Quantifying swarm reorganization in soldier crabs under external threats

Claudio Feliciani[1†], Zeynep Yücel[2], Hisashi Murakami[3], Yuto Uesugi[4]
Takenori Tomaru[3], Tamao Maeda[5], Sakurako Tanida[1]

[1]Graduate School of Engineering, The University of Tokyo, Tokyo, Japan
(E-mail: feliciani@g.ecc.u-tokyo.ac.jp)
[2]Department of Environmental Sciences, Informatics and Statistics, Ca' Foscari University of Venice, Venice, Italy
[3]Faculty of Information and Human Science, Kyoto Institute of Technology, Kyoto, Japan
[4]Graduate School of Science, The University of Tokyo, Tokyo, Japan
[5]Research Center for Integrative Evolutionary Science, The Graduate University of Advanced Studies, Hayama, Japan

Abstract: This study investigates the collective behavior of soldier crab swarms in response to external threats. Using aerial video observations and custom computer vision techniques, we identify how swarm density influences behavioral shifts. Preliminary analysis reveals distinct responses based on local organization: isolated or loosely grouped crabs adaptively reorganize, while dense swarms remain largely unresponsive. A framework for detecting swarm boundaries is introduced, enabling future quantitative studies relevant to both biological swarms and swarm robotics.

Keywords: Soldier crab, Swarming, Collective vigilance, Environmental stimulus, Swarm size

1. INTRODUCTION

Swarming is a common behavior in social animals such as fish (milling), birds (flocking), sheep (herding), wolves (packing), and insects like locusts and ants [1, 2]. Humans also form self-organized groups in crowds. These formations typically arise without centralized control in air, water, or on land, a phenomenon known as swarm intelligence [3].

A key feature of swarms is their ability to adapt to environmental changes. For example, birds can reorganize their flock to evade predators [4]. This adaptability is highly relevant to swarm robotics, where coordinated group behavior must respond dynamically to external conditions. However, although animal swarm reorganization has been studied, most works focus on isolated swarms and localized adaptations.

In previous research [5], we investigated the swarm behavior of soldier crabs, a species native to tropical Japan. Their swarms exhibit continuous merging and splitting, driven by local conditions and resource availability. They also react to threats based on swarm state, suggesting optimized collective behavior. However, our earlier study was qualitative. Here, we introduce a method for quantitatively analyzing these behaviors using ad hoc computer vision tools. Preliminary results align with our past observations.

2. OBSERVATIONS

Aerial observations were conducted on a sandy tidal flat, the natural habitat of soldier crabs, near a straight road. During these sessions, we observed that crabs reacted collectively when large buses passed, typically moving away from the road. Qualitative video analysis revealed that responses varied with swarm conditions (see Fig. 1).

Three distinct behaviors were identified:

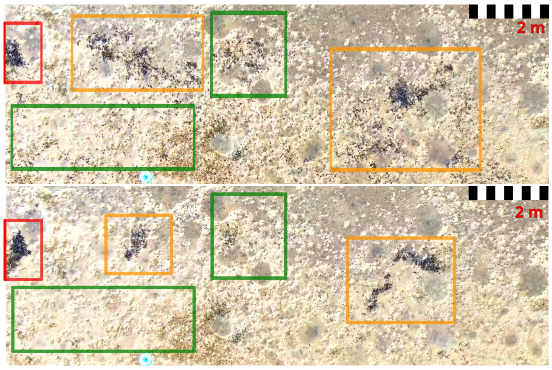

Fig. 1 Change in collective behavior of soldier crabs following a perceived threat. The top image shows the swarm 10 seconds before a bus passes; the bottom, 30 seconds after. Green indicates isolated individuals, yellow synchronized motion, and red dense swarms.

- *Green boxes:* Isolated crabs showed individual behavior, often burrowing into the sand to avoid the threat.
- *Yellow boxes:* Loosely grouped crabs reorganized into compact swarms after the bus passed, indicating adaptive self-organization.
- *Red box:* Dense swarms showed little or no response, with minimal changes in configuration.

3. VIDEO ANALYSIS

The aim of this study is to determine under which conditions soldier crabs adopt the behaviors described above and to identify possible swarm density thresholds that trigger behavioral shifts. A central challenge lies in defining what constitutes a "swarm." While it's generally accepted that a swarm is a group of animals staying together and moving similarly, how close individuals must be remains unclear.

