A Surveillance System based on Multiple Mobile Sensors

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Abstract: *A methodology for surveillance of multiple targets through a distributed mobile sensor network is proposed in this paper. We examine coordination among sensors that monitor a rectangular surveillance zone that is crisscrossed by targets. After a target is detected, monitoring sensors either remain stationary or begin following their targets. The decision to remain stationary or to track a target is based on a complex priority ascription to the target and the coordination mechanism between the sensors. The priorities are computed with a fuzzy inference scheme. Coordination between sensors considers the geometry of the future target path and the number of expected observations a sensor is likely to make on the target. Simulation results validate the efficacy of the proposed methodology.*

1 Introduction

The problem of multi sensor surveillance involves detection of multiple intrusions and/or tracking through coordination between the sensors. Detection and target tracking has been researched from multiple viewpoints. Some efforts have focused on the problem of identifying targets from a given set of data through particle filters (Schulz et. al, 2001) and probabilistic methods (Schulz and Burgard, 2001). The problem of data association or assigning sensor measurements to the corresponding targets were tackled by Joint Probabilistic Data Association Filters by the same researchers such as in (Schulz et. al, 2001). Kluge and others (Kluge, Kohler and Prassler, 2001) use dynamic timestamps for tracking multiple targets. Krishna and Kalra (Krishna and Kalra, 2002a) presented clustering based approaches for target detection and further extended it to tracking and avoidance in (Krishna and Kalra, 2002b). The focus of these approaches has been on building reliable estimators and trackers. They do not use distributed sensors and are not directly useful for the problem of large area surveillance.

The thrust of this paper is an attempt to solve the following problem: "Given a distributed sensor network and multiple targets that cross a surveillance area, how do the sensors coordinate to decide:

1. How should each sensor reason about all targets and other sensors in its selecting a target?
2. How should each sensor reason about its decision to either to stay stationary or to follow a target?

Within this context, literature related to distributed task allocation and sensor coordination is more closely related to ours. For instance, the ALLIANCE architecture of Parker (Parker, 1999) proposed a scheme for delegating and withdrawing robots to and from targets. The protocol for allocation was one based on "impatience" of the robot towards a target while the withdrawal was based on "acquiescence". Jung and Sukhatme (Jung and Sukhatme, 2002) present a strategy for tracking multiple intruders through a distributed mobile sensor network. Lesser's group have made significant advances to the area of distributed sensor networks (Horling, et. al. 2001) and sensor management (Horling, et. al. 2003).

In (Jung and Sukhatme, 2002) robots are distributed across a region using density estimates in a manner that facilitates maximal tracking of targets in that region. The decision for a robot to move to another region or to stay in its current region is based on certain heuristics. The method presented does not address collaborative or shared reasoning strategies for decision-making and action selection such as the decision for moving to a new area. The coordination between sensors is restricted to communicating their respective positions. Strategies presented by Lesser's group deal with sensor coordination from the point of view of tracking only one target.

The scheme presented here addresses surveillance of many targets. The coordination between sensors involves reasoning about their current states (states can be one of stationary, moving or homing) and priorities and is not limited to their awareness of each other sensor's positions alone. Each detected target in the system is associated a global priority based on a number of parameters. Each robot ascertains its own preference for a target, which is the local priority for that target for that sensor. A weighted combination of global and local priorities is used to compute a balanced priority for a target from the point of every sensor. Thus, each sensor maintains a list of balanced priorities for every target. A coordinated decision is taken for the target with highest balanced priority for a given sensor by that sensor. This decision characterizes whether the sensor allocates itself to the target and the modality by which it allocates itself (being stationary with respect to the target or by following it).

2 Problem Description

Multi-sensor surveillance finds many military applications such as border patrol, beachfront surveillance and reconnaissance of secured rural areas and cities. Surveillance in military domain often involves rugged and uneven terrain over large areas with possible natural and manmade obstructions. In the formulation presented we make certain abstractions while transforming the real world situation to a simulated environment in that it does not have representations of the actual features of the landscape. The main thrust of this paper, which is one of reasoning about targets and coordination between sensors ***is essentially independent of the approximations of the real world made*** in simulation models.

