 1 and 2, and no robot in the area 0. In this situation, a flag noted in Table 2 is used to determine the turning direction.

This flag information is changed when the case in Figure 2 (a) or (b) is occurred. When the robot is situated in other cases, or, when the robot observes one or more robots in the area 0, or when there are no robots in the area 0 or some robots which are not equal to one in the area 1 or 2, the robot takes the proceeding forward.

Table 2: Action-selection by observed information around a robot

Observed Information	Action
case 1	Left Turning (α [deg])
case 2	Right Turning (α [deg])
case 3	Left/Right Turning* (α [deg])
others	Proceeding

(*Select the direction to turn by flag information in which the last case either 1 or 2 is memorized)



(a) case 1 (b) case 2 (c) case 3

***Figure 2:** The situations of other robots location in the vision areas which are to be used in turning action*

3.4 Interactions in Multiple Robots

Each elemental robot undertakes the locomotion, obstacle avoidance and the following actions which are already explained and thereby the dynamic interactions occur among the many robots, resulting in the emergence of a particular configuration such as circle formation in the multiple robots system.

4. Robot Behaviors in Circle Formation

In this chapter, we will explain some of typical robot behaviors in a process of the circle formation observed in the simulation study. Moving around in a simulation space according to the action selection rules described in 3.3, some robots happen to take a circle formation. We define the circle formation as a ring formation by robots which are circulating around harmoniously, and this is observed as if they are connected for a certain time duration. The robot circle formed by a certain number of robots may grow or collapse when other robots happen to join the circle. Figure 3 shows a schematic model of the dynamic interactions to be occurred

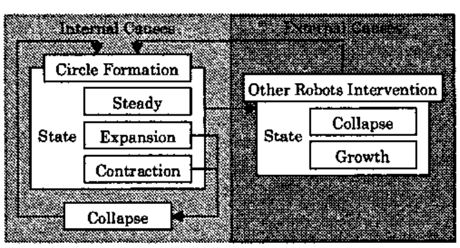
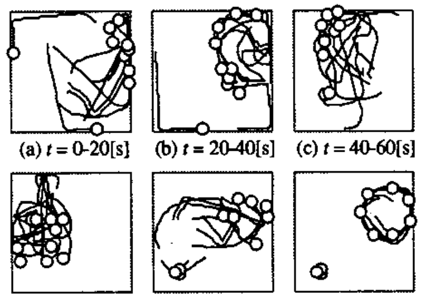


***Figure 3:** Model of dynamic interactions in the circle formation in a given area*

in the circle formation. We will explain some of the typical behaviors of robots circle formation.

4.1 Emergence of Circle Formation

Figure 4 (a)-(f) show the time-wise pictures of robot trajectories observed in the computer simulation, where empty circles show the robot location at the end of each time duration and solid lines are the robot trajectories. These figures can show a process of a circle formation emergence in multiple robots. The simulation area size is 3 [m]×3 [m] and it is enclosed by walls. The population of robots in the simulation area is 10 robots and the parameters for the robot vision specified in Figure 1 are α=17.6, β=30, γ=90 [degree] selected according to the study [7], and R=100 [cm]. The robots with no trajectory line are ceased to move and are in dead-lock. As the robots always move around except for the dead-lock situation and some of them hit the circle, the circle formation is broken and again happen to take place and then is not stationary.

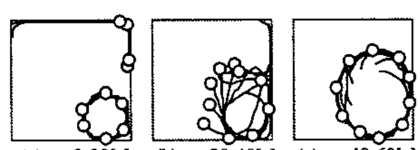


(a) t = 0-20[s] (b) t = 20-40[s] (c) t = 40-60[s]

(d) t = 60-80[s] (e) t = 80-100[s] (f) t = 100-120[s]

***Figure 4:** Time-wise process of circle formation (a)-(f) (α=17.6, β=30, γ=90 degrees, Population=10 robots)*

When the robots are in a circle formation, due to their action algorithm (see 3.3) each robot attempts to follow its front robot. However, there are two kinds of disturbance to the harmonious behavior of circle formation. One is the invasion of other robots to the circle formation, and the other is the internal instability of a circle formation as shown schematically in Figure 3. The latter is caused by a kind of mismatch between the population of robots in the circle formation and the set of parameters α, β, and γ. This is simply explained as follows. When any robots come close to the circle formation within the vision range R, they are absorbed into the circle formation suddenly. This absorption is due to the algorithm of the robot behavior described in 3.3. As a result, the population of robots in a circle formation increases, however, this growth of the population of robots



(a) t = 0-20[s] (b) t = 20-40[s] (c) t = 40-60[s]

***Figure 5:** Growth of robot population in a circle formation*

may cause the internal instability due to the mismatch above and then the circle formation is broken.

