Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

Multi-agent Coordinated Motion Planning for Monitoring and Controlling the Observed Space in a Security Zone

Ji Min Kim*, Jeong Sik Choi*, Beom Hee Lee*

**School of Electrical Engineering and Computer Science, Seoul National University, Seoul, Korea (e-mail: {torin00, jsforce, bhlee}@snu.ac.kr)*

Abstract: Monitoring and control of observed space in a security zone equipped with multi cameras and security robots are essential for efficient invader detection. For controlling the observed space, a coordinated motion planning technique is essential when a centralized motion planning solution is realized by a single supervisory system. This technique, however, is known to be very difficult to realize because concurrent multi-agent planning involves high computational complexity. We propose a new method for monitoring and controlling the observed space for a multi-agent security system with applicable computational burden. To identify time-varying observed space, two new tools, the extended overlap map (EOM) and the time-global surveillance coverage ratio graph (TGSG), are developed. Using these tools, we can properly monitor the time-varying observed space. In addition, to overcome the high complexity in the centralized motion planning, the priority is assigned to multi-agents. Finally, the observed space is monitored and controlled by planning multi-agents motions interactively using the EOM and the TGSG. The proposed method is then applied to conventional multi-agent security systems.

1. INTRODUCTION

Security services have been essential in our lives for a long time because we have many precious belongings which we want to protect from being stolen. So far, we have been using multi cameras and security teams for security. This camera-human system, however, are expected to be replaced with a new one, i.e., camera-robot system in the near future, because recent security robots are equipped with various devices for detecting and capturing invaders and can patrol a wide security zone without any breaks for a long time. Therefore, developing a multi-agent security system is another challenging and practical research topic in robotics.

Three types of sensors (static, rotational, moving) have been considered for monitoring, tracking, and capturing invaders in the previous researches. The placement, scheduling, and motion planning of the sensors have been important issues in security robotics. A notable one is 'Chvatal's art gallery problem' which dealt with the issue of determining where sensors should be located to view every point in the surveillance space (Chvatal, 1975). O'Rourke first examined this problem exclusively and presented the minimum number of mobile guards which were the general case of edge guards in his monograph (O'Rourke, 1987). Since O'Rourke's work, many research results dealing with the problem have been presented and they are well summarized in (Shermer, 1992).

In other researches, the effective search methods using multiple rotational cameras have been investigated. Sugihara et al. referred to this issue as the 'Searchlight scheduling problem' which is to find a schedule to slew multiple cameras for invader detection in a finite time (Sugihahra and Yamashita, 1990; Yamashita *et al*., 2004). Mobile agents, referred to as guard, searcher, or moving sensor, have been studied as effective devices in security issues. The issue based on the moving sensor is sometimes referred to the 'Polygon search problem'. It was first introduced by Suzuki and Yamashita (Suzuki and Yamashita, 1992).

Recently, a vast and complicated security zone has led to the increase in the number of sensors and the integrated operation of the various sensors. This change has been found in some papers (Rybsi *et al*., 2000; Yseng *et al*., 2007). Thus, the coordinated control of various multiple sensors is an emerging topic in the modern security service. Jung and Sukhatme have introduced some problems such as visibility maximization and overlap subtraction, which are closely related with the topic in (Jung and Sukhatme, 2002).

This paper will concentrate on the monitoring process in a large space observed by two types of sensors (rotational cameras and robots). More specifically, we will attempt to improve the monitoring performance in terms of coverage by identifying and controlling observed space which refers to the area where sensors succeed in detecting invaders. Its size usually varies with time since both sensors are continuously moving. If the observed space becomes smaller in an instant, it may bring a very critical problem such as multiple intrusions. To prevent it, the observed space should be monitored and controlled. Thus, the purpose of this paper is to present a practical method to monitor and control the observed space by planning the multi-agent motion.

There are, however, two problems. First, there are few tools to identify the overlapping between different sensors. The second is the computational complexity which is an inherent problem in the centralized motion planning. Akella and

Hutchinson have already shown that multi-agent motion planning is an NP-hard problem (Akella, Hutchinson, 2002).

