Optimal Camera Placement Considering Mobile Robot Trajectory

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Abstract - **In the near future robots will be used in home environments to provide assistance for the elderly and challenged people. The arrangement of sensors influences greatly the quality of information provided to the robot. We, therefore, examine the problem of the optimal arrangement of vision sensors for the case of a robot following a pre-defined path. A methodology to evaluate the arrangement of sensors is proposed, focusing on the case of a home environment with ceiling cameras. Simulation results indicate that we can obtain sub-optimal and practical arrangement with the minimum number of sensors which satisfies the necessary condition.**

Index Terms - optimal camera arrangement, steepest descent method, importance weighting of space

I. INTRODUCTION

In the near future, autonomous mobile robots will be used in home environments to provide assistance for the elderly and challenged people. Sensors placed on the environment can be used for the recognition and localization of the robot and of surrounding objects. Much research has been done on robot and object localization techniques with different types of sensors [1, 4, 5]. There has been also some research on sensor placement, but it was mostly limited to the placement of only one sensor [3, 7], or to the special case of marker detection [2]. In [10] the problem of finding the optimal camera placement for accurate reconstruction is approached using a multicellular genetic algorithm. However, for the case of robots following predefined paths and executing tasks at a home environment, it has not been discussed extensively how to arrange multiple sensors in the optimal way. Where to fix sensors and how many sensors are needed at least is an important requirement, when we design a robotic environment.

This sensor placement problem is closely related to the guard placement problem (AGP). The guard placement problem is the problem of determining the minimum number of guards required to cover the interior of an art gallery. It is addressed by the art gallery theorem [9, 11]. In AGP all guards are assumed to have similar capabilities. In this study, however, we also consider cameras with different field-of-views. Additionally, contrary to the guard placement problem, the field-of-view in our sensor model is restricted due to sensor properties. We also perform importance weighting of space. In other words, we assign importance values to different regions in space considering the robot trajectory and design the sensor placement taking into consideration this partitioning, as explained in the following Section.

In Section II we define an optimization problem of sensor arrangement. In Section III we define a methodology to evaluate the arrangement of sensors and in Section IV an algorithm to design the optimal arrangement. In Section V simulation results are presented.

II. DEFINITION OF THE OPTIMIZATION PROBLEM

We assume the condition of a robot moving at a constant height in a room where ceiling cameras are installed. The robot executes home service tasks following a pre-defined path. The ceiling cameras provide the robot with information about its position, as well as its environment. The amount of information provided depends highly on the total area visible by the ceiling cameras. Putting it in another way, it is necessary that the total field of view of all cameras covers a reasonable area of the room. Thus, it will be possible for the robot to acquire enough information about its working space. However, it is also reasonable to assume that the region near the path followed by the robot is more important than the rest area of the room. On the other hand, some other areas may not be important at all and may not need to be covered by the cameras. Therefore, importance values are assigned to different regions in space [8]. The importance weighting of space at the height at which the robot is moving is illustrated in Fig. 1, where darker regions are more important than white ones, except for black pixels which mark the border of the space or static obstacles. The requirement of the design is, therefore, to maximize the area which is visible by the cameras over a required threshold, taking into consideration the importance weighting of space. Moreover, it is better to have fewer cameras, considering the cost. Accordingly, the optimization problem is defined as follows:

The optimization problem is, given the map of the room, the importance weighting of space, and a required threshold, to find the minimum number of cameras, whose optimal arrangement can satisfy the necessary condition that the weighted ratio of the visible to the total area of the room is above the required threshold.

Our approach to this problem consists of the following two steps. First, we fix the number of cameras and maximize the weighted ratio of visible to total area of the room by changing the arrangement of cameras. Secondly, we find the minimum number of cameras satisfying the necessary condition that the weighted ratio of the area which is visible from the cameras to the total area of the room is above the given threshold. As a result, the minimum number and the closely optimal arrangement of cameras are found.

