Local Collision Avoidance of Multiple Robots Using Avoidability Measure and Relative Distance

Nak Yong Ko*
Department Information, Control, and Instrumentation Engineering, Chosun University, 375 Seosuk-Dong, Dong-Gu, Gwangju 501-759, Korea
Dong Jin Seo
Department Control and Instrumentation Engineering, Chosun University
Koung Suk Kim
Department Mechanical Information Engineering, Chosun University, Korea

This paper presents a new method driving multiple robots to their goal position without collision. To consider the movement of the robots in a work area, we adopt the concept of avoidability measure. The avoidability measure figures the degree of how easily a robot can avoid other robots considering the velocity of the robots. To implement the concept to avoid collision among multiple robots, relative distance between the robots is proposed. The relative distance is a virtual distance between robots indicating the threat of collision between the robots. Based on the relative distance, the method calculates repulsive force against a robot from the other robots. Also, attractive force toward the goal position is calculated in terms of the relative distance. These repulsive force and attractive force are added to form the driving force for robot motion. The proposed method is simulated for several cases. The results show that the proposed method steers robots to open space anticipating the approach of other robots. In contrast, since the usual potential field method initiates avoidance motion later than the proposed method, it sometimes fails preventing collision or causes hasty motion to avoid other robots. The proposed method works as a local collision-free motion coordination method in conjunction with higher level of task planning and path planning method for multiple robots to do a collaborative job.

Key Words : Relative Distance, Avoidability Measure, Motion Coordination, Multiple Robots, Collision Avoidance, Efficiency Measure

1. Introduction

Recently, two or more robots frequently work as a team. They are used to perform a complicated task, such as moving a large and heavy object, manipulating a large object (fixing one end of a object as well as moving the other end of the object), surveillance and reconnaissance, and so on. Some of the research works on multiple robots include the works on architecture (Alur et al., 2001 ; Simmons et al., 2002), communications, motion coordination (Alami et al., 1995 ; Saffiotti et al., 2000), formation control (Balch and Arkin, 1998), robotic soccer (Tews and Wyeth, 1999 ; Groen et al., 2001 ; Weigel, 2002 ; Wong et al., 2001), collision avoidance and tracking (Arai and Ota, 1989 ; Wong, 2001 ; Jongusuk and Mita, 2001), motion planning (Latombe, 1990), localization and navigation (Noborio and Yoshioka, 1998 ; Wang, 1989 ; Arkin, 1990) and so on.

* Corresponding Author,
E-mail : nyko@mail.chosun.ac.kr
TEL : +82-62-230-7108; **FAX** : +82-62-224-1987
Department Information, Control, and Instrumentation Engineering, Chosun University, 375 Seosuk-Dong, Dong-Gu, Gwangju 501-759, Korea. (Manuscript **Received** June 16, 2003; **Revised** November 19, 2003)

Especially, collision avoidance between robots was investigated since local collision avoidance is indispensible for safe and successful motion of multiple robots (Arai et al., 1989). For example, every robot in a robot soccer team decides its role according to a strategy, and moves to their own position. The strategy plans task and path of each robot. While moving locally, they should avoid collision among them, as well as moving as fast as possible. In this respect, we propose a new method for local collision avoidance of multiple robots in a work area.

It is preferred for the robots to go to their goal positions as soon as possible through a trajectory with shorter length. Until now, some methods such as potential field methods (Khatib, 1986; Borenstein and Koren, 1991) and curvature based methods (Simmons, 1996; Ko and Simmons, 1998) are used for collision avoidance. Though many of the conventional collision avoidance methods can be adapted for collision avoidance of multiple robots, they are not able to consider the movement of robots effectively, because they are developed for static obstacle avoidance.

To consider the movement of the robots in a work area, we adopt the concept of avoidability measure (AVM). The avoidability measure figures the degree of how easily a robot can avoid other robots considering the velocity of the robot and the other robots as well. To implement the concept in multiple mobile robot environment, a virtual distance between the robots, called the relative distance (RD) is derived. The relative distance is shorter than real distance if the threat of collision is high, while it is longer than the real distance if the threat of collision is low. In terms of the relative distance, the attractive force to the goal position and the repulsive force from other robots are calculated to guide a robot safely.

The proposed method is simulated for several cases. We compare these results with that of the conventional artificial potential field method using real distance. The results show that the proposed method steers robots to open space anticipating the approach of other robots. In contrast, since the usual potential field method initiates avoidance motion later than the proposed method, it sometimes fails to prevent collision or causes hasty motion to avoid another robots.

We can also assign motion priority to each robot in a work area. The robots with higher priority disregard the motion of robots with lower priority, and plan their motion with no attention to collision with the robot of lower motion priority. The robots with lower priority avoid robots with higher priority, that is, collision avoidance is up to the lower priority robots-robots with higher priority is exempted from collision avoidance motion. If there is no priority, all the robots try to avoid each other simultaneously. Comparing these two cases through simulation, it is found that the sum of trajectory length of all the robots is longer in case with priority than in case of no priority. Also, in case with priority, the time required for all the robots to get to their goal positions is longer while higher priority robot moves faster along shorter path than in the case of no priority.

We begin with problem formulation in section 2. In section 3, follows the definition of AVM and RD. RD is a function of three variables: the distance between the two robots and the outward speeds of the two robots under consideration for collision avoidance. In section 4, an RD based method calculating driving force for a robot is presented. Some computer simulations show the effectiveness of the proposed method in section 5. Finally, we present a few concluding remarks in section 6.

2. Problem Formulation

We use the following nomenclature in solving the collision-free motion coordination problem.

$p_j(t)$	position of the robot j at time t
$P_{sj}=(x_{sj}, y_{sj})$	starting position of robot j
$P_{gj}=(x_{gj}, y_{gj})$	goal position of robot j
r_j	radius of robot j
$t_i(i=0, \cdots)$	the i-th sampling time

In this paper, the robot j is assumed to be circular with the radius r_j. Using the above nomenclature, the collision-free motion coordination problem is formulated as the followings.

[Collision-free motion coordination problem]

For N robots, given the starting position P_{sj}, $j=1, 2, \cdots, N$ and the goal position P_{gj}, $j=1, 2, \cdots, N$ of the robots, plan and control the robot motion avoiding collision among them as efficiently as possible. It is assumed that every robot j knows its position $p_j(t)$, velocity $\dot{p}_j(t)$ and the position and velocity of the other robots $p_k(t)$, $\dot{p}_k(t)$, $k \neq j$, $k=1, 2, \cdots, N$.

