Coverage Problem in Wireless Sensor Networks by Holonic Multi-Agent Approach

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Abstract: A wireless sensor network will collaborate for a common application such as environmental monitoring. One fundamental issue in sensor networks is the coverage problem. We present in this article a Holonic Multi-agent approach that solves the coverage problem when using wireless sensor networks. Complex systems are characterized by large number of entities in interaction, exhibiting emergent behaviors. The holons in holonic multi-agent systems are not required to coordinate the work of a physical resource, but instead may coordinate the work of several information agents that only exist virtually. A super-holon is, internally, a community of holons that cooperate to achieve a commonly agreed objective or task. On the other hand, Multi-Agent Systems (MAS), stand out as a paradigm for the design of Complex Systems.

Key words: Agent, clustering, coverage, holon, modeling, multi-agents, Holonic organization, Holonic multi-agent systems, sensors network.

INTRODUCTION

A sensor is an equipment having the capability to perceive the environment where it is established or the phenomenon that justified its implementation. It must also be able to transmit data perceived. These types of sensors are called scalar sensors.

There exist other types called multimedia sensors. They include the equipments being able to allow a video, audio, fixed images perception without forgetting the scalar data resulting from environment.

A wireless sensor network is composed of a great number of sensors, deployed massively for the observation of a phenomenon [AKY 02]. Since sensors may be spread in an arbitrary manner, one of the fundamental issues in a wireless sensor network is the coverage problem.

In [MES 01], localized exposure-based coverage and location discovery algorithms are proposed, a sensor coverage metric called surveillance that can be used as a measurement of quality of service provided by a particular sensor network. Their approach consists in combining computational geometry and graph theoretic techniques, specifically the Voronoi diagram and graph search algorithms.

In the literature, this problem has been formulated in various ways, for example: as a decision problem, whose goal is to determine whether every point in the service area of the sensor network is covered by at least k sensors, where k is a predefined value [CHI 03]. The coverage can be considered as the measure of quality of service of a sensor network. For example [MEG 01], in a fire detection sensor networks, one may ask how well the network can observe a given area and what the chances are that a fire starting in a specific location will be detected in a given time frame.

In [MIH], the most discussed coverage problems in literature can be classified in 3 types: area coverage, point coverage and barrier coverage. The barrier coverage consist in of minimizing the probability of undetected penetration through the barrier (sensor
network). In the point coverage problem, the objective is to cover a set of points. In the area coverage problem, the main objective of the sensor network is to cover an area or a region.

We interest to the area coverage problem, and we suppose that a set of sensors is arbitrarily distributed in an area. The nodes proceed to deploy themselves in such a way that they maximize the area covered. We propose an approach based on the Holonic Multi-agent organization.

Our motivations: Sensor networks are open systems and organizationally. We have autonomous sensor nodes with the capacity to collaborate therefore to form a set of groups. In the holonic approach, a group can behave like one atomic entity; therefore we can build the patrol of sensors using the holonic concept.

The rest of the paper is organized as follow. In Section 2, we present state of the art. In Section 3, we present the Holonic multi-agent systems, a clustering algorithm for the construction of our Holonic organization. The Coverage problem in the wireless sensors networks is presented in Section 4. We finish by the conclusion and our future research directions.

1. The coverage problem

One of the fundamental issues that arises in sensor networks, in addition to location calculation, tracking, and deployment, is coverage. Due to the large variety of sensors and applications, coverage is subject to a wide range of interpretations. The coverage can be deterministic or stochastic. In the first case, the predefined locations of the sensors can be uniform in different areas of the sensor field. The problem of coverage of the sensor field reduces to the problem of coverage of one cell and its neighborhood due to the symmetric and periodic deployment scheme. In the second case, the sensors are randomly distributed in the environment. The stochastic random distribution scheme can be uniform, Gaussian, Poisson or any other distribution based on the application at hand [MEG 01]. “Meguerdichian and al” have assumed a centralized control server, where nodes are connected using a gateway. For the context of coverage, resolution strategies and negotiation are needed to integrate information from this stage to be used in related contexts such as tracking mobile objects in the network and handling obstacles. [CHI 03] formulate this problem as a decision problem, whose goal is to determine whether every point in the service area of the sensor network is covered by at least k sensors, where k is a predefined value. [CHI 04] formulate the coverage problem, as a decision problem, whose goal is to determine whether every point in the service area of the sensor network is covered by at least • sensors, where • is a given parameter and the sensing regions of sensors are modeled by balls (not necessarily of the same radius). He shows that tackling this problem in a 3D space is still feasible within polynomial time. The proposed solution can be easily translated into an efficient polynomial-time distributed protocol.

