Graph Embedding for the Division of Robotic Swarms

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***Abstract*— A key decision in human-swarm teaming is dividing a swarm into sub-swarms to address separate issues or to accomplish a task over a large area. As the swarms grow in complexity, the cognitive load needed to manually divide the swarm grows in magnitude. We propose a new multimodal graph embedding method to construct a unified representation that fuses multiple information modalities to describe and divide a swarm. Our approach takes into account diverse relationships in the swarm, such as spatial relationships, communication capabilities, and hierarchical structures. The relationship modalities are encoded as directed graphs which are embedded into a unified representation for each swarm agent. Experimental results show that our method successfully decides correct sub-swarms based on swarms' multifaceted internal structures, and outperforms baseline methods.**

I. Introduction

Because of their robustness and flexibility, robotic swarms are being increasingly researched and used in large-scale applications, such as search and rescue and area exploration [1]. However, as the number of robots in a swarm increases, the swarms become cognitively more difficult for humans to understand and command [2]. At scale, the complexities of internal relationships become difficult for human operators to conceptualize. Figure 1 provides an illustration of how robots can appear organized in physical space, but also contain hierarchical relationships or communication capabilities within the swarm that are more difficult to perceive. These relationships are further complicated by swarm member interactions with obstacles and the surrounding environment. When combined, these challenges result in swarm states that are both difficult for a human operator to accurately perceive and for a system to display.

To address these problems, we propose a novel multimodal graph embedding approach to encode diverse relationships of robots in a swarm as graphs and integrate the multiple graphs into a unified representation that is applied to divide a swarm into sub-swarms, without the intervention of a human operator. We model each internal relationship of the robots in a swarm using a directed graph as an information modality. Given a set of member relationships, we construct multiple graphs that are applied as the input to our approach. Then, we propose a new multimodal Katz index to integrate multiple graphs of robot relationships and embed them into a unified representation for each robot in a swarm. Then, the constructed representation is used to identify subdivisions of a swarm based upon unsupervised learning. Our multimodal graph-embedded swarm division is capable of fusing diverse swarm member relationships and identifying divisions without requiring explicit knowledge of tasks.

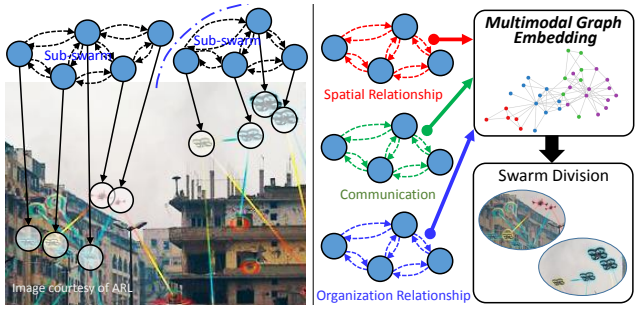

Fig. 1. A motivating example of automatic swarm division and our solution based on multimodal graph embedding. In real-world swarm systems, robot members in a swarm typically have a variety of relationships, such as spatial relationships, communication connectivity, and organization hierarchy. This complexity makes swarm division a difficult or impossible problem for a human operator. Our proposed multimodal graph embedding approach can integrate multiple relationship graphs and identify effective sub-swarms.

II. Approach

In real-world swarm deployment, members within a swarm typically have a multiple various relationships (e.g., spatial relationships, communication connectivity, and organization hierarchy). We encode the swarm with M graphs, where $\mathcal{G}_m$ is the graph describing the m-th relationship of swarm members. Each graph $\mathcal{G}_m$ is described by an adjacency matrix $\mathbf{A}_m \in \mathcal{R}^{N\times N}$, where each element a_{ij} is the weight of the edge connecting vertex v_i to vertex v_j.

To achieve our objective of encoding multiple graphs and embedding them into a single vector representation, we propose a new multimodal formulation of the Katz index [3] that is able to take multiple graphs as the input modalities and form a single similarity matrix $\mathbf{S} \in \mathcal{R}^{N\times N}$ that integrates the information of all graphs. To do this, we introduce a weight w_m for each $\mathbf{A}_m$ describing the importance of the relationship encoded by $\mathcal{G}_m$, where $\sum_{m=1}^{M} w_m = 1$. We then construct the multimodal similarity matrix $\mathbf{S}$ that embeds information of all graphs as follows:

$$\mathbf{S} = \left(\mathbf{I} - \alpha \sum_{m=1}^{M} w_m \mathbf{A}_m\right)^{-1} - \mathbf{I} \tag{1}$$

In order to create a lower-dimensional representation than $\mathbf{S}$, which is necessary when embedding big graphs of a large-scale swarm, we perform Singular Value Decomposition: $\mathbf{S} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^T$. To further reduce the dimensionality of the

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