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Coverage Control of Mobile Wireless Sensor Networks With Distributed Locations of High Interest

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Abstract:
Formation control is an important part of any system that utilizes multiple mobile agents to achieve its particular goals. One of those applications is the mobile wireless network sensor. This field has become increasingly more popular in recent times due to the advancement of technology, especially in the fields of miniaturization and telecommunications. The main problem of this research is the relatively untested sensing capability of a mobile wireless sensor network in an operating area that has distributed and/or multiple locations of high interest. The purpose of this research is to discover the compatibility of a multiple-agent coverage control system with several examples of interest functions that have multiple and/or distributed points of global maximum value in order to explore more thoroughly the performance of a given system in a varying environments.

Keywords: *Mobile Wireless Sensor Network, Coverage Control, Interest Function*

1. Introduction

A mobile wireless sensor network is a system that employs multiple mobile sensors to achieve a particular goal. In order for a mobile wireless sensor network system to be functional, it must have at least two parameters: a sensing function and an interest function. A sensing function is a representation of how well an agent does its jobs, while an interest function is a representation of how important sensing the location is. The combination of both the sensing and interest function is called the objective function, and it is used to measure the sensing performance of the mobile wireless sensor network. One advantage of using mobile wireless sensor network is that they are mobile, which means that the systems can move from place to place. They utilize multiple agents, so if one of the agents is down, the whole system does not entirely fail. Mobile wireless sensor networks have many potential applications, e.g. to operate in places too dangerous for humans to access, such as an area struck by disaster; or too difficult to access, such as an underground cave system.

A mobile sensor network can be programmed to operate in two different ways. The first way is to program it to maintain the formation (i.e. the position of the agents relative to each other) while sacrificing overall coverage capability. The second way is to optimize the sensing capability while sacrificing the formation of the agents. This research is concerned with the second way of operating the mobile wireless sensor network. Coverage control is an important part of any system that utilizes multiple mobile agent to achieve its particular goals. One of those applications is the mobile wireless network sensor. This is a field that has become increasingly popular in recent times due to advancement of technology, especially in the fields of miniaturization and telecommunications.

The field of coverage control started to gain popularity in 2002 with the release of the paper from Cortés, Martínez, Karatas, and Bullo [3]. After that point, more papers about coverage control were published. Those papers have varying foci of research, such as: more efficient algorithms [7, 9, 11–13, 16, 18, 19], coverage control algorithm with non-ideal conditions [4, 17], coverage control algorithm for a complex field of operations [1,2,5,8,14,15], and its application using real hardware [6]. There have not been any studies that examine the performance of a mobile wireless sensor network systems that operates in an area that has multiple points of high interest. The lack of performance data in this particular setup presents a considerable gap of knowledge in this field, since there is a high possibility that a real-life system would be required to be able to handle such a scenario.

The main problem in this research is the relatively untested sensing capability of a mobile wireless sensor network system in an operating area that has distributed and/or multiple locations of high interest. While previous researches have dealt with the problem of a mobile sensor network system operating in a various operating areas like in previously mentioned studies [1, 2, 5, 8, 14, 15], the performance of a mobile wireless system network system in an operating area that has distributed and/or multiple locations of high interest is relatively unknown. The main reason for the importance of this problem is that having a mobile wireless sensor network system that could operate in an operating field that has a multiple and/or distributed locations of high interest could offer more flexibility in the real-life application of said system. While in the original research it was never mentioned that this system cannot perform well in an operating field that has distributed and/or multiple locations of high interest, the performance in said operating field is relatively unknown. The purpose of this research is to discover the compatibility of a multiple-agent coverage control system under several examples of interest functions that have multiple and/or distributed points of global maximum value, in order to explore more thoroughly the performance of a given system in a varying environments. Based on the previously mentioned purpose, this research aims to contribute by giving several samples of behavior of a mobile wireless sensor network system under the a condition to determine the compatibility of an existing coverage control algorithm. The proposed method to achieve the objective of this research is to empirically formulate several new examples of interest functions with multiple and/or distributed points of high interest using relatively simple mathematical expressions in order to minimize modifications to the existing algorithm, and then to run a simulation of a mobile wireless sensor network system with existing algorithms in said interest functions. It is hypothesized that while using the same algorithm, the swarm will be able to converge on those multiple interest points albeit with reduced performance, such as increased time until convergence, non-optimal steady state coverage, or taking a winding path in the early stages of the deployment.