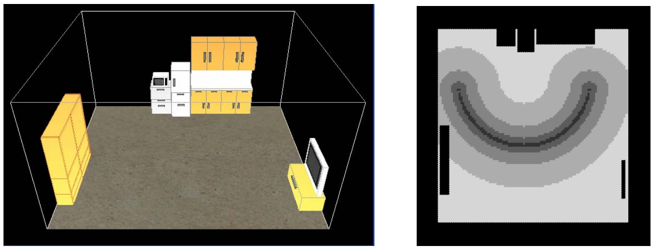

(a) (b)

Fig. 1. (a) Virtual 3D room environment and (b) 2D cut of the room at a specific height and importance weighting of space considering the robot path

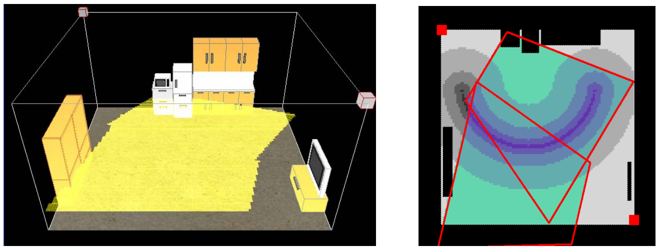

(a) (b)

Fig. 2. (a) Virtual 3D room environment with two cameras and (b) 2D cut of the room at a specific height including camera viewing frustrums projections

III. EVALUATION FUNCTION

The evaluation function of each arrangement is defined as the weighted ratio of the visible to the total area of the room. Assuming that all the cameras are calibrated, the viewing frustrum of each camera can be calculated from the focal length, the angle of view and the pose of the camera and it has the form of a rectangular pyramid. At a specific height, the total visible area from all the cameras can be calculated from the projections of the viewing frustrums of all the cameras at that height. In that case, the total area of the room takes the form of an obstacled rectangular environment. The visible area is this enclosed by the projections of the viewing frustrums of the cameras.(Fig. 2(a), (b)).

The total area is sampled by a rectangular grid of N points O_i of equal distance. Each point O_i (x, y) is assigned a weight value w_i, which depends on its *importance.* We estimate the importance of each point, according to the minimum distance d of the point from the robot trajectory C. Therefore, the weight value w_i of a point O_i is defined as follows:

$$w_i = \begin{cases} W_1 & (\text{if } d < D_1) \\ W_2 & (\text{if } D_1 \le d \le D_2) \\ \cdots & \\ W_m & (\text{if } D_{m-1} \le d) \end{cases} \tag{1}$$

where m is the number of the weighting partitions (we assume $m \geq 2$), d is the minimum distance of the point O_i from the robot trajectory C, and $D_1 \ldots D_{m-1}$ and $W_1 \ldots W_m$ are fixed values, where ($W_1 \geq W_2 \geq \ldots \geq W_m$). Then, the weighted ratio r is calculated as follows:

$$F = \frac{\sum_{i=1}^{N-M} f(O_i) \cdot w_i}{\sum_{i=1}^{N-M} w_i}, \quad \text{where } f(O_i) \rightarrow \{0, 1\} \tag{2}$$

The function $f(O_i)$ is one if the point O_i is visible by one or more cameras or zero if it is not visible by any camera. M is the number of points in the grid that are always occluded by static obstacles and therefore are not included in the calculation.

Therefore, F is an estimation of the ratio of the area visible by the cameras to the total area of the room, considering the importance distribution of the total area.

IV. DESIGN OF THE SUB-OPTIMAL ARRANGEMENT OF SENSORS

We discussed in Section II that the plausible requirement in arranging the cameras is to increase the weighted ratio of the area which is visible from the cameras to the total area of the room. In this section we describe the algorithm for the design of the arrangement with respect to the above requirement.

A. *Assumptions and Conditions*

We make the following assumptions:

1. the robot is moving at a known path and executing tasks at a constant height
2. the map of the room is given
3. the focal length and tilt value (rotation angle on the horizontal axis) of the cameras is constant
4. importance values are assigned to different regions of space according to the importance of each region

B. *Formulation of the Sub-optimal Arrangement of Sensors*

The first step is to maximize the ratio of the visible to the total area in the environment with n cameras, where n is fixed. This process can be expressed as the formula (3), and our first objective is to maximize the evaluative function F defined below:

$$F \rightarrow \max \tag{3}$$

The second step is to find the minimum number of cameras which satisfies the given value K, which is the *acceptable* threshold for the evaluation function. In Eq. (3) the number of cameras is fixed. However, when we change this number and search for the arrangement with each number of cameras, we can find how many cameras are needed at least. Our second objective can be expressed as the formula (4) assuming that $Conv(n)$ denotes the maximized value of the formula F in case of n cameras.

