Abstract—In a multi-robot system, the outcome depends significantly on how well the motion of individual robots are coordinated. The research challenge lies in formulating computational paradigms and strategies that allow a real-time search for optimal coordinated motions of individual robots under excessive search complexity. In this paper, the concept of the "mappeable zone" is proposed which represent a set of environment positions that the robot or a group of robots can map first, should it choose to do so at time $t$ against the same attempt of another robot or a group of robots. A systematic way of computing various forms of mappeable zones is presented. Based on such concept, a group of robots can identify whether an object can be mapped or not, and which strategy is appropriate for the group. The coordinated motions of individual robots are then determined based on the chosen strategy. Some simulation results are shown.

Keywords: Coordination, Planning, Multi-robot, Competitive Environments.

I. INTRODUCTION

The major concern of coordinated motion planning in team competition is planning motions of individual robots in such a way as to take advantage against the opponent team. This problem is quite challenging due to the fact that the situation of the opponent team robots may vary constantly so that the complexity of search space involved is rather excessive. Therefore, the goal is to formulate computational paradigms and strategies that allow a real-time search for optimal coordinated motions of individual robots under excessive search complexity as well as the low-level control laws. In fact, if we take such time as a function of the initial and final velocity, the maximum acceleration, and the initial orientation, a difference and location of border line would have resulted.

II. MAPPEABLE ZONES OF ROBOT TEAMS

The mappeable zone — in correct English should be "able to map" zone — of a robot $A$ against an opponent $B$ at time $t$ will be denoted as $M(A \text{ vs } B)$, which represents a set of environment positions that the robot $A$ can reach first against the opponent $B$.

Figure 1 illustrates $M(A \text{ vs } B)$ and $M(B \text{ vs } A)$ zones, assuming that the time for robots $A$ and $B$ to reach a position $Z$ is proportional to the distances from their actual positions. Notice that this assumption is non-realistic: the time for $A$ or $B$ to reach each environment position $Z$ is a function of the velocity, the acceleration, the orientation, as well as the low-level control laws. In fact, if we take such time as a function of the initial and final velocity, the maximum acceleration, and the initial orientation, a difference and location of border line would have resulted.

We can define $M(A \text{ vs } B_{\text{TEAM}})$ as a set of environment positions that robot $A$ can reach against the $B$ team, i.e., robots located at $B_1$ and $B_2$ as illustrated in Figure 2.

Looking at the figure 2, the next property holds:

$$M(A \text{ vs } B_{\text{TEAM}}) = M(A \text{ vs } B_1) \cap M(A \text{ vs } B_2) \quad (1)$$

We can also denote $M((A_1 \oplus A_2) \text{ vs } B_{\text{TEAM}})$ to define a set of environment positions that robot $A_1$ can reach against
B_1 and B_2 with the help of A_2. That is, robot A_2 can block the motion of B_1 or B_2 in such a way as to extend the mappeable zone of the robot A_1 (see figure 3).

In figure 4(a), M((A_1, O) vs. B_{TEAM}) is assumed motionless on Z, and (b) the object moves along path P. Depending on the locations and speeds of B_{TEAM} robots and the object, the object may or may not trespass B_1 and B_2 to reach an specific region. Again, another property holds:

\[
M((O, A_i) vs B_{TEAM}) = M((O, A_i) vs B_1) \cap M((O, A_i) vs B_2)
\]

III. COMPUTATION OF MAPPEABLE ZONES

Figure 4 illustrates that M((A_1, O) vs B_{TEAM}) = [P].

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M((O, A_i) vs B_{TEAM}) = M((O, A_i) vs B_1) \cap M((O, A_i) vs B_2)
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In figure 4(a), M((A_1, O) vs. B_{TEAM}) is assumed motionless on Z, and (b) the object moves along path P. Depending on the locations and speeds of B_{TEAM} robots and the object, the object may or may not trespass B_1 and B_2 to reach an specific region. Again, another property holds:

\[
M((O, A_i) vs B_{TEAM}) = M((O, A_i) vs B_1) \cap M((O, A_i) vs B_2)
\]

