Model AI Assignment:

Collective Intelligence from a Synthetic and Biological Perspective

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In this project we study collective intelligence from two different aspects: First, we build a system exhibiting collective behavior. We show how single-robot solutions can be scaled to achieve collective behavior. Here students will design *synthetic behavior*, that is being tested on a real robot system. In a second part we take a closer look into a natural system of collectively behaving fish. In combination with a biomimetric robot the natural system helps us to validate and test hypothesis about *natural behavior* of animals.

This assignment uses distance estimation as an example study case. The ability to estimate distance is an essential aspect for self-orientation, allowing animals to move in a natural environment. In particular when animals move in teams (e.g. fish schools, flocking birds), they seem to localize themselves relative to their neighbors - efficient and accurate enough such that quite astonishing behaviors arise. Throughout this assignment students will develop a synthetic approach simulating simple collective behavior, which will be deployed onto a real robotic platform.

The first part of this assignment is about *creating synthetic behavior*: estimating distance to neighboring agents (Section 1), motion planning (Section 2) and the combination of both for testing robot behavior in the real world in a multi-agent setting (Section 3). The second part is about *analyzing natural behavior* (Section 4). With help of a robot that mimics appearance and behavior of conspecifics, students embody hypotheses regarding agent perception (e.g. distance estimation) and interactions and probe those in real world settings.

1 Distance Estimation

Distance estimation is an essential part of scene recognition and orientation, allowing agents to move in a natural environment. In particular, when animals move in teams (e.g. fish schools, flock of birds), they seem to be very capable of doing this - moving together as a whole without colliding or bumping into each other. Different sensor systems but also different strategies of movement enable these agents to localize themselves relative to another. Vision is probably the sensor system that is studied in greatest detail and will be the focus of the first assignment part.

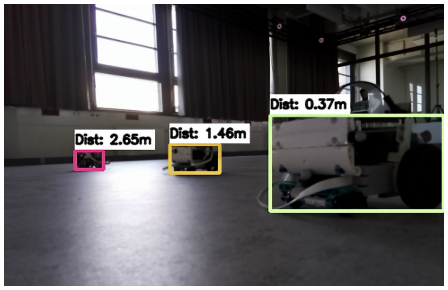

Figure 1: **Distance estimation** to neighboring Lego robots.

This part provides an introduction into analytical and learning based approaches for distance estimation. While there are several cues to extract information about distance the focus of this assignment lies on object appearance and its relative size. Objects appearing at greater distance will appear smaller than objects nearby. This is one of the fundamental principles of perspective projection. A classical object detector (YOLOv5 small/nano) will be extended with the ability to estimate distance. *When does a system benefit from learning?*, *When should estimates be computed following known physical principles instead of being learned from data?* This part of the assignment aims at implementing both solutions to distance estimation - the analytical computation and a multilayer perceptron (MLP), analyzing pro/cons of each approach and finally draws a decision with respect to the algorithm's deployment onto a real robot. The developed system is tested and evaluated on provided video frames coming with the assignment.

Theory

- Introduction into object detection with YOLO
- Training, validation and testing in machine learning
- Perspective projection

Practice (Implementation)

- Implementation of distance estimation based on perspective projection
- Implementation of an MLP for robot distance estimation (`pytorch`)

Practice (Testing)

- Testing on prerecorded video data.

Reading Material

[3] Yi Ma et al. *An invitation to 3-d vision: from images to geometric models.* Vol. 26. Springer, 2004.

[4] Marek Vajgl, Petr Hurtik, and Tomáš Nejezchleba. “Dist-YOLO: fast object detection with distance estimation”. In: *Applied sciences* 12.3 (2022), p. 1354.

[5] Glenn Jocher. *YOLOv5 by Ultralytics.* Version 7.0. 2020. DOI: `10.5281/zenodo.3908559`. URL: `https://github.com/ultralytics/yolov5`.

