# Capture of Multi Intruders by Cooperative Multiple Robots using Mobile Agents

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Abstract: Detecting and capturing intruders are two of the most important function of multi-robot systems. In this paper, we propose an effective approach to capture agile intruders with not-so-agile mobile robots. In general, it is difficult to drive several robots to pursue moving objects while adjusting their behaviors. We make mobile robots cooperate using two mobile software agents that control the mobile robots. The mobile software agents migrate from one robot to another robot that is located at much suitable positions for guiding moving robots to the target location. This control manner contributes to not only reduction of movement cost of the mobile robots, but also their efficient movement without interference from other robots. We have implemented a simulator, on which we demonstrated effectiveness of our control manner for intruders-capturing system.

## 1 INTRODUCTION

The advent of a combination of multiple robots and multiple software agents is realizing a new stage of cooperation of mobile robotic agents and humans. We have engaged studies of mobile software agents, and implemented several applications such as multi-robot systems that cooperatively search objects (Nagata et al., 2013) and cooperatively compose formations (Shintani et al., 2011) (Kambayashi et al., 2019). The persuasion is based on the finding that those systems are not only feasible but also enjoy the energy saving and efficiency (Takimoto et al., 2007).

In this paper, we focus our attention on detection and capture of multiple intruders in a building. Detecting and capturing intruders are two of the most important applications of multi-robot systems. We introduce a novel control system for chasing multiple intruders into a corner in a building by multiple small not-so-agile mobile robots. Considering the current robotics technologies and safety requirements, it is hard to obtain mobile robots as agile as human beings. In order to cover the laggardness of mobile robots, we have employed multiple small robots and mobile software agents. We can arrange multiple small robot sparsely distributed in a building, and make them cooperate using mobile software agents that control mobile robots. Since software agents can instantly move from a robot to another robot, it can migrate to the most suitably located mobile robot to capture the intruder. In addition to the instant migration of mobile software agents, they can easily duplicate themselves and simultaneously control multiple mobile robots to achieve highly cooperative activities such as capturing intruders. In this paper, we describe the features of mobile software agents and explain how they can make multiple mobile robots cooperate to capture several intruders.

The rest of this paper is organized as follows. The second section describes the background. The third section describes the method for coordinating multiple mobile robots using the mobile software agents. Our mobile agent system consists of two kinds of mobile software agents, i.e. ant agents and pheromone agents. We describe each of them and present the role and algorithm to implement the control system for multiple robots' coordination. The fourth section describes the experiments on the simulator, and we conclude our discussion in the fifth section.

## 2 BACKGROUND

We have previously presented a framework for controlling intelligent multiple robots connected by wire-



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less communication networks (Shintani et al., 2011). The framework makes the multiple mobile robots indirectly cooperate one another and accomplishes highly coordinated actions. The core of the framework consists of two kinds of mobile software agents, namely pheromone agents and ant agents. The idea of pheromone agents is inspired by the behaviors of social insects, i.e. ants. In the algorithm, agents mimic the behaviors of ants communicating with each other by an indirect communication mediated by modifications of the environment called stigmergy. The behavioral scientists Goss et al. found that ants exchanged information by laying down a trail of a chemical substance called pheromone that is followed by other ants (Goss et al., 1989). Dorigo et al. abstracted the behaviors of ants and applied the extracted algorithm to derive a quasi-optimal solution for NP-complete problems (Dorigo et al., 1996). Later, Dorigo et al. successfully applied the idea to control and coordinate swarm robots (Dorigo, 2005). Their SWARM-BOTS project is today considered as the pinnacles of many multi-robot projects. There are also studies that aim to compose a circle formation in a two dimensional orthogonal coordinate system using mobile agents and their sensors (Yang and Wang, 2019), (Song et al., 2019).

Kambayashi et al. presented capturing single intruder strategy using vector value between robots (Kambayashi et al., 2020). We improved this strategy more effectively and adapted for multiple intruders. We aim to capture intruders using vector values that points mobile agents on multiple robots and intruders.

# 3 SINGLE INTRUDER STRATEGY

Captor robots are small mobile robots. They do not attack an intruder violently. They quietly chase and drive him or her into the designated capture location. Kambayashi's system (Kambayashi et al., 2020) consists of robots and two kinds of mobile software agents, namely ant agents and pheromone agents. All the controls for the mobile robots are achieved through ant agents. Each mobile robot has Wi-Fi capability. They are connected through wireless LAN. Each ant agent can freely move among the herd of mobile robots. Since the ant agents control the robots, captor robots without ant agents just sit and sense the environments quietly, while ant agents are hopping from a robot to another robot to patrol the sensing area by checking the quietly sitting robots' sensors. We assume the captor robots have enough sensors such as optical cameras and ultrasonic sensors to detect an intruder.