Thus the multiple robots repeat this kind of dynamics and they show the circle formation and circle collapse intermittently (See Figure 3). Figure 6 shows some circle formations generated in a large simulation area (10 [m] × 10 [m]) in which 40 robots are introduced. This figure shows a large circle of 10 robots, a medium one of 7 robots and 2 small one of 5 robots, and the location of these circles looks at random.

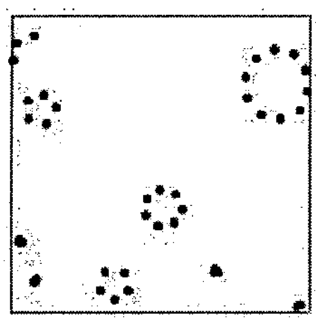
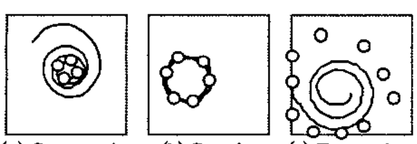


Figure 6: Circle formation takes place at random position and the size of the circles is different

4.2 Behavior of Robot Circle Formation

Figure 7 shows in summary the typical trajectories of one robot in the course of contracting the circle formation (a), steady state of circle formation (b), and expanding the circle formation (c). In this figure, the empty circles indicate the robots involved in the circle formation and the solid line is one of their trajectories. The other robots associating with the circle formation also show the similar trajectories.



(a) Contraction (b) Steady (c) Expansion

Figure 7: Three types of robot behavior of circle formation

5. Robot Population Density and Circle Formation

When considering the possibility of a large-scale circle formation in the multiple robots system, the most influence factors seem to be the robot population and the robot-working area size. To clarify the effect quantitatively, we carry out a computer simulation study with focussing on the parameters, the population of robots and the simulation area size. The important parameters of the robot vision for circle formation emergence are set as α=17.6, β=30, γ=90 [degree]. We selected the parameter values because the circle formation is most probable under these parameters (see [7]). Other parameters used in the simulation are summarized in Table 3. The robot population varies from 5 to 1800 so that the population density may cover the 10 cases for each working area size. The initial position of each robot is at random. We carry out the simulation of 10 runs for each set of the robot population and the working area size.

Table 3: Parameters used in the simulation study

Body Diameter	10.0 [cm]
Velocity	15.1 [cm/s]
Observation Range R	100.0 [cm]
Δt	0.05 [s]
Turning Angle α	17.6 [degree]
Front View Angle β	30 [degree]
Side View Angle γ	90 [degree]
Robot Population	5 – 1800 [robots]
Simulation Time	200,000 [step]
Simulation Area Size	5×5, 10×10, 15×15, 20×20, 30×30 [m×m]

In the computer simulation we observed the dynamic process of circle formation emergence, or circle formation, circle growth, and/or circle collapse. These are schematically pictured in Figure 8, where the vertical axes indicate the circle size, and the horizontal one indicates time. The empty circle indicate the time of the circle formation emergence and the mark like an explosion means its collapse. As mentioned above, the robots in the simulation area repeat the circle formation emergence and the circle collapse. To evaluate the this kind of dynamic behavior of the circle formation, we pay attention to the frequency, the duration of robot circle formation, and also the circle size and the number of formed circles. When the following conditions are satisfied, we say that a circle formation has taken place.

(i) A robot links up with the one existing in the nearest within the vision range.
(ii) If the robots linked up look like a loop, we start to count the time for the duration of circle formation.
(iii) When the duration exceeds a certain threshold value, say 100 time steps, it can be recognized as a circle formation.