The robots perform surveillance over a rectangular (square) surveillance zone. The surveillance zone is divided into number of square shaped cells as shown in figure 1 for the sake of modeling. The sensors indicated by circles are placed along the diagonals of the zone at the corners of the cell.

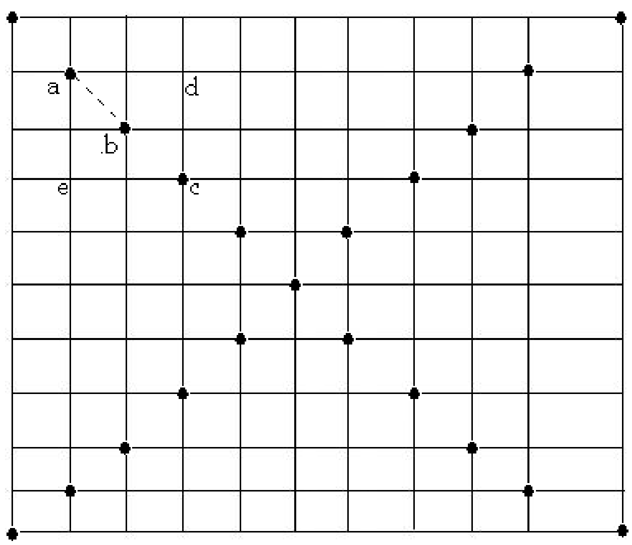


Figure 1. The rectangular surveillance zone with the sensors shown as circles placed along the two zone diagonals at the corners of the cells. The sensors have a radius of vision equal to the diagonal of the cell

The radius of vision of the sensor equals the length of the diagonal of the cell. However the sensor only considers those targets that lie within its four neighboring cells as targets within its field of vision. In other words a sensor positioned at 'a' in figure 1 considers only targets within the square region 'adce' as those within its field of vision.

The four sides of the zone define its four boundaries. Boundaries serve as entry and exit points for the moving targets. Targets move across the area by entering from one boundary and leaving through any of the other three boundaries. Sensors model the path of the target as linear. Targets can change their directions but at any instant sensors model target trajectories as straight line paths along their current motion direction.

3 The Methodology

The following notations may be useful before embarking on the discussion for ascribing priorities to targets. Let n_s represent the total number of sensors and n_t the total number of targets in the system. Let N_S be the set of all sensors in the system, i.e., $N_S = \{s0, s1, ..., sn_s\}$, where si denotes the sensor with label i. Hence n_s is the cardinality of N_S or $n_s = |N_S|$. In the same vein N_T is the set of all targets, $N_T = \{t0, t1, ..., tn_t\}$ and n_t is the cardinality of N_T. We define S_{ti} as the set of all sensors currently monitoring target ti and T_{si} as the set of all targets being monitored by sensor si. Then $\overline{S}_{ti}$ is the set of all sensors currently not detecting ti. We denote the number of samples a target ti is likely to be detected or observed by sensor sj by o_{tisj}, where $sj \in S_{ti}$. If the time for which ti is likely to be within the field of vision of sj is t_{tisj} and the sampling interval is dt then $o_{tisj} = t_{tisj} / dt$. The sampling time indicates the time interval between two successive scans of the environment by the sensors. SF_{ti} is the set of all sensors that are *likely* to detect ti in the future though they are not observing it currently. Hence $SF_{ti} \subset \overline{S}_{ti}$.

3.1 Priority ascription to targets

Sensors reason about targets by ascribing priorities to them. Priorities serve as a handle for decision making. Whenever a sensor detects a target it updates information about the target regarding its current position, velocity and motion direction to a whiteboard. The whiteboard is a common pool of resources that includes public methods and variables, which can be modified and accessed by other programs of the project. Other sensors can come to know about this target by accessing these variable or invoking methods from this common pool.

Every target has associated with it a global priority that portrays the priority to that target from the point of view of the entire sensing apparatus.