Once an ant agent arrives at a captor robot who senses an intruder, it drives the robot to hunt down the suspect and simultaneously dispatches pheromone agents to rally nearby robots to bring the intruders to the bay. We describe the ant agents and pheromone agents in the following sections.

## 3.1 Ant Agent

The ant agent (AA) has the following six capabilities. 1) It drives a robot on which it resides depending on the specific state they can take. 2) It can migrate from a robot to another robot through wireless LAN. 3) It has the IP addresses of all the participating robots. 4) It creates pheromone agents that attract other mobile robots. 5) It can have four states and changes its state as the situation changes. 6) It can acts depending on the current state.

Without AAs, mobile robots cannot even move; they are just sitting quietly. Therefore, at the initial phase, we make a number of AA migrate into the herd of the mobile robots. Each AA looks for an idle robot (a robot without AA) that it can drive. Once an AA arrives on a robot, it is in the "search" state. After that, AA changes its state depending on the environmental conditions. The idea of changing state to make AA perform different kinds of tasks is inspired from (Takahashi et al., 2014).

Initially, the AA is in the "search" state. In this state, the AA makes the robot randomly walk to find a suspect. The robot has basic capability for collision avoidance by ultrasonic sensors and electronic circuit. Each robot has basic capabilities to survive by on-board controller without AA's interference. The robot's visual sensor can sense objects in the fan-shaped area with 45 degrees to the right and left from its driving direction. When the AA finds an intruder in its fan-shaped sensing area through robot's visual sensor, it changes its state to "chase."

In the "chase" state, the AA drives its robot toward the intruder while it gives intimidation by warning sound and flashing light, and tries to drive the intruders to the designated capture location. Since the mobile robots are not as agile as human intruder, it cannot capture or drive the intruders into the capture location alone. It needs fellow robots to drive the intruders in cooperation with them. In order to obtain the cooperation from other robots that do not sense the intruders, the chasing robot changes its state into "attract" temporarily, and creates and dispatches pheromone agents.

In the "attract" state, AA creates and dispatches pheromone agents as many as it can find other AAs in search state. A pheromone agent (PA) is the other kind of mobile agents, and its purpose is to share information about the intruders with other robots in search state within the wireless communication range. PA has a vector value that points from the robot that creates the PA to the intruder, so that the PA can tell another robot to which direction the robot should move to find the intruder. After dispatching PAs, the AA resume to the "chase" state, and continues to chase the intruder.

When an AA receives a PA from a chasing AA, the AA transits to be in the "guided" state, as shown in Figure 1. In the guided state, the AA moves following the vector value that is given by the arriving PA until it finds the intruder. When AA finds the intruder, it changes its state from "guided" to "chase" and starts chasing the intruder based on its own sensor information. If AA cannot find the intruder after certain period, it changes its state to "search" again, and starts random walk. We describe how a PA plays its role in the next section.

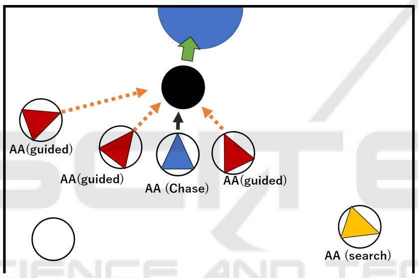

Figure 1: AA's method.

## 3.2 Pheromone Agent

The pheromone agent (PA) is a mobile agent that guides AA to the destination of vector value which it has. Figure 2 and Figure 3 show how a PA guides and makes a searching robot chase an intruder in cooperation with other chasing robot. AA1 finds a robot controlled by AA2 and is randomly walking while it is chasing an intruder. Since each robot has a visual sensor, AA1 can calculate the intruders coordinate $V_t$. Since mobile robots are not agile enough to capture an intruder alone, it needs the other robots' assistance. AA1 finds a robot, and also finds AA2 is driving the robot. AA1 decides to make that robot participate in the chase. AA1 creates a pheromone agent with the vector value $V_{new}$ that points to the intruder, and dispatches the PA to the robot where AA2 is driving. The vector value $V_{new}$ is calculated by the equation(1).

$$V_{new} = V_t - V_n \quad (1)$$

Upon receiving the PA, AA2 changes its state "search" to "guided" and starts following the guidance of PA. When AA2 find an intruder, AA2 changes its state to "chase" and then "attract", and dispatches PA to yet another robot as shown in Figure 4.