$$\min\left\{n \mid Conv(n) \geq K\right\} \tag{4}$$

$$\text{where } Conv(n) \equiv \max\left\{F(n) \mid n \textit{ fixed}\right\},$$

n: number of cameras

K: given threshold of ratio of visible to total area of the room

C. Algorithm to Minimize the Evaluation Function F

We apply the algorithm of optimal arrangement of artificial landmarks in Tashiro *et al.* [6], in order to achieve the objectives defined in the previous Section. By means of this algorithm we find the arrangement of *n* cameras which gives the maximum value of the evaluative function *F*.

We start from the initial arrangement of cameras generated randomly and shift the cameras one by one following some strategy until the convergent arrangement is obtained. The strategy consists of two methods described below:

A. change position value by the *steepest descent method*

B. stay at the same place if A does not make the present value of *F* greater.

When adopting the method A in our strategy, we change the present position $P(x, y)$ by

$$\nabla F = \left(\frac{\partial F(x,y,r)}{\partial x}, \frac{\partial F(x,y,r)}{\partial y} \right) \tag{5}$$

Therefore, the present position P of the target camera is shifted by ∇F and the next position of the camera will be $(P + \nabla F)$. Note that F is the evaluative function defined in Eq. (2). The values (x, y) denote the coordinates of the target camera in the plane of the ceiling of the room. The r value is the angle of the camera corresponding to rotation on the vertical axis (perpendicular to the ceiling). The r value is set at each position to the value that gives the best F for that particular position. This value can be easily found by a sequential search at the [0, 360) degrees range. We assume that the height of the cameras is constant, as the cameras are always attached on the ceiling. Also, we assume that the tilt value (rotation angle of the camera on the horizontal axis) is constant for simplification purposes. If we can not make the value of F greater than the present value, the camera stays at the same place (Fig. 3). The position and angle value of each camera are changed one by one. The process is repeated until there is no camera movement that can increase the value of F, which means that F converges. Although this is not a global-optimization method, we can obtain closely maximized and practical arrangement of cameras promptly.

V. SIMULATION

Given the threshold of the ratio of the visible to the total area at a specific height in the robot's navigation space, we find the minimum number of cameras and the arrangement satisfying this necessary condition.

A. Assumptions and Conditions in the Simulation

In this simulation, first we demonstrate that an initial arrangement of cameras set randomly can be transformed into the arrangement that has the maximized value of F by the algorithm proposed in section IV.

We mention a brief statement about how to implement the *steepest descent method*. In this simulation, we use the following formula instead of ∇F, as an approximation of Eq. (5) in Section IV.

$$\Delta F = \left(\frac{F(x+h, y, r2_{opt}) - F(x, y, r1_{opt})}{h}, \frac{F(x, y+h, r3_{opt}) - F(x, y, r1_{opt})}{h} \right)$$

$$P_{i+1} = P_i + K \cdot \Delta F \tag{6}$$

Where

P_i : (x, y) position of camera at step-*i*

h : small constant value for partial-differential

K : coefficient

ΔF : negative of steepest descent direction

$r1_{opt}$, $r2_{opt}$, $r3_{opt}$ rotation angles that result in the maximum F value in positions P_i, $P_i(x+h, y)$ and $P_i(x, y+h)$ respectively, found by sequential search at the range [0, 360).

The system is set up as the following:

1. The environment is a 5.78[m] x 5[m] x 3[m] 3D room as shown in Fig. 1(a).
2. Each simulated camera has a zoom lens of 3[mm], a horizontal viewing angle of 42 [deg] and a 4/3 image width – height ratio.
3. The height at which we assume the robot is executing home service tasks, and at which the non-visible and the total area are calculated, is set to 0.56 [m].
4. The tilt value of each camera is fixed to 50 [deg]
5. The parameters of the steepest descent method are $h = 0.05$ [m], $K = 0.25$.
6. The parameters of the evaluation function, as defined in Section III are set to $m = 5$, $N = 10^5$ points, $[W_1, W_2, W_3, W_4, W_5]$= [1.0, 0.8, 0.6, 0.4, 0.2], $[D_1, D_2, D_3, D_4]$= [80, 300, 760, 1680] [mm].