[XIA] give efficient distributed algorithms to optimally solve the best-coverage problem raised in [MES 01]. They are interested in designing a localized algorithm that finds a path connecting a point and a point t, which maximizes the smallest observability of all points on the path. They are called the best coverage problem. In [MIH], the sensor coverage problem has received increased attention recently. This problem is centered around a fundamental question: How well do the sensors observe the physical space? The most discussed coverage problems in literature can be classified in the following types: area coverage, point coverage and barrier coverage. He considers the barrier coverage as being the coverage with the goal of minimizing the probability of undetected penetration through the barrier (sensor network). In the area coverage problem, the main objective of the sensor network is to cover (monitor) an area (also referred sometimes as region), each point of the area is monitored by at least one sensor. In the point coverage problem, the objective is to cover a set of points (i.e., a set of sensors randomly deployed to cover a set of points).

2. Hierarchical structure, clustering and Holons

2.1. Holon and clustering

The holon term was introduced by the Hungarian philosopher Arthur Koestler in 1967. Arthur Koestler coined the term holon as an attempt to conciliate holistic and reductionist visions of the world. A holon represents a whole-part construct that can be seen as a component of a higher level system or as a whole composed of other holons as sub-structures.

In its initial idea, it refers to a natural or artificial structure; its direction is not absolute. According to Koestler, a holon must observe three conditions: (1) be stable, (2) have a capacity of autonomy, (3) be able to cooperate. Stability means that the holon must be able to react well when strong disturbances occur. Autonomy means that the holon must be able to be self-managed in order to achieve its goals. Cooperation means that the holon must be able to work jointly in a project, the goals being divided with the other holons or the other layers of holons.

A holon is a self-similar structure composed of holons as sub-structures. A hierarchical structure composed of holons is called a holarchy [ROD 07]. The Holonic Organization (HO) represents the organization of a single super-holon at a specific level in the holarchy [ROD 03].

The concept of Holon is specialized from the Agent [COS 06]. This definition of holon integrates the production and holonic aspects, the approach being described as organizational. An agent in our approach defines a particular context of interaction between roles belonging to different organizations. This aspect is depicted in Figure 1.
A holon can play several roles in different organizations and can be composed of other holons. A composed holon is called super-holon. It contains at least a single instance of a holonic organization to precise how members organize and manage the super-holon.

It also contains a set of production organizations describing how members interact and coordinate their actions to fulfill the super-holon tasks and objectives.

An illustration of the definition of holon is depicted in Figures 1.

The holonic aspect considers how members organize and manage the super-holon. A specific organization, called Holonic organization, is defined to describe the management of a holon and its structure.

Depending on the level of abstraction, a super-holon can be considered as an atomic entity (at level n) or as an organization of holons (at level n-1) [COS 06].

The clustering consists of a virtual network division in close groups of nodes geographically [NAT 06]. These groups are called clusters. They are generally identified by a particular node called cluster-head (or chief of group). In the majority of clustering algorithms, the clusters are built using a particular metric which makes it possible to assign a head with each cluster; the cluster is then formed of the cluster-head and all the nodes which are attached to it.

2.2. Construction of the holonic organizations

Assumptions

There are some assumptions.

a. Every sensor node has one unique ID.

b. Every sensor node can sense and communicate in some range.

c. Direct sensor node’s communication range is equal to sensing range.

d. Every sensor node can detect and send messages to another node within communication range.

With the aim of building our holonic organization, we propose the following approach.

A priori, a holon is a sensor or a set of sensors. Let us define:

\( C_i \) : sensor identifier i

\( CH_i \) : field of sensor \( C_i \)

\( D \) : set of communicational distance in the holarchy

Definition:

\( \exists \) The field \( (CH_i) \) of a sensor is the area in which the emitted signal still has a non-zero power.

\( \exists \) Any sensor \( C_k \epsilon CH_i \) (with \( C_k \neq C_i \)) will be in the vicinity of \( C_i \)

\( \exists \) In order to form \( D \), if we suppose a sensor \( C_i \) and \( r_i \) his radius caverage, then we define \( d_k = k*r_i \) for a given \( k \), \( d_k \) define a communicational distance of \( C_i \) in the holarchy.

\( \exists \) Let us consider the set \( V_i \) of sensors located in the communicational neighbourhood of the sensor \( C_i \). Let us \( D \) the set of the distances \( d_k \) from \( C_i \) to each sensor of \( V_i \), we have \( D = \{d_1, d_2, ..., d_r \} \). The set \( D_n \) of the sensors of distance \( d_{n-1} \leq d(C_i,C_j) \leq d_n \) will be known as of range \( n \).