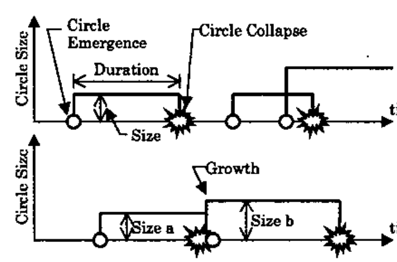


Figure 8: Schematic picture of robot circle formation phenomena observed in the simulation

As it is clear that a relation between the circle formation frequency, or how many times the circle formation takes place for a certain period, and its duration is trade-off, we pay attention to the total value of the duration of circle formation as described by Equation 1.

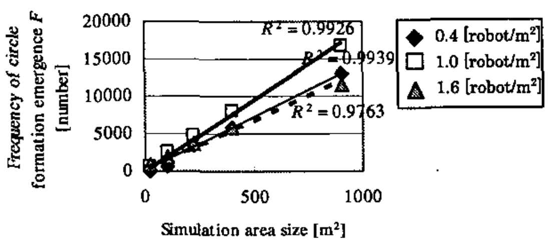
$$D_S = \sum_{k=1}^{F} D_k \quad ......(1)$$

where

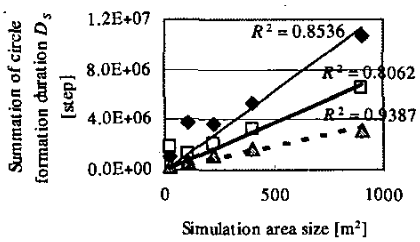
F: circle formation frequency [number],

D_k: duration of the k-th circle formation [step].

Figure 9 (a) shows the frequency of circle formation emergence and Figure 9 (b) shows the total duration D_S mentioned above for the case of population density equal to 0.4, 1.0, and 1.6 robots per one square meter. The x-axis indicates the working area size, and the y-axis indicates the frequency (a) and D_S (b), respectively. The figures show at glance that the frequency F and D_S-value increase in proportion to the working area size in specific population densities. The thick and thin solid lines and the dotted one are the least-mean-square fitting applied to the data points. Their correlation coefficient R^2 is generally more than 0.9 for the circle formation frequency. Although the R^2-value is about 0.8 at low population density in Figure 9 (b), it becomes more than 0.9 if the fitting was applied to the data points for larger working area. From these figures, the circle formation is linearly dependent to the simulation area size or the population of robots at a specific population density if the simulation area size is large.



(a) Frequency of circle formation emergence



(b) Summation of circle formation duration

***Figure 9:** A global characters of the circle formation dynamics*

Because we are interested in the multiple robotic morphology formation in large robot population, we will focus on the case of large simulation area size of 30 square meters. Figure 10 shows the frequency and its duration. The x-axis indicates the population density, the left-hand side y-axis indicates the number of circle formation frequency over the 10 simulation runs, and the right-hand side y-axis indicates the summation of the duration over all the circle formation (D_S). The peak in the circle formation frequency appears at the population density equal to 0.8 [robot/m^2], and the peak in the summation of the duration appears at 0.4 [robot/m^2]. These values of the population density are closely related to the robot view area size. Considering the geometry in Figure 1, the robot view area size is evaluated as

$$S_V = \pi R^2 \cdot \frac{2\gamma}{360} = \frac{1}{2}\pi R^2 \approx 1.57[m^2/robot] \Rightarrow 0.64[robot/m^2] \quad \text{......(2)}$$

where γ is the side view angle (90 [degree]) of a robot. If one robot locates in the robot view area S_V, the robot can take the following action which is the most fundamental mechanism for the circle formation to take place. Considering the values S_V and those for the peaks in the circle formation frequency and the sum of its duration, the robot view area size is one of the key parameters to determine the population density for the circle formation in the multiple robots system.

