Universal Journal of Computational Analysis **9 (2021), 25-29**
www.papersciences.com **EU Academy of Sciences (EUAS) e-Symposium**

Centre for the Advanced Study of Collective Behavior

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Abstract
Since 2009 the excellence cluster "Centre for the advanced study of collective behavior" at the University of Konstanz has been working together with the Max Planck Institute for Animal Behavior on researching animal swarms. Together we form a globally unique ensemble of research institutions in this field. Many animal species, like humans, not only make decisions as individuals, but also coordinate them collectively. Understanding the dynamics of swarms is therefore also an access to understanding social decision-making processes in humans. In the cluster quantitative methods are being developed to precisely measure and describe swarm behavior and to derive general mechanisms from it. Since the causality within swarms is particularly difficult to determine, we try to actively influence the behavior of individuals and swarms with virtual environments. The centre is jointly led by the authors[1].

Key Word and Phrases
Collective Behavior, Quantitative Studies, Tracking, Machine Learning, Visualization.

1. Introduction

The behavior of collectives can be striking and captivating. But what are the mechanisms that lead to the seemingly coordinated movements of flocking birds, the division of labor in social insects, or the emergence of fashions and fads in humans? Capitalizing on comprehensive multidisciplinary expertise, institutional build-up, and a unique infrastructure, the University of Konstanz and the Max Planck Institute for Animal Behavior are joining forces to create the Centre for the Advanced Study of Collective Behavior. Its mission will be to increase our understanding of collective phenomena through theoretically informed yet highly quantitative approaches in a vibrant and globally attractive hotspot for research.

Data-oriented research on collective behavior requires the study of dynamic, multi-scale and interdependent feedback processes: individual behavior influences higher-order collective properties (through multilayer networks of interaction), which then influence the behavior of other individuals, which in turn affects collective properties, and so on.

Simultaneously, it must account for heterogeneity in the actions, traits, and states of individuals as well as changing conditions in their physical and social environments. By bringing together expertise in biology, social psychology, behavioral economics, physics, and computer science, we will develop experimental approaches that will take these complexities into account in order to create a coherent understanding of collectives. Not only will our synergies provide fresh inspiration to the study of collective behavior, they will also enrich the contributing disciplines at the same time. Cutting-edge imaging and tracking technology – including the space-borne ICARUS system, and a forthcoming research building with unique facilities – will enable detailed observation in the wild as well as controlled experiments in virtual environments. Together, this will allow us to address fundamental questions regarding a wide range of species, from insects to humans, and over multiple scales, from neural mechanisms via individual perception and preferences to collective outcomes in groups or entire societies.

Developing an understanding of and, in some cases, governing collective behavior is essential for progress in many natural, social, and technological domains. The insights and paradigms generated by our quantitative studies will have implications that range from the fundamental

[1] Further information can be found at: https://www.exc.uni-konstanz.de/collective-behavior

through to the practical. Controlling pest insect swarms, curbing disease transmission, sensing speculative bubbles, incentivizing cooperation, and the decentralized control of robot swarms and drones are but a few examples. The captivating dynamic and visual nature of collective behavior will furthermore give us a distinctive opportunity to engage students and the public in the science behind the complex patterns that interacting individuals create.

