Optik 125 (2014) 2220–2224

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Coverage performance analysis of multi-camera networks based on observing reliability model

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ARTICLE INFO

Article history:
Received 15 May 2013
Accepted 12 October 2013

Keywords:
Multi-camera networks
Coverage performance
Camera model
Observing reliability model
Capture rate

ABSTRACT

Coverage control is a fundamental problem in sensor networks, which has been explored thoroughly based on a traditional scalar sensing model. However, camera sensors are different from traditional scalar sensors as different cameras from different positions can form distinct views of the target. Hence, Target size and geometric structure of camera nodes can greatly influence the surveillance ability of a camera network. In view of this, a novel observation reliability model of a camera network is proposed, and relationship between surveillance ability and observing reliability for the target is studied. On the basis, a camera network coverage model which considers about obstacles and interesting area of the environment is investigated, and optimized by dynamic planning method. Simulation results show that our method can effectively improve the target capture rate of the network and also we can observe the target from a better view.

1. Introduction

Recently, multi-camera networks [1–3] have attracted tremendous research interests due to their vast and significant applications in areas such as security monitoring, locating and tracking people and traffic management.

Modeling the coverage of a sensor network is an important step in a number of design and optimization techniques. Existing work on this problem suggests a very simple model on characterizing the coverage, in which a target is considered to be covered if it is within the sensor's field of view, which can be a disk [4] or sector [5]. With this model, extensive studies have been devoted to the problem of coverage over a given target area. In general, their innovations are either new sensing and environment models [6–10] or new algorithms [11–15] on improving coverage rate in a multi-camera network.

Mittal and Davis [6] investigated a coverage model and scene structure in a multi-camera networks. They dealt with the tasks of determining measures for evaluating their performance and of determining good sensor configurations for better system performance. Zhao and Cheung [7] developed a general camera networks model, and studied the multi-camera networks coverage enhancement in 3-D environment. Wu et al. [8] proposed a probabilistic sensing model to realize minimal k-coverage set problem in directional sensor networks. However, the camera sensing ability was only related with distance between camera and a target. Tezcan and Wang [9] considered obstacles in the environment, and realized the maximum coverage problem with minimize overlap regions among adjacent sensors, in which the number of targets to be covered is maximized whereas the number of sensors to be activated is minimized. In [10], Tan et al. proposed the rotatable 2D directional sensing model. The directional sensor networks can achieve the enhanced area coverage performance by adjusting the sensing orientations of cameras with fixed locations. Based on [10], Tan et al. [11] proposed a potential field based coverage-enhancing algorithm. They proposed a concept of coverage area "centroid", and translated this coverage-enhancing problem into a uniform distribution problem of centroid points to eliminate the sensing overlapping regions and coverage holes. Adriaens et al. [12] presented an optimal polynomial time algorithm for computing the worst-case breach coverage in camera sensor networks. Cheng et al. [13,14] proposed a distributed greedy algorithm to enhance the entire coverage performance of multi-camera networks, and this method was proved to be with good convergence. The authors of [15] discussed multiple directional cover sets problem of organizing the directions of sensors into a group of non-disjoint cover sets in each of which the directions cover all the targets so as to maximize the network lifetime.

All of the studies mentioned above are taken coverage rate as the final index. However, camera sensors are different from traditional scalar sensors. Camera sensors may generate very different views of the same object if they are from different view angles, shown in Fig. 1. On account of that traditional Boolean and probabilistic sensor model do not consider this intrinsic property of a camera

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http://dx.doi.org/10.1016/j.ijleo.2013.10.052

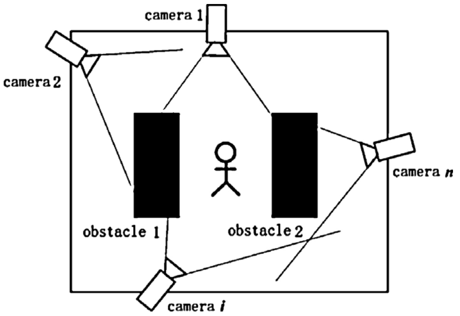

Fig. 1. Multi-camera networks.

sensor, we propose a novel observing reliability model of a camera network, and optimize coverage rate and sensing reliability of the multi-camera network simultaneously.