2. Theoretical Background

The interest function represents the importance of a certain location inside an operating area. It can be expressed as $\phi(q) : \mathbb{R}^2 \rightarrow \mathbb{R}$, where q is an arbitrary point in the operating field. In this case, the interest function takes the 2D position of a point and assigns said point a value of importance. Higher value could mean higher importance or higher probability of an occurrence of an object or an event of interest. Sensing function represents the capability of an agent to perform its task. This function takes the position and sensing capability, in this case represented by the distance of a point in the operating field from the sensor, as the inputs, and gives its sensing reliability as the output. This function can be expressed as $f(p_i, q) : \mathbb{R}^2 \times \mathbb{R}^2 \rightarrow \mathbb{R}$, where p_i is the 2D position of the i-th agent in the operating field and q is an arbitrary point in the 2D operating field. In this case, the reliability is calculated from the 2D sensing model of the sensor and the 2D position inside the operating area.

Coverage control algorithm handles the positioning of the agents of a mobile wireless sensor network system to assure that each agent be given an optimum position to provide its maximum possible contribution. The overall reliability of a mobile wireless sensor network system takes account of all of its agents' individual reliability, which heavily rely on the sensing function, and the objective function of the operating field. With those factors accounted for, the overall reliability $R(p_1, ..., p_n)$ can be expressed as

$$R(p_1, ..., p_n) = \sum_{i=1}^{n} \int_{W_i} f(q, p_i)\phi(q)dq \quad (1)$$

where $f(q, p_i)$ relates to the sensing function of i–th agent, $\phi(q)$ refers to the interest function, and W_i indicates the sensing region of the i–th agent.

For this study, the Lloyd-Max algorithm will be used [10]. This algorithm was originally used in the field of signal and telecommunications to optimize quantization in pulse-code modulation, but it is also applicable in the field of coverage control. In the case of the Lloyd-Max algorithm for coverage control, the sensing region of an agent is the Voronoi region of the sensor, since this algorithm works under the assumption that only the best sensing value is used for each location inside was operating field. The Voronoi region of an agent can be expressed as

$$W_i = \{q | r(q, p_i) < r(q, p_j)\};\ i \neq j;\ i, j \in [1, ..., N] \quad (2)$$

with

$$r(q, p) = \sqrt{(q_x - p_x)^2 + (q_y - p_y)^2} \quad (3)$$

where the positions of all N agents act as the generator points for the Voronoi decomposition.

In order to achieve agents' optimal position, the value of $R(p_i)$ has to be minimized. Using the Lloyd-Max algorithm to solve this locational optimization problem, the optimal position of every agents can be calculated. Then, according to [3], with agents' sensing function of

$$f(q, p_i) = r(q, p)^2 \quad (4)$$

the position of the agents is governed by the equation

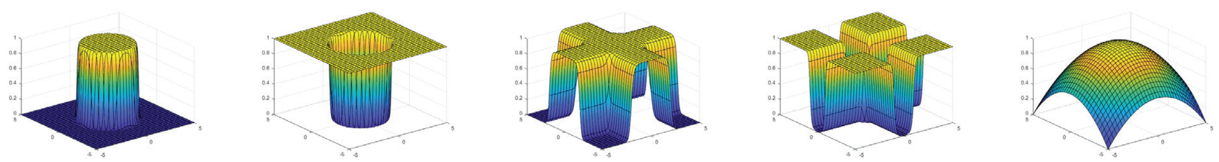
$$\dot{p} = 2M_{Wi}(C_{Wi} - p_i) \quad (5)$$

with p_i denoting the position of the i-th agent, and M_{Wi} and C_{Wi} calculated using

$$M_{Wi} = \int_{W_i} \phi(q)dq \quad (6)$$

and

$$C_{Wi} = \frac{1}{M_{Wi}} \int_{W_i} q\phi(q)dq \quad (7)$$



(a) (b) (c) (d) (e)