Generally, the efficiency of robot motion is measured with the criterion of motion time and path length. In multiple robot motion coordination problem, we need some more criterion for performance evaluation. The motion efficiency of a robot j is evaluated with the following five measures.

[Efficiency measure]

(1) Motion Time (MT): The time period from the initial time to the time at which the robot j reaches its goal position.

(2) Path Length (PL): The length of the path from the initial position to the goal position of the robot j.

(3) Time Efficiency (TE): The time period from the motion start to the time when the robot j enters into collision-free state.

(4) Spatial Efficiency(SE): The length of the motion trajectory from the starting position P_{sj} to the position where the robot j enters into collision-free state.

(5) Safety Margin(SM): The shortest distance from the robot j to the other robots during the coordination motion.

Since the efficiency measures are defined for each robot, we calculate these measures with respect to every robot and compare the efficiency measures resulting from the proposed method with those of other methods. While it is desirable to have larger SM for safer motion, smaller value of MT, PL, TE, and SE is favorable for faster motion with shorter path length. Defining TE and SE, the criterion for the collision-free state for a robot j is as the following.

[Criterion for collision-free state]

The robot j is in the collision-free state at

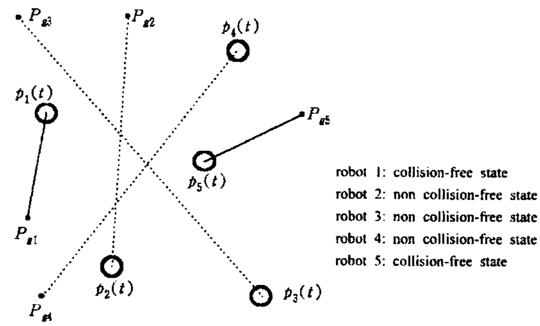

Fig. 1 Criterion for collision-free state

time t if the shortest distance between the line segments $\overline{p_j(t)P_{gj}}$ and $\overline{p_k(t)P_{gk}}$ is larger than (r_j+r_k) for all the k such that $k \neq j$, $k=1, 2, \cdots, N$.

The collision-free state means the robot j doesn't collide with other robots if all the robots move straight to their goal position from the time t. Figure 1 explains the collision-free state. In the Figure 1, robot 1 and robot 5 are in collision-free state, while the others are not in collision-free state.

3. Avoidability Measure and Relative Distance

To control robot motion in stationary object environment, it is sufficient to consider only the position of the robot and objects. On the other hand, in the collision avoidance of multiple mobile robots, motion control of a robot requires attention to the mobility of the robots to look ahead the possibility of collision between them. To consider the mobility of robots, we adopt the concept of the AVM. Hereafter, the robot we are to control is called the "controlled robot," and the robot with which the controlled robot should avoid collision and work in corporation is called the "companion robot."

3.1 Avoidability measure (AVM)

The distance between a controlled robot and a companion robot can be used for detection of collision between them. Also, the threat of collision between the robots increases if the robots move toward each other robot. So, the possibility of collision can be measured by the distance and the outward or inward speed of the controlled robot and the companion robot. In other words, the distance and outward speed indicate the possibility of collision avoidance. Thus, we select the distance and the outward speed as the state variables describing the possibility of collision avoidance. AVM is defined as a function of these three state variables in the following.

Definition: Avoidability measure (AVM) at time t is a function of the distance $d_{jk}(t)$ and the outward speed $v_{jk}(t)$, $v_{kj}(t)$ satisfying the following conditions.

(1) Condition 1: AVM increases as the distance $d_{jk}(t)$ increases.

(2) Condition 2: AVM increases as the outward speed $v_{jk}(t)$ increases.

(3) Condition 3: AVM increases as the outward speed $v_{kj}(t)$ increases.

In the definition, the distance $d_{jk}(t)$ and outward speed $v_{jk}(t)$ are defined as the followings.

$$d_{jk}(t) = \| p_j(t) - p_k(t) \| - (r_j + r_k) \qquad (1)$$

$$v_{jk}(t) = \dot{p}_j(t) \cdot \frac{p_j(t) - p_k(t)}{\| p_j(t) - p_k(t) \|} \qquad (2)$$

In the Definition, $v_{jk}(t)$ is the projection of the j-th robot velocity on the unit vector from the k-th robot to the j-th robot. So, it increases as the j-th robot moves away from the k-th robot and it becomes negative if the j-th robot approaches to the k-th robot; that is, it reflects the motion of the j-th robot relative to the k-th robot. Figure 2 explains the outward speed. In terms of the AVM, collision-free motion coordination problem becomes to control the motion of the j-th robot ($j=1, \cdots, N$) keeping the AVM between the j-th robot and the k-th robot ($k \neq j$, $j=1, \cdots, N$) above a safe limit value to guarantee collision-free motion. To calculate driving force to a controlled robot, our work uses relative distance as an AVM.

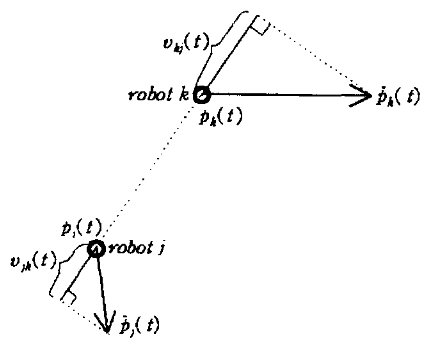

Fig. 2 Outward speed

3.2 Relative distance (RD)

There exist infinite number of functions satisfying the conditions for AVM. To calculate the driving force for a robot using AVM, we propose a function called the relative distance (RD) as an example of AVM. The relative distance between the robot j and robot k, $rd_{jk}(t)$ is defined as the following.

$$rd_{jk}(d_{jk}(t), v_{jk}(t), v_{kj}(t)) = \sqrt{\frac{\alpha + v_{jk}(t)}{\alpha}} \cdot \sqrt{\frac{\beta + v_{kj}(t)}{\beta}} \cdot d_{jk}(t) \qquad (3)$$

where

$$\alpha > \max\{|v_{jk}(t)|\} > 0, \quad \beta > \max\{|v_{kj}(t)|\} > 0 \qquad (4)$$

We abbreviate $rd_{jk}(d_{jk}(t), v_{jk}(t), v_{kj}(t))$ as $rd_{jk}(t)$ in the following. The $rd_{jk}(t)$ increases as $d_{jk}(t)$ or $v_{jk}(t)$ or $v_{kj}(t)$ increases; so, it satisfies the conditions for AVM. We set the j-th robot to begin the avoidance motion when $rd_{jk}(t)$ decreases to a certain value. As $rd_{jk}(t)$ decreases, the repulsive force from the k-th robot to the j-th robot increases.

