A Method for Local Collision-free Motion Coordination of Multiple Mobile Robots

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Abstract : 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. To implement the concept in collision avoidance of 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. 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. 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.

Keywords : relative distance, avoidability measure, motion coordination, multiple robots

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 architecture(Alur et al., 2001; R. 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. Especially, collision avoidance between robots is 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, many of the methods such as potential field methods(Khatib, 1986; Borenstein and Koren, 1991), curvature based methods(Simmons, 1996; Ko and Simmons, 1998) are used for collision avoidance. Though many of the conventional collision avoidance method can be adapted for collision avoidance of multiple robots, they are not effective for considering the movement of robots 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 preventing collision or causes hasty motion to avoid another robots.

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. COLLISION-FREE MOTION COORDINATION PROBLEM

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
$t_i(i=0,\dots)$	the i-th sampling time

In the 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 between 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 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. 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 time t if the line from $p_j(t)$ to P_{gj} doesn't overlap with the lines from $p_k(t)$ to P_{gk}, $k \neq j$, $k=1,2,\cdots,N$.

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.

3. AVOIDABILITY MEASURE AND RELATIVE DISTANCE

For collision avoidance of multiple mobile robots, motion control of a robot requires attention to the mobility of the other 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 threat of collision between the robots increase 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. 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) AVM increases as the distance $d_{jk}(t)$ increases.
(2) AVM increases as the outward speed $v_{jk}(t)$ increases.
(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.

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

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

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. 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.

3.2 Relative Distance(RD)

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.

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

where

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

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 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.

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.

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

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

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), $rd_{jk}(t)$ 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).

The attractive force is directed from the position of the robot 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.

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

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}. On account of the function $\Lambda(rd_{jg})$ 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.

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

where

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

$\Lambda(rd_{jg})$ 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 around its goal position within the relative distance ε_{att}, 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 $0< rd_{jg}< \infty$.

Like the problem of local minima in artificial potential field methods, 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) Case1 and case2: Compare the simulation result of the proposed method with that of artificial potential field method based on real distance.
(2) Case3 and case4: Change the parameter values of α β, and compare the simulation results.

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. 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 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

$$
\begin{aligned}
U_{art}\ &(p_j(t), p_k(t), P_{gj}) \\
&= U_k(p_j(t), p_k(t)) + U_g(p_j(t), P_{gj})
\end{aligned}
$$

$$
U_k(p_j(t), p_k(t)) = \begin{cases} \frac{1}{2}\eta\left(\frac{1}{d_{jk}(t)} - \frac{1}{\varepsilon_d}\right)^2, & \text{if } d_{jk}(t) \le \varepsilon_d \\ 0, & \text{if } d_{jk}(t) > \varepsilon_d (\varepsilon_d > 0) \end{cases}
$$

$$
U_g(p_j(t), P_{gj}) = \frac{1}{2}\zeta \| p_j(t) - P_{gj} \|^2
$$

In the case 2, the parameters $\eta, \varepsilon_d, \zeta$ 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 are the same for all the five robots.

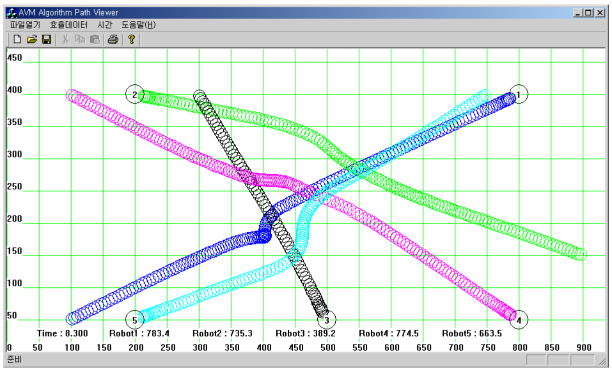
Table 1. Starting position and goal position of the robots for the cases 1 and 2.

Robot	Starting position	Goal position
Robot1	(100, 50)	(800, 400)
Robot2	(900, 150)	(200, 400)
Robot3	(300, 400)	(500, 50)
Robot4	(100, 400)	(800, 50)
Robot5	(750, 400)	(200, 50)

Table 2. Parameter values for the case 1.

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

Figure 1 and Figure 2 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.



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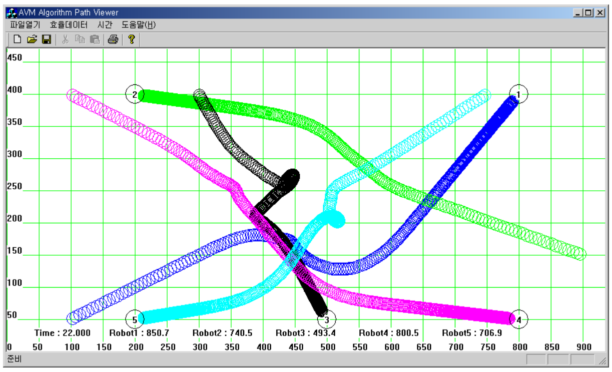
Time : 8.300    Robot1 : 783.4    Robot2 : 735.3    Robot3 : 389.2    Robot4 : 774.5    Robot5 : 663.5
```

Figure 1. Robot motion trajectory for the case of using the proposed relative distance based method(case 1).



