A Context-Aware Method for Sensor Network Deployment and Coverage Optimization

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Introduction

In recent years, sensor networks have been increasingly used for different applications ranging from environmental monitoring, tracking of moving objects, development of smart cities and smart transportation system, etc. [1]. A sensor network usually consists of numerous wireless devices deployed in a region of interest [2]. Despite the advances in the sensor network technology, the efficiency of a sensor network for collection and communication of the information may be constrained by the limitations of sensors deployed in the network nodes. These restrictions may include sensing range, battery power, connection ability, memory, and limited computation capabilities [3]. These limitations create challenging problems for the users of the sensor networks, which has pushed researchers from different disciplines in recent years to study various problems related to the design and deployments of efficient sensor networks. Also sensor networks have some limitations when it comes to the modeling, monitoring, and detecting environmental processes. Environmental elements like obstacles, which exist in both static and dynamic natures, are also important to be considered in a realistic sensor networks deployment. Other examples of such elements include contextual information of the sensors environment and physical phenomena in the network. It is necessary to know how to use such information to make an appropriate and efficient sensor network deployment. For this purpose, one needs to introduce relevant models of the phenomena type, the accessibility or inaccessibility of the observation area, environmental conditions, spatial relations, information availability, etc. The complexity of the sensing environment with the presence of diverse obstacles may result in several uncovered areas in sensor networks. Consequently, sensor placement affects how well a region is covered by sensors as well as the cost for constructing the network [4]. Hence, a fundamental issue in a sensor network is the optimization of its spatial coverage. Several optimization algorithms are developed and applied in recent years to meet this criterion. Most of these algorithms often rely on oversimplified sensor and network models [5]. In addition, they do not consider environmental information such as terrain models, human built infrastructures, and the presence of diverse obstacles in optimization process.
The impact of the quality of initial datasets used to deploy sensors in the networks is another aspects of the complexity of wireless sensor network [6]. Therefore, choosing the way of deploying sensors and the data accuracy needed to set up a sensor network in an optimal manner are difficult due to the abundance of available deployment algorithms as well as design of a consistent, reliable, and robust network. Thus, study of wireless sensor networks is a challenging task, as it requires multi-disciplinary knowledge and expertise.

Methods

Based on mentioned issues on sensor networks, this extended abstract presents an approach to improve sensor deployment processes by integrating geospatial information and knowledge with optimization algorithms. To achieve this objective, the following approach that contains three specific parts is defined. First, a conceptual framework is proposed for the integration of contextual information in sensor network deployment processes. Then, a local context-aware optimization algorithm is developed based on the proposed framework. The extended approach is a generic local algorithm for sensor deployment, which accepts spatial, temporal, and thematic contextual information in different situations. Next, the accuracy assessment and error propagation analysis is conducted to determine the impact of the accuracy of contextual information on the proposed sensor network optimization method.

1- A Conceptual Context-Aware Framework for Sensor Network Deployment

Many parameters directly affect the sensing coverage, for example, topological relations among the sensors in the network, the interactions between the sensors and the environmental elements, and the relationship among the environmental elements themselves. Here, such information and relations are called network Contextual Information (CI). Specifically, CI defines the spatial dependencies between spatially adjacent nodes, nodes and obstacles, and obstacles themselves as well as the temporal dependencies between historical movements of nodes in the deployment process. The so-called CI is used in the proposed framework to find good candidates positions of sensor nodes to fill uncovered areas, and decide about the sensor's adequate actions in order to guide sensor network deployment.

