

Behavior-Based Coordination of Large-Scale Robot Formations

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1 Introduction

To address a wide range of multi-robot coordinated movement tasks we seek a formation strategy that offers:

- **scalability**: the approach should easily scale to any number of agents,
- **locality**: the behaviors should depend only on the local sensors of each agent,
- **flexibility**: the behaviors should be flexible so as to support many formation shapes.

To provide these features we introduce a new behavior-based approach to robot formation-keeping. The new strategy is based loosely on the way molecules form crystals. From the point of view of each robot in the group, every other robot has several local “attachment sites” other robots may be attracted to. This type of attachment site geometry roughly corresponds to molecular covalent bonding. Just as different crystal shapes result from different covalent bond geometries, robot formation shapes are influenced by the attachment site geometries employed. Figure 1 illustrates the four attachment site geometries examined in this work.

2 Behaviors for formation

The formation component of the robots’ behavior is accomplished in two steps: first, a perceptual process, **detect_formation_position**, determines the robot’s proper position in formation based on current sensor data; second, the motor process **maintain_formation**, generates motor commands to direct the robot toward the correct location. The motor schema paradigm enables the formation behavior to be simultaneously active in combination with other navigation behaviors.

The overall navigational strategy integrates the formation behavior with other navigational schemas in a manner similar to the approach developed in earlier research by the authors. The motor schemas **move_to_goal**, **avoid_static_obstacles**, **avoid_robots** and **maintain_formation** implement the overall behavior for a

robot to move to a goal location while avoiding obstacles, collisions with other robots and remaining in formation. An additional background schema, **noise**, serves as a form of reactive “grease”, dealing with some of the problems endemic to purely reactive navigational methods such as local maxima, minima and cyclic behavior.

Each attachment site geometry is characterized by three parameters:

- r , the distance from the center of the robot to each attachment site,
- N , the number of sites available, and
- θ , the offset in degrees with respect to the front of the robot (straight ahead) where the first site is positioned.

We assume the N sites are positioned uniformly around each robot. In the example geometries presented here, $r = 1.5$ meters in all cases; $N = 2$ for *column* and *line* geometries and $N = 4$ for *diamond* and *square*; $\theta = 0^\circ$ for *column* and *square*, $\theta = 45^\circ$ for *diamond* and $\theta = 90^\circ$ for *line* formations.

To determine a formation position each robot builds a list of all potential attachment sites for all of the robots within sensor range based on the formation type it is using. An attractive vector is generated towards the closest site.

In addition to the motor schemas mentioned earlier, a low-gain attractive force, **move_to_unit_center**, is added to draw all of the robots together. As the team converges, the robots “snap” into position, and a regular geometric shape emerges. Example formations resulting from the integration of these behaviors are illustrated in Figure 2.

3 Results

As illustrated in Figure 2 the formation behaviors enable robot teams to maintain formation while navigating through an obstacle field. As expected, different attachment site geometries lead to different team formation geometries.

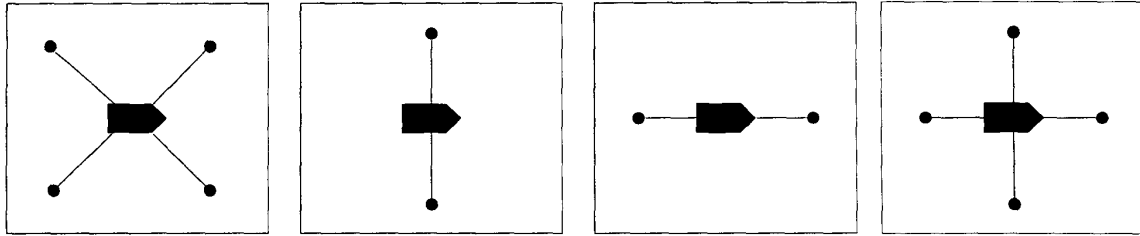


Figure 1. From the point of view of each robot in the group, every other robot has several local “attachment sites” other robots may be attracted to. Attachment site geometries for different formations are illustrated above. From left to right: *diamond*, *line*, *column* and *square*. Robots are represented as five-sided polygons moving from left to right; attachment sites are shown with small circles.

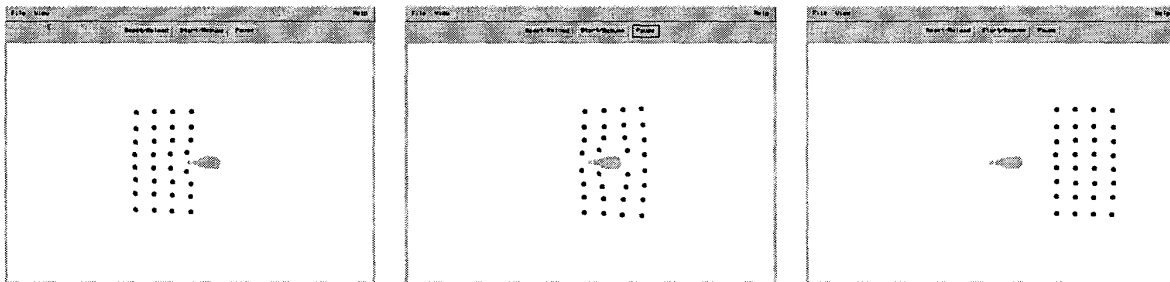


Figure 2. Example of a large-scale formation of 32 robots using the *square* attachment site geometry. The robots (black circles) start on the left side of the field and navigate to the right around a group of obstacles in the middle of the field. Note how the formation splits around the obstacle, but rejoins once past it.

Additionally these behaviors are easily scalable. As an example, consider the team of 32 robots illustrated in Figure 2.

The key extension that distinguishes the new approach from previous work is the perceptual technique used to determine the proper formation position for each robot. Individual robots are not assigned to particular locations but are instead attracted to the closest position in the formation. The approach is based loosely on molecular crystal formation: each robot is drawn to “attachment sites” arranged with respect to its teammates. The resulting robot team geometry is determined by the arrangement of the attachment sites.

The design goals for the new strategy are met; specifically:

- **scalability:** the approach easily scales to any number of agents,
- **locality:** the behaviors depend only on the local sensors of each agent,
- **flexibility:** the behaviors are flexible so as to support many formation shapes.

Simulation experiments illustrate the approach and demonstrate the relative performance of several formation geometries. Performance was evaluated for groups of 1 to 8 robots using each of three different formation geometries. The results confirm earlier work that indicates column formations are best for traversing an obstacle field.

The approach is scalable because each agent only relies on locally available information; namely, the locations of nearby robots. Global communication of robot position is not required, instead, local sensors (perhaps vision) can be utilized to generate effective formation behavior in large robot teams. Scalability of the approach is demonstrated in a large team composed of 32 simulated robots.