Autonomous Shape Formation and Morphing in a Dynamic Environment by a Swarm of Robots

Extended Abstract

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ABSTRACT

We present an algorithm by which a swarm of unicycle robots can simultaneously fill multiple planar solid polygonal shapes and also morph between different shapes. By decomposing the desired shape into triangles and defining formation points that lie on each triangle, the robots fill the shape using a divide-and-conquer strategy. Each robot is equipped with limited range and bearing sensors that are used for localized communication and for collision avoidance. The proposed algorithm also allows the swarm to operate in and adapt to dynamic environments, for example, while navigating through narrow passages or avoiding dynamic obstacles. The algorithm is designed to prevent oscillatory behaviour and deadlocks while enabling collision avoidance. We demonstrate the effectiveness of the algorithm through simulations using the iRobot Create mobile robots.

CCS CONCEPTS

• **Computing methodologies → Multi-agent systems**; *Mobile agents*; *Cooperation and coordination*; • **Computer systems organization → Robotics**;

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1 INTRODUCTION

We present an algorithm for autonomous shape formation that allows a swarm of unicycle robots to form multiple disconnected shapes, and morph between them, from any initial configuration in a bounded environment using a divide-and-conquer strategy, thus making it quicker than existing algorithms. The use of the modified Hybrid Reciprocal Velocity Obstacle (HRVO) [11] and Velocity Obstacle (VO) [6] modules lends novelty. Each robot is assumed to be equipped with sensors to determine its position and orientation and to communicate with other robots within a limited range. These features distinguish the proposed approach from: [3] and [4], where a leader robot coordinates other robots to form the desired shape, with constraints on the initial configuration; [10] and [12], where shapes and patterns are built sequentially with the help of seed robots; and [2], where a homogeneous, reactive and memory-less swarm forms a desired shape using a significantly large number of actions. In the context of dynamic environments, [5] present an approach where the collision between robots is dependent on thresholds being set appropriately and [13], where, the robots are limited to a set of pre-allocated formations, which are selected by reaching a consensus in the swarm. This limits the flexibility of the proposed algorithms in dynamic environments.

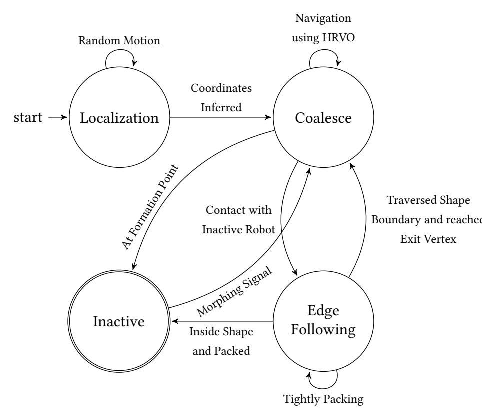

Figure 1: Robot behaviour transition diagram

2 SHAPE FORMATION ALGORITHM

Shape Processing: This module decides how the robots fill shapes that are concave or convex polygons, with no holes. The shape, described by its vertices, is divided into a mesh of triangles. In each triangle, the mid point of a particular edge is selected as a formation point - the black dots in Fig. 2a. This edge is the one with the lowest absolute value of its slope passing through the vertex with the lowest coordinate value, along some chosen axis. These points are used in the HRVO module of the robots' behaviour to navigate to different parts of the shape. This approach helps in defining proper stopping conditions, avoiding certain deadlocks, and allowing most of the robots to accumulate in the interior of the shape, so that the shape may filled simultaneously and hence, more quickly. It can be shown that each triangle has a unique bottom edge and hence, a unique formation point. The algorithm consists of the following primitive behaviours:

1. *Localization*: This is performed once, to localize the robots in the same reference frame with a common origin, either using an

