Overview of “Distributed Algorithms for Multi-Robot Observation of Multiple Moving Targets”

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- Approach
- Experiments
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Introduction

**Application:** Many security, surveillance, and reconnaissance tasks require autonomous observation of the movements of targets navigating in a bounded area of interest.

**Key of problem:** determining where sensors should be located to maintain the targets in view.

**Strategy:** to use a cooperative team of autonomous sensor-based robots for applications in this domain, developing the distributed control strategies that allow the team to attempt to minimize the total time in which targets escape observation by some robot team member in the area of interest, given the locations of nearby robots and targets and considering the following three cases:

- **fixed robot positions** (Fixed)
- **non-weighted local force vectors** (Local)
- **random robot movements** (Random)
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Problem Description

Cooperative Multi-Robot Observation of Multiple Moving Targets (CMOMMT):

S : a two-dimensional, bounded, enclosed spatial region

V: a team of m robot vehicles \( (v_i, i = 1,2,...m) \) with 360° field of view observation sensors that are noisy and of limited range

\( O(t) \): a set of n targets \( (o_j(t), j = 1,2,...n) \), such that target \( o_j(t) \) is located within region S at time t

sensor coverage \( (v_i) \): the region visible to robot \( v_i \)'s observation sensors, for \( v_i \in V \). In general, the maximum region covered by the observation sensors of the robot team is much less than the total region to be observed.

\[
\bigcup_{v_i \in V} \text{sensor coverage}(v_i) \ll S.
\]
Problem Description

Assumption:

- The robots have a broadcast communication mechanism that allows them to send (receive) messages to (from) each other within a limited range. The range of communication is assumed to be larger than the sensing range of the robots, but (potentially) smaller than the diameter of S. This communication mechanism will be used only for one-way communication. Further, this communication mechanism is assumed to have a bandwidth of order $O(mn)$ for $m$ robots and $n$ targets.

- For all $v_i \in V$ and for all $o_j(t) \in O(t)$, $max_{vel}(v_i) > max_{vel}(o_j(t))$, where $max_{vel}(a)$ gives the maximum possible velocity of entity $a$, for $a \in V \cup O(t)$. This assumption allows robots an opportunity to collaborate to solve the problem. If the targets could always move faster, then they could always evade the robots and the problem becomes trivially impossible for the robot team (i.e., assuming "intelligent" targets).

- The robot team members share a known global coordinate system.
Problem Description

Define an $m \times m$ matrix $B(t)$ as follows:

$$B(t) = [b_{ij}(t)]_{m \times n} \text{ such that } b_{ij}(t) = \begin{cases} 1 & \text{if robot } v_i \text{ is observing target } o_j(t) \text{ in } S \text{ at time } t \\ 0 & \text{otherwise} \end{cases}$$

Then the goal is to develop an algorithm (A-CMOMMT) that maximizes the following metric $A$:

$$A = \sum_{t=1}^{T} \sum_{j=1}^{n} \frac{g(B(t), j)}{T}$$

$$g(B(t), j) = \begin{cases} 1 & \text{if there exists an } i \text{ such that } b_{ij}(t) = 1 \\ 0 & \text{otherwise} \end{cases}$$

**GOAL:** to maximize the average number of targets in $S$ that are being observed by at least one robot throughout the mission that is of length $T$ time units.

**Note:** do not assume that the membership of $O(t)$ is known in advance.

**Implication:** fixed robot sensing locations or sensing paths will not be adequate in general, and that instead, the robots must move dynamically as targets appear in order to maintain their target observations and to maximize the coverage.
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Approach

Overview

In the A-CMOMMT approach has been incorporated a distributed, real-time reasoning system utilizing motivations of behavior to control the activation of task achieving control mechanisms. For the purposes of fault tolerance, has been utilized no centralized control, but rather enable each individual robot to select its own current actions. moreover it does not make use of negotiation among robots, but rather rely upon broadcast messages from robots to announce their current activities.

In the A-CMOMMT approach, robots use weighted local force vectors that attract them to nearby targets and repel them from nearby robots. The weights are computed in real-time and are based on the relative locations of the nearby robots and targets. The weights are aimed at generating an improved collective behavior across robots when utilized by all robot team members.
Approach

Target and robot detection

the robots use a global positioning system to determine their own position and the position of targets within their sensing range, and to communicate this information to the robot team members within their communication range. Each robot communicates to its teammates the position of all targets within its field of view.