To this end, we first developed two new tools: the extended overlap map (EOM) and time-global surveillance coverage ratio graph (TGSG). Next, to reduce the complexity in multi-agent motion planning, we considered a prioritization method using the analysis of frequency of visitations.

2. PROBLEM DESCRIPTION

2.1 Conditions, Definitions, and Assumptions

In this section, we will describe the problem of this paper, i.e., multi-agent motion planning for monitoring and controlling the observed space. We first define a security zone and initial conditions of sensors are defined as follows:

S : a two-dimensional security space

$\mathcal{A}$: a set of n moving sensors a_i, $i = 1, 2, \ldots, n$ (e.g. mobile robot) with a sensing area

$\mathcal{B}$: a set of m rotational sensors b_j, $j = 1, 2, \ldots, m$ (e.g. camera) with a sensing area

$\mathcal{P}_A$: a set of paths of moving sensors p_{a_i}, $i = 1, 2, \ldots, n$. (p_{a_i} is a closed-loop path.)

$\mathcal{P}_B$: a set of paths of the focus of rotational sensors p_{b_j}, $j = 1, 2, \ldots, m$. (p_{b_j} is a round-trip path.)

$\mathcal{V}_{0a}$: a set of maximum velocity profiles of moving sensors along time t, $v_{0a_i}(t)$, $i = 1, 2, \ldots, n$

$\mathcal{V}_{0b}$: a set of maximum velocity profiles of rotational sensors along time t, $v_{0b_i}(t)$, $i = 1, 2, \ldots, n$

$\mathcal{Tr}_{0a}$: a set of trajectories of moving sensors along time t when the velocity profile is given as $\mathcal{V}_{0a}$, $tr_{0a_i}(t)$, $i = 1, 2, \ldots, n$. Define $tr_{0a_i}(t) = \int_0^t \left|v_{0a_i}(q)\right| dq$

$\mathcal{Tr}_{0b}$: a set of trajectories of rotational sensors along time t when the velocity profile is given as $\mathcal{V}_{0b}$, $tr_{0b_i}(t)$, $i = 1, 2, \ldots, n$. Define $tr_{0b_i}(t) = \int_0^t \left|v_{0b_i}(q)\right| dq$

Two types of the sensors $\mathcal{A}, \mathcal{B}$ move with initial conditions and observe parts of the security space at sampling time t. We define the observed space and the size of area as

$S_{a_i}(t)$: a subset of S that is observed by a moving sensor a_i at time t

$S_{b_j}(t)$: a subset of S that is observed by a rotational sensor b_j at time t

$Area(S')$: an area of S' (S' is a subset of S)

To identify the time-varying observed space in the security zone, the formulation of the observed space and path information of robots are required. It is possible to use various geometric model of the observed space and to allow the paths to have arbitrary shapes. However, it would require more computational efforts to identify of the observed space. Thus, in this study, we took three assumptions for simple description of the observed space and paths as follows:

- $S_{a_i}(t)$ and $S_{b_j}(t)$ are modeled as circles with radius r_a and r_b, respectively; then $Area\left(S_{a_i}(t)\right) = \pi {r_a}^2$ and $Area\left(S_{b_j}(t)\right) = \pi {r_b}^2$ for all i and j.

- The focus of b_j (i.e. the center of $S_{b_i}(t)$) moves along p_{a_i}, i.e. p_{a_i} includes p_{b_j}.

- $S_{a_i}(t) \cap S_{a_j}(t) = \emptyset, S_{b_i}(t) \cap S_{b_j}(t) = \emptyset$ for all i and j that $i \neq j$. This means that any paths between robots or cameras do not overlap.