Ascribing global priority:
The global priority for a target ti is determined by three parameters namely:

- $p1_{ti}$: The maximum number of times target ti is likely to be further observed by one of the sensors currently monitoring it. In other words $p1_{ti} = \max_{sj}(o_{tisj}) \forall sj \in S_{ti}$
- $p2_{ti}$: The number of sensors currently not detecting ti but are expected to detect it in future. $p2_{ti} = |SF_{ti}|$
- $p3_{ti}$: The measure of possibility that sensors in SF_{ti} would be in a position to monitor ti in the future. This is elaborated in the subsequent section on sensor coordination. $p2_{ti} = \sum_{sj} m_{tisj} \forall s_j \in SF_{ti}$, where m_{tisj} is the measure of the possibility of sj to take care of ti

The fuzzy rulebase that infers the global priority gp_{ti} for any target in the system is tabulated in table 1. For notational convenience we remove the suffix ti associated with the parameters henceforth.

p1	p2	p3	gp
H	L	X	M
H	M	X	LM
H	H	X	L
L	L	X	H
L	M	X	HM
L	H	X	M
H	X	H	L
H	X	L	LM
L	X	H	M
L	X	L	H

Table 1: Fuzzy rulebase for global priority inference. The linguistic labels for the fuzzy sets are: H=high, L=low, M=medium. LM=low medium and HM=high medium

The membership functions associated with the antecedent and consequent variables are not shown here due to brevity of space.

Ascribing local priority:

Every target ti is associated a local priority from the point of view of every sensor si in N_S. The parameteric basis for local priority computations vary marginally with regard to whether si belongs to S_{ti} or not. If $si \in S_{ti}$ the local priority is based on the time for which si would have to track S_{ti} before another sensor engages ti. If $si \notin S_{ti}$ the computation is based on the time for which si would have to wait for ti before si can engage ti. The local priority for a target ti from the point of view of a sensor sj is denoted as lp_{sj}. Denoting either of the times used as t_{wait} the rulebase for computing local priority is tabulated in table 2 where the symbols carry the same linguistic labels as in table 1.

t_{wait}	lp_{sj}
L	H
M	M
H	L

Ascribing balanced priority:

The balanced priority for ti from the point of view of sj is obtained by fusing local and global priorities as follows:
$bp_{sj} = w_{g'}(gp) + (1 - w_{g'})lp_{sj}$, where $w_{g'} = w_g(1 - w_{ab})$. Here w_g takes unitary value if $sj \in S_{ti}$, else its value decreases linearly with the time taken by ti to enter the field of vision of sj. w_{ab} represents the autonomy bias of a sensor towards its own preference towards the target (local priority) rather than the preference as ascribed to the target by the entire system (global priority). Under high values of w_{ab} the balanced priority would reflect more the individual sensor's preference towards the target than the global preference. A detailed exposition to the outcome of this bias would be dealt elsewhere.

3.2 Sensor Coordination

All communication between sensors is effected through the whiteboard. Coordination between sensors occurs due to three different requirements listed here.

Coordination for global priority computation: Computation of global priority for a target ti is not from the point of view of a particular sensor. Hence this computation is performed as one of the methods in the whiteboard. The computation of parameter $p3$ entails exchange of data from the whiteboard to the set of sensors in SF_{ti} and vice versa. The request to the sensors is a request for the possibility measure for monitoring ti in future. Sensors in SF_{ti} come to know of this request when they access the whiteboard for possible requests. The requested sensors evaluate the possibility that they would be in such a position that the target would pass through its field of vision in the future. This possibility is returned back to the whiteboard by invoking an appropriate method.

Coordination for resource allocation

Resource allocation is the problem of allocating a sensor to a target. Let the target with the highest balanced priority for a sensor sj is denoted as t_{sj}^{m} and the sensor which would detect a target ti for maximum number of times amongst the set of sensors currently observing it be represented as s_{ti}^{m}. The superscript m indicates maximum. Then coordination between sj with another sensor sk for resource allocation with regard to target ti is based on a set of rules relating to visibility relations of sj, sk with respect to ti and the priority of ti from the point of view of either of the sensors. A few of those rules for coordination are listed below. The entire set of rules is omitted for brevity