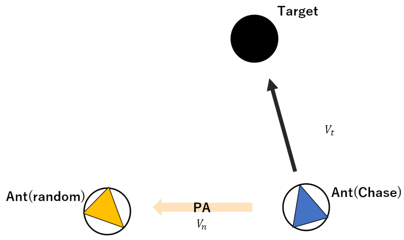

Figure 2: Before: PA how to attract AA.

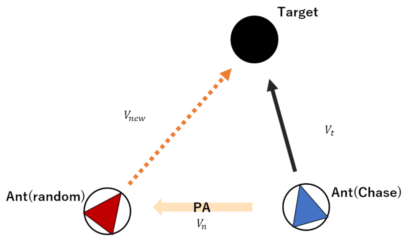

Figure 3: After: PA how to attract AA.

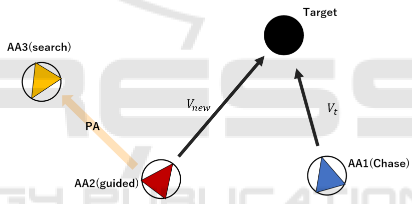

Figure 4: Dispatching PA repeatedly.

# 4 MULTIPLE INTRUDERS STRATEGY

Our previous method worked well for a single intruder. On the other hand, it did not effectively work for multiple intruders shown in later comparative experiment. Also, as the number of robots is increased, we have observed that robots frequently collided with each other. Since the collision, consumes a lot of steps for recovering from it, so that the time cost to capture intruders increases. Thus, in order to achieve efficiently capturing multiple intruders, we had to solve these problems. We address this problem through introducing sophisticated guidance to colleague AAs so that they can move to more suitable positions to capture intruders, We also provide collision control mechanism based on agent migration.

## 4.1 Ant Agent

In our previous approach, we often observed that an intruder stacked in corners that are not the goal position. That is because AAs chase an intruder in a straight way, and therefore it cannot escape once it is driven to the corner. In order to avoid this situation, we give an AA different behaviors depending on three areas that are determined with relative positions of the AA and the goal. We call the areas "Inside", "Outside" and "Behind" as shown in Figure 5.

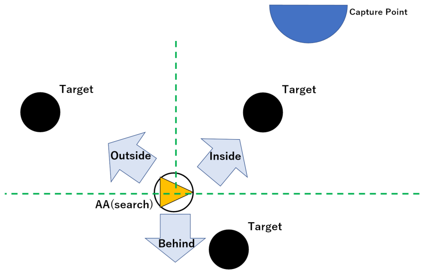


Figure 5: Situation with positions.

If an intruder is in "Inside" area, it means the intruder is closer to the goal than the robot with AA, the AA basically performs the same behaviors as our previous method. Once AA finds an intruder, it changes its state from "search" to "chase" and "attract". In the "attract" state, we have improved AAs' behavior. They create PAs in fan-shaped formation so that they attract other robot only in front of them. We explain the details of this improvement in the next section.

If an intruder is in "Outside" area, it means the intruder is far from the line between the robot with the AA and the goal, but the intruder's position is closer to the goal than the AA's robot. In this situation, the AA creates PAs, and dispatches them to other robots in the other side of the line between the intruder and the goal as shown in Figures 6 and 7. In this situation, if AA chases an intruder straightly, the intruder can escape to a corner of the field and stack there. On the other hand, since other robots with AAs attracted by our PAs chase from the corner side, we can avoid that situation where the intruders to stack at any corners.

If an intruder is in "Behind" area, it means the intruder is behind of the chasing robot, the driving AA changes its state to "Jump" to migrate to another robot behind the intruder as shown in Figure 8. In the figure, the chasing AA migrates (jumps) to a free robot R2, which is at a more favorable position than R1. In other words, in "Jump" state, AA looks for a free robot, i.e. in this case R2, which is within the range of PA, and behind the intruder, and migrates to the free robot through wireless LAN.

At the same time, AA creates a PA, with a vector

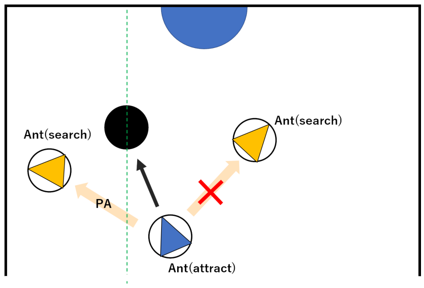


Figure 6: Before: AA dispatches for limited robot.