2.2 Performance Index

Here, we propose two performance indexes for the evaluation of a security system in monitoring and controlling the observed space.

a. Surveillance coverage ratio

The monitoring coverage in a security zone is an important criterion for system evaluation. To show the coverage accurately, we propose a performance index, *surveillance coverage ratio* of a sensor a_i at time t:

$$\gamma_{a_i}(t) = Area\left(S_{a_i}(t)\right)/Area(S) \tag{1}$$

In a security space equipped with multiple sensors, we define *global surveillance coverage ratio γ(t)* at time *t* as:

$$\gamma(t) = Area\big(S_{ob}(t)\big)/Area(S) \tag{2}$$

where *global observed space* is written as:

$$S_{ob}(t) = \left[\cup_{\forall i} S_{a_i}(t)\right] \cup \left[\cup_{\forall j} S_{b_j}(t)\right] \tag{3}$$

Using (3), $Area\big(S_{ob}(t)\big)$ in (2) is calculated as::

$$Area\big(S_{ob}(t)\big) = \textstyle\sum_i Area(S_{a_i}(t)) + \sum_j Area(S_{b_j}(t)) - \sum_i \sum_j Area(S_{a_i}(t) \cap S_{b_j}(t)). \tag{4}$$

Note that $Area(S_{a_i}(t))$ and $Area(S_{b_j}(t))$ are considered constants by the assumptions. Therefore, $Area\big(S_{ob}(t)\big)$ depends on only $\sum_i \sum_j Area(S_{a_i}(t) \cap S_{b_j}(t))$. This relation indicates that if $\sum_i \sum_j Area(S_{a_i}(t) \cap S_{b_j}(t))$ is minimized at the time t, then $\gamma(t)$ is maximized.

Using (2), we can propose a specific value of the performance index as:

$$\gamma(t) \geq \gamma_{desired} \quad \text{for all time } t \tag{5}$$

where $\gamma_{desired}$ is a desired surveillance coverage ratio of a security system.

b. Visit frequency

The concept of idleness of nodes in a security zone has been considered as another important criterion. In this paper, we propose a similar concept, *visit frequency,* as a performance index. We define the visit frequency of a moving sensor a_i as follows:

$$freq(a_i) = \frac{1}{period(a_i)} \tag{6}$$

where $period(a_i)$ is the traveling time which refers to the necessary time for the completion of the navigation of a_i with path p_{a_i}. The whole visit frequency of a security system, which is called the *global surveillance visit frequency,* can be expressed as the minimum value in the frequencies of $\mathcal{A}$:

$$F(\mathcal{A}) = \min_{a_i \in \mathcal{A}} freq(a_i). \tag{7}$$

If we have a desired surveillance visit frequency $F_{desired}$,

$$F(\mathcal{A}) \geq F_{desired}. \tag{8}$$

should be satisfied. Note that $freq(a_i)$ is maximized when $tr_{a_i}(t) = tr_{0a_i}(t)$, i.e., a_i moves with its full speed. Thus, $F(\mathcal{A})$ is also maximized in the case of $\mathcal{T}r_a = \mathcal{T}r_{0a}$.

3. EXTENDED OVERLAP MAP (EOM)

3.1 Overlap Length

We will explain the concept of the extended overlap map (EOM) which is a key technique in this paper. It is similarly defined with the concept of the collision map (Lee and Lee, 1987). Now, we present a method to obtain EOM in detail. Figure 1 shows two paths of a robot i and a camera j. The path p_{a_i} is denoted to cover the length from $tr_{a_i}(t_s)$ to $tr_{a_i}(t_f)$. The other path p_{bj} lies in p_{a_i} and its range is from $tr_{bj}(t_s) = tr_{a_i}(t_1)$ to $tr_{bj}(t_f) = tr_{a_i}(t_2)$. The radii of the observed areas of the robot and the camera are r_a and r_b respectively. If we use the obstacle space scheme, the observed area by the camera can be represented as the area

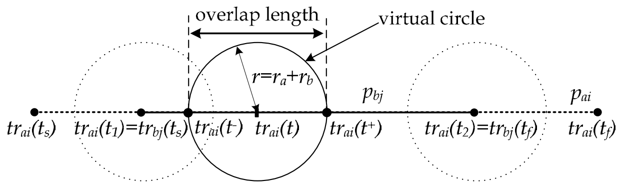


Fig. 1. Two paths of $\boldsymbol{p_{a_i}}$ and $\boldsymbol{p_{bj}}$ and overlap length