To take the advantage of the RD based method, the values of the parameters α and β should be chosen appropriately. In equation (3), as α increases, the less the $v_{jk}(t)$ influences $rd_{jk}(t)$. As β increases, the less the $v_{kj}(t)$ influences $rd_{jk}(t)$. So, if α and β increase, the real distance has more influence on the collision-free trajectory than the outward speeds do. On the contrary, as α or β decreases, relative distance is more sensitive to the change of outward speed, and collision avoidance motion reacts more sensitively to the outward speed. However, too small α or β may result in too sensitive trajectory change of the controlled robot in response to the companion robot's motion. Thus, too small values of α and β causes oscillatory or unnecessary roundabout motion. It is required to set the values of the α and β as small as possible provided that the robots don't show unnecessary roundabout path or oscillatory motion. Since the optimal values of these parameters cannot be found by an analytical method, they are chosen through a number of trials in the simulations.

If $v_{jk}(t)=v_{kj}(t)=0$, that is, the robot j and the robot k do not move in the direction of the line $\overline{p_j(t)p_k(t)}$, or the robot j and robot k are stationary, then $rd_{jk}(t)=d_{jk}(t)$. If α and β are very large compared with $|v_{jk}(t)|$ and $|v_{kj}(t)|$, then $rd_{jk}(t)\cong d_{jk}(t)$, that is the outward speed $v_{jk}(t)$ and $v_{kj}(t)$ hardly influence the $rd_{jk}(t)$. So α and β should be tuned by trial and error considering the sensitivity of collision free robot trajectory to the outward speed $v_{jk}(t)$ and $v_{kj}(t)$.

With the definition of $rd_{jk}(t)$ in (3), $rd_{jk}(t)>0$ if and only if $d_{jk}(t)>0$. Thus, the condition for the robot j to avoid the other robots is

$$rd_{jk}(t)>0 \text{ for all } k\neq j,\ k=1,2,\cdots,N,\ t\geq t_0 \tag{5}$$

So, in terms of the $rd_{jk}(t)$, the collision-free motion coordination problem becomes to plan and control the robot trajectory $p_j(t)$, $j=1,2,\cdots,N$ from P_{sj} to P_{gj}, satisfying the condition of the inequality (5).

4. Driving Force in Terms of the Relative Distance

A method of keeping the relative distance above some positive limit value becomes collision avoidance method of multiple robots. We derive a method calculating the driving force of a robot based on the relative distance. The driving force $f_{d,j}(t)$ for a robot j is the sum of the attractive force $f_{a,j}(t)$ toward its goal position and the repulsive force $f_{r,j}(t)$ exerted by the other robots, as the equation (6).

$$f_{d,j}(t)=f_{r,j}(t)+f_{a,j}(t) \tag{6}$$

The repulsive force $f_{r,j}(t)$ is a function of the relative distance between the robot j and the companion robots $k(k\neq j,\ k=1,2,\cdots,N)$. Every companion robot $k(k\neq j,\ k=1,2,\cdots,N)$ exerts repulsive force $f_{r,jk}(t)$ to the controlled robot j. So, the repulsive force $f_{r,j}(t)$ is obtained as the following.

$$f_{r,j}(t)=\sum_{k=1}^{N}f_{r,jk}(t) \quad (k\neq j) \tag{7}$$

The repulsive force $f_{r,jk}(t)$ from robot k to robot j is the function of the relative distance $rd_{jk}(t)$. In this paper, $f_{r,jk}(t)$ is set to be

$$f_{r,jk}(t)=\begin{cases}0, & \text{if } rd_{jk}\geq\varepsilon_{rep}\\ K(rd_{jk})\cdot\dfrac{p_j(t)-p_k(t)}{\|p_j(t)-p_k(t)\|}, & \text{if } 0<rd_{jk}<\varepsilon_{rep}\end{cases} \tag{8}$$

where

$$K(rd_{jk})=\frac{1}{\sin\left(\pi\cdot\dfrac{rd_{jk}}{2\varepsilon_{rep}}\right)}-1 \tag{9}$$

In the equation (8), $rd_{ik}(t)$ is abbreviated as rd_{jk}. The repulsive force from robot k to robot j is directed to the direction from robot k to robot j. The magnitude of the force is zero if the relative distance between the robots is above some boundary distance ε_{rep}. If the robot j is within the work area of radius ε_{rep} from the robot k, measured by the relative distance, repulsive force with the magnitude proportional to the trigonometric function of cosec repels the robot j as shown in the equation (9). Since the value of the trigonometric function cosec rises sharply as the variable $\pi\dfrac{rd_{jk}}{2\varepsilon_{rep}}$ decreases, the repulsive force increases sharply as the robot j gets near to robot k. The magnitude of the repulsive force $f_{r,jk}(t)$ decreases to zero as rd_{jk} increases to the boundary value of ε_{rep}. At $rd_{jk}=\varepsilon_{rep}$, $f_{r,jk}(t)$ and its derivative is zero. So, the magnitude and its derivative of $f_{r,jk}(t)$ are continuous for $0<rd_{jk}<\infty$, and abrupt change of repulsive force is avoided.

