Behavior-Based Formation Control for Multi-robot Teams
Authors

- Tucker Balch & Ronald Arkin
- B.S. and Ph.D. from Georgia Tech.
- 1988-1995 flew F-15 (not computer game)
- Recent work: learning in multi agent societies and behavioural diversity.
- Tucker is a war expert!
Introduction

- Goal: Navigate to waypoints, avoid hazards, keep the formation.
- Formation is important e.g. limited sensor asset
- Robots in this observation are heterogeneous in terms of functionality.
Formation Background

- Animals in a herd
  - Minimize encounter with predators
  - Maximizing predator/food detection
- Emerged in Computer Graphics for simulating bird Flocks movement
  - Aspects: collision avoidance, velocity matching, flock centring.
  - Better models account for dynamics of individual e.g. fish muscles.
Previous Work

• Maintain position relative to neighbour or leader.

• It did not include interaction for obstacle avoidance and navigation.

• The proposed technique has formation, obstacle avoidance, and navigation, simultaneously active and co-operatively combined.
Approach

- Formation maintenance has two steps.
  - Detect formation position.
  - Maintain formation position.
Motor Schema-Based Formation Control

• Behavior-based robotics
• Overall behavior has following schemas
  • move-to-goal
  • avoid static obstacle
  • avoid robot
  • maintain formation.
Motor Schema-Based Formation Control

### Table I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>avoid-static-obstacle</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gain</td>
<td>1.5</td>
<td>meters</td>
</tr>
<tr>
<td>sphere of influence</td>
<td>50</td>
<td>meters</td>
</tr>
<tr>
<td>minimum range</td>
<td>5</td>
<td>meters</td>
</tr>
<tr>
<td><strong>avoid-robot</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gain</td>
<td>2.0</td>
<td>meters</td>
</tr>
<tr>
<td>sphere of influence</td>
<td>20</td>
<td>meters</td>
</tr>
<tr>
<td>minimum range</td>
<td>5</td>
<td>meters</td>
</tr>
<tr>
<td><strong>move-to-goal</strong></td>
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<td></td>
</tr>
<tr>
<td>gain</td>
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<td></td>
</tr>
<tr>
<td><strong>noise</strong></td>
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<tr>
<td>gain</td>
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<td></td>
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<tr>
<td>persistence</td>
<td>6</td>
<td>time steps</td>
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<tr>
<td><strong>maintain-formation</strong></td>
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<td></td>
</tr>
<tr>
<td>gain</td>
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<td>meters</td>
</tr>
<tr>
<td>desired spacing</td>
<td>50</td>
<td>meters</td>
</tr>
<tr>
<td>controlled zone radius</td>
<td>25</td>
<td>meters</td>
</tr>
<tr>
<td>dead zone radius</td>
<td>0</td>
<td>meters</td>
</tr>
</tbody>
</table>
Simulation Results

Fig. 6. Four robots in leader-referenced (a) and unit-center-referenced (b) formations. (c) and (d) show results with multiple corridors.

Fig. 7. Comparison of (a) leader-referenced and (b) unit-center-referenced formations.
Performance

TABLE II
Performance for a 90 Degree Turn for Both Unit-Center and Leader-Referenced Formations, Smaller Numbers are Better. The Standard Deviation is Indicated Within Parameters

<table>
<thead>
<tr>
<th>Formation Type</th>
<th>Path Ratio</th>
<th>Position Error</th>
<th>Time out of Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unit</td>
<td>Leader</td>
<td>Unit</td>
</tr>
<tr>
<td>diamond</td>
<td>1.03 (0.08)</td>
<td>1.06 (0.08)</td>
<td>6.8 (0.2) m</td>
</tr>
<tr>
<td>wedge</td>
<td>1.04 (0.09)</td>
<td>1.06 (0.09)</td>
<td>9.4 (4.5) m</td>
</tr>
<tr>
<td>column</td>
<td>1.04 (0.06)</td>
<td>1.16 (0.02)</td>
<td>8.4 (5.6) m</td>
</tr>
<tr>
<td>line</td>
<td>1.04 (0.10)</td>
<td>1.05 (0.06)</td>
<td>8.5 (5.5) m</td>
</tr>
</tbody>
</table>

TABLE III
Performance for Navigation Across an Obstacle Field

<table>
<thead>
<tr>
<th>Formation Type</th>
<th>Path Ratio</th>
<th>Position Error</th>
<th>Time out of Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unit</td>
<td>Leader</td>
<td>Unit</td>
</tr>
<tr>
<td>diamond</td>
<td>1.05 (0.04)</td>
<td>1.08 (0.05)</td>
<td>5.2 (1.9) m</td>
</tr>
<tr>
<td>wedge</td>
<td>1.04 (0.04)</td>
<td>1.08 (0.05)</td>
<td>5.2 (1.4) m</td>
</tr>
<tr>
<td>column</td>
<td>1.05 (0.04)</td>
<td>1.08 (0.04)</td>
<td>3.4 (1.6) m</td>
</tr>
<tr>
<td>Line</td>
<td>1.05 (0.05)</td>
<td>1.05 (0.04)</td>
<td>5.3 (1.5) m</td>
</tr>
</tbody>
</table>
Mobile Robot Simulation

Fig. 9. Telemetry and photos of Shannon and Sally moving into and then traveling in column formation. Top row: column formation telemetry with no obstacles present. Middle row: column formation telemetry with obstacles present. Bottom row: photos of the robots in column formation with obstacles present. The photo sequence corresponds to telemetry in the middle row with obstacles (wastebaskets) present. This experiment was recorded in the foyer of the Georgia Tech Manufacturing Research Center, looking down on the robots from 20 feet above so that formation positions are more easily observed.