The proposed conceptual context-aware framework consists of the following steps. First the appropriate CI is extracted from the real world. After introducing the CI to the framework, spatial and network databases are created. Spatial database contains CI related to the physical environment, while the network database comprises the CI belongs to sensors' configuration and relations. Accordingly, a knowledge base is defined considering both databases. In the next step, a reasoning engine is applied using the predefined knowledgebase. The optimization algorithm is also specified regarding the introduced local CI and tasks at hand. Afterward, the rules extracted from the reasoning engine along with the determined optimization method are applied to perform context-aware deployment actions. This may include a sensor move, delete or insert. These actions may change the topology of the network, the configuration of the adjacent nodes, and consequently, the local coverage. As a result, local CI may be updated. Then, the information in the knowledge base is changed and so on. This is an iterative algorithm and these actions are done till the desired level of deployment is achieved. The process of local optimization in the framework means that network configuration is changed locally at each step until the best coverage is obtained by considering the spatial, temporal, and thematic contextual information in the network (Figure 1).

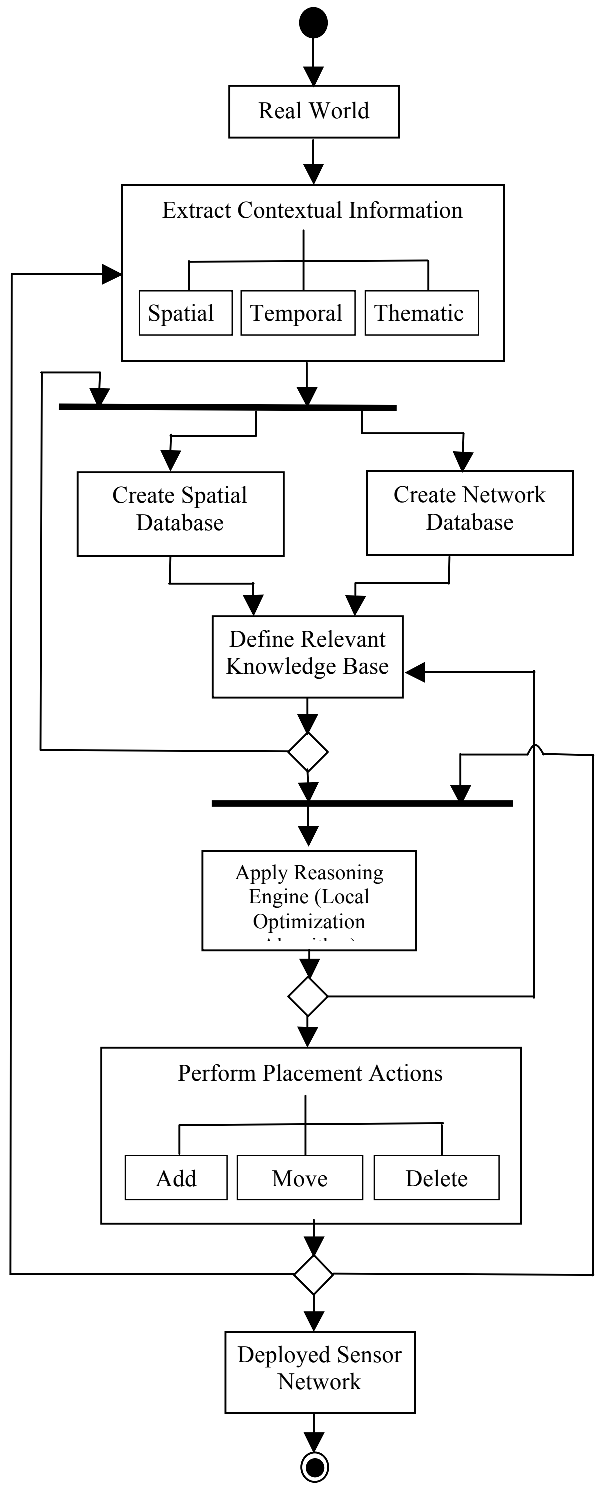

Figure 1: Context-aware sensor network deployment framework

2- Local Context-Aware Optimization Algorithm for Sensor Network Deployment

According to the proposed framework for sensor network deployment, a local optimization algorithm is developed to tackle the sensors placement problem and maximize the spatial coverage of the network. In the extended algorithm, sensors are ordered in a priority queue, in order to be sorted based on their coverage gain obtained by considering different CI, and following related moves in the network. Then the sensor with the maximum gain is selected, which is obtained the highest coverage improvement by its movement in the network, and stands at the top of the queue. The movement types of sensors are related to the local CI as well as sensor network mission. By changing the position of the topmost sensor