In figure 4(b), the length of path P depends on the relative speed between the object and the robot A. Formally, note that we can take the uncertainty involved in the object motion into consideration for M((A_1, O) vs B_{TEAM}) by:

\[
M((A_1, O) vs B_{TEAM}) = M((A_1, O) vs B_2) \cap M((A_1, O) vs B_2)
\]
generation for a 2 degrees of freedom manipulator in the Cartesian space [1]. With the time computed for A1, A2, B1, B2, and O to reach \((i, j)\), we can calculate various mappable regions defined in section II:

- \(M(A_{i}, vs B_{j})\) can be obtained as a collection of \(Z(i, j)\) at which the time for \(A_{i}\) to reach \((i, j)\) is shorter than the time for \(B_{j}\).
- \(M(A_{i}, vs B_{TEAM})\) is a collection of \(Z(i, j)\) at which \(A_{i}\) precedes both \(B_{1}\) and \(B_{2}\) in time. Or it can be obtained by the intersection of \(M(A_{i}, vs B_{1})\) and \(M(A_{i}, vs B_{2})\) based on property (1).
- \(M((A_{i} \oplus A_{j}) vs B_{TEAM})\) can be obtained from \(M(A_{i}, vs B_{TEAM})\), \(M(A_{j}, vs B_{1})\), \(M(A_{j}, vs B_{2})\), \(M(A_{2} vs B_{1})\), and \(M(A_{2} vs B_{2})\) based on property (2).
- \(M((A_{i}, O) vs B_{j})\) can be obtained as a collection of \(Z(i, j)\) at which \(A_{i}\) precedes \(O\), and \(O\) precedes \(B_{j}\) in time.
- \(M((A_{i}, O) vs B_{TEAM})\) can be obtained as a collection of \(Z(i, j)\) at which \(A_{i}\) precedes \(O\) and \(O\) precedes both \(B_{1}\) and \(B_{2}\) in time. Or, it can be obtained from \(M((A_{i}, O) vs B_{1})\) and \(M((A_{i}, O) vs B_{2})\) based on property (3).
- \(M((O, A_{i}) vs B_{j})\) can be obtained as a collection of \(Z(i, j)\) at which \(O\) precedes \(A_{i}\).
- \(M((O, A_{i}) vs B_{TEAM})\) can be obtained as a collection of \(Z(i, j)\) at which \(O\) precedes both \(B_{1}\) and \(B_{2}\). Or, it can be obtained from \(M((O, A_{i}) vs B_{1})\) and \(M((O, A_{i}) vs B_{2})\) based on property (4).

IV. Coordinated Motion Strategy in Robot Soccer Environment

In this section, the robot soccer environment will be used to show some results. In a like manner to human competitive games, the proposed coordinated motion strategy starts with classifying the situation of the system at time \(t\) as an offensive mode or a defensive mode. Let us assume that the two teams, \(A_{TEAM}\) and \(B_{TEAM}\), consist of \(\{A_{1}, A_{2}\}\) and \(\{B_{1}, B_{2}\}\) as their respective offensive and defensive robots. The environment includes the ball as an object to reach and push toward some specific directions: to the robot mate, to the opponent goal, etc. Hereafter, the ball will be considered as the object \(O\) to be mapped, as defined in section II. Therefore, the concept "to possess the ball" is synonymous to "able to map the ball against another team", as stated in section I.

The situation of the system at time \(t\) is declared as an offensive mode for \(A_{TEAM}\) if \(A_{1}\) or \(A_{2}\) robots possesses the ball or \(M(A_{1}, Ball) vs B_{TEAM} \neq 0\), or \(M(A_{2}, Ball) vs B_{TEAM} \neq 0\) at time \(t\). Otherwise, it is declared as a defensive mode.

A trespassing region will be defined as a collection of \(Z(i, j)\) which lies on or behind the nearest defender and is connected from any mappable region in front of the nearest defender. Then, in an offensive mode, the \(A_{TEAM}\) can generate coordinated motions of its individuals robots by identifying such pattern and applying the corresponding strategy, as described in the following rules set:

- Capturing: If \(A_{1}\) does not possess the ball but \(M(A_{1}, Ball) vs B_{TEAM} \neq 0\), the robot \(A_{1}\) moves to capture the Ball while \(A_{2}\) moves in such a way as to maximum \(M((A_{1} \oplus A_{2}) vs B_{TEAM})\).
- Trespassing: If \(A_{1}\) possess the Ball and \(M((A_{1} \oplus A_{2}) vs B_{TEAM})\) is not a subset of trespassing region, then \(A_{1}\) trespass the Ball into the trespassing region; while \(A_{2}\) blocks either \(B_{1}\) or \(B_{2}\) depending on whether \(M(A_{1} vs B_{1}) \cap M(A_{2} vs B_{2})\) or \(M(A_{1} vs B_{2}) \cap M(A_{2} vs B_{1})\) makes better in trespassing.
- Pushing: If \(A_{1}\) possess the Ball and \(M((A_{1} \oplus A_{2}) vs B_{TEAM})\) is a subset of trespassing region and \(M((Ball, A_{1}) vs B_{TEAM} \subseteq M((A_{2}, Ball) vs B_{TEAM})\), then \(A_{1}\) pushes the object to \(A_{2}\).
- Searching: If the situation is none of the above ones, then move \(A_{1}\) and \(A_{2}\) in such a way to maximize \(M(A_{1} vs B_{TEAM}) \cup M(A_{2} vs B_{TEAM})\).

Concerning with the strategy rules in a defensive mode, to disturb or spoil the opponent team in using the offensive strategies could be accepted as a good behaviour, but not discussed in this paper.

For the determination of better choice between \(M(A_{1} vs B_{1}) \cap M(A_{2} vs B_{2})\) and \(M(A_{1} vs B_{2}) \cap M(A_{2} vs B_{1})\) as well as in maximizing \(M(A_{1} vs B_{TEAM}) \cup M(A_{2} vs B_{TEAM})\), a quality index will be defined. To do so, weights to individual grid points will be assigned in such a way that the points near the goal point (where the \(A_{TEAM}\) will finally push the Ball) gets higher weights. Hence, the quality indices associated with various mappable regions together with the above strategy rules allow to determine the coordinated motion of individual players.

V. Simulation Results

In simulation the discretized environment space will contain 26×18 grids. Related to the real robot soccer platform, the cell size is about 5cm×5cm squares. The time for a robot to reach a position \(Z(i, j)\) is a function of many parameters as stated earlier. In this simulation the velocity of the robot is assumed to be constant \((V_{c})\) so that no accelerations must be considered. In addition, the robots are fully holonomics, that is, the initial orientation will be a negligible parameter. Therefore, the time to reach the position \(Z(i, j)\) from \(Z(\text{initial cell})\) can be calculated using the next formula:

\[
l = \frac{\left| Z(i, j) - Z(\text{initial cell}) \right|}{V_{c} (0)}
\]  

(5)

According to the quality index, weights are added around the middle-top point (goal point of \(A_{TEAM}\)) as depicted in figure 6. Then, the closer distance to the opponent team, the higher weight it gets. After that, the cells have been grouped according to \(M(A vs B)\) functions which are described above. From these \(M(A vs B)\) functions and the position of the Ball, the implementation
of the coordinated motions (capturing, trespassing, and pushing) results in a collection of points. Therefore, the points from each robot to the direction of middle-bottom top point (goal point of B\textsubscript{TEAM}) are selected. And the robots just follow these connected points.

In figure 6 situation, we first calculate areas $S_1$ and $S_2$ and choose to block the opponent robot $B_2$, which creates larger area. In this case, area $S_2$ is greater so that $A_2$ so that $A_2$ goes to block the robot $B_2$. By $A_2$ moving toward $B_2$, the mappeable zone of $A_1$ becomes larger, and $A_1$ who possesses the Ball moves toward the region behind the blocking.

The simulation shows that the problem of maximize $M((A_1 \oplus A_2) \times B_{TEAM})$ can be solved by including additional parameters in the environment, i.e. the quality index defined earlier. In fact, such problem is similar to the local minimal phenomenon when using potential fields methods in the robot soccer system [2].

VI. CONCLUSIONS

A novel method of determining a coordinated motion of robot teams in competitive environments is presented. The use of mappeable zones provides powerful yet efficient means of representing strategies and coordinated motions. Simulation results show this effect but further development and analysis are needed to make the proposed method matured, including the complexity analysis with the increase of the number of robots and the inclusion of uncertainties in measured data and time computations.

Concerning with the number of robots, the use of K-means technique is more appropriate and faster than Voronoi diagrams techniques. However, the way to maximize $M((A_1 \oplus A_2) \times B_{TEAM})$ seems to be more complex so that AI search techniques might be taken into account.

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