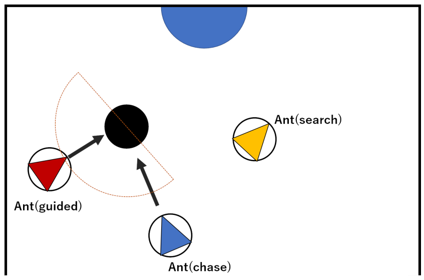


Figure 7: After: AA dispatches for limited robot.

value that shows the location in accordance with following equation (2). In the equation, PA's vector $\vec{V_{RP}}$ is determined as enclosing the intruder with the robot R2 with the AA and the other robot attracted by PA. as follows:

$$\vec{V_{RP}} = \vec{V_{RT}} + \vec{V_{R1R2}} \tag{2}$$

Once PA are created in "Jump", the AA dispatches PA to robots behind the intruder. At the same time, it migrates to the robot R2. Once AA jumps to R2, R2 with AA1 goes toward the target after checking around R2.

If AA cannot find any robot to which it migrates, the AA just creates and dispatches PA to robots behind the intruder, changes its state from "chase" to "search" and gives up chasing the intruder. In "search" state, AA drives a robot randomly. Once PA migrates to a robot with such AA, the AA changes its state to "guided", where AA drives a robot along guidance shown by a vector value of the PA.

## 4.2 Pheromone Agent Creation

In the improved method, we also made some adjustments to the creation of Pheromone Agent. In the previous PA creation manner, AA simply creates PA behind the intruder. Such a creation manner works well for a single intruder, but for multiple intruders, it causes a lot of escapes. In our new creation manner, the AA creates PAs in fan-shaped formation as enclosing intruders as shown in Figures 10 and 11. The fan-shaped creation is achieved as follows: 1) AA ro-

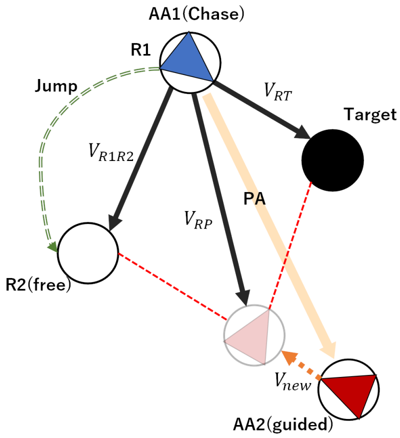


Figure 8: Before: Jump behind the intruder.

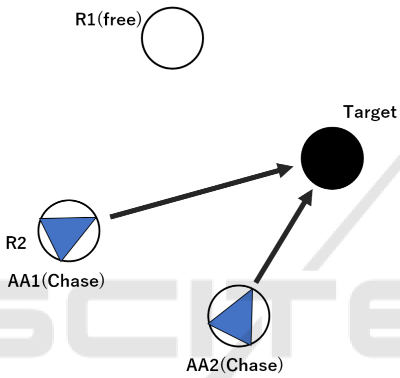


Figure 9: After: Jump behind the intruder.

tates the robot by facing with an intruder, and 2) the AA creates two PAs in both sides respectively with a little incline as shown in Figures 10 and 11.

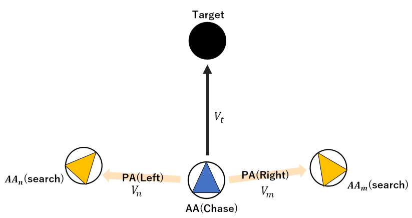


Figure 10: Before: Fan-shaped formation with PA.

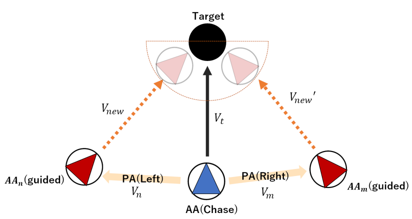


Figure 11: After: Fan-shaped formation with PA.

Notice that each PA is dispatched to robots where they are at least robot size apart. Once other AAs drive their robots and reach the designated points based on guide of the PAs, they start chasing the intruder.