The innermost range is the sensing range of $v_i$, within which the robot can use a sensor-based tracking algorithm to maintain observation of targets in its field of view.

The middle range is the predictive tracking range of the robot $v_i$, which defines the range in which targets localized by other robots $v_k \neq v_i$ can affect $v_i$'s movements.

The outermost range is the communication range of the robot, which defines the extent of the robot's communicated messages.
Approach

A robot can know two types of targets:
- those that are directly sensed
- those that are virtually sensed through predictive tracking.

When a robot receives a communicated message regarding the location and velocity of a sighted target that is within its predictive tracking range, it begins a predictive tracking of that target's location, assuming that the target will continue linearly from its current state. This predictive tracking will then give the robot information on the likely location of targets that are not directly sensed by the robot, so that the robot can be influenced not only by targets that are directly sensed, but also by targets that may soon enter the robot's sensing range.
Approach

Local force vector calculation

The local control of a robot team member is based upon a summation of force vectors which are attractive for nearby targets and repulsive for nearby robots. The relative magnitude of the attractive forces of a target within the predictive tracking range of a given robot.

Note that to minimize the likelihood of collisions, the robot is repelled from a target if it is too close to that target (distance < do1). The range between do2 and do3 defines the preferred tracking range of a robot from a target.

The attraction to the target falls off linearly as the distance to the target varies from do3. The attraction goes to 0 beyond the predictive tracking range, indicating that this target is too far to have an effect on the robot's movements.
Approach

the magnitude of the repulsive forces between robots. If the robots are too close together (distance < dr1), they repel strongly. If the robots are far enough apart (distance > dr2), they have no effect upon each other in terms of the force vector calculations. The magnitude scales linearly between these values.

Weighting the force vectors
to enhance the control approach have been weighted the contributions of each target's force field on the total computed field. The weight $w_{ik}$ reduces robot $r_i$'s attraction to a nearby target if that target is within the field of view of another nearby robot and helps reduce the overlap of robot sensory areas toward the goal of minimizing the likelihood of a target escaping detection.
Approach

The weighted local force vectors are combined to generate the commanded direction of robot movement. This direction of movement for robot \( v_i \) is given by:

\[
\sum_{k=1}^{n} w_{ik} f_{ik} + \sum_{i=1, i \neq l}^{m} g_{ii}
\]

where \( f_{ik} \) is the force vector attributed to target \( ok \) by robot \( v_i \) and \( g_{ii} \) is the force vector attributed to robot \( vi \) by robot \( v_i \). To generate an \((x; y)\) coordinate indicating the desired location of the robot corresponding to the resultant force vector, we scale the resultant force vector based upon the size of the robot. The robot's speed and steering commands are then computed to move the robot in the direction of that desired location. Both of these computed commands are functions of the angle between the robot's current orientation and the direction of the desired \((x; y)\) position.

The velocity and steering command can be overwritten by an Avoid Obstacles behavior, which will move the robot away from any obstacle that is too close. This is achieved by treating any such obstacle as an absolute force field that moves the robot away from the obstacle.
Approach

- 5 targets: o1, o2, o3, o4, o5,
- 2 robots, v₁ and v₂, within vᵢ's communication range.

The magnitude of the force vectors attracting robot vᵢ to targets o2 and o3 is equivalent to the maximum value, since those targets are within vᵢ's sensing range but not within any other robot's sensing range.

The attraction of vᵢ to target o1 is less than that for o2 and o3, because o1 is outside the sensing range of vᵢ.

The force vector to target o4 is weighted less due to o4's presence within v₁'s sensing range. Finally, there is no attraction to target o5, because it is outside vi's predictive tracking range.

Robot vᵢ also experiences a repulsive force due to robot v₂, because of the close proximity of the robots. There is no repulsion due to v₁, since v₁ is sufficiently distant.
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Experiments

Overview

- **Simulations**: the simulation studies allow to test larger numbers of robots and targets.
- **Physical Robot**: the physical robot experiments allow to validate the results discovered in simulation in the real world.

**cooperative observation policies:**
1. A-CMOMMT (weighted force vector control)
2. Local (nonweighted force vector control)
3. Random (robots move random/linearly)
4. Fixed (robots remain in fixed positions)

The Local algorithm computes the motion of the robots by calculating the same local force vectors of A-CMOMMT, but without the force vector weights.