2 Multi-Robot Collision Avoidance

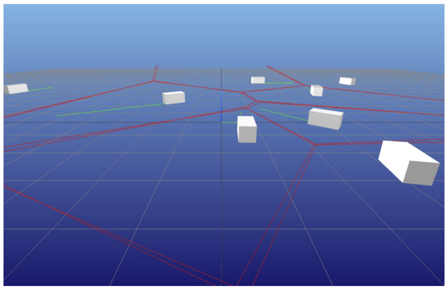

Figure 2: **Multi-robot collision avoidance** via Buffered Voronoi Cells.

One of the foundational behaviors for a team of robots is to be able to move in their environment without any collisions with other robots or obstacles. In multi-robot motion planning, we typically assume that the environment is fully known and that we can plan in a centralized fashion for the whole team of robots. In collision avoidance, we take a more reactive approach, where each robot changes its motion based on the robot’s perceptual input to avoid collisions in a distributed fashion. This part provides practical insights into Buffered Voronoi Cells (BVC), a modern approach for distributed collision avoidance that only requires the sensing of neighbor positions. Together with single-robot planning techniques, it can be effectively used to plan smooth motions for many mobile robots, including differential-drive robots, car-like robots, and multirotors. We program in Python and verify the resulting approach using our own robotics simulator, assuming that we know the relative positions between the robots.

Theory

- Robot Dynamics (differential drive, as common for vacuum cleaning robots)
- Robot Control (PID)
- Differential Flatness and Motion Planning using Bézier-curve Optimization
- Buffered Voronoi Cells (BVCs)

Practice (Implementation)

- Learn how a simple simulator with dynamics and visualization can be build (`numpy`, `meshcat`)
- Implement and tune a robot controller

- Implement a convex optimization problem (`cvxpy`)
- Execute and visualize Voronoi decomposition (`scipy`)
- Implement multi-robot collision avoidance by combining all techniques from above

Practice (Testing)

- Testing and tuning the developed algorithm in simulation

Reading Material

[6] Dingjiang Zhou et al. “Fast, on-line collision avoidance for dynamic vehicles using buffered voronoi cells”. In: *IEEE Robotics and Automation Letters* 2.2 (2017), pp. 1047–1054.

[7] Y. Kanayama et al. “A Stable Tracking Control Method for an Autonomous Mobile Robot”. In: *IEEE International Conference on Robotics and Automation (ICRA).* 1990, pp. 384–389.

[8] Wolfgang Hönig et al. “Trajectory Planning for Quadrotor Swarms”. In: *IEEE Transactions on Robotics, Special Issue on Aerial Swarm Robotics* 34.4 (2018), pp. 856–869.

3 Synthesizing Collective Behavior

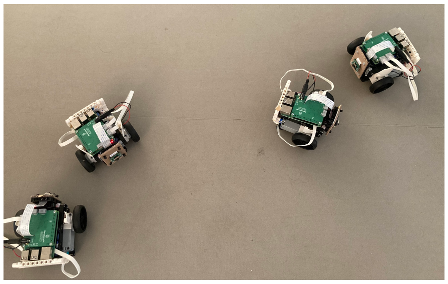

Figure 3: **Synthesizing behavior** and testing on mutiple lego robots.

The goal of this part is to demonstrate that the simulated synthesized behavior of the first two parts works on a real robotic team. To this end, we connect the perception pipeline from the first assignment part to multi-robot motion planning from the second part. We use Lego Mindstorm robots (robot inventor) equipped with a Raspberry Pi 4, the Raspberry Pi camera V3 and the Raspberry Pi build HAT as a robot platform. Lego allows an individual and flexible design of the robot body design. All these materials are commercially off-the-shelf, affordable, and frequently used for robotics education.

While the robot design is provided, integrating the two algorithmic approaches - distance estimation and motion planning - developed in first two assignment parts and deploying those onto a physical robot still requires a careful attention to its interfaces. As an example case, successful integration of both codes requires a unified representation of distance. To this end students will implement a consistent and easy interpretable representation of relative position. Additionally, the students need to learn how to connect to the robots and how to move from interactive Python notebooks to pure Python code. The code is tested an deployed on multiple Lego robots - a minimum of two robots is needed.

Practice (Implementation)

- Implementation of relative position estimates (Section 1) in Cartesian coordinates of the