Figure 3 depicts the magnitude of $f_{r,jk}(t)$ as a function of rd_{jk}. Here, ε_{rep} is the limit distance of repulsive force influence. As the value of ε_{rep} increases, repulsive force from the other robots increases and repulsive force influences larger area around the robots. If ε_{rep} is too small, the robots may collide because repulsive force arises only when the robots get too close. With small ε_{rep}, even though the robots can avoid collision, they should change their trajectory abruptly. On

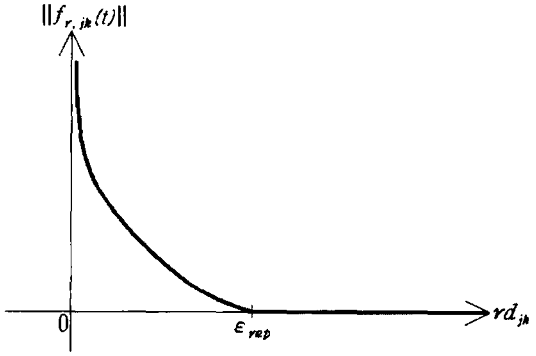

Fig. 3 Graph of $f_{r,jk}(t)$ as a function of rd_{jk}

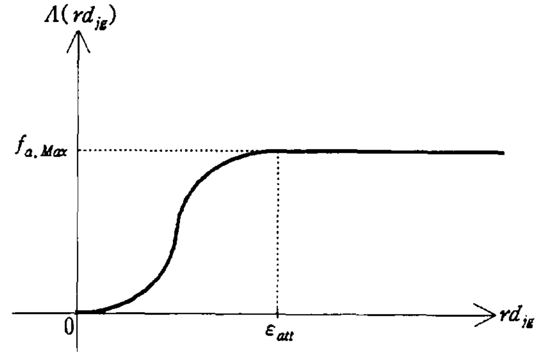

Fig. 4 The function $\Lambda(rd_{jg})$

the contrary, if ε_{rep} is too large, the robots move away even if they are far apart from each other. So, ε_{rep} should be chosen as small as possible provided that collision avoidance between the robots are guaranteed and abrupt trajectory change doesn't happen.

The attractive force is directed from the position of the robot j to the goal position. The attractive force $f_{a,j}(t)$ acting on the robot j by the goal position P_{gj} is as the following.

$$f_{a,j}(t)=\Lambda(rd_{jg})\cdot\frac{P_{gj}-p_j(t)}{\|P_{gj}-p_j(t)\|} \qquad (10)$$

The magnitude of the attractive force is a function of the relative distance rd_{jg} between the robot j and the goal position P_{gj}. The function $\Lambda(rd_{jg})$ accounts for the attractive force is maintained maximally if the robot is far beyond some limit relative distance, and decreases when the robot gets near to its goal position. $\Lambda(rd_{jg})$ is derived as the following.

$$\Lambda(rd_{jg})=\begin{cases} f_{a,Max}, & \text{if } rd_{jg}>\varepsilon_{att} \\ A\cdot rd_{jg}^3+B\cdot rd_{jg}^2, & \text{if } 0\le rd_{jg}\le\varepsilon_{att}\end{cases} \qquad (11)$$

where $A=-2\frac{f_{a,Max}}{\varepsilon_{att}^3}$, $B=3\frac{f_{a,Max}}{\varepsilon_{att}^2}$

$\Lambda(rd_{jg})$ is at its maximal value $f_{a,Max}$ if the robot j is far apart from its goal position. As the robot j enters into the work area of radius ε_{att} (in relative distance) around its goal position, the attractive force decreases gradually to stop the robot at the goal location. The function $\Lambda(rd_{jg})$ is chosen so that it increases continuously with rd_{jg}, and its derivative is also continuous for $0<rd_{jg}<\infty$. Figure 4 shows the function $\Lambda(rd_{jg})$.

As the robot approaches to its goal position within the distance of ε_{att}, it slows down to stop at its goal position. With too large ε_{att}, the attractive force decreases too early before the robot gets sufficiently close to the goal position, and the robot arrives at its goal position too slowly. If ε_{att} is too small, the robot doesn't slow down even if it approaches its goal position. So, the robot cannot stop at its goal position, and go back and forth around the goal position before it stops. As for $f_{a,Max}$, large $f_{a,Max}$ induces large attractive force. If $f_{a,Max}$ is too large, repulsive force becomes negligible compared to the attractive force, and hardly influences the robot motion. So, the robots move directly to their goal positions, and collision among them can take place.

Like the problem of local minima in artificial potential field method, this method can't completely remove the possibility of trap situation. However, the robot can get out of the trap using some heuristic method. In addition, the trap situation for a controlled robot usually occurs temporally, and disappears by itself as the companion robots move. Besides, the driving force $f_{d,j}(t)$ may drive the robot out of the robot's motion capability. In this case, the magnitude of $f_{d,j}(t)$ is scaled down to its maximal value.

5. Simulation Results

The proposed method is tested by simulation. Simulation results for the following six cases are examined and discussed.

(1) Case 1 and case 2: Compare the simulation result of the proposed method with that of artificial potential field method based on real distance.

(2) Case 3, case 4, and case 5 : Change the parameter values of α, β, and ε_{rep}, and compare the simulation results.

(3) Case 6 : Assign priority on robot motion, and examine the influence of assigning priority on robot motion.

5.1 Comparison of the method with conventional potential field method

We compare the performance of the method with the method guiding robots under artificial potential field formed in terms of real distance. The approach using the artificial potential field (APF) is one of the major research topics for collision avoidance of mobile robots. Also, in real implementation for collision avoidance, the approach has been most frequently used. So, the APF based approach has been modified until now and has much number of variants, such as Vector Field Histogram (Borenstein and Koren, 1991), new potential-field based methods (Wang and Chirikjian, 2000; Haddad et. al., 1998; Chengqing et. al., 2000), and so on. The work by Khatib (1986) is one of the methods proposed in early stage, and is generally acknowledged as one of the representative work on APF approach. As a leading work on APF, the method shows typical aspects of the APF method. Thus the method has been frequently and generally referred. To compare the method proposed in this paper with the most commonly and frequently used method, the most generally accepted method by Khatib (1986) is selected, even though it is published fairly long time ago.