Fig. 1. A 3D representation of five interest functions to be tested in this research. Four new interest functions, namely: (a)"plateau", (b)"basin", (c)"ridge", and (d)"valley"; as well as (e) one classic case with one point of global maximum value as a baseline performance comparison

where W_i is the Voronoi region of i-th agent. This algorithm can be interpreted as the next optimal position for every agent and its centroid of the current weighted Voronoi region, therefore, a steady state can be achieved if all agents are in their respective optimal positions.

3. New Interest Functions

3.1. Experiment Preparation

The entirety of the research process is done using a software simulation. This is done because of the relatively untested nature of the topic of this research. Due to the current national health and safety protocols, said guideline renders the access to several computers in laboratory unavailable would be utilizable otherwise. Therefore, since the experiment will be conducted in one device with relatively weaker computing power, several simulation limitations will also be imposed on this research.

This research begins with a literature review to find out the underlying mechanisms of a mobile wireless sensor network system. The next step is to formulate candidates of several interest functions that will be tested with existing control algorithm. After several promising new interest functions have been formulated, the next step is to check their compatibility with the existing control algorithm. The compatibility of said interest functions and the control algorithm will be measured by monitoring the value of the overall sensing reliability $R(p_1, ..., p_n)$ over time.

3.2. New Interest Function Properties and Formulation

In order to thoroughly explore the idea of interest functions that have multiple and/or distributed points of high interest, it is improbable to only have one new interest function that is capable of being an example of multitude of possibilities of configurations. Hence, several new interest functions will be proposed. These interest functions, as per the goal of this research, have more than one point of global maximum value that will be distributed in differing manners, contrary to their classical counterparts which only have one. Other necessary properties are the limitations to be respected, namely, the boundaries of the operating field and the value of $\phi(q)$. The operating field must have a set boundaries, in order to be able to be decomposed into several Voronoi regions with finite size, and $\phi(q)$ is a semi-definite positive function.

For this research, in order to ease analysis of the results of the compatibility test, all of the interest functions in this research are normalized to have the the value of $\phi(q)$ between 0 and 1, and with a rectangular operating area bounded at $-5 \leq q \leq 5$. Four interest functions were formulated empirically, each with its own unique distribution of areas with high interest, namely:

$$\phi(q) = \frac{1}{1 + e^{(5\sqrt{{q_x}^2+{q_y}^2}+2.5)(5\sqrt{{q_x}^2+{q_y}^2}-2.5)}} \tag{8}$$

$$\phi(q) = \frac{1}{1 + e^{(-5\sqrt{{q_x}^2+{q_y}^2}+2.5)(-5\sqrt{{q_x}^2+{q_y}^2}-2.5)}} \tag{9}$$

$$\phi(q) = \frac{1}{(1 + e^{(-5{q_x}^2+2q_x-1)})(1 + e^{(-5{q_y}^2+2q_y-1)})} \tag{10}$$

$$\phi(q) = 1 - \frac{1}{(1 + e^{(-2{q_x}^2+8q_x-8)})(1 + e^{(-2{q_y}^2+8q_y-8)})} \tag{11}$$