2. Camera model

2.1. Directional sensor model

It is necessary to design reasonable camera model in order to describe the sensing capability in multi-camera networks. In some former research, 2-D Boolean model with direction optionally is usually used, shown in Fig. 2, which can be defined as a four parameter array $\left(\boldsymbol{C}, R, \boldsymbol{V}(t), \theta\right)$. Where $\boldsymbol{C}$ represents the location of the camera; R represents the sensing radius; $\boldsymbol{V}(t)$ is the sensing direction at time t, and θ represents the sensing angle of the camera.

At time t, the sensing area is a sector, as the sensing direction changes with time, the camera can coverage a circle with radius R.

If a target X can be covered by a camera, Eq. (1) should be satisfied,

$$d \le R, \quad \beta < \frac{\theta}{2} \tag{1}$$

2.2. Observing capability of a camera

In fact, the observing capability model of a camera is more complex than Boolean model. As people's eyes, there is also best observing distance, either too near or too far away from the target can decrease the sensing capability. Therefore, we develop a camera observing function to describe its sensing ability.

According to optical transfer function, spatial resolution of an optical detection system can be described by the number of black-and-white stripes in a field angle. And Johnson's criteria describe the probability that an object can be detected, which is related to the number of stripes across the minimum dimension of a target [16]. The detection probability can be calculated by Eq. (2),

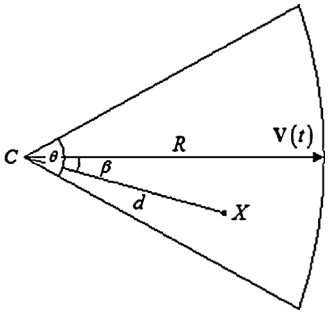

Fig. 2. Camera model.

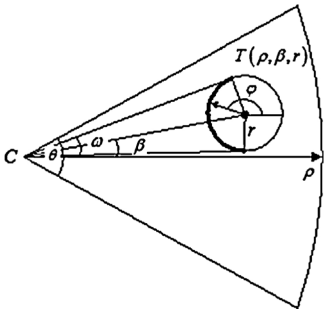

Fig. 3. Camera observing capability for a target.

$$P(N) = \frac{(N/N_{50})^E}{1 + (N/N_{50})^E}, \quad E = 2.7 + 0.7\left(\frac{N}{N_{50}}\right) \tag{2}$$

where N represents the actual number of stripes, and N_{50} is the required number of stripes for a 50% level of performance.

As shown in Fig. 3, define a target $T(\rho, \beta, r)$ with center (ρ, β) and radius r in polar coordinate system. According to Johnson's criteria, the camera sensing capability function can be defined as Eq. (3).

$$P(\omega) = \frac{(\omega/\alpha_C)^E}{1 + (\omega/\alpha_C)^E}, \quad E = 2.7 + 0.7 \times \left(\frac{\omega}{\alpha_C}\right) \tag{3}$$

where ω represents the field angle from the object to the camera, α_C represents the critical observing angle of a camera, which is related to spatial resolution of a camera.

From Eq. (3), it is can be found that, for a certain camera, the larger of the target, the higher probability that a camera can detect it. On the other hand, a camera with higher spatial resolution will get more details of a target.

2.3. Observing reliability model of a camera

We define the observing reliability of a camera for target $T(\rho, \beta, r)$ as Eq. (4)

$$g(T) = \frac{1}{2\pi} \cdot P(\omega) \cdot \int_0^{2\pi} D(\varphi)\, d\varphi \tag{4}$$

where $D(\varphi)$ is the observing reliability function defined on the target described as Eq. (5),

$$D(\varphi) = \begin{cases} -\cos(\gamma), & \left|\pi - (\varphi - \beta)\right| < \dfrac{\pi}{2} - \dfrac{\omega}{2} \\ 0, & \text{else} \end{cases}, \qquad \gamma$$

$$= \frac{r + \rho\cos(\varphi - \beta)}{\sqrt{\rho^2 + r^2 + 2\rho r\ \cos(\varphi - \beta)}} \tag{5}$$

Field angle ω from the target to the camera is shown in Eq. (6),

$$\omega = \arcsin\frac{r}{\rho} \tag{6}$$

If there is only part of the target in the field of view of a camera, which is shown in Fig. 4, the observing reliability function is defined as Eq. (7),

$$D(\varphi) = \begin{cases} -\cos(\gamma), & \left|\pi - (\varphi - \beta)\right| < \dfrac{\pi}{2} - \min\left(\dfrac{\omega}{2}, \dfrac{\theta}{2} - \beta\right) \\ 0, & \text{else} \end{cases} \tag{7}$$