Five robots move to their goal positions in a work area. The starting position and goal position of each robot is shown in the Table 1. For the same starting position and goal position, case 1 uses the proposed method while case 2 uses artificial potential field method. The artificial potential field method calculates the driving force $F_{art}(p_j(t), p_k(t), p_{gj})$ for a robot j exerted by a companion robot at $p_k(t)$ and goal position

Table 1 Starting position and goal position of the robots for the cases 1 and 2

Robot	Starting position	Goal position
Robot 1	(100, 50)	(800, 400)
Robot 2	(900, 150)	(200, 400)
Robot 3	(300, 400)	(500, 50)
Robot 4	(100, 400)	(800, 50)
Robot 5	(750, 400)	(200, 50)

P_{gj}, as the following (Khatib, 1986).

$$\begin{aligned} &F_{art}(p_j(t), p_k(t), P_{gj}) \\ &= -\nabla U_{art}(p_j(t), p_k(t), P_{gj}) \\ &= -\nabla U_k(p_j(t), p_k(t)) - \nabla U_g(p_j(t), P_{gj}) \\ &= F_k(p_j(t), p_k(t)) + F_g(p_j(t), P_{gj}) \end{aligned} \tag{12}$$

In the equation (12), the potential field value $U_{art}(p_j(t), p_k(t), P_{gj})$ at a location $p_j(t)$ is defined as

$$\begin{aligned} &U_{art}(p_j(t), p_k(t), P_{gj}) = U_k(p_j(t), p_k(t)) + U_g(p_j(t), P_{gj}) \\ &U_k(p_j(t), p_k(t)) = \begin{cases} \frac{1}{2}\eta\left(\frac{1}{d_{jk}(t)} - \frac{1}{\varepsilon_d}\right)^2, & \text{if } d_{jk}(t) \le \varepsilon_d \\ 0, & \text{if } d_{jk}(t) > \varepsilon_d (\varepsilon_d > 0) \end{cases} \\ &U_g(p_j(t), P_{gj}) = \frac{1}{2}\zeta \| p_j(t) - P_{gj} \|^2 \end{aligned} \tag{13}$$

In equation (13), ε_d represents the limit distance of the potential field influence, and $d_{jk}(t)$ is the real distance from the location $p_j(t)$ to $p_k(t)$. At the position $p_j(t)$ farther away from the position $p_k(t)$ than the distance ε_d, there is no force by the robot k. As ε_d increases, the $U_k(p_j(t), p_k(t))$ influences larger range, thus the robot j begins avoidance motion farther apart from the robot k. The parameter ε_d works in the same way as the parameter ε_{rep} does in the RD based method. The η and ζ are constant coefficients for repulsive and attractive potential field respectively. Like the parameter $f_{a,Max}$ in the RD based method, large ζ induces large attractive force. If ζ is too large, repulsive force becomes negligible compared to the attractive force, and hardly influences the robot motion. So, the robots move directly to their goal positions, and collision among them can take place. In the case 2, the parameters η, ε_d, ζ are set to be $\eta=250000$, $\varepsilon_d=150$, $\zeta=0.005$. Table 2 shows the parameter values used for the case 1. The parameter values

Table 2 Parameter values for the case 1

Parameters	α	β	ε_{rep}	ε_{att}	$f_{a,Max}$
value	180	180	150	50	3

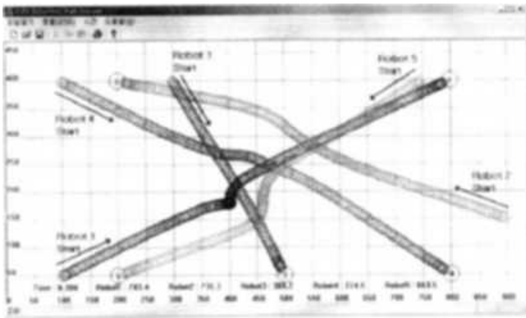

Fig. 5 Robot motion trajectory for the case of using the proposed method (case 1)

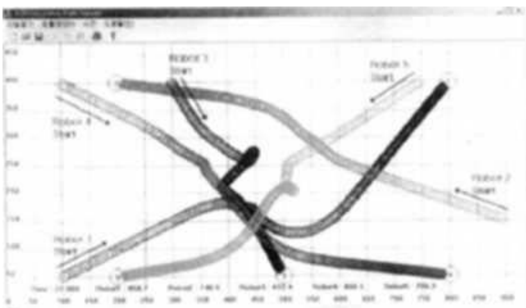

Fig. 6 Robot motion trajectory for the case of using the APF based method (case 2)

are the same for all the five robots.

Figure 5 and Figure 6 show the trajectory for the case 1 and case 2 respectively. Table 3 and 4 show the efficiency measure for the cases 1 and 2 respectively.

As shown in the Figs. 5 and 6, all the robots move smoother in case 1 than in the case 2. Also, the path lengths of all the robots are shorter in case 1 than in the case 2 as shown in Table 3 and 4. Since the robots in case 1 respond to the relative distance, they start avoidance motion as they are approaching each other even if they are apart from each other. On contrast, the artificial potential field method initiate avoidance motion later than the RD base method, because it only responds as the distance decreases to some limit, regardless of the motion of the robots. As

Table 3 Efficiency measure for the case 1

efficiency measure / robot	PL	MT	SE	TE	SM
robot 1	783.394	8.25	378.505	4.5	28.50
robot 2	735.337	6.85	381.074	3.5	46.89
robot 3	389.211	3.4	257.691	2.15	65.26
robot 4	774.452	7.4	446.491	4.5	46.89
robot 5	663.524	6.55	345.922	3.3	28.50

Table 4 Efficiency measure for the case 2

efficiency measure / robot	PL	MT	SE	TE	SM
robot 1	850.711	21.35	506.167	5.85	43.24
robot 2	740.463	19.9	357.173	3.55	57.61
robot 3	493.411	21.75	317.278	8.7	44.90
robot 4	800.481	21.45	514.386	6.85	47.69
robot 5	706.939	21.95	481.139	8.7	43.24

shown in the Table 3 and 4, most of the efficiency measures except the safety margin are better in the case 1 than in the case 2.

In the proposed RD based method, the trajectory of a robot changes as the value of the parameters α, β, ε_{rep}, ε_{att}, and $f_{a,Max}$ changes. Likewise, as for the APF based method, the parameter values η, ε_d, and ζ influences the performance of the robot motion. In both methods, the change of trajectory of a robot also changes the trajectories of the other robots. With improper selection of parameter values, the RD based method may result in less efficient motion than the APF based method.

In the paper, values of the parameters for both the proposed method and APF base method are determined through a number of empirical trials as the values resulting the best safe, smooth and efficient robot movement. It may be possible to find another values of the parameters η, ε_d, and ζ, which result in better performance than the values listed in the paper. Nevertheless, it is obvious from equation (3) that the RD based method looks ahead the collision between robots because the relative distance becomes shorter than the real distance if the robots move toward each other. So, the proposed method initiates avoidance motion earlier than the APF based method if the robots approach each other. The simulation results show that the two methods can drive the robots to their goal position without collision. The difference is that the proposed method considers the movement of robots and can avoid complicated situation which brings about abrupt change of robot trajectory as the APF based method does in the case 2.