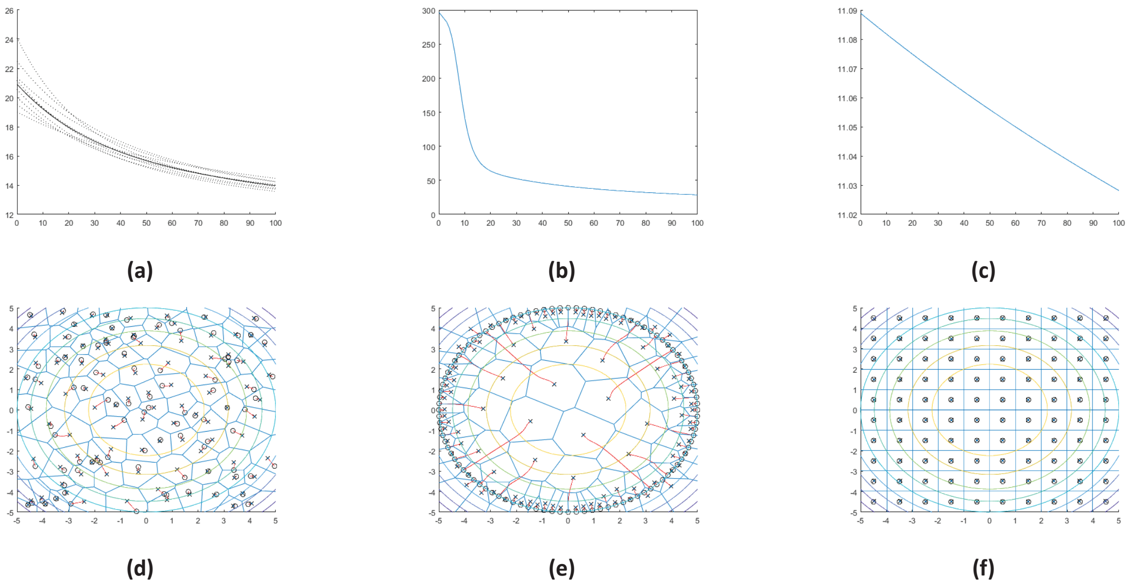


Fig. 2. Experiment result for the classic case. Left to right columns are "random", "circle", and "grid" starting configuration respectively. Top row are the graphs of values of overall sensing reliability over time. Bottom row are images of the agents' trajectory over time. Black circles denote initial positions. Black crosses denote final positions. Red lines show the movement of agents from initial to final positions. Blue lines show the border of each agents' Voronoi region in their final positions. The contour of the interest function is also shown

For the sake of ease in associating the interest functions with their results in this paper later, these interest functions will be non-formally called "plateau", "basin", "ridge", and "valley" for equations (8) to (11) respectively. A 3D graphical representation of those four interest functions can be found in Figure 1 on the previous page.

4. Compatibility Analysis

4.1. Baseline Performance Formulation

To measure the compatibility of the new interest functions with the existing control algorithm, two parameters will be considered. The first is the overall sensing reliability of the mobile wireless network system over time, to check its general performance, and the second is the individual agent's position over time, to check for inefficiencies of agents' movement, if any. Since the focus of this research is to see the effects of the different interest functions, other parameters are made to be as similar as possible between one interest function and another. For every interest function, all four new and one old, there will be 100 agents, having sensing function of (4), and the calculations will be run for 100 timesteps. Three initial configurations are used for the starting positions, namely: "random", "circle", and "grid". "Random" configuration spreads 100 agents in a random position with uniform distribution. Simulations using this initial configurations will be executed ten times in order to give a better picture of the performance under a random starting location for each agent, and to reduce the variance that could arise due to the random nature of this starting configuration. "Circle" configuration places 100 agents in a circle around the origin, while the "grid" starting configuration spreads 100 agents evenly in a ten-by-ten grid inside the operating area.

In order to be able to measure compatibility, a classic interest function is also put into the experiment, in this case

$$\phi(q) = 1 - \frac{{q_x}^2 + {q_y}^2}{50} \tag{12}$$

in order to comply with the limitations previously stated. The performance of the control algorithm under this interest function is to be made a baseline performance which the performance of the new interest functions are compared against.