Algorithm for building the holonic organization:

- Initially, build up the set of cluster using the concept of neighbourhood as metric define (by the distance between sensors) and accessibility (ability to receive data from another), with or not a hierarchy according to the energy level

Thus, in a organization, a holon will be formed:

- \( \exists \) Either from a sensor having a specific energy level.

- \( \exists \) Or a set of sensors including energy belonging to a certain range.

- \( \exists \) At the top of the hierarchy for example we can have the holon with the most energy. This one must ensure the densest class of the traffic.

- Initially, each cluster is consider as a holon

- Within each organisation, do a local optimization of the coverage (the organization can use for example the repulsion model)

- The local optimization involve the dynamic holon describe below

A holonic organization provides two major functions:

- Communication function

- Coverage function

At a holon will be involved a class of traffic. If the correspondent holon does not exist, then a higher level holon or a lower level holon will be requested according to the energy required by the traffic. A holon can move from one energy level to another, as its gains or loses energy.

Dynamic holons:

The satisfaction measures the progress of the holon towards achieving its current goal. The compatibility of two holons means that they can help each other to
attain their goal. Two holons are compatible if they have shared goals and complementary services.

The process of merging allows the creation and the integration of a new super-holon in the system.

The new super-holon can be created:

1. either from an existing set of holons,
2. either by decomposition of a holon into sub-components.

In Figure 2, the agents $C_i$, $C_j$, and $C_k$ in an holonic organization (OH) move according to the direction force $F_{kj}$, $F_{ijk}$, and $F_{ijk}$.

These directions forces represent the gradients between sensors, which graft in coalition.

This figure presents a repulsion model between 3 agents. The agent $C_m$ will can to enter in the coalition if it arrives to communicate with at least one agent of the organization. In this case, theirs directions forces will modify, and we obtain a new holon in the system by the process of merging.

3. Coverage problem in the wireless sensors networks

3.1. Coverage of two sensors agents

Let us consider two sensors $C_i$ and $C_j$ of cover ray $r_i$ and $r_j$ respectively.

The distance from $C_i$ to $C_j$ is noted $d_{ij} = d(C_i, C_j)$.

To have a set of sensors $C_k$ in its communicational field, a sensor $C_j$ must calculate $L_k$. The following formula describe the way to determine $L_k$:

$$L_k = \prod_{h=1}^{k} D_h \text{ with } k \leq N \quad N \text{ is a maximum range define by the holarchy.}$$

Consequently: The communicational field of a sensor agent in the holarchy stretch to an arbitrary level.

Lemma 1:

After execution by a sensor agent of the corresponding algorithm, if $L_1$ is empty, then $L_k (k >1)$ will be also empty.

Proof:

If $L_1$ is empty, there is not sensor of range 1 in the field of $C_j$, and in consequence of range 2..., $k$. Therefore $L_k$ will be empty.

Lemma 2:

After execution by a sensor agent of the corresponding algorithm, if $L_1$ is empty, then the $C_j$ sensor will be isolated from sending and not necessarily receiving data.

Proof:

According to the lemma 1, $L_1$ empty implies $L_k$ empty. Consequently, there is no sensor in the field of $C_j$. Thus, the $C_j$ sensor is isolated from sending. In this case, if it is within the sensing range of a sensor of greater radius, it will not isolated necessarily receiving data.

Let us consider two sensors $C_i$ and $C_j$ with coverage radii $r_i$ and $r_j$ respectively. As shown in the figure below, the common surface coverage is defined by:

$$S_{ij} = r_i^2 \cdot \alpha + r_j^2 \cdot \arcsin(r_i \cdot \sin(\alpha)/r_j)$$

$$- r_i \cdot \sin(\alpha) \cdot (r_i \cdot \cos(\alpha) + r_j \cdot \cos(\arcsin(r_i \cdot \sin(\alpha)/r_j)))$$

For given $r_i$ and $r_j$ the performance of the equation (1) gives us the curve Figure 3.

Let us pose $S_i$ and $S_j$ the respective surfaces of sensors $C_i$ and $C_j$. The coverage area of these two sensors will be defined by: $Z_{ij} = S_i + S_j - S_{ij}$

3.2. Cover of sensors network

Let us consider a network of $N$ sensors. A sensor $C_i$ has a coverage radius $r_i$.