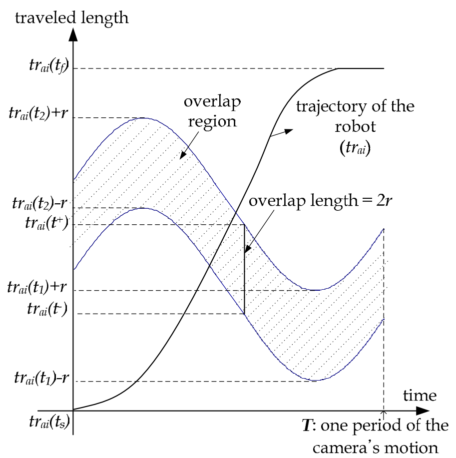


Fig. 2. Overlap map (OM)

which is called a 'virtual circle' with the radius $r = r_a + r_b$ and the observed area by the robot can be considered as a point.

These two areas may potentially overlap each other where the virtual circle moving along the path p_{bj} meets p_{a_i}. In Fig. 1, two points, $tr_{a_i}(t_1) - r$ and $tr_{a_i}(t_2) + r$ indicate the range of the potential overlap. When the virtual circle is located in a point at time t, the overlapping part on the path is called as 'overlap length' and its two endpoints are represented as $tr_{a_i}(t^-) = tr_{ai}(t) - r$ and $tr_{a_i}(t^+) = tr_{ai}(t) + r$ respectively. Since the center of the virtual circle always moves in p_{bj}, if the range of the potential overlap is included in p_{a_i}, the overlap length is a constant, i.e., the diameter of virtual circle $2r$.

3.2 Overlap Region and Overlap Map

The motion of a robot consists of the continuous information of position and time. Thus, to identify the time-varying overlap, we should examine the existence of the overlap length at every instant of sampling time. From the examination, we can collect a set of overlap lengths and it constructs a region which is called 'overlap region' as shown in Fig. 2. Note that the overlap region is periodic information because of the reciprocating motion of a virtual circle. Two dimensional figure in which an overlap region and a trajectory are represented simultaneously, is named as 'overlap map' (OM).

Figure 2 shows one period of overlap region in an OM. The two marks, $tr_{a_i}(t_1) - r$ and $tr_{a_i}(t_2) + r$, in the vertical axis indicate the range of the potential overlap region. The overlap region is drawn as a wave form with the width $2r$. In the OM, if the trajectory of the robot touches or crosses over the overlap region, it indicates that two observed spaces have overlapped. However, identifying where there is any overlapping does not inform us of the size of observed space which is necessary to coverage analysis. Thus, we need to conduct more study on the overlapping for monitoring the observed space.

In the Fig. 3, two observed spaces of a robot and a camera approach each other. The robot is denoted as a point and the virtual circle is used according to the obstacle space scheme. We define $d_{ab}(t)$ as the distance between two centers of the robot and virtual circle and consider the distance only in the case where there is overlap. When the robot touches the virtual circle at time t_A, $d_{ab}(t)$ is the maximum, i.e., $d_{ab}(t_A) = r = r_a + r_b$. Then, in the movement of the robot, the size of overlap area increases consistently as the distance $d_{ab}(t)$ decreases (e.g. at time t_B). Finally, when the two points coincide (t_C), i.e., $d_{ab}(t_C) = 0$, the overlap area is the largest. Thus, we can see that the distance $d_{ab}(t)$ and the size of observed space has a direct relation with each other. Additionally, note that the accumulated observed space over time is related with the lasting time of $d_{ab}(t)$. For example, if two observed spaces move with the same velocity and direction and their center coincide, the lasting time of $d_{ab}(t_C) = 0$ becomes long, which results in low performance in terms of coverage.

Using the OM, we propose a method to improve the coverage of the observed space. First, we assume that robots pass though the overlap region at full speed to minimize the lasting time of $d_{ab}(t)$ at every distance. Then, to control the observed space over time, we can use several trajectory modification methods such as time delay and speed reduction (Lee and Lee, 1987). In this approach, the optimal solution is to find the trajectory to minimize the duration time t_d which is period that the trajectory meets the overlap region as depicted in Fig. 4. From the OM in the figure, we are able to find a relation. We refer to the angle between the trajectory and the tangent of the center line of the overlap region as *cross angle*(θ). The physical meaning of cross angle is the difference between the velocities of two observed spaces. Thus, a small cross angle indicates that two spaces have the same direction and a similar velocity. Figure 4 clearly shows the relation that duration time decreases in the proportion with the cross angle.