We prepare several initial arrangements of cameras generated randomly. Each initial arrangement is transformed into the convergent arrangement, and we adopt the one that has the most maximized convergent value of F.

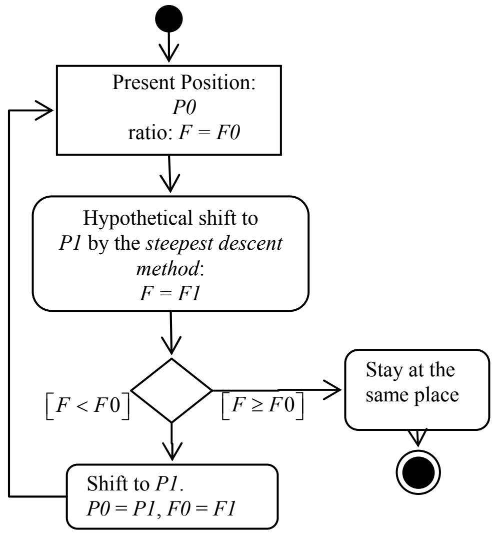
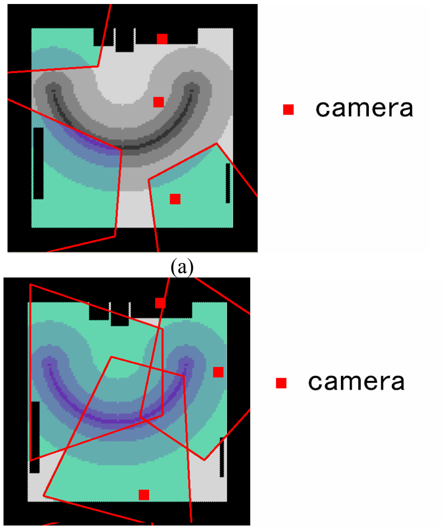


Fig. 3. Activity diagram of shifting camera-*i*.

B. *Results of Simulation*

We show the initial arrangement in case of three cameras and the arrangement after 86 steps in Fig. 4. As one step we define one camera position and rotation change, as described in Fig. 3. After the arrangement the weighted ratio of the visible to total room area becomes 0.9597. The transition graph of the evaluation function is shown in Fig. 5. We change the number of cameras, maximize the function F in each case and find the convergent arrangement with each number of cameras. Fig. 6 indicates that if the acceptable ratio is 90%, we need at least three cameras. And if the ratio is 99%, we need at least four cameras.



(a)

(b)

Fig. 4. (a) Initial random arrangement of three cameras. Weighted ratio is 0.3373 (b) Arrangement of three cameras at step 86, weighted ratio is 0.9597

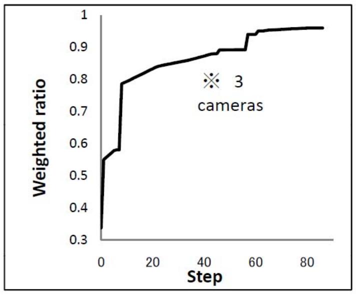


Fig. 5. Transition of the ratio to the convergent value for the case of three cameras

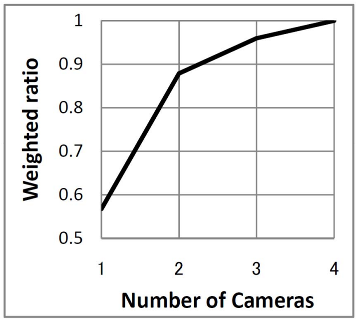


Fig. 6. Maximized weighted ratio for different number of cameras

V. CONCLUSION

In order to establish the methodology to design a sub-optimal arrangement of cameras, we defined the optimization problem in arranging ceiling cameras, and introduced the evaluation function to evaluate our simulation. Then, we formulated the optimization problem and proposed the algorithm to design the arrangement of cameras. Simulation results indicate that given the map of a room, we can find the minimum number of cameras which satisfies the required weighted ratio. For the tested room environment, if the given threshold is 90%, three cameras optimally arranged are enough. If it is 99%, four cameras are needed at least. For each case, the closely optimal position and rotation angle of the cameras are found.

We could design very practical arrangement of sensors although this arrangement is not globally optimal. We use cameras as one good example of sensors. However, by changing appropriately the evaluation function, the proposed method can be easily applied to other kinds of sensors.

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