2. Research Methodology

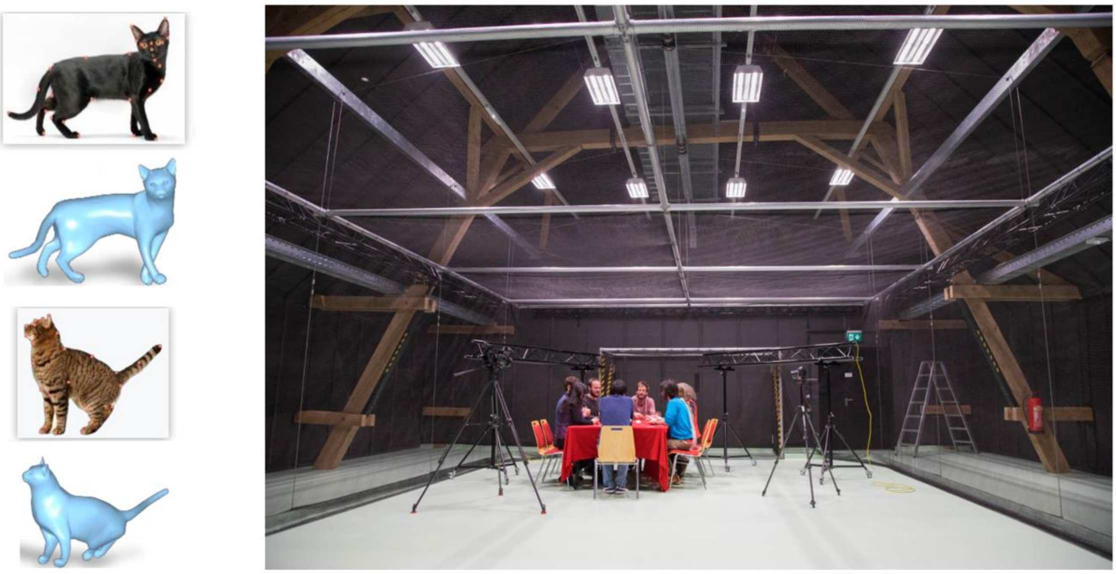
Pursuing our centre's research objectives requires that a number of new, quantitative tools and methodologies for measurement, analysis and modeling of collective behavior be established. This requires innovations in a wide range of computational approaches, including automated tracking of movements and body postures in both humans and animals; unsupervised methods to identify behavioral and physiological states; computational reconstruction of the sensory input; techniques to map sensory input to behavioral output; and new approaches to data management, visualization and analysis.

Recent advances in computer vision, largely driven by cost-effective and ubiquitous massively- parallel computational hardware (such as programmable graphics processing units) and corresponding transformation in the capabilities of deeply stru7ctured artificial neural networks (deep learning), now make it possible to achieve 3D reconstruction of complex structures, including the bodies of humans [1], [2] and animals (Figure 1).

Such technology sets the scene for the precise estimation of body postural/pose changes of organisms, providing crucial data that is required to quantify behavioral repertoires of individuals, including within collectives. The means by which such data can be obtained include stereo cameras, depth-sensing cameras and also marker-based (e.g. [3])) and marker-less [4], [5] motion capture systems (see [6] for a review).

For many organisms, including insects, fish and birds, such new approaches will provide vital information about how animals acquire information from their physical and social environment. These data can be combined with biological information about the eyes of each organism, such as motion-processing elements, or photoreceptor density and distribution (allowing us to estimate the acute centre(s) of their visual field; some species of birds have two foveae [7]).

These approaches will allow us, for the first time, to study the dynamics of highly naturalistic interactions, such as when animals or people meet, eat, or make decisions together. Our Imaging Hangar within the VCC, our new research building, which will be completed in spring 2021, and the existing Imaging Barn (15mx8mx4m, see Figure 1b) at the Max-Planck Institute, which is equipped with state-of-the- art tracking and projection technology, will be core facilities for such analyses. We will conduct highly controlled experiments on a diverse range of species, from swarm forming locusts to bird flocks and human groups, and over an unprecedented scale. We will address the considerable computational challenges of achieving accurate tracking and body posture reconstruction within such large volumes. As outlined below, we will furthermore seek to achieve both this and automated behavioral classification in real-time – something not currently possible. The Imaging Barn and Hangar will also be instrumented for real-time 3D sound localization, and for the controlled presentation of odours, providing a globally unique facility for the investigation of multi-modal sensing and communication.



(a) (b)

Fig. 1: a) Accurate body posture (pose) from images can be obtained for animals as well as humans (image modified from [11]); b) The existing Imaging Barn allows us to perform unprecedented studies on animals and humans.