3.3 Extended Overlap Map and Time-Global Surveillance Coverage Ratio Graph

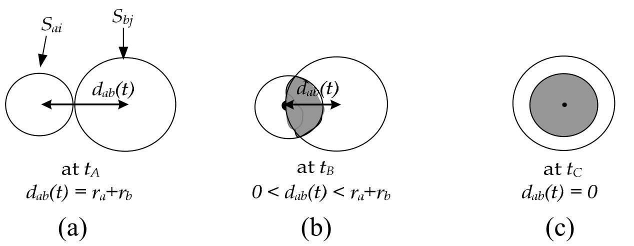


Fig. 3. Relation between distance $d_{ab}(t)$ and the size of overlap area. (a) The robot denoted as a point touches the virtual circle at t_A. (b) The robot is inside the virtual circle at t_B. (c) The robot is located at the center of the virtual circle at t_C.

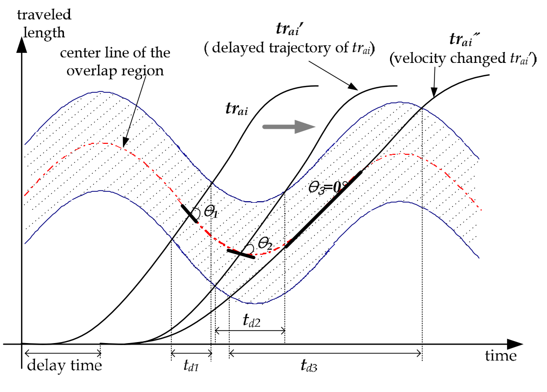


Fig. 4. Relation between duration time t_d and cross angle θ in OM. In this figure, $\theta_3 < \theta_2 < \theta_1$ and $t_{d1} < t_{d2} < t_{d3}$

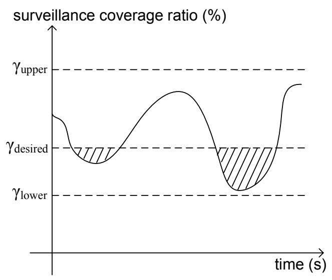


Fig. 5. Primitive time-global surveillance coverage graph

This paper considers a security system equipped with multiple cameras and robots. Thus, we extend the overlap map scheme for a single camera to multiple cameras. With multiple cameras, one may view the different parts in the same path. Each part of the path is represented as a different overlap region. Since no cameras view the same part of the path in the assumptions, the overlap regions are separated in the figure. The figure includes the several overlap regions and a trajectory and is called the 'extended overlap map (EOM)'. Note that an EOM can provide the information on the size of observed space along time in a security zone equipped with a robot and multiple cameras. Thus, we can incorporate the information of all EOMs of multi-agents into a single graph which shows the whole observed space along time. See Fig. 5 where the vertical axis is the surveillance coverage ratio and the horizontal axis is travelling time. The graph is the time-global surveillance coverage ratio graph (TGSG) that can be said to be the final result of the monitoring of the observed space. In the following sections, we will discuss the EOM and the TGSG further.

4. MULTI-AGENT MOTION PLANNING

In this section, we investigate the motion planning methods to control the observed space. As stated in Section 2, we plan multi-agent motions to satisfy a desired surveillance coverage ratio $\gamma_{desired}$, which is the primary performance index in this paper. For the multi-agent motion planning, the result of the monitoring is essential information because it shows exactly the time-varying surveillance coverage ratio in a security zone. In other words, the proposed multi-agent motion planning is based on the TGSG.

If a $\gamma_{desired}$ is given, the TGSG clearly indicates parts under the $\gamma_{desired}$. The goal of motion planning is to eliminate all the parts in the TGSG. In Fig. 5, there are two parts under a $\gamma_{desired}$. Various methods in motion planning can be considered for the elimination of the parts. In this paper, we examine a method using the time-delay introduced in (Lee and Lee, 1987) to control the observed space. Note that the elimination should be successively performed according to time information. That is, the part nearest to the origin of the vertical axis in the TGSG should be eliminated first. This is because the modification of a part affects all the following parts of the trajectory. This suggests that the TGSG can be changed in the motion planning.