### 4.3 Collision Avoidance

Many robots may be in the same field. In such a situation, many collisions will occur. Such collisions tend to disturb convergence of the system. In order to suppress the frequent collisions, we introduce mobile agent based collision avoidance mechanism. The collision avoidance is achieved by simple migration of a mobile agent between robots. For example, a robot moving on a line is blocked by another robot on the line as shown in Figure 12. In a mobile agent model, the most important mission is making the robot that it is driving. If the mission is to continue moving on the line, the mobile agent on a robot can continue moving through migrating to the other robot and continue moving as shown in Figure 13. In our system, an AA has this migration property, which contributes to its smooth movement as collision avoidance.

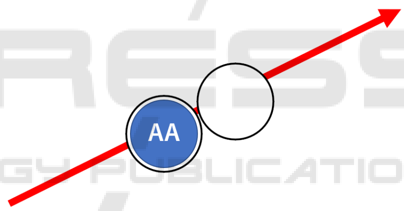


Figure 12: Before Agent Exchange.

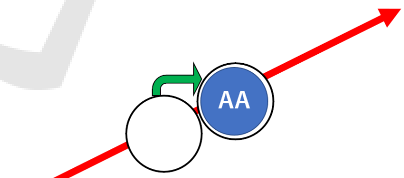


Figure 13: After Agent Exchange.

## 5 EXPERIMENTAL RESULTS

In order to investigate the feasibility of our detection and capture system for multiple intruders, we have implemented our system on a simulator and conducted numerical experiments and comparative experiments with our previous method. In the experiments, we assume the following conditions.

- Robots are scattered in a 500 x 500 square field in the simulator.

- The capture location is set at one edge of the field.
- The number of robots and AAs is selected from 5, 10, 30, 50, 75, 100 and 200.
- The number of AAs is limited to the number of robot.
- The maximum number of intruders is 5.
- Robots and intruders are randomly placed in the field.
- The range of communication network for each robot is 200 units and the range of sensor is the same.
- Each robot can move 1 unit and each intruder can move 1.5 units in each step in the simulator.
- In each trails, the maximum number of steps is limited to 10,000 and the trail is counted to "miss" trail.

We have conducted 100 trails for each number of AAs, robots and intruders, and measured the duration time to drive intruders to the capture location. Figure 14 shows an image of simulation with 200 robots, 75 AAs and 3 intruders.

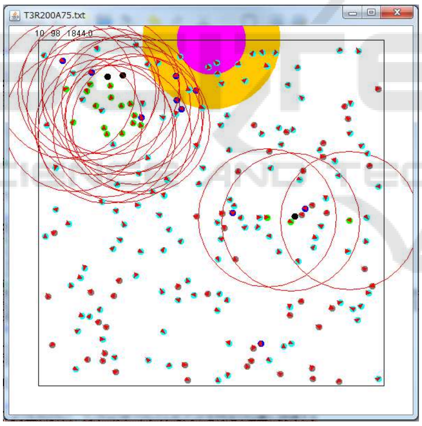


Figure 14: Experiment Example.

Figures 15 and 16 show the results for relation of the efficiency between the number of robots and the number of intruders in fixing the number of AAs to 30. The vertical axis represents the number of steps needed to drive intruders, where each bar represents the number of intruders driven into the capture location. The horizontal axis is the number of participating robots. Figures 17 and 18 show the results for the relation between the number of AAs and the number of intruders in fixing the number of robots to 200, where horizontal axis represents the number of participating AAs. Figures 15 and 17 show the results with the previous method, and Figures 16 and 18 show the results with our improved method.

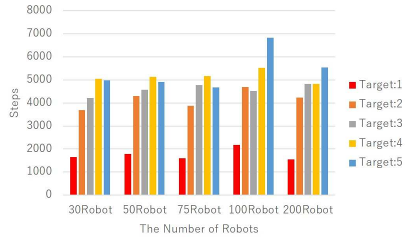


Figure 15: Previous: The number of Steps with 30 AAs.

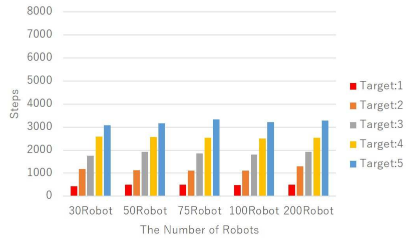


Figure 16: Improved: Steps with 30 AAs.

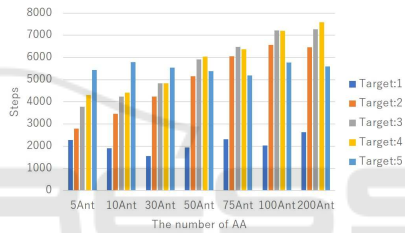


Figure 17: Previous: The number of Steps with 200 robots.