5.2 Effect of α, β, and ε_{rep} change on robot motion

In this section we test the performance of the proposed method and examine the effect of parameter value change. For easy comparison, we take an extreme example. In cases 3, 4, and 5, the starting position and goal position of the robots are shown in the Table 5. The starting position and goal position of robot 1 and robot 4 are placed symmetrically with respect to the robot 3's straight line trajectory, i.e., the line $\overline{P_{s3}P_{g3}}$. Also, the starting position and goal position of robot 2 and robot 5 are placed symmetrically with respect to the line $\overline{P_{s3}P_{g3}}$. If all the robots move with the same speed to their goal positions, robot 1 and 4 will collide at the location (450, 225). Likewise, the robot 2 and 5 will collide at the location (550, 225). In case 3, the parameter values for all the robots are the same. In case 4 and case 5, we set some of the parameter values different from robot to robot. In case 4, the value of parameters α and β are different for each robot. The parameter values for the robots in case 3 are shown in Table 6. In case 4, all the values except α and β are the same as those in the case 3. The values of α and β for the case 4 are shown in the Table 7. For both cases, the robot motion trajectory of the robots are depicted in the Figure 7 and Figure 8, and the efficiency measures are shown on the Table 8 and Table 9.

As shown in the Fig. 7, robots 1, 3 and 4 moves in parallel for a while from the x-axis location 500, and then robot 1 detours abruptly upward to avoid robot 4. Then robot 4 moves toward its goal position. If one of the robot 1 and robot 4

Table 5 Starting position and goal position of the robots for the cases 3, 4, and 5

Robot	Starting position	Goal position
Robot 1	(100, 50)	(800, 400)
Robot 2	(900, 50)	(200, 400)
Robot 3	(100, 225)	(900, 225)
Robot 4	(100, 400)	(800, 50)
Robot 5	(900, 400)	(200, 50)

Table 6 Parameter values for the case 3

Parameters	α	β	ε_{rep}	ε_{att}	$f_{a,Max}$
value	180	180	150	50	3

Table 7 Parameter values for the case 4

parameter / robot	α	β
robot 1	220	220
robot 2	200	200
robot 3	180	180
robot 4	160	160
robot 5	140	140

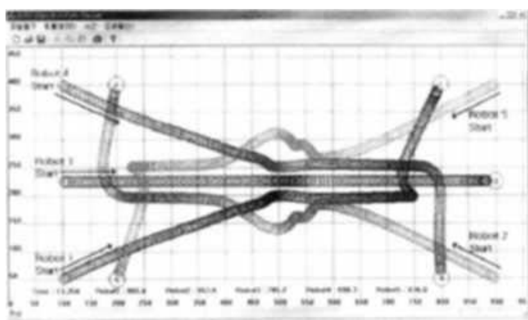

Fig. 7 Robot motion trajectory for the case 3

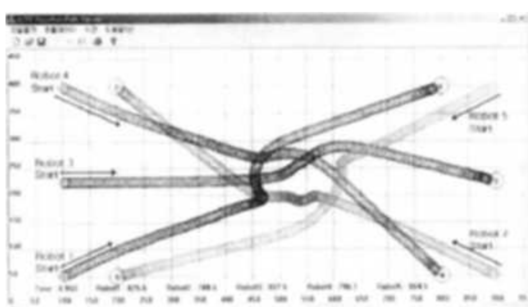

Fig. 8 Robot motion trajectory for the case 4

Table 8 Efficiency measure for the case 3

efficiency measure / robot	PL	MT	SE	TE	SM
robot 1	885.642	12.2	677.526	9.75	20.54
robot 2	953.774	13.2	741.083	10.8	24.38
robot 3	785.243	7.1	484.011	4.4	28.47
robot 4	898.255	12.0	693.333	9.75	20.54
robot 5	936.014	13.3	731.911	10.8	24.38

Table 9 Efficiency measure for the case 4

efficiency measure / robot	PL	MT	SE	TE	SM
robot 1	825.608	8.65	459.723	5.4	26.51
robot 2	788.606	8.5	447.077	5.4	26.51
robot 3	807.554	7.2	569.76	5.0	32.97
robot 4	796.109	8.3	484.966	5.4	44.87
robot 5	804.53	8.9	397.47	4.95	32.97

yields the path to the other robot in early stage of its motion, they can move more efficiently. However, since the robot 1 and robot 4 moves with the same value of parameters α, β, and ε_{rep}, they exhibits the same pattern of motion.

In case 4, for most of the robots except the robot 3, all the efficiency measures are improved compared with the case 3. Case 3 results in better efficiency measure only for robot 3, except the safety margin (SM). As a whole, the case 4 results in more efficient motion than the case 3. This is because the robots have different values of α and β. With smaller α and β, relative distance is more sensitive to relative motion of the controlled robot and the companion robots. So, the collision avoidance begins earlier with smaller α and β value, while collision avoidance begins later with larger α and β. As shown in case 3, the robots with the same value of α and β begins avoidance motion nearly at the same time, and some of them often behaves symmetrically. In case 3, the robot 1 and robot 4 go in parallel for a while and it takes much longer to find collision free path. Also, the robot 2 and robot 5 behave in a similar manner. In contrast, in case 4, robot 4 begins

Table 10 Parameter value of ε_{rep} in case 5

parameter / robot	ε_{rep}
robot 1	180
robot 2	165
robot 3	150
robot 4	135
robot 5	120

avoidance motion earlier than the robot 1, and robot 5 begins avoidance motion earlier than robot 1. Hence, they don't behave symmetrically, and their motion is more harmonious and efficient than in the case 3.

Comparing Figs. 7 and 8, it is noticeable that case 4 results in smoother and shorter trajectory than case 3. The robots in case 4 avoid other robots in different manner from those in the case 3. This is because the robots have different values of parameters. So, some of the robots starts avoidance motion earlier and other robots later. They exhibit less confliction finding their collision-free path. That is, they break the side by side state earlier and can find collision-free path more efficiently.

Assigning different values of ε_{rep} to each robot also results in efficient coordination motion. In case 5, ε_{rep} differs from robot to robot. All the values of the parameters except the ε_{rep} are the same as in the case 3. The value of ε_{rep} assigned to each robot is as in Table 10. The motion of robots for the case 5 is shown in Fig. 9. Also, the efficiency measure is as shown on Table 11.