4.2. Sensing Reliability Analysis

From the data shown in figures 2.a, 2.b, and 2.c for a classic example and Figure 3 for the new cases, it can be observed that in both old and new cases, the system operates in a similar fashion. It starts at a relatively high value, then decreases over time, both respective to its interest function. Another interesting observation is that the value of $R(p_i)$ is decreasing in an exponential-like behavior under the "random" and "circle" starting configurations, and almost linearly under "grid" starting configuration, regardless of

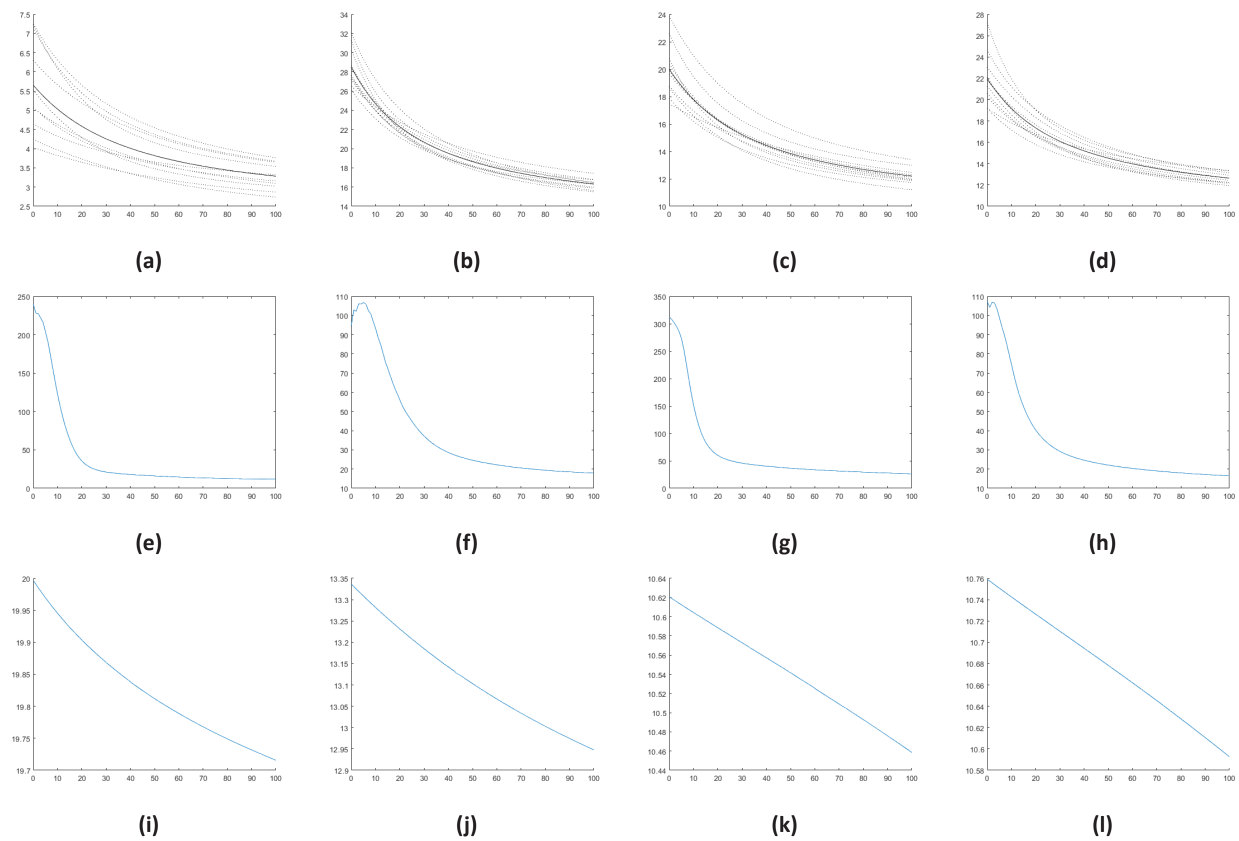


Fig. 3. Total sensing reliability $R(p_1, ..., p_n)$ against time for four new cases and three starting configuration. Top to bottom rows are for "random", "circle", and "grid" starting configuration respectively. Left to right columns are for "plateau", "basin", "ridge", and "valley" interest functions respectively