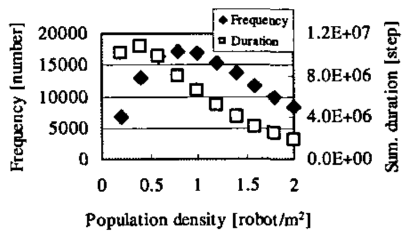


***Figure 10:** Circle formation frequency and its duration for population density (30 square meters)*

Figure 11 shows the average value of the duration of one circle formation. The larger the population density becomes, the smaller the average duration is. The reason for this decrease is the disturbance of other robots which will take place more frequently when the population density becomes large.

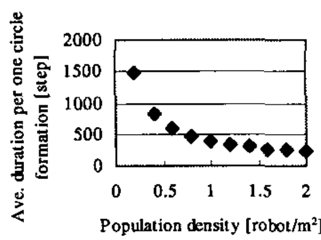


***Figure 11:** Average value of the duration of one circle formation*

Figure 12 shows the pacentage of filling-up time of circle formation with respect to the number of circle formation to the whole simulation time. For example, in the case of the population density is equal to 1.0 [robot/m^2], this percentage is about twenty to whole simulation time for the two circles formed in the given working area. In the lower population density, e.g. 0.2 or 0.4 [robot/m^2], the percentage distribution is much similar each other, and we can see that there are larger number of circles formed for these low population densities. However, for higher population densities, we can obtain a small number of the circle formation occurrance.

We can evaluate the expectation of the number of robot circles formed at a specific time from the percentage distribution shown in Figure 12 for each population density. Figure 13 shows the expected value of circle formation number which gradually decreases with increase of population density, but at the population density of about 0.4 [robot/m^2], it takes a peak value. The gradual decrease in the expected number may be caused by the circle collaption owing to the disturbance made by other robots, when the population density grows.

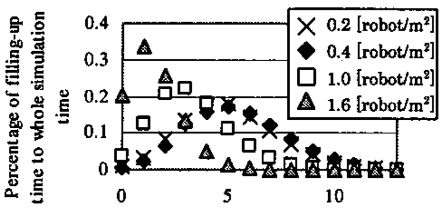


Figure 12: Percentage of filling-up time to the whole simulation time against the number of circle formation in a simulation space

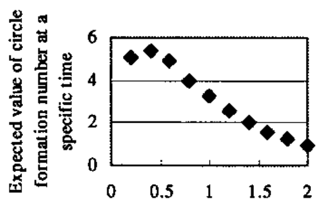


Figure 13: Expectation of circle formation number at a specific time

Finally, we focus on the circle size which represented by the number of robots consisting one circle formation. Figure 14 shows that the circle size distribution against the duration of a circle formation in the case of population density is 0.4 [robot/m^2] which is the most probable population density of circle formation. We may find that the circle size may have the limits for the longer duration. The reason cannot be discussed for lack of space, but that may be related to a robot parameters α, β, and γ (see [8]). The robot circle size of longer duration shown in Figure 14 implies that the circle formation is stable for the circle size about from 5 to 8.

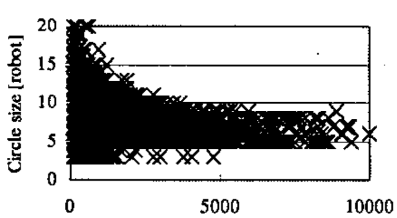


Figure 14: Circle size distribution for its duration of circle formation

6. Conclusions and Future Work

In this paper, we carried out the computer simulation to investigate the characteristics of robot circle formation with respect to the robot population and working area size in the multiple robots system. As a result of computer simulation, we have found the following results: In the case of the simulation area size is enough large (more than about 15 square meters), the frequency and duration of robot circle formation are almost linearly increased to the simulation area size or population of robots for given robot population density. Then we investigated in details the circle formation characteristics for the cases of large number of robots moving around in the 30 square meters area, and then we showed that the robot view area size is one of the key parameters to determine the population density for the circle formation which was about 0.4–0.8 [robot/m^2] for the most probable circle formation. Also, we showed that this robot population density can produce a number of circle formations. Futhermore, the circle cize of longer duration is found to be related to the robot parameters such as turning angle α, front view angle β, and side view angle γ.

One of the future works is to investigate how to emerge the robot morphology formation by combining several robot circles appeared in the multiple robots. Then it will be expected that a large scale robot morphology may be generated by autonomously combining these robot circles.

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