1. If $t_{sj}^{m} \in T_{sj}$ and $t_{sj}^{m} \in T_{sk}$, $j \neq k$ and $sk = s_{ti}^{m}$ and $t_{sj}^{m} \neq t_{sk}^{m}$ then sj waits for the resource allocation decision of sk before making its decision. Based on the decision sk, sj may or may not allocate itself to ti. The above rule states sj coordinates with sk for allocation with regard to target ti if ti is the target with maximum balanced priority for sj, is currently being detected by sj and would also be detected more number of times by another sensor sk and ti is *not* the target with maximum balanced priority for sk. The above rule motivates a sensor sj to give credence to the decision of another sk, if sk would detect ti for a longer time than sj though ti is not the target with highest priority for sk.
2. If $t_{sj}^{m} \in T_{sj}$ and $t_{sj}^{m} \in T_{sk}$, $j \neq k$ and $sk = s_{ti}^{m}$ and $t_{sj}^{m} = t_{sk}^{m}$ then sj does not allocate itself to ti and considers the next highest priority target for possible allocation. Here sj reasons that sk would allocate itself to ti since ti would be within the field of vision of sk longer than sj and since ti is also the target with highest priority for sk.

Coordination for baton exchange

When target ti pursued by sensor sj enters the field of vision of another sensor sk that is not in motion (following another target tj), sk signals to sj about this event through the whiteboard that leads to sj withdrawing its pursuit of ti.

3.3 Decision Making

The minimum number of times a target needs to be detected for having a complete and accurate characterization of it is denoted by n_{th}. A sensor that has allocated itself to a target decides whether to remain stationary or pursue the target based on the following conditions.

If $o_{tisj} \leq k.n_{th}$ *and* $p3_{ti} \leq p_{th}$ then sj follows ti else sj remains stationary.

4 Simulation Results

The simulations presented do not consider occlusion relations. In other words a target is considered visible for a sensor if it falls in its field of vision. Tracking is done by moving the sensor along a path parallel to the target and as far as possible at a distance that is less than or equal to half of the radius of vision of the sensor.

Figure 2 depicts the simulation system for multi-sensor surveillance on Java using Borland JBuilder as the IDE. The figure shows interfaces for controlling the behavior of the sensors both at individual levels as well as at the level of the whole group. These interfaces are on the left of the figure. They have been developed from the point of view facilitating human control of the system by modifying individual and group parameters on the fly. These are not discussed here. The sensors used in this simulation are fifteen in number labeled as $s0, s1, \ldots$ and the targets are labeled as $t0, t1, \ldots$.

The figure also depicts target exchange. It shows the instant when sensor $s0$ withdraws pursuit of target $t0$ as $t0$ enters the field of vision of $s1$.