Configuration	Classic		Plateau		Basin		Ridge		Valley	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Random, Best	19.02	13.57	4.03	2.74	26.15	15.51	17.49	11.20	19.18	12.15
Random, Worst	24.07	14.47	7.26	3.76	32.07	17.44	23.89	13.40	27.28	13.34
Random, Average	20.92	13.97	5.65	3.28	28.50	16.33	19.99	12.2	21.95	12.63
Circle	296.71	28.59	240.05	11.90	94.64	17.93	312.24	26.33	107.43	16.46
Grid	11.09	11.03	20.00	19.72	13.34	12.95	10.62	10.46	10.76	10.59

Tab. 1. Overall sensing reliability for all combinations of interest functions and starting configurations. Both values for initial condition and on 100th timestep are given

Starting Configuration	Classic	Plateau	Basin	Ridge	Valley
Random					
-Min	0.0079	0	0*	0	0*
-Max	0.8714	0.9061	1.4901	0.9796	1.2621
-Average	0.2007	0.0632	0.2363	0.1846	0.2021
Circle					
-Min	0.1127	0.0161	0.0791	0.0279	0.0063
-Max	3.7413	3.7638	1.8436	3.9779	2.4813
-Average	0.5842	0.263	0.5328	0.5458	0.4090
Grid					
-Min	0.0046	0*	0*	0*	0.0002
-Max	0.04	0.1494	0.1802	0.0892	0.0617
-Average	0.0231	0.0285	0.029	0.0276	0.0323

Tab. 2. Summary of agents' movement. Asterisks denote that said agent's movement is smaller than 10^{-4}, which, for all intents and purposes, can safely be rounded down to zero