of the queue, the network configuration is updated. Next, the coverage gain of the adjacent sensors of moved sensor is recalculated and their ordering in the priority queue is updated. In the next iteration, the (new) topmost sensor of the queue is chosen to move, and so on. This optimization process is conducted iteratively until one of the predefined stopping criteria is reached.

3- Impact of the Spatial Data Quality on Sensor Network Deployment

The sensor placement optimization algorithms that are applied in our experimentation use spatial information to calculate spatial coverage. This way, visible and invisible objects are identified and hence, covered and uncovered areas in the region of interest are defined. The quality of spatial data has a direct impact on the estimation of these values. Among different data quality elements, positional accuracy and completeness were selected to study because of their direct impact on the estimation of the visibility. The positional accuracy may be presented as a small displacement in the position of the objects, which can be either horizontal or vertical or both. Even a few centimeters inaccuracy in horizontal or vertical positions of objects or sensors can block the line-of-sight between a sensor and a target. Same reasoning may be applied for incompleteness of databases.

Experimentations and Results

The study area of the experiments is a part of old Quebec City with a dimension of 180 m by 170 m. For the experiments, 12 sensors have been assumed to be deploying as the traffic cameras with 360 degrees horizontal, ±90 degrees vertical sensing angle, and 35 meters of effective sensing range (Figure 2).

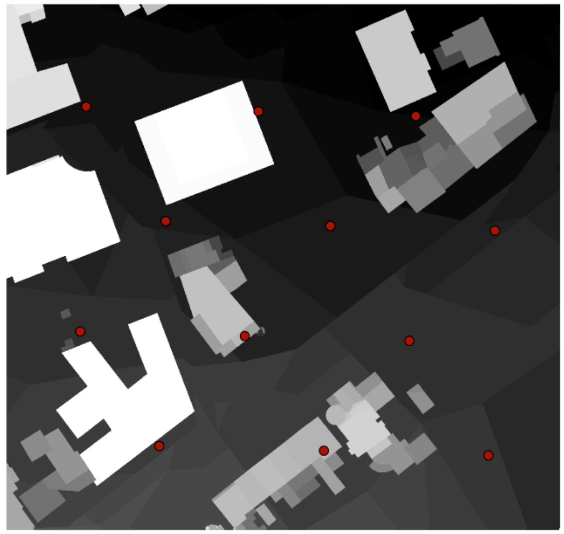

Figure 2: The triangular lattice initial positions of sensor deployment optimization

The first category of CI is the terrain model and information on the network. Having this information the elevation of the objects in study area is provided, and as a result the obstacles bared the sensing field of the sensors. Figure 3 depicts the coverage improvement during the optimization algorithm and Figure 4 represents the final sensor positions and covered regions.

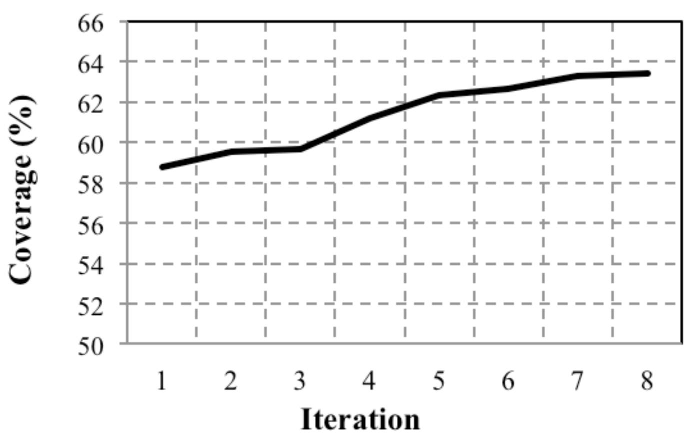

Figure 3: Coverage improvement over iterations of the context-aware method, considering the terrain model