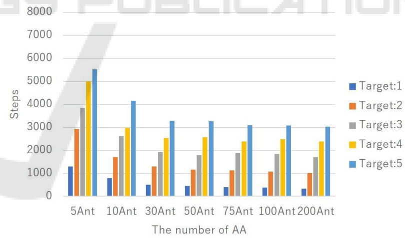


Figure 18: Improved: The number of Steps with 200 robots.

Comparing the two methods, the improved method shows obvious advantage regardless of the number of robots. The advantage becomes more remarkable as the number of intruders decreases. Also we can observe that the advantage become more remarkable as the number of AAs increases. The result shows that our improvement enhances the effectiveness of the mobile agents in our system.

Figures 19 and 20 show the result for the relation of the efficiency between the number of AAs and the number of robots in fixing the number of intruders to three. The vertical axis represents the number of steps needed for driving the intruders into the capture location, and horizontal axis is represents the number of participating mobile agents and each bar represents the number of robots. As shown in the figures, our system becomes more efficient as the number of AAs increases in improved method than in the previous method. As shown in Figure 21, the number of AA exchanges increases dramatically as the number of robots increases. This phenomenon represents exchanging agents contributes to the reduction of the steps.


Figure 19: Previous: The number of Steps with 3 intruders.

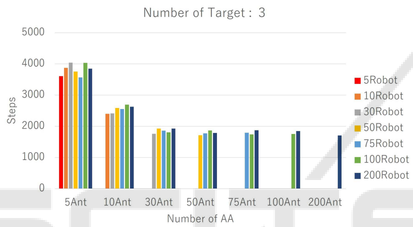


Figure 20: Improved: The number of Steps with 3 intruders.

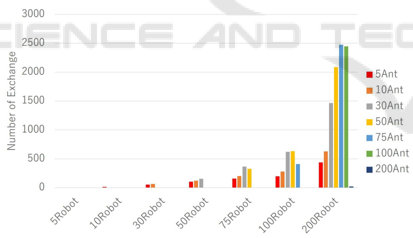


Figure 21: The number of Exchange with 3 intruders.

Figure 22 shows the efficiency of the AA's "Jump" algorithm. We can observe that the smaller the number of AA is, the greater the advantage of jump behind of the intruder is obtained. On the other hand, the advantage decreases as the number of AA increases.

Finally, we show the number of "miss" trails in Figures 23 and 24. Our improved method especially contributes to the achievement of capturing intruders compared with previous method.

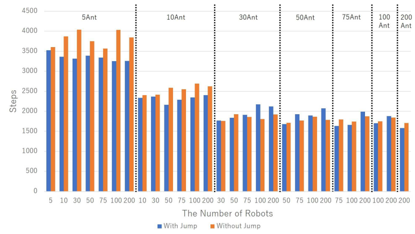


Figure 22: Left:with jump, Right:without jump.

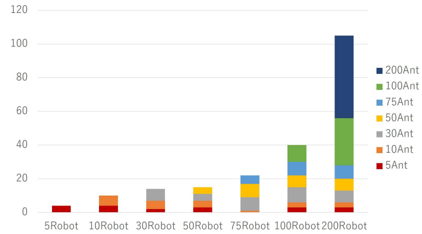


Figure 23: Previous: The number of Miss with 3 intruders.

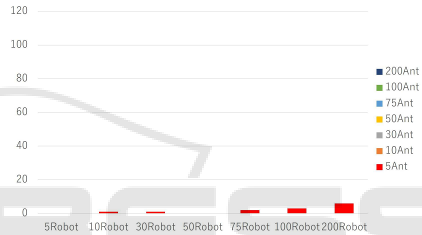


Figure 24: Improved: The number of Miss with 3 intruders.



# 6 CONCLUSIONS

We have proposed a method for chasing multiple intruders that is an improved version of our previous method that chases a single intruder. We implemented the algorithm for capturing intruders. Since human intruders faster than robots, we have made the captor robots cooperate by using mobile agents. With the full use of agent mobility in the cooperation, we have successfully made mobile robots chasing intruders in the behind them. This is achieved through changing chasing robots by migration of driving mobile agents. The chasing manner contributes to efficient capturing. Also, our collision management based on migration contributes to reduce failure of capturing intruders.

In order to show the feasibility of our idea, we have implemented a simulator of our mobile robot system and demonstrate the effectiveness. We are going to implement this intruder capturing system with an actual mobile robots.

## ACKNOWLEDGEMENTS

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