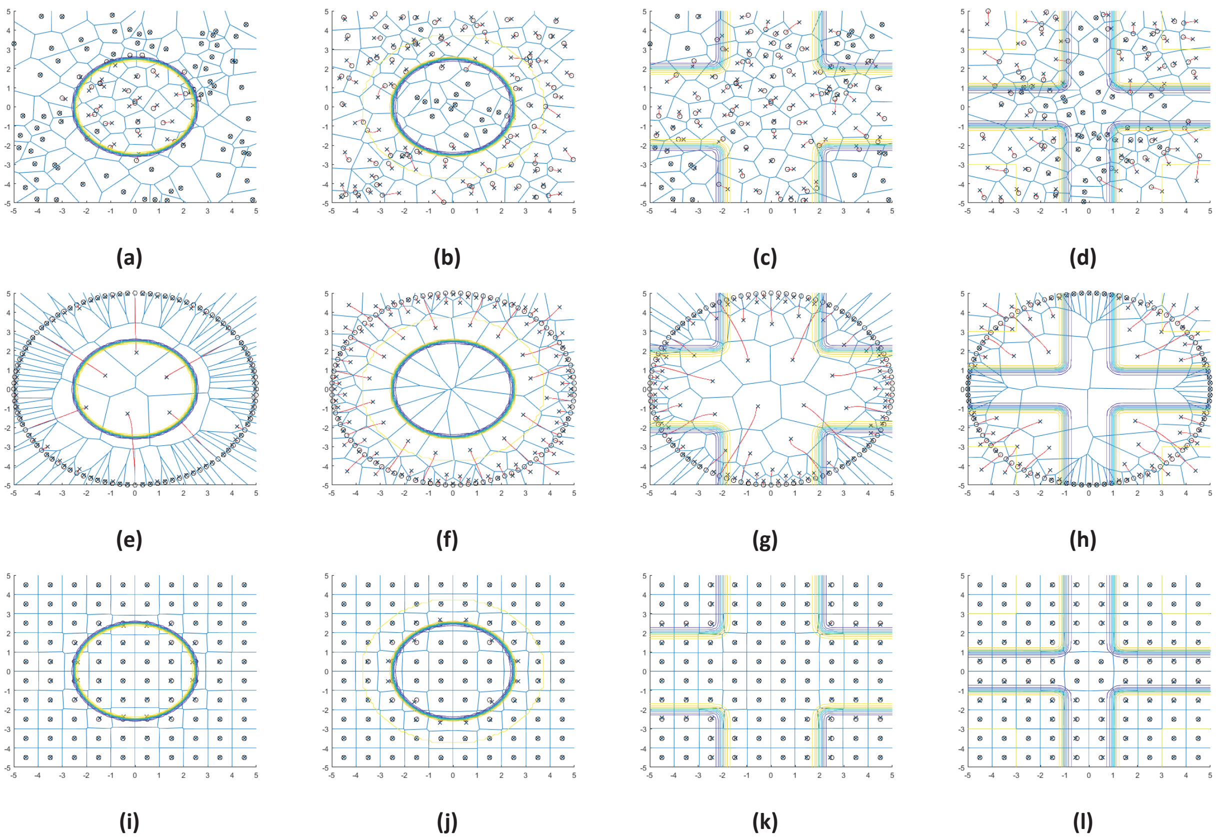


Fig. 4. Agents' trajectory through time for four new cases and three starting configurations. Top to bottom rows are for "random", "circle", and "grid" starting configurations, respectively. Left to right columns are for "plateau", "basin", "ridge", and "valley" interest functions, respectively. Black circles denote initial positions. Black crosses denote final positions. Red lines show the movement of agents from initial to final positions. Blue lines show the border of each agent's Voronoi region in their final positions. The contour of the interest function is also shown

the interest function. It is also an observation of interest that final value of the sensing reliability is dependent on the starting position of the agents. This implies that it is possible for a system with worse initial coverage but more favorable agents spread to outperform another system with better initial coverage but less favorable spread at the 100th timestep. A summary of sensing reliability over time that contains numerical value of $R(p_i)$ at initial and 100th timestep for most of the experiment can be found in Table 1 on the previous page.

4.3. Agents' Movement Analysis

From the example result of agents' trajectory in figure 4, it can be seen that several agents that started in areas with low importance move for a negligible distance or do not move at all, resulting in a suboptimal utilization of the resources given. This phenomenon is very rare in the classic example, as shown in figures 2.d, 2.e, and 2.f. The reason for the occurrence of this phenomenon can be narrowed down by examining both the equation that governs the movement of the agent and the values of all variables involved in the calculation. In these cases, for agents that have the entirety of Voronoi region at the minimum value, said agents' value of M_W becomes very small or zero. Since $\dot{p} = 2M_{Wi}(C_{Wi} - p_i)$, if the value of M_W is very small or zero, the value of $\dot{p}$ will also be very small or zero, resulting in negligible or no movement of said agent. In order to prevent this phenomenon from happening, a positive offset to the entirety of interest function can be added. A summary of the agents' movement, which contains minimum, maximum, and average distance traveled, can be found in Table 2 on the previous page.

5. Conclusion

Based on the result of the simulations, a sample of performance of a mobile wireless sensor network system in an operating area which has distributed and/or multiple locations of high interest has been successfully obtained. Beside that, several other findings can be observed.

Under the new interest functions, it can be observed in the experiment results that the algorithm is still able to perform its duty of maximizing overall sensing reliability by minimizing the locational optimization function, as seen in Figure 3. Figure 4 shows the initial position of the agents, the final position of the agents after the 100-timesteps limit, the path taken by each agents, the contour of the interest function, and the Voronoi region decomposition of the operating field based on the final position of the agents. Note that the final position achieved in this research is not the most optimal position possible for the given agents' starting positions and interest functions, since the experiment ran for only 100 timesteps due to computing power and time constraints.

Another noteworthy finding is that it is possible to model a relatively complex interest functions using a relatively simple mathematical expressions while maintaining compatibility with the existing control algorithm. This finding is considered noteworthy since this opens the possibility of using of more complex or arbitrary interest functions.

For further research, similar research with extended number of timesteps can be performed in order to be able to analyze the algorithm's steady state performance. Another possibility is to use different sensing functions to examine the performance under a similar interest function. Moreover, an application using physical agents in a comparable setup could be conducted to have a better understanding of its real life capabilities.

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