A further technology that we will develop is Virtual Reality (VR) and Augmented Reality (AR), including fully immersive VR for freely moving animals [8]. This allows individuals to be embedded in a photorealistic synthetic world in which they can move and interact with virtual organisms, or inspect, and move around, virtual obstacles, as they do in the real world. To achieve this, we exploit the anamorphic illusion to create a virtual world in full 3D with depth cues. This illusion is highly realistic and allows us to embed organisms in dynamic, and reactive, environments of arbitrary complexity. It is particularly appropriate for the insects, fish, and birds we will study in the centre, because many species in these systems have no, or relatively local and limited, binocular capabilities [9]. However, since we must distort each scene such that it represents the correct view of the 3D virtual space from the perspective of one animal, it is not (yet) possible to do so for multiple animals simultaneously (the virtual world will only have the correct volumetric projection for one of the individuals and would look distorted to others). We can solve this by networking multiple VR systems together, which allows many real animals to coexist in the same virtual world. In later years we will explore AR hardware for animals to directly influence their perception of the world.

In addition to these tools, ICARUS will allow for the previously impossible global tracking of small animals, and for the collection of data without requiring tag recovery, almost anywhere on the planet via the International Space Station (ISS). All components of the system arrived at the ISS in February 2018. We have a roadmap to create tags that are small and light enough to be deployed on insects, including locusts (by approximately 2022). Using solar power, ICARUS tags will allow us to observe the behavior and physiology of individuals over their entire lifetime in aquatic, terrestrial, and aerial realms. Remote sensing, and in some cases the bio-loggers themselves, will also sample the environment, reporting variables such as humidity or chemical composition (CO_2, NOX). Currently, sound is being added as an additional recording channel because of its importance in many social interactions within animal groups.

The above-mentioned systems and sensors impose tough constraints on run-time and task-based performance of data analysis. Our experiments on collectives will require real-time analysis to track individuals in the group and, in turn, fast rendering of reactive digital environments. Additionally, data must be analysed to detect and predict (exceptional) events that require very fast actions. To cope with the required low-latency and vast amounts of data, we will devise so-called "anytime" methods to priorities and filter these data in dynamic and intelligent ways.

The volume and heterogeneity of our data will be immense. The University of Konstanz and the Max-Planck Institute have pioneered the management, storage and visualization of animal movement data with the free, online animal tracking database Movebank (https://www.movebank.org). Co-developed by the University of Konstanz, Movebank currently includes roughly 1 billion GPS points on animal locations from approximately 4,000 studies from over 700 taxa. We will require advanced means to visualize the complex and multi-scale data generated in the centre. Building on our considerable expertise in visual analytics and our advanced visualization facilities available at the University of Konstanz, and also within the existing Transregional Research Centre "Quantitative Methods for Visual Computing" located at the Universities of Konstanz and Stuttgart (together with the MPI for Biological Cybernetics in Tübingen), we will develop tools to integrate the analytic capabilities of computers (e.g. machine learning) with the perceptual and cognitive capabilities of researchers. By supporting hypothesis development and testing, machine learning will be a powerful tool for helping us manage the complex data generated by our research, and for elucidating causality in relationships.

In humans, we will investigate both natural social networks as well as more controlled set- ups of groups within the laboratory environment. Our analyses will include the observation of face-to-face interactions in terms of their underlying processes (such as verbal and non-verbal communication) and outcomes (such as who knows what, and from whom). These will be complemented by setting up computer-based experiments that allow us to control important aspects of social interaction (e.g. availability of communication, information conditions, and feedback) and social learning. In addition to establishing novel laboratory experiments, we will set up an infrastructure to conduct online experiments with large groups of people simultaneously. Not only will this allow us to access larger samples, and a larger variety of people, it will also provide the opportunity to fully control and manipulate all aspects of network structure. We will further leverage our interdisciplinary expertise in human and animal behavior to create protocols that are comparable across species, for instance by establishing game-theoretically equivalent incentives or identifying transferable physiological treatments.

3. Conclusions

The Centre for the Advanced Study of Collective Behavior is a unique place for the quantitative exploration of swarm behavior. We combine quantitative measurements with theory and experimental observation in the lab and in the field for species ranging from insects, birds, fish and different kinds of mammals up to the human.

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