This issue is compounded by the limitations of the video

† Claudio Feliciani is the presenter of this paper.

data: soldier crabs appear extremely small (about 5×5 pixels), lack distinguishing features, and cannot be individually tracked, even with advanced algorithms. Therefore, in this research, we define a swarm as any video region with one of the following characteristics:

- A dark black area, representing dense swarms. These are distinguishable from reflective puddles and exclude isolated individuals.
- A region showing collective motion in a consistent direction. Sparse swarms exhibit aligned movement, detectable via areas of high velocity, even if not densely packed.

The analysis focuses on identifying swarm boundaries, allowing us to estimate density by comparing the area covered by crabs (black regions) to the total swarm area. This process is illustrated in Fig. 2.

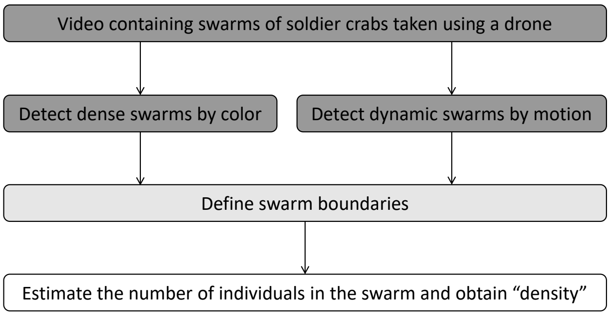

Fig. 2 Process to detect swarms and determine the density. In this preliminary work the operations highlighted in gray are presented.

This work focus on the initial part of the process aimed at defining the boundaries of the swarm and examine some changes in swarm configuration using a limited set of results.

4. PRELIMINARY RESULTS

Fig. 3 presents an example of the analysis performed using the methods described above.

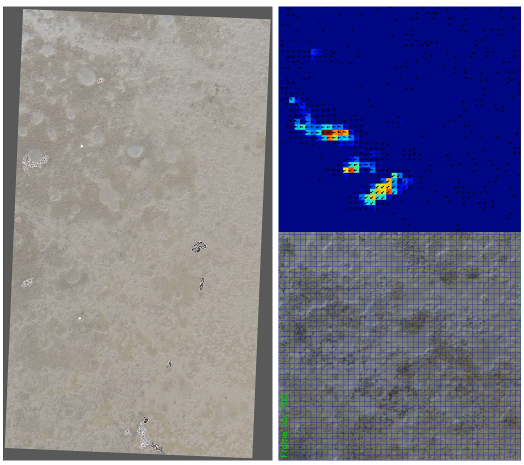

Fig. 3 Video processing based on visual information (left) and speed (right). The goal is to extract information for both dense and sparse swarms.

The image on the left shows a frame analyzed based on color information. Densely packed swarms, identified by black areas, are highlighted, with red dots indicating the center of mass for each swarm. The image on the right illustrates the method used to detect sparse swarms, where crabs move in similar directions. A region with high speed and uniform velocity orientation is visible in the top portion of the image.

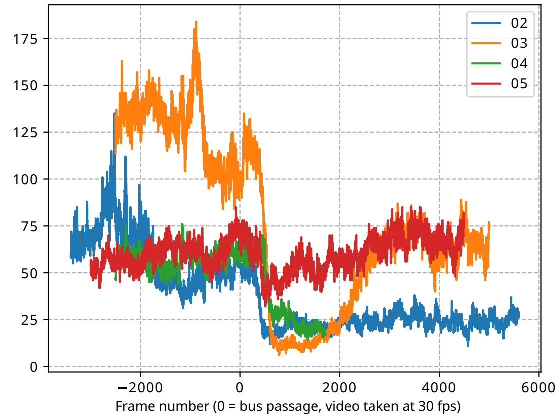

Fig. 4 Change in the number of swarms following threat detection (time 0). Each color represents a different observation (observation 01 was excluded due to low video quality).

Fig. 4 presents preliminary results from the analysis based on the detection of dark areas. As shown in the graph, there is a notable change in the number of swarms detected following the passage of the bus (time 0). However, this initial analysis only includes the color-based detection; the speed-based method is still under development. Both methods, along with more detailed results and their interpretation in the context of swarm robotics and collective animal behavior, will be presented at SWARM 2025.

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