The computational complexity is a major problem in the centralized multi-agent system. Thus, the method to reduce the complexity is also examined in this paper. If a central planner identify k related robots among n robots in a part under the $\gamma_{desired}$, we have *O(k!)* computational load instead of *O(n!)* to investigate a solution to eliminate the part. This is the traditional NP-hard problem in the centralized motion planning. To overcome this problem, we applied the concept of the prioritization to our approach.

In prioritization, an assignment rule is the most important. We selected the visit frequency as the assignment rule, which is the second performance index in Section 2. To control the observed space subject to a minimum loss of surveillance visit frequency, we give priority to the robot with the higher visit frequency. In this strategy, the computational load for the elimination is reduced to *O(klogk)* because the priorities can be assigned to multi-agents directly by using the sort methods such as Quicksort (Cormen , 2001).

Then, the central planner sequentially modifies the trajectories of the robots according to the priority until the observed space becomes larger than that of the $\gamma_{desired}$. In the modification, we note that the observed space is bounded by (3). It has the upper bound when

$$\sum_i \sum_j Area\left(S_{a_i}(t) \cap S_{b_j}(t)\right) = 0 \qquad (9)$$

The lower bound can also be calculated. In Fig. 5, the bound is represented as the two dotted lines. Consequently, if a $\gamma_{desired}$ is determined within the bound, we can control the observed space by planning multi-agent motions with our systematic processes in low computational burden.

5. SIMULATION RESULTS

We carried out simulation experiments to evaluate the effectiveness of our approach in the environment depicted in Fig. 6. Table 1 shows the given conditions of the environment, the physical constraints of cameras and robots, and individual observed spaces. The robots and cameras are assumed to have the same constraints. From (2) and (3), we obtained the bound of surveillance coverage ratio of the simulation ($\gamma_{lower} = 0.6$ and $\gamma_{upper} = 0.85$). Thus, the desired surveillance coverage ratio $\gamma_{desired}$ was assigned 0.7 within the bound.

The set of the full speed trajectory $\mathcal{T}r_{0a}$ was applied to the multi-agent motions at the beginning of the simulation and we did not modify any motions to satisfy the requirement, i.e., $\gamma_{desired}$. Figure 7 (a) shows TGSG assigned $\mathcal{T}r_{0a}$. There are three under parts PT_1, PT_2, PT_3 with periods denoted as t_{PT1}, t_{PT2}, t_{PT3} respectively. Using the information in the TGSG, we modified the motions of the robots for the satisfaction of the requirement as follows.

Table 1. Physical conditions of robots and cameras

Notations and meaning		robot	camera
r_a, r_b	radius of observed area (m)	32.5	37.5
v_0, $\mathcal{T}r_{0a}$	maximum velocity (m/s)	5	5
	acceleration (m/s^2)	2	2
	rotation velocity (°/s)	90	
S	Security space (m^2)	66690	
$\gamma_{desired}$	Desired surveillance coverage ratio	0.7 (70%)	

Table 2. Result of the simulation

Agent	$\mathcal{T}r_{0a}$		$\mathcal{T}r_{1a}$		$\mathcal{T}r_{2a}$	
	Freq	Part	Freq	Part	Freq	Part
a_1	7.87	$PT_{1,3}$	7.87	PT'_1	7.30	-
a_2	7.19	$PT_{1,2,3}$	7.19	PT'_1	7.19	-
a_3	*6.02	$PT_{1,2}$	*6.02	PT'_1	*6.02	-
a_4	12.05	$PT_{1,2,3}$	11.11	PT'_1	11.11	-

(Freq : 10^{-3}/s , * : global surveillance visit frequency)