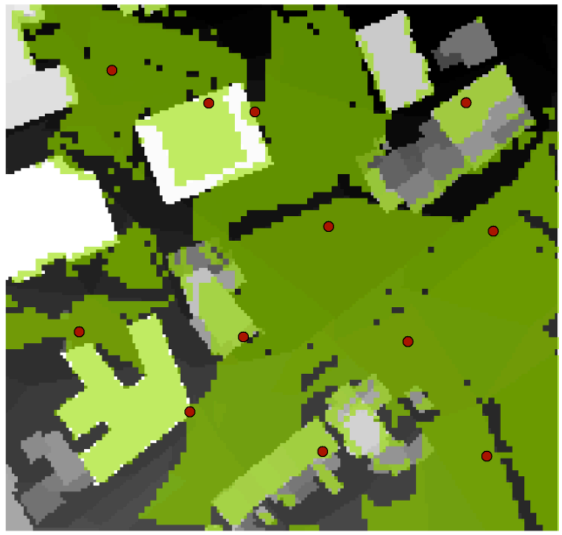

Figure 4: Coverage map of deploying 12 sensors using the context-aware method, considering the terrain model.

Thematic information is the next category of CI used in sensor network optimization. For example, several locations may be legally forbidden for the deployment of sensors. Considering restricted areas in context-aware optimization, sensor action is changed, and new moves are defined. To evaluate the case of considering the restricted area, two buildings and a street have assumed in the study area as the places that sensors could not be set up. Figure 5 shows the final coverage results considering these restricted areas (red zones).

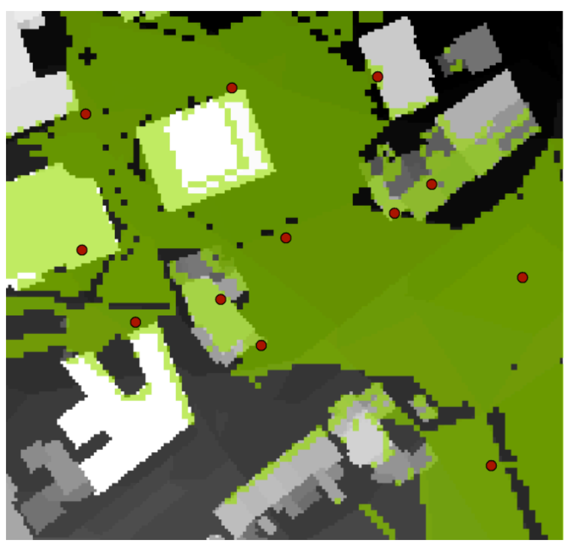

Figure 5: Coverage map of deploying 12 sensors using the context-aware method, considering the street, and buildings as the restricted area (the red border zones).

Desirability of coverage is another type of thematic information that can be considered in the optimization process. Suppose that there are some places in the study area, where sensors cannot be set up, but there is a high interest on those regions to be covered. Hence, a street in the study area was introduced as the area with high interest to be covered, while it is unauthorized zone for sensors to be deployed. Figure 6 represents the final sensor positions and the covered area.

