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Collaborative visual area coverage☆

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HIGHLIGHTS

- Visual area coverage using aerial agents.
- Collaborative control of aerial agents subject to agents' altitude constraints.
- Overlapping of sensed areas does not increase the overall visually covered area.

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ABSTRACT

This article examines the problem of visual area coverage by a network of Mobile Aerial Agents (MAAs). Each MAA is assumed to be equipped with a downwards facing camera with a conical field of view which covers all points within a circle on the ground. The diameter of that circle is proportional to the altitude of the MAA, whereas the quality of the covered area decreases with the altitude. A distributed control law that maximizes a joint coverage-quality criterion by adjusting the MAAs' spatial coordinates is developed. The effectiveness of the proposed control scheme is evaluated through simulation studies.

1. Introduction

Area coverage over a planar region by ground agents has been studied extensively when the sensing patterns of the agents are circular [1,2]. Most of these techniques are based on a Voronoi or similar partitioning [3–6] of the region of interest and use distributed optimization, model predictive control [7,8] or game theory [9] among other techniques. There is also significant work concerning arbitrary sensing patterns [10–12] avoiding the usage of Voronoi partitioning [13,14]. Both convex and non-convex domains have been examined [15,16].

Many algorithms have been developed for mapping by MAAs [17–20] relying mostly in Voronoi-based tessellations or path–planning. Extensive work has also been done in area monitoring by MAAs equipped with cameras [21,22]. In these pioneering research efforts, there is no maximum allowable height that can be reached by the MAAs and the case where there is overlapping of their covered areas is considered an advantage as opposed to the same area viewed by a single camera. There are also studies on the connectivity and energy consumption of MAA networks [23,24], as well as ground target detection and tracking [25].

In this paper the persistent coverage problem of a convex planar region by a network of MAAs is considered. The MAAs are assumed to have downwards facing visual sensors with a conical field of view, thus creating a circular sensing footprint. The covered area as well as the coverage quality of that area are dependent on the altitude of each MAA. MAAs at higher altitudes cover more area but the coverage quality is lower compared to MAAs at lower altitudes. A partitioning scheme of the sensed region, similar to [13], is employed and a gradient based control law is developed. This control law leads the network to a locally optimal configuration with respect to a combined coverage-quality criterion, while also guaranteeing that the MAAs remain within a desired range of altitudes. The main contribution of this work is the guarantee it offers that all MAAs will remain within a predefined altitude range, guaranteeing the safe operation of all MAAs. In addition to that, the criterion used differs with other works in the way it takes into account regions covered by multiple agents. More precisely, when a region is covered by multiple MAAs, only the MAA with the best coverage quality over that region is taken into account, in contrast to [21,22] where all MAAs covering that region are taken into account, thus in our work overlapping between the MAAs sensing regions is avoided if possible. Both approaches to handling regions covered by multiple MAAs can be useful depending on the particular use case of the control scheme. Finally, algorithmic

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implementations of the control scheme are provided both in pseudocode and as on open-source (Matlab-based) code.

The problem statement and the joint coverage–quality criterion are presented in Section 2. The chosen quality function is defined in Section 3 and the resulting sensed space partitioning scheme in Section 4. The distributed control law is derived and its most notable properties explained in Section 5. The stability of the altitude control law and its property to restrict the nodes' altitude is examined in Section 6. Simulation studies highlighting the efficiency of the proposed control law are provided in Section 8 followed by concluding remarks.

2. Problem statement

Let $\Omega \subset \mathbb{R}^2$ be a compact convex region under surveillance. We assume a swarm of n MAAs, each positioned at the spatial coordinates $X_i = [x_i\ y_i\ z_i]^T,\ i \in I_n$, where $I_n = \{1, \dots, n\}$. We also define the vector $q_i = [x_i\ y_i]^T,\ q_i \in \Omega$ to note the projection of the center of each MAA on the ground. The minimum and maximum altitudes each MAA can fly to are $z_i^{\min}$ and $z_i^{\max}$ respectively with $z_i^{\min} < z_i^{\max}$, thus $z_i \in [z_i^{\min},\ z_i^{\max}],\ i \in I_n$. It is also assumed that $z_i^{\min} > 0,\ \forall i \in I_n$, since setting the minimum altitude to zero could potentially cause some MAAs to crash.

Instead of using a complicated dynamic model, such as the quadrotor helicopter dynamics in [26], a simplified dynamic model is used. Each MAA is approximated as a point mass, thus the simplified kinodynamic model is

$$\dot{q}_i = u_{i,q}, \quad q_i \in \Omega,\ u_{i,q} \in \mathbb{R}^2,$$
$$\dot{z}_i = u_{i,z}, \quad z_i \in [z_i^{\min},\ z_i^{\max}],\ u_{i,z} \in \mathbb{R} \tag{1}$$

where $\left[u_{i,q}, u_{i,z}\right]$ is the corresponding 'thrust' control input for each MAA (node). The minimum altitude $z_i^{\min}$ is used to ensure the MAAs will fly above ground obstacles, whereas the maximum altitude $z_i^{\max}$ guarantees that they will not fly out of range of their base station. In the sequel, all MAAs are assumed to have common minimum $z^{\min}$ and maximum $z^{\max}$ altitudes.