Figure 9 shows the role of parameter ε_{rep}. As the value of ε_{rep} is the biggest for robot 1, the robot 1 starts avoidance motion far apart from the other robots. Robot 5 starts avoidance motion near the other robots, because the value ε_{rep} for the robot 5 is the smallest among the robots. The robot 1 slightly curves to right from the start, and avoids other robots with large meandering detour. Meanwhile, robot 5 deviates only slightly from the straight line $\overline{P_{s5}P_{g5}}$. Unlike in the case 3, each robot has different characteristics of avoidance motion in case 4 and case 5, so, the robots move along smooth and short trajectory to their

Table 11 Efficiency measure for the case 5

robot \ efficiency measure	PL	MT	SE	TE	SM
robot 1	825.649	9.05	507.157	6.1	46.13
robot 2	849.362	8.90	448.231	5.2	26.40
robot 3	814.63	7.65	566.076	5.35	26.40
robot 4	867.654	9.75	513.258	6.55	21.57
robot 5	787.962	9.35	493.611	6.55	21.57

Table 12 Efficiency measure for the case 6

robot \ efficiency measure	PL	MT	SE	TE	SM
robot 1	768.781	6.75	576.002	4.85	18.00
robot 2	896.228	8.45	465.211	4.5	18.00
robot 3	831.807	6.70	628.642	4.85	40.87
robot 4	784.142	8.00	570.446	5.95	19.51
robot 5	959.748	9.95	522.607	5.95	19.51

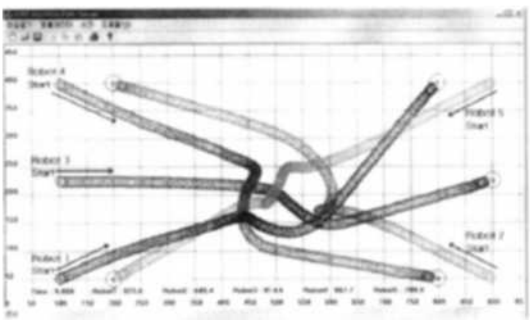

Fig. 9 Robot motion trajectory for the case 5 (varying ε_{rep})

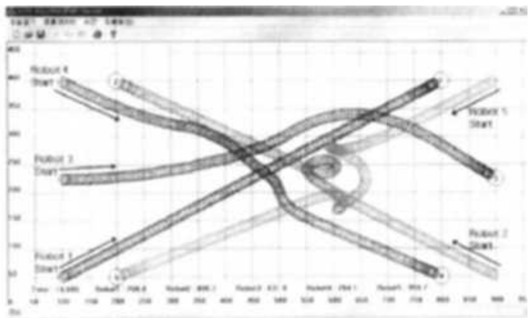

Fig. 10 Robot motion trajectory in case with motion priority (case 6)

goals.

5.2 Simulations for the case of robots with motion priority

Sometimes, some of the robots in a work area should move through a specific trajectory to do their job or some of them should reach their goal position faster than others. In this case, collision can be prevented if other robots avoid the selected robots. Our method can deal with such a case by assigning discriminatory motion priority to each robot. Robots with higher priority disregard the motion of lower priority robots and robots with lower priority avoid the higher priority robots. In case 6, robots with smaller number have higher motion priority than the robots with larger number. So, the robot 1 has the highest priority and moves with no regard to other robots' motion. The robot 5 has the responsibility to avoid collision with all the other robots. The parameter values are the same as those in the case 3. We compare the result of case 6 with the results of no motion priority (cases 3, 4, and 5). The Figure 10 shows the motion trajectory of each robot for the case 6. The efficiency measure for the case 6 is presented in the Table 12.

In case with motion priority, robot 5 detours more than the cases with no priority. This is because robot 5 should avoid all the other robots while the other robots don't care to avoid robot 5. Therefore, with priority, the path length and motion time of robot 5 are longer than others, while robot 1 moves faster with shorter path length. Besides, the sum of path lengths (PM) of all the robots is the longest among the cases 4, 5, and 6. In addition, it takes the longest time to complete the motion of all the robots. In conclusion, compared with the case 4 and 5, case 6 results in better efficiency for the robot 1 (the highest priority robot), at the cost of overall efficiency degradation of the system. Compared with the case 3, case 6 also shows that even though the robots have the same parameter values, they can avoid deadlock or side by side state by discriminating their motion priority, and move more efficiently.

The simulation example for the cases 3 to 6 is an extreme case where the robots are placed symmetrically and the robots have difficulty in collision avoidance if they have the same priority and parameter values. Comparing the case 3 with the cases 4, 5, and 6, it is generally recognized that robots can behave more efficiently and harmoniously when each robot has different values of parameters or motion priority.

5. Conclusions

This paper presents a method driving multiple mobile robots locally to their goal position without collision. The followings are some remarks on the method.

(1) Since it uses relative distance, it looks ahead the collision between robots considering the mobility of robots, and initiates avoidance motion earlier if the robots are getting closer. Conversely, if the robots are getting farther away, the robots don't care other robots even if they are located close.

(2) As shown in the simulations, the method results in efficient motion with respect to the criterion of time and path length. Compared with the artificial potential field method, it detects threat of collision earlier via relative distance, and initiates avoidance motion earlier.

(3) Though discriminating motion priority degrades the motion efficiency of lower priority robots, it is useful to let some of the robots move through their own given trajectory with no regard to the motion of other robots. Also, by assigning different priority to each robot, we can avoid side by side state which can arise in the case where every robot has the same parameter values.

(4) To achieve efficient and harmonious motion, it is necessary to assign parameter values differently from robot to robot. If we use the same parameter values and motion priority for every robot, the robots sometimes move in parallel with each other and it results in unnecessary roundabout trajectory.

One of the application examples of the method is controlling the position of the robots in a robot soccer team. This method can be implemented as an individual robot's motion control unit (distributed system) (Pirjanian and Matarić, 2000 ; Matarić, 1992) or as a central motion control unit (central system) (Dias and Stentz, 2001). To use for a distributed system, the position and velocity of robots should be sensed by or transfer to every robot in the work area. In the central system, the position and velocity of the robots are processed by the central system and the robot motion commands are also issued by the central system.