**Set of simulated experiments:**
- target movements:
  - random/linear
  - evasive
- circular region $S$ with no obstacles (other than the boundary).

**Set of physical robot experiments**
- random/linear target movements.
- work area $S$ is a rectangular area.
Experiments

Simulations

**TEST 1:**
- Targets move according to a random/linear movement
- Targets are randomly assigned a fixed speed between the values of 0 and 150 units/second,
- Robots are assigned fixed speed of 200 units/second.
- Robots and targets are randomly positioned and oriented in the center region of S
- $S = a$ circle of radius $R$,
- the range of robot sensing at 2,600 units of distance, treated robots and targets as points, and included no obstacles within S

**TEST 2:**
- Targets move evasively,
- sensing range = 1.5 times
- Targets are randomly assigned a fixed speed between the values of 0 and 150 units/second,
- Robots are assigned fixed speed of 200 units/second.
- Robots and targets are randomly positioned and oriented in the center region of S
- $S = a$ circle of radius $R$,
- the range of robot sensing at 2,600 units of distance, treated robots and targets as points, and included no obstacles within S

If a target doesn’t see a robot within its FOV, it moves linearly along its current direction of movement, with boundary reflection.
Experiment's results

**TEST 1:**
3 robots and 6 targets
(a) Fixed,
(b) Random
(c) Local, and
(d) A-CMOMMT.

- black circles = positions of the robots
- gray squares = positions of the targets
- gray circles = sensing range of that robot.
- large black circle = boundary of the area S

In the Local approach, the robots tend to cluster near the center of mass of the targets, with some separation due to the repulsive forces between the robots. This leads to several targets being under observation by multiple robots, while other targets escape observation.

In the A-CMOMMT approach, the robots exhibit more distribution due to the weights on the force vectors that cause them to be less attracted to targets that are already under observation by a nearby robot. Thus, more targets remain under observation.
Experiments

Simulation’s results

TEST 2:
3 robots and 6 targets
(a) Fixed,
(b) Random
(c) Local, and
(d) A-CMOMMT.

- black circles = positions of the robots
- gray squares = positions of the targets
- gray circles = sensing range of that robot.
- large black circle = boundary of the area S
Experiments

Simulation’s results

TEST 1:
Percentage improvement in simulation of $A$-CMOMMT over Local, for $R > 10,000$, $r = 2600$, and random target movements

<table>
<thead>
<tr>
<th>n/m</th>
<th>1/5</th>
<th>1/2</th>
<th>1</th>
<th>4</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$-CMOMMT</td>
<td>-8%</td>
<td>0%</td>
<td>14%</td>
<td>27%</td>
<td>31%</td>
</tr>
</tbody>
</table>

Graphs showing normalized averaged performance for different ratios of work area and target movements.

- (a) $n/m = 3/5$, Targets move randomly
- (b) $n/m = 1/2$, Targets move randomly
- (d) $n/m = 4$, Targets move randomly
- (e) $n/m = 10$, Targets move randomly
Experiments

Robot implementation

Purposes:
- to illustrate the feasibility of our approach for physical robot teams,
- to compare the results with the results from simulation,
- to determine the impact of random scattered obstacles on the effectiveness of the proposed approach

Robot Design:
- wheeled vehicles with tactile,
- infrared,
- ultrasonic,
- 2D laser range
- indoor global positioning systems.
- radio Ethernet for inter-robot communication.

Parameters:
- work space = 12.8m x 6.1m
- robot diameter = 0.61m
- Obstacles averaged a footprint = .6m²
Experiments

Physical Robot Experimental Results

As the target is moved, the two observers also move in the same direction, due to the attractive forces of the target that is moving away.

If the target exits the area of interest, the observers are no longer influenced by the moved target, and again draw nearer to the stationary target, due to its attractive forces.
Experiments

Physical Robot Experimental Results

Results of physical robot experiments with no obstacles.

Results of physical robot experiments with scattered random obstacles.
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Conclusions

The experimental results show that

**BENEFITS:**

1) the A-CMOMMT approach is significantly superior to the Local approach for the difficult situations in which there are more targets than robots.

2) The A-CMOMMT is successful in achieving its goal of maximizing the observation of targets in the more challenging instantiations of the CMOMMT problem.

**DISADVANTAGES:**

for experiments in which there are many more robots than targets, the weights on the local force vectors used in the A-CMOMMT approach cause robots to occasionally lose targets, and thus perform worse than in the Local approach.