Let us note HS the surface covered by the network,

$$HS = \sum_{i=1}^{N} S_i = \sum_{i=1}^{N} \left( S_i - \sum_{j=i+1}^{N} S_{ij} \right)$$

$H$ is the set of identifiers of holonic system.

$S_i$ is the surface covered by a sensor.

$S_{ij}$ is the common surface to both sensors $C_i$ and $C_j$.

Definition:

Let $VE_i$ be the set of extended neighbours of the sensor $C_i$.

A sensor $C_j \in VE_i$ if and only if $d(C_i, C_j) \leq r_i + r_j$ where $r_i$ and $r_j$ are the coverage radii of sensors $C_i$ and $C_j$ respectively.
\( d(C_i, C_j) \) is the distance between the sensors \( C_i \) and \( C_j \)

**Proposition**

Let \( VE_i \) be the set of extended sensor \( C_i \) neighbours

Let \( VE_j \) be the set of extended sensor \( C_j \) neighbours

if \( C_j \in VE_i \) then \( C_i \in VE_j \)

likewise : if \( C_i \in VE_j \) then \( C_j \in VE_i \)

(or) \( C_i \in VE_j \) if and only if \( C_j \in VE_i \)

**Proof :**

\[
C_i \in VE_j \Leftrightarrow d(C_i, C_j) \leq r_i + r_j \\
\Leftrightarrow d(C_j, C_i) \leq r_j + r_i \\
\Leftrightarrow C_j \in VE_i
\]

**Algorithms for estimating HS**

An agent sensor \( C_i \) of a holonic organization \( H_k \) executes the following algorithm:

Determine the set of its extended neighbours \( VE_i \)

For each sensor \( C_j \in VE_i \)

add the coverage \( S_i \) to \( HS_k \)

if \((r_i < r_j) \) or \((r_i = r_j \text{ and } id_i < id_j) \) then

- Evaluate the surface \( S_{ij} \)
- Remove \( S_i \) to \( HS_k \)
endif

Positioning and resolution of the coverage problem

The algorithm to be performed by each sensor \( C_i \) of a holonic organization \( H_k \) is as follows (case a):

Identify the set \( V_i \) of the sensors located in its field

For each sensor \( C_j \in V_i \)

1. Evaluate the moving direction
2. Evaluate the possible moving: this movement must respect the dynamics of the holon
3. if \((r_i < r_j) \) or \((r_i = r_j \text{ and } id_i > id_j) \) then

Move following items 1 and 2

Update \( V_i \)
endif

In the aim to see the behavior of our organization, we have implemented (case b) the algorithm above with a slight difference in point 3.

3. if \((r_i > r_j) \) or \((r_i = r_j \text{ and } id_i > id_j) \) then

Move following items 1 and 2

Update \( V_i \)
endif

**4. Simulation of coverage problem**

We do a simulation with sixteen sensors, deployed randomly for area monitoring. The environment is continuous. The sensors are distributed randomly in a plane by reference \( \{ \text{latitude, longitude, altitude} \} \{ (12,30,0) (12,33,0) (17,30,0) \} \). The coordinates \((x, y)\) of the simulation environment are \( \{ (0,0), (800,0), (800,500) \} \).

The initial window implementation is as follows:

According to the above figure, the sensor \( C_{14} \) is in the sensor’s field \( C_{11} \). The sensor \( C_2 \) is isolated so it cannot send data to any sensors. From lemma 2, there are no sensors in the network able to perceive \( C_2 \). The sensors \( C_0, C_1 \) and \( C_8 \) can send data from the one to the other.

After a dynamic discovery of the neighbourhood and a relative positioning with respect to them, case a: we get the Figure 5, where coverage increase 18%, and case b: we get the window of performance Figure 6, where coverage increase 32%.

Thus, with a move of the sensor having the greatest radius of coverage, we obtain the best coverage.

Thus, compared to its neighbours, the sensor having the greatest radius of coverage will move because it requires less energy. On equal radius of coverage, the one of greater identifier will move.

The simulation with 25 sensors, deployed randomly for area monitoring give the initial and final
windows implementations as follows:

5. Conclusion

We presented a network architecture of sensors by using the framework of the multi-agents systems, in particular the holonic approach. The holon was defined like a set of roles according to various forms of organisational interactions in a specific context. We model the coverage problem with the holonic approach, whose goal is to do that each location of the target sensing area is sufficiently covered. We are currently working on these applications and extensions, and the related results will be reported in our future papers. As short-term prospect, we intend to examine the simulation of the methods of clustering on several coverage problems in order to validate our holonic multi-agents organization approach.

REFERENCES