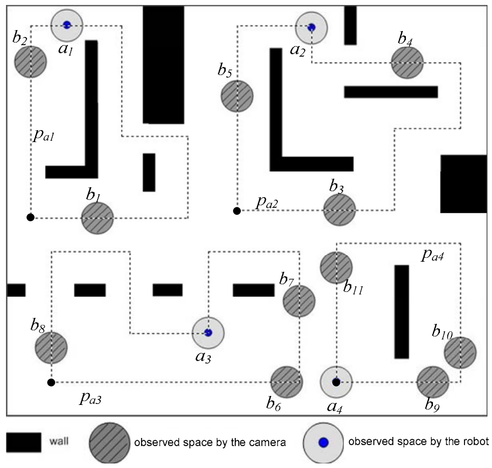
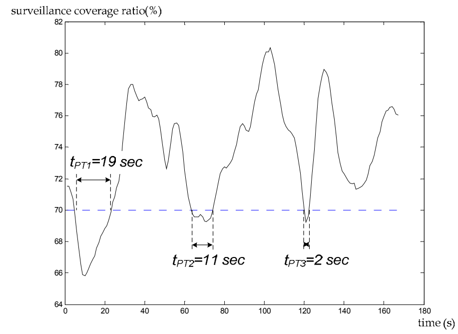
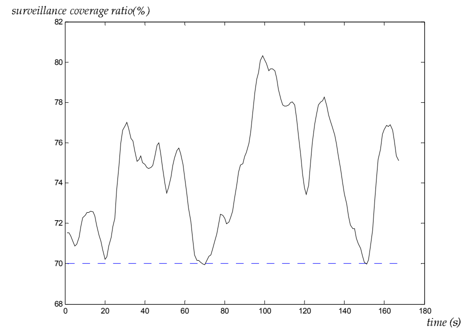


Fig. 6. Map for the simulation. 4 mobile robots and 11 cameras were used to observe the space simultaneously. The black points in the robots' paths indicate starting points and robots move counterclockwise.



(a) TGSG assigned initial motions, $\mathcal{T}r_{0a}$. t_{PT1}=19 sec, t_{PT2} = 11 sec, t_{PT3} = 2 sec.



(b) TGSG assigned modified motions, $\mathcal{T}r_{2a}$.

Fig. 7. TGSGs of the simulation. The dotted line represents the $\gamma_{desired}$ = 0.7

The central planner identified the related robots at every part. In the first part PT_1, all robots were related as presented in Table 2. According to the proposed priority assignment rule, since the agent a_4 had the highest visit frequency, it was assigned the highest priority and its motion was modified first by the time delay method. Then, by using the relation between the coverage and the delay time in EOM of a_4, the starting time of the trajectory was delayed up to 7 sec.

The elimination procedure was repeatedly to satisfy the requirement, and is shown in Table 2 and Fig. 7. At last, we obtained the solution $\mathcal{T}r_{2a}$ satisfying the requirement as shown in Fig. 7 (b). In addition, we considered this result in terms of the second index, visit frequency. Table 2 shows that the surveillance visit frequency was always 6.02×10^{-3}/s in the simulations. That is, there was no loss of $F(\mathcal{A})$ while the observed space was controlled.

6. DISCUSSION

Multiple types of sensors have been used for more reliable security service in real applications and their cooperative control has been strongly required as well. The purpose of our research is to provide a new method to monitor and control the observed space over time with applicable computation burden. For this purpose, we closely formulated our problem and developed two tools: extended overlap map (EOM) and time-global surveillance coverage ratio graph (TGSG). In addition, for applicable computation burden, we assigned priorities to multi-agents according to visit frequency of the agents.

Based on our results, we were able to make the following contributions. First, we could exactly monitor the time-varying observed space by using the two proposed tools. In addition, to monitor time-varying observed space, we also presented several important concepts such as overlap length, overlap region, and overlap map. With the tools based on the concepts, we were able to successfully perform a simulation satisfying a coverage requirement in Fig. 7 and Table 2. Moreover, there was no loss of the surveillance visit frequency. In the previous researches, the overlap between sensing areas had only been considered as one part such as a coverage calculation (Jung and Sukhatme, 2002). Thus, our systematic process for monitoring the whole observed space is a new achievement in this field.