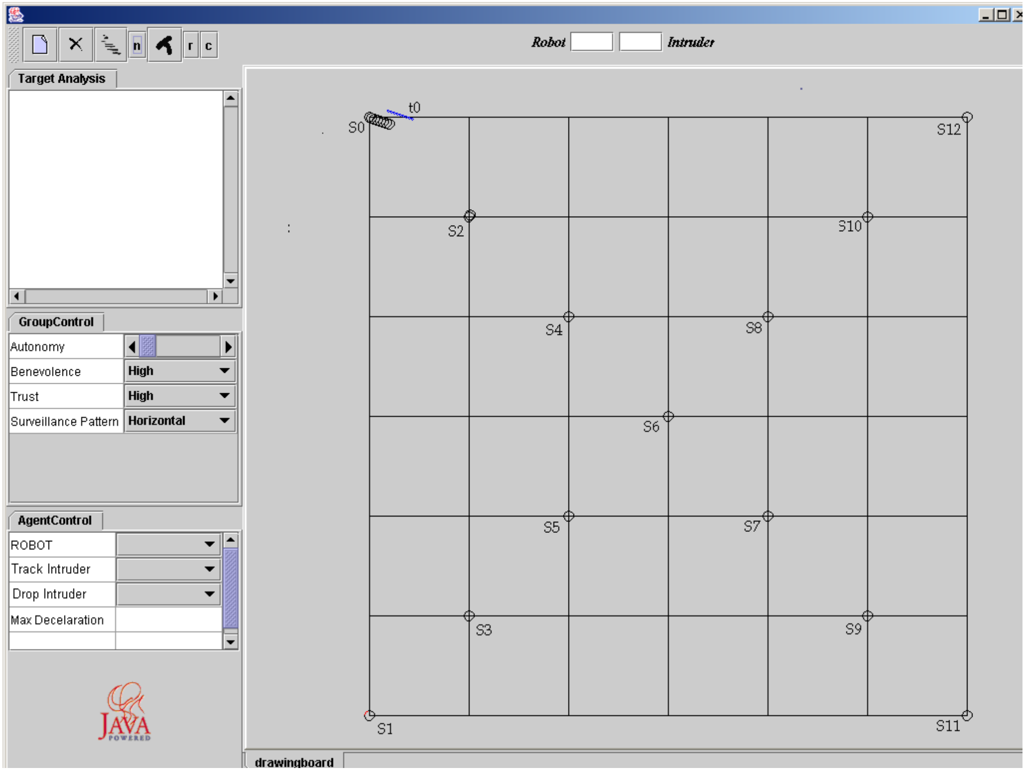


Figure 2: The simulation system with interfaces for human control of sensor behaviors at individual and group levels. The figure also shows exchange of target $t0$ from sensor $S0$ to sensor $S1$.

Figure 3a shows a snapshot at the fifth sample from the start of simulation. The resource allocation of sensors to targets at samples 2 and 5 of the simulation is tabulated in table 3. At the second sample, S2 gets allocated to t0 through rule 2 mentioned in section 3.2 Here sensor sk is S2 about which sensor sj, here S0 reasons based on rule 2. Essentially S0 and S2 have t0 as their target with highest priority. However since t0 would be in the field of vision of S2 for a longer time S0 reasons that S2 would allocate itself to t0 and hence allocates itself to the target with the next highest priority, t3. At the fifth sampling instant t1 enters the field of vision S2 and becomes the target with highest priority for S2. S0 finds that t0 though would remain for a longer time in the field of vision of S2 is no more the target with highest priority for S2. Hence it communicates regarding t0 to S2 via the whiteboard. Rule 1 of section 3.2 is being effected here. When S2 decides to follow t1, S1 decides to follow t0. If on the other hand S2's decision making module had adopted stationary monitoring for t1, S1 would have allocated itself to the next target on the priority list, since this effectively would have been the same situation as in sample 2. S2 deciding to move after t1 implies t0 would not be in its field of vision much longer resulting in S0 allocating itself t0.

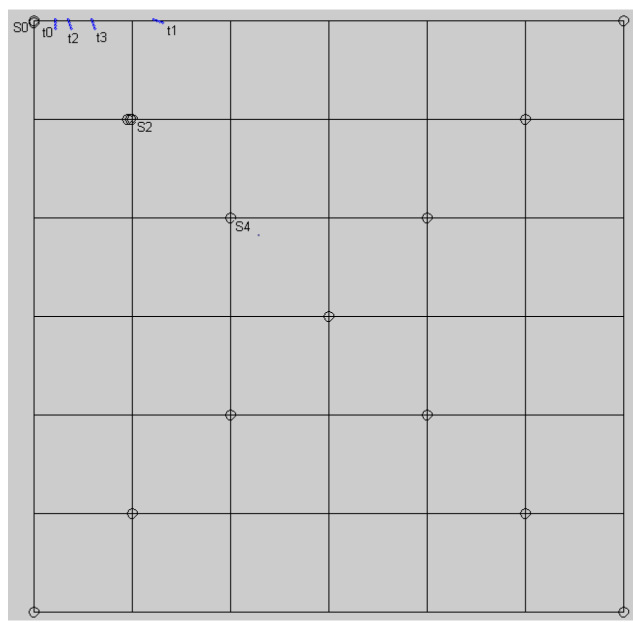
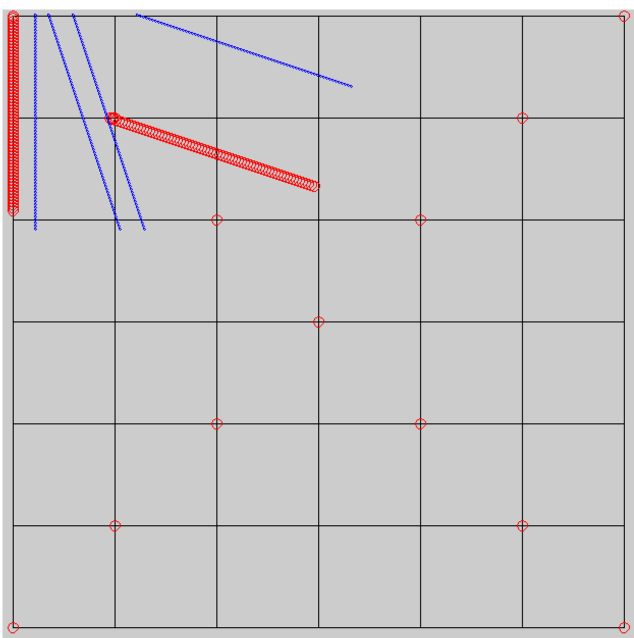