Acknowledgment

This study was supported by research funds from Chosun University, 2003.

References

Alami Rachid, Robert Frederic, Ingrand Felix and Suzuki Sho'ji, 1995, "Multi-robot Cooperation through Incremental Plan-Merging," in Proc. IEEE International Conference on Robotics and Automation (ICRA'95), Nagoya (Japan), pp. 2573~2579.

Alur, R., Das, A., Esposito, J., Fierro, R., Hur, Y., Grudic, G., Kumar, V., Lee, I., Ostrowski, J. P., Pappas, G., Southall, J. Spletzer, J. and Taylor, C., 2001, "A Framework and Architecture for Multirobot Coordination," Experimental Robotics VII, D. Rus and S. Singh (eds.), Springer, LNCIS 271, pp. 303~312.

Arai, T. and Ota, J., 1989, "Motion Planning of Multiple Mobile Robots Using Virtual Impedance," *Journal of Robotics and Mechatronics*, Vol. 8, No. 1, pp. 67~74.

Arkin, R., 1990, "Integrating Behavioral, Perceptual, and World Knowledge in Reactive Navigation," Robotics and Autonomous Systems, Vol. 6, pp. 105~122.

Balch, T. and Arkin, R., 1998, "Behavior-Based Formation Control for Multi-Robot Teams," *IEEE Transactions on Robotics and Automation*, Vol. 14, No. 6, pp. 926~939.

Borenstein, J. and Koren, Y., 1991, "The Vector Field Histogram-Fast Obstacle Avoidance for Mobile Robots," *IEEE Transaction on Robotics*

Automation, Vol. 7, No. 3, pp. 278～288.

Chengqing, L., Ang, M., Krishnan, H. and Lim, S., 2000, "Virtual Obstacle Concept for Local-Minimum Recovery in Potential-Field Based Navigation," Proc., 2000 IEEE Int. Conf. Robotics and Automation, San Francisco, USA, pp. 983～988.

Dias, M. B. and Stentz, A., 2001, "A Market Approach to Multirobot Coordination," Technical report CMU-RI-TR-01-26, Robotics Institute, Carnegie Mellon University.

Groen, F. C. A., Roodhart, J., Spaan, M., Donkervoort, R. and Vlassis, N., 2001, "A Distributed World Model for Robot Soccer that Supports the Development of Team Skills," in Proc. 13th Belgian-Dutch Conf. on Artificial Intelligence, Ben Krose, Maarten de Rijke, Guus Schreiber, and Maarten van Someren, editors, pp. 389～396, Amsterdam, The Netherlands.

Haddad, H., Khatib, M., Lacrox, S. and Chatila, R., 1998, "Reactive Navigation in Outdoor Environments Using Potential Fields," Proceedings of 1998 IEEE Int. Conf. Robotics and Automation, Leuven, Belgium, pp. 1232～1237.

Jongusuk Jurachart and Mita Tsutoumu, 2001, "Tracking Control of Multiple Mobile Robots: A Case Study of Inter-Robot Collision-Free Problem," in Proceedings of the 2001 IEEE Int. Conf. on Robotics and Automation, Seoul, Korea, pp. 2885～2890.

Khatib, O., 1986, "Real-Time Obstacle Avoidance for Manipulators and Mobile Robots," *The Int. J. Robotics Research*, Vol. 5. No. 1, pp. 90～98.

Ko, N. Y. and Simmons, R., 1998, "The Lane-curvature Method for Local Obstacle Avoidance," in Proc. International Conference in Intelligent Robots and Systems (IROS 1998), pp. 1615～1621, Victoria, B. C., Canada.

Latombe, J. C., 1990, "Robot Motion Planning," Kluwer.

Matarić, M., 1992, "Distributed Approaches to Behavior Control," in Proc. SPIE Sensor Fusion V, pp. 373～382.

Noborio Hiroshi and Yoshioka Takashi, 1998, "Sensor-Based Navigation of a Mobile Robot under Uncertain Conditions," Practical Motion Planning in Robotics, K. Gupta and A. P. del Pobil Ed., John Wiley & Sons, pp. 325～347.

Pirjanian Paolo and Matarić J. Maja, 2000, "Multiple Objective vs. Fuzzy Behavior Coordination," Lecture Notes in Computer Science on Fuzzy Logic Techniques for Autonomous Vehicle Navigation, D. Drainkov and A. Saffiotti, eds.

Saffiotti, A., Zumel, N. B. and Ruspini, E. H., 2000, "Multi-Robot Team Coordination using Desirabilities," in Proc. of the 6th Intl. Conf. on Intelligent Autonomous Systems (IAS), pp. 107～114, Venice, Italy.

Simmons, R. G., 1996, "The Curvature-Velocity Method for Local Obstacle Avoidance," in Proc. 1996 IEEE International Conference on Robotics and Automation, pp. 3375～3382, Minneapolis MN.

Simmons, R., Smith, T., Dias, M. B., Goldberg, D., Hershberger, D., Stentz, A. and Zlot, R., 2000, "A Layered Architecture for Coordination of Mobile Robots," in Multi-Robot Systems From Swarms to Intelligent Automata, A. Schultz and L. Parker (eds.), Kluwer.

Tews, A. and Wyeth, G. F., 1999, "Multi-Robot Coordination in the Robot Soccer Environment," in Proceedings of the Australian Conference on Robotics and Automation, pp. 90～95, Brisbane.

Wang, P. K. C., 1989, "Navigation Strategies for Multiple Autonomous Mobile Robots," in Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems, pp. 486～493.

Wang, Y. and Chirikjian, G. S., 2000, "A New Potential Field Method for Robot Path Planning," Proc., 2000 IEEE Int. Conf. Robotics and Automation, San Francisco, USA, pp. 977～982.

Weigel, T., Gutmann, J. -S., Dietl, M., Kleiner, A. and Nobel, B., 2002, "CS Freiburg: Coordinating Robots for Successful Soccer Playing," IEEE Trans. on Robotics and Automation, Vol. 18, No. 5, pp. 685～699.

Wong, C. -C., Chou, M. -F., Hwang, C. -P., Tsai, C. -H. and Shyu, S. -R., 2001, "A Method for Obstacle Avoidance and Shooting Action of the Robot Soccer," in Proceedings of the 2001 IEEE Int. Conf. on Robotics and Automation, Seoul, Korea, pp. 3778～3782.