As far as the sensing performance of the MAAs (nodes) is concerned, all members are assumed to be equipped with identical downwards pointing sensors with conic sensing patterns. Thus the region of Ω sensed by each node is a disk defined as

$$C_i^s(X_i, a) = \{q \in \Omega : \|q - q_i\| \le z_i \tan a\}, \quad i = 1, \dots, n, \tag{2}$$

where a is half the angle of the sensing cone. As shown in Fig. 1, the higher the altitude of an MAA, the larger the area of Ω surveyed by its sensor.

The coverage quality of each node is a function $f(z_i) : [z^{\min},\ z^{\max}] \to [0, 1]$ which is dependent on the node's altitude constraints $z^{\min}$ and $z^{\max}$. The coverage quality of node i is assumed to be uniform throughout its sensed region C_i^s. The higher the value of $f(z_i)$, the better the coverage quality. It is assumed that as the altitude of a node increases, the visual quality of its sensed area decreases. The exact definition and properties of $f(z_i)$ are presented in Section 3.

For each point $q \in \Omega$, an importance weight is assigned via the space density function $\phi : \Omega \to \mathbb{R}^+$, encapsulating any a priori information regarding the region of interest. Thus the coverage-quality objective is

$$\mathscr{H} \triangleq \int_\Omega \max_{i \in I_n} f(z_i)\, \phi(q)\, dq. \tag{3}$$

3. Coverage quality function

A uniform coverage quality throughout the sensed region C_i^s can be used to model downward facing cameras [27,28] that provide uniform quality in the whole image. The uniform coverage quality function $f(z_i) : [z^{\min},\ z^{\max}] \to [0, 1]$ was chosen to be

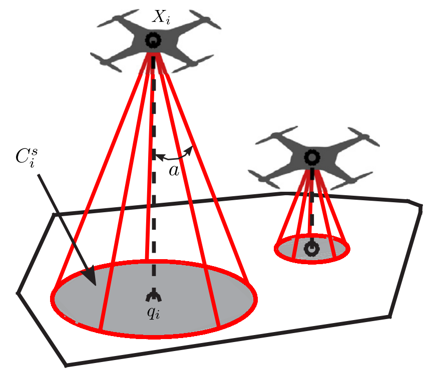

Fig. 1. MAA-visual area coverage concept.

$$f(z_i) = \begin{cases} \dfrac{\left(\left(z_i - z^{\min}\right)^2 - \left(z^{\max} - z^{\min}\right)^2\right)^2}{\left(z^{\max} - z^{\min}\right)^4}, & q \in C_i^s \\ 0, & q \notin C_i^s. \end{cases} \tag{4}$$

A plot of this function can be seen in Fig. 2 [Left]. This function was chosen so that $f(z^{\min}) = 1$ and $f(z^{\max}) = 0$. In addition, $f(z_i)$ is first order differentiable with respect to z_i, or $\frac{\partial f(z_i)}{\partial z_i}$ exists within C_i^s, which is a property that will be required when deriving the control law in Section 5.

The derivative $\frac{\partial f(z_i)}{\partial z_i} : [z^{\min},\ z^{\max}] \to [f_d^{\min}, 0]$ is evaluated as

$$f_d(z_i) \triangleq \frac{\partial f(z_i)}{\partial z_i} = \begin{cases} \dfrac{4\left(z_i - z^{\min}\right)\left[\left(z_i - z^{\min}\right)^2 - \left(z^{\max} - z^{\min}\right)^2\right]}{\left(z^{\max} - z^{\min}\right)^4}, & q \in C_i^s \\ 0, & q \notin C_i^s \end{cases} \tag{5}$$

where $f_d^{\min} = f_d\left(z^{\min} + \frac{\sqrt{3}}{3}\left(z^{\max} - z^{\min}\right)\right) = -\frac{8\sqrt{3}}{9\left(z^{\max} - z^{\min}\right)}$. A plot of this function can be seen in Fig. 2 [Right].

It should be noted that $f(z_i)$ and $f_d(z_i)$ are 4th and 3rd degree polynomials respectively and as a result continuous functions of z_i; any strictly decreasing and differentiable with a continuous derivative function $f(z_i) : [z^{\min},\ z^{\max}] \to [0, 1]$ can be potentially used.

4. Sensed space partitioning

The assignment of responsibility regions to the nodes is achieved in a manner similar to [13], where only the subset of Ω sensed by the nodes is partitioned. Each node is assigned a cell

$$W_i \triangleq \left\{q \in \Omega : f(z_i) \ge f(z_j),\ j \ne i\right\} \tag{6}$$

with the equality holding true only at the boundary ∂W_i, so that the cells W_i comprise a complete tessellation of the sensed region.

Because the coverage quality is uniform, $\partial W_j \cap \partial W_i$ is either an arc of ∂C_i if $z_i < z_j$ or of ∂C_j if $z_i > z_j$. In the case where $z_i = z_j$, $\partial W_j \cap \partial W_i$ is chosen arbitrarily as the line segment defined by the two intersection points of ∂C_i and ∂C_j. Hence, the resulting cells consist of circular arcs and line segments.

If the sensing disk of a node i is contained within the sensing disk of another node j, i.e. $C_i^s \cap C_j^s = C_i^s$, then $W_i = C_i^s$ and $W_j = C_j^s \setminus C_i^s$. An example partitioning with all of the aforementioned cases illustrated can be seen in Fig. 3 [Left], where the boundaries