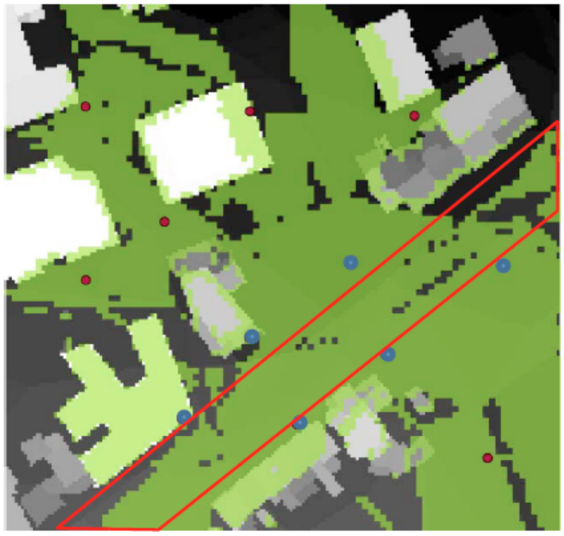

Figure 6: Coverage map of deploying 12 sensors using the context-aware method, considering the street as the desired region to be covered (the red border).

Sensor placement in an environment considering a critical asset is the next thematic CI side of the context-aware algorithm. Let assume a critical asset to be monitored for preventing any undesired access with a slight activity in its environment, which is located beside a street with high level of activities. Thus, there is an interest to monitor any intrusions within the fenced area, but not having the sensor always activated due to the traffic or other activity on the street. Figure 7 has the final sensor positions and the covered regions considering the environment activities as the CI.

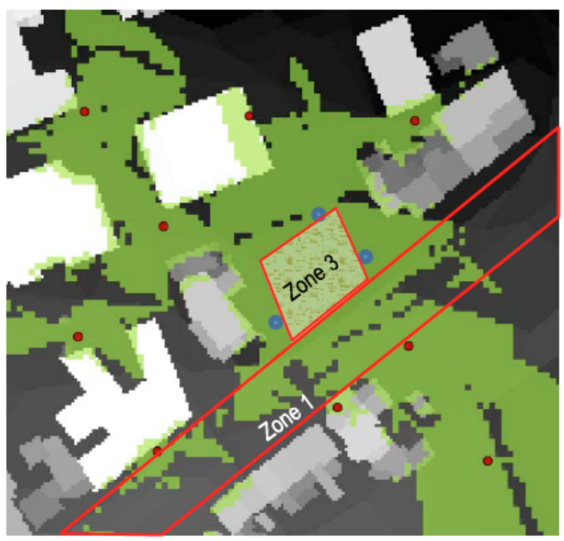

Figure 7: Coverage map of deploying 12 sensors using the context-aware method, considering the activity in the network; Zone 3: the area with low activity, but high interested to be covered.

Finally, to investigate the impact of positional accuracy and completeness of the dataset on the spatial coverage of a sensor network, we prepared 5 maps with different resolutions from the same area. The resolution variation is from 500 cm (low resolution) to 50 cm (high resolution) and a map with 10 cm resolution is considered as the ground truth dataset to validate the results. All maps are from the same area, which previous tests were done. The experimentation consists of deploying eight sensors considering the first category of CI (terrain model) inside the study area. Table I shows the results.

Table 1: Results obtained from the context-aware method, considering the terrain model.

Resolution (cm)	Avg. coverage (%)	Best coverage (%)	Best coverage from best configuration over 10cm resolution (%)	Average coverage over 10cm resolution (%)
500	45.55	47.19	43.14	42.21
300	47.83	51.07	45.87	45.37
200	40.06	43.82	42.43	40.51
100	44.38	45.77	44.25	42.83
50	46.59	48.16	45.64	44.32

Conclusions

The purpose of this paper was certainly not to overcomplicate the optimization process, but rather to find a flexible methodology that can locally accommodate all relevant information that would have an impact on sensor placement. To do so, a local optimization framework was introduced. The extended optimization algorithm can come up with different sensor placement configuration according to the various circumstances, environmental information, and/or sensor parameters encountered. Consequently, if there are any changes in sensor parameters or environment, the context-aware algorithm can simply take in new contextual inputs and regenerate a new sensor placement design adapted to the new situation. The outstanding advantage of the proposed context-aware algorithm was that it was designed independent of any specific CI. Thus, it is able to take into consideration different types of information based on specific network applications and tasks at hand.

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