Vehicle (HMMWV) equipped with position, vision and hazard sensors, control computers and actuation devices for steering and speed control. Four UGVs were built by Lockheed Martin, and up to three have been operated simultaneously in formation (Fig. 1). This section shows how formation behaviors were adapted for use on these autonomous robots.

The UGV Demo II Architecture differs from the motor schema method where behaviors generate both a direction and magnitude. Instead, in the UGV Demo II Architecture, separate motor behaviors are developed for the speed and turning components of a behavior. The behaviors are coordinated by speed and turn arbiters. Each arbiter runs concurrently and accepts votes from the various active motor behaviors. For turning, behaviors vote for one of 30 discrete egocentric steering angles; the angle with the most votes wins. A behavior may actually cast several votes for separate headings at once, where the votes are spread about a central angle with a Gaussian distribution. In speed voting, the lowest speed vote always wins. Details on the mathematical formation of the arbitration process are available in [11]. One strength of the formation behaviors lies in their ability to be easily reformulated for this and other alternate behavior-based coordination methods.

As in the case of motor schema-based robots, the UGVs must simultaneously navigate to a goal position, avoid collisions with hazards and remain in formation. This is accomplished by concurrent activation of independent behaviors for each. Here we will deal only with the formation behaviors.

For the UGV, formations and formation positions were determined in the same way as described in Section II. The approach described here for maintaining a given formation position is equally applicable to unit-center, leader, and neighbor referenced formations, but only unit-center was implemented. We now focus on the control strategies for moving a robot into formation, given the desired position is known.

Car-like nonholonomic constraints on UGV movement call for a revision of the formation motor behavior. In the nonholonomic case the robot's heading during formation corrections significantly impacts its ability to remain in position. Not only should the vehicle be in the right location, but its heading should be aligned with the axis of the formation. If it is very far off heading, the robot will quickly fall out of position either laterally, fore-aft or both. A technique used by pilots for aircraft formation [9] is well suited for this.
• UGV is a High Mobility Multipurpose Wheeled Vehicle with sensors and steering/speed control.

• Motor-schema architecture needs to be converted to UGV architecture. Behaviors generate speed and steer/turn

• Deal with a nonholonomic robot.
  • Maintain formation speed
  • Maintain formation Steer

• Arbiter coordinates behaviors findings.
UGV Demo II
Architecture

Maintain Formation Speed

\[ V_{\text{speed}} = R_{\text{mag}} + K \times \delta_{\text{speed}} \]

- **Ballistic zone**: 1.0;
- **Controlled zone**: magnitude varies linearly from a maximum of 1.0 at the farthest edge of the zone to zero at the inner edge;
- **Dead zone**: in the dead zone the magnitude is always zero.
UGV Demo II
Architecture

Maintain Formation Steer

**Ballistic zone**  90°, i.e. head directly toward the axis.

**Controlled zone**  the turn varies linearly from a maximum of 90° at the farthest edge of the zone to 0° at the inner edge.

**Dead zone**  0°, i.e. head parallel to the axis.

left/right of formation
stopped conversion to steer

\[
H_{\text{desired}} = F_{\text{dir}} - \delta_{\text{heading}}.
\]

\[
H_{\text{desired}} = F_{\text{pos}} - R_{\text{pos}}.
\]

\[
V_{\text{steer}} = H_{\text{desired}} - R_{\text{dir}}.
\]
A one-kilometer course across open undulating terrain while smooth shifting from a formation (Figs. 16 and 17). The HMMWV’s followed approach would be unsuccessful.

It was felt that since the leader would never slow down to keep formation and a trailer could never speed up if it fell behind due to architectural limitations, a leader-referenced approach was used on the UGV demo II architecture. The AuRA implementation is conceptually simpler and applicable to holonomic robots, while the approach has been demonstrated successfully in the laboratory on mobile robots, and its performance in these tests was limited by a communications system that induced up to 7 s of latency in robot to robot position reports. This problem points to the utility of using explicit exchange of location based on DGPS readings. The three robot formations have run satisfactorily. Performed in the text to maintain a unit-center-referenced formation expert software tool was developed and integrated into the UGV demo II architecture which provides the ability for a robot to slow down to keep formation.

On two reactive robotic architectures, AuRA and the UGV demo II implementation addresses the additional complexity of nonholonomic vehicle control.

Separate experiments in simulation evaluated the utility of reactive behaviors for four formations and three formation references in turns and across the various formation types and references as they traverse the field.

The robot at the top of the line formation. The robot at the top of the wedge formation. The robot at the top of the formation.
Drop Guns!
Drink Beer!
AuRA Architecture

Learning
- Plan Recognition
- User Profile
- Spatial Learning
- Opportunism
- On-line Adaptation

User Input
- User Intentions
- Spatial Goals
- Mission Alterations
- Teleautonomy

Mission Planner
- Spatial Reasoner
- Plan Sequencer

Hierarchical Component

Reactive Component

Schema Controller
- Motor
- Perceptual

Actuation
Sensing

Figure 1. High-level AuRA schematic.