In addition, we presented a method with which one can control the observed space with low computational complexity. Using the TGSG in monitoring, we were able to find out exactly some robots related to the parts that did not satisfy the requirement in TGSG. When k robots were identified among n robots in the part, by assigning the priority to the robots, we were able to reduce the computational complexity from $O(n!)$ to $O(k\log k)$ ($k<=n$). So far, many researches on multi-agent security service have been based on the distributed approach (Parker, 1997) because of the complexity and heavy computational burden at the expense of highly coordination. However, owing to the low complexity in our approach, the proposed motion planning method gives the centralized security robot systems requiring highly coordination practical ways.

7. CONCLUSIONS

The results of this study show that time-varying observed space in a security zone with two types of sensors can be monitored and controlled with our new tools: extended overlap map (EOM) and the time-global surveillance coverage graph (TGSG). The EOM can present time-varying overlap between a moving robot and multi rotational cameras clearly, thus it is useful for planning motions of robots precisely. The TGSG is drawn by incorporating surveillance coverage information in EOMs, which is the final result of monitoring. The control of observed space is realized by analyzing the TGSG and planning multi-agent motions interactively with 5 processes. In developing the tools, we considered the computational complexity problem of multi-agent motion planning. To overcome it, we analyzed the visitation frequency of multi-agents and used it as a criterion for prioritizing robots. Consequently, when a security system is required to monitor more than a desired surveillance coverage ratio in a space every time, we can achieve the requirement completely by using the proposed tools. Since our proposed approach to a security service using different two sensors is systematic and has low computational burden, it can be applied to various applications in the multi-agent security robotics.

ACKNOWLEDGEMENTS

This work was supported in part by the Ministry of Commerce, Industry and Energy, Automation and Systems Research Institute (ASRI) in Seoul National University, and the Brain Korea 21 Project.

REFERENCES

Akella, S. and S.Hutchinson (2002). Coordinating the Motions of Multiple Robots with Specified Trajectories, *Proc. of the 2002 IEEE Int. Conf. on Robotics & Automation*, Washington DC.

Chvatal, V. (1975). A combinatorial theorem in Plane Geometry, *Journal of Combinatorial Theory (B)* , **vol. 18**, pp. 39-41.

Cormen, T.H., C.E.Leiserson, R.L.Riverst, and C.Stein (2001), *Introduction to algorithms*, The MIT Press.

Lee, B.H., C.S.G.Lee (1987), Collision-Free Motion Planning of Two Robots, *IEEE Transactions on Systems, Man, and Cybernetics*, **vol. SMC-17, no.1**, pp.21-31.

O'Rourke, J. (1987), *Art gallery theorems and algorithms*, Oxford university press, UK.

Parker, L.E. (1997), Behavior-based cooperative robotics applied to multi-target observation, *Intelligent robots: Sensing, modeling, and planning*, World scientific.

Rybsi, P.E., S.A.Stoeter, M.D.Erickson, M.Gini, D.F.Hougen (2000), A Team of robotic agents for surveillance, *Proc. of Int. Conf. on Autonomous agents*, pp. 9-16, Spain.

Shermer, T.C. (1992), Recent results in art galleries, *Proc. of IEEE*, **vol. 80, no. 9**.

Sugihahra, K., I., and M.Yamashita (1990), The searchlight scheduling problem, *SIAM Journal of Computing*, **vol. 19, no. 6**, pp. 1024-1040.

Suzuki, I. and M.Yamashita (1992), Searching for a mobile intruder in a polygonal region, *SIAM Journal of computing*, **vol. 21, no. 5**. pp. 863-888.

Yamashita, M., I.Suzuki, and T. Kameda (2004), Searching a polygonal region by a group of stationary k-searchers, *Information Proc. Letters*, **vol. 92, no. 1**, pp. 1-8.

Jung, Y, B. and G.Sukhatme (2002), Tracking targets using multiple robots: the effect of environment occlusion, *Autonomous robots*, **vol. 13, no. 3**, pp. 191-205.

Yseng, Y.S., Y.C.Wang, K.Y.Cheong, and Y.Y.Hsieh (2007), iMouse: An integrated mobile surveillance and wireless sensor system, *Computer*, **vol. 40, no. 6**. pp. 60-66.