```
Time : 22.000    Robot1 : 850.7    Robot2 : 740.5    Robot3 : 493.4    Robot4 : 800.5    Robot5 : 706.9
```

Figure 2. Robot motion trajectory for the case of using artificial potential field method(case 2).

Table 3. Efficiency measure for the case 1.

efficiency robot	PL	MT	SE	TE	SM
robot 1	783.394	8.25	361.971	4.3	28.50
robot 2	735.337	6.85	356.575	3.25	46.89
robot 3	389.211	3.4	244.938	2.05	65.26
robot 4	774.452	7.4	417.531	4.3	46.89
robot 5	663.524	6.55	328.335	3.05	28.50

Table 4. Efficiency measure for the case 2.

efficiency robot	PL	MT	SE	TE	SM
robot 1	850.711	21.35	478.182	5.5	43.24
robot 2	740.463	19.9	337.854	3.25	57.61
robot 3	493.411	21.75	312.582	8.30	44.90
robot 4	800.481	21.45	479.231	8.35	47.69
robot 5	706.939	21.95	460.334	8.30	43.24

As shown in the Figure 1 and 2, all the robots move smoother in csae 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 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.

5.2 Effect of α, β 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 and 4, 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 we set some of the parameter values different from robot to robot. In case 4, the value of parameters α and β differ from robot to 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 3 and Figure 4, and the efficiency measures are shown on the Table 8 and Table 9.

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

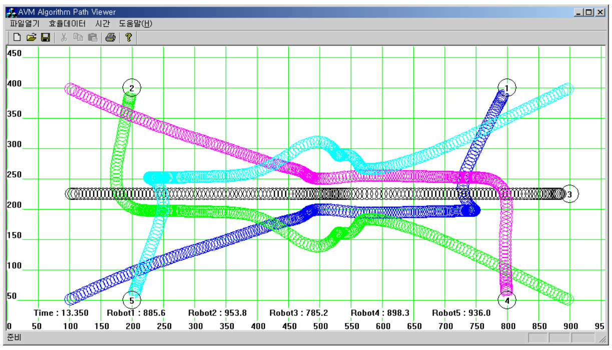
Robot	Starting position	Goal position
Robot1	(100, 50)	(800, 400)
Robot2	(900, 50)	(200, 400)
Robot3	(100, 225)	(900, 225)
Robot4	(100, 400)	(800, 50)
Robot5	(900, 400)	(200, 50)

Table 6. Parameter values for the case 3.

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

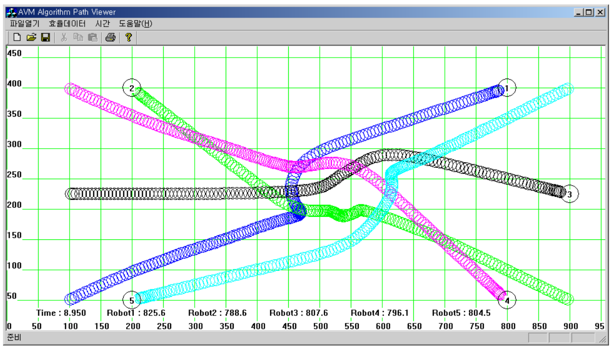
Table 7. Parameter values for the case 4.

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



Time : 13.350 Robot1 : 885.6 Robot2 : 953.8 Robot3 : 785.2 Robot4 : 898.3 Robot5 : 936.0

Figure 3. Robot motion trajectory for the case 3.



Time : 8.950 Robot1 : 825.6 Robot2 : 788.6 Robot3 : 807.6 Robot4 : 796.1 Robot5 : 804.5

Figure 4. Robot motion trajectory for the case 4.

Table 8. Efficiency measure for the case 3.

efficiency robot	PL	MT	SE	TE	SM
robot 1	885.642	12.2	677.281	9.70	20.54
robot 2	953.774	13.2	739.677	10.75	24.38
robot 3	785.243	7.1	411.104	3.55	28.47
robot 4	898.255	12.0	691.388	9.70	20.54
robot 5	936.014	13.3	731.784	10.75	24.38

Table 9. Efficiency measure for the case 4.

efficiency robot	PL	MT	SE	TE	SM
robot 1	825.608	8.65	443.526	5.25	26.51
robot 2	788.606	8.5	443.046	5.2	26.51
robot 3	807.554	7.2	531.384	4.7	32.97
robot 4	796.109	8.3	468.46	5.25	44.87
robot 5	804.53	8.9	382.323	4.75	32.97

As shown in the Figure 3, 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 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 improve 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 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 Figure 3 and Figure 4, 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.

6. 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) 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 J Matariċ, 2000; Matariċ, 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.

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