Figure 3a: A snapshot at the fifth sample from start of simulation with four targets. S0 allocates itself to t0 and S2 to t1

Sample Instant	Sensor sj	Targets in sj (T_{sj})	Target priorities (sj 's viewpoint)	Target Allocation
2	S0	t0 t2 t3	t0 = 0.72 t2 = 0.43 t3 = 0.59	t3 Static tracking
	S2	t0 t2 t3	t0 = 0.69 t2 = 0.41 t3 = 0.54	t0 Mobile tracking
5	S0	t0 t2 t3	t0 = 0.71 t2 = 0.40 t3 = 0.56	t0 Mobile tracking, after waiting for S2's decision
	S2	t0 t1 t2 t3	t0 = 0.68 t1 = 0.76 t2 = 0.40 t3 = 0.53	t1 Mobile tracking

Table 3: Table showing resource allocation of sensors to targets at various sampling instants.

Figure 3b depicts the snapshot of the system after several samples from the start of simulation when no further targets have been introduced.



Limitations: Currently two limitations have been identified which are the tendency of a sensor to swap between targets that affects performance if the sensor is in motion and the swapping of targets between sensors. For example if S0 tracks t0 and S1 tracks t2 the system at times exhibits tendency to swap the targets between the sensors. This can possibly occur at a more general level between many sensors.

Future Scope: The future scope of this effort is multifarious that includes defining performance metrics to quantify system performance, introduce social primitives such as benevolence and provide for human control of the entire sensor network by tuning autonomy and benevolence that enhances system performance.

5 Conclusions

A methodology for surveillance of multiple targets through a network of multiple sensors capable of being mobile has been presented. Simulation results obtained confirm the efficacy of the system to handle a number of targets introduced simultaneously or in rapid succession. Targets are assigned priorities at global (system) level and at local (sensor) levels through a fuzzy inference scheme. Resource allocation of sensors to targets involves coordination between sensors and reasoning about the actions of one another. The future scope of this effort is rich and diverse.

References:

Horling, B; Vincent, R; Miller, R; Shen, J; Becker, R; Rawlins, K and Lesser, V. 2001, "Distributed Sensor Network for Real Time Tracking", In *Proceedings of the 5th International Conference on Autonomous Agents*:. 417-424.

Horling, B; Miller, R; Sims, M; and Lesser, V. 2003, "Using and Maintaining Organization in a Large-Scale Distributed Sensor Network", In *Proceedings of the Workshop on Autonomy, Delegation, and Control (AAMAS03)*.

Jung, B and Sukhatme, G.S. 2002, "Multi-Target Tracking using a Mobile Sensor Network", Proc., *IEEE Intl. Conf. On Robotics and Automation*

Kluge, B; Kohler, C; and Prassler, E. 2001, "Fast and robust tracking of multiple objects through a laser range finder", *IEEE International Conference on Robotics and Automation*, 1165-1170

Krishna, K. M; and Kalra, P. K., 2002a "When does the robot perceive a dynamic object", *Journal of Robotic Systems*, 19(2)

Krishna, K. M; and Kalra, P. K., 2002b, "Detection tracking and avoidance of multiple dynamic objects", *Journal of Intelligent and Robotic Systems*, 33(4): 371-408

Parker, L. 1999, “Cooperative robotics for multi-target observation”, *Intelligent Automation and Soft Computing,* 5(1):5-19

Schulz, D; Burgard, W; Fox, D; and Cremers, A. 2001, “Tracking multiple moving targets with a mobile robot using particle filters and statistical data association”, *IEEE International Conference on Robotics and Automation*, 1165-1170

Schulz, D; and Burgard, W. 2001, “Probabilistic state estimation of dynamic objects with a moving mobile robot”, *Robotics and Autonomous Systems*.