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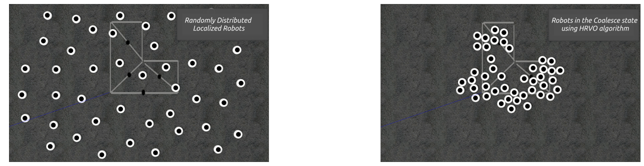
initially localized origin robot or by introducing a virtual robot. The robots move about randomly until they come into communication range with a localized robot and in turn, act as a reference for other robots; this feature makes the algorithm scalable. This can be done using an Infrared range and bearing sensor [7].
2. *Coalesce*: A robot navigates to the closest formation point using the HRVO module - which is chosen to aid a robot to avoid collisions with other stationary/moving robots, as well as dynamic obstacles. As several robots may be navigating to the same formation point, the standard HRVO algorithm is augmented with additional conditions to ensure a transition out of the Coalesce state.
3. *Edge Following* (EF): The robots accumulated at a formation point use this behaviour to enter the shape boundary and fill it in densely. It is implemented by modifying the standard VO algorithm implementation, by fixing the direction of motion while avoiding obstacles, for instance, in the clockwise direction. The robots in this state follow the boundary of the shape formed so far by the robots in the Inactive state, in the form of a procession where they maneuver around the Inactive robots while maintaining a distance of separation from them. Robots moving inside the shape towards the shape boundaries, revolve around formation points and enter other triangles in the shape, thus filling internal triangles. With the proposed EF behaviour, they traverse circular arcs to fill the shape. The shape is filled analogous to a beaker being filled by water from the bottom up.
4. *Inactive*: The robots stop their movements. This happens when a robot has found its place inside the shape, at the edge, or cannot enter the shape. These happen when a robot is the first to reach a formation point while in the Coalesce state; or when it approaches one of the shape boundaries while in the EF state; or it approaches an Inactive robot that requires rotation past the limit.

Robots filling shapes transition between these behaviours according to the state transition diagram shown in Fig. 1.

3 FEATURES

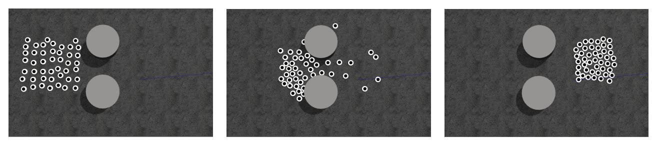
The modifications made to the VO and HRVO modules are briefly described. For a robot in the EF state and outside the shape boundary, the center of the VO cone points towards the direction of the closest Inactive robot. Once inside the shape, the target direction is towards the formation point of the triangle it is in. Given these situations, robots in the EF state can block each others' paths inside the shape boundary, as they enter the shape from different directions and are not necessarily in a procession. To prevent a deadlock, the VO module is modified by adding limits on a robot's rotational motion. Thus, between 2 EF robots which can collide, the limit on rotation prioritises the one which would need to turn more, thus enabling it to cut ahead of other EF robots in the procession. When the path of a robot in the EF state is blocked by a robot in another state, it will wait for that robot to move ahead instead of trying to maneuver around it. The HRVO module makes it possible for the robot swarm to morph between shapes, reform a shape in a different location as well as form multiple space-separated shapes simultaneously. By providing a "Morphing signal" with the new shape information, the robots in the swarm switch to the Coalesce state which makes it possible for the swarm to change its shape, its



(a) Initially randomly distributed robots **(b) Robots coalescing at formation points**

(c) Edge Following robots **(d) Inactive robots (Final shape)**

Figure 2: L-shape formation stages



(a) Initial shape location **(b) Swarm deformation between the obstacles** **(c) Reformation in a different location**

Figure 3: Reformation of a square on either side of obstacles

location or both. Robots form multiple shapes by traversing from a shape whose boundary it has covered, to a different uncovered shape by switching to the EF state to move to an "Exit Vertex" of the covered shapes and using the Coalesce state to traverse between the boundaries of shapes. It repeats this process, moving between covered shapes, until it reaches the closest uncovered shape.

4 IMPLEMENTATION AND RESULTS

Experiments are performed on the Gazebo software [8] with the ROS framework [9]. The Delauney triangulation algorithm from the CGAL library [1] is used to decompose the shape. Simulation parameters include the separation distance between robots in the Coalesce/EF states and robots in the EF/Inactive states as well as the linear and angular speeds. Snapshots of the robots forming an L-shape as well as reforming while avoiding obstacles are shown in Figs. 2 and 3. The time complexity of the proposed algorithm for n robots and m formation points can be derived to be $O(\max(n_i))$, where n_i, $i = 1 \cdots m$, is the number of robots aggregated at formation point i. Thus, the worst case time complexity is $O(n)$ if all the robots aggregate at one formation point and the best case time complexity is $O(n/m)$ if all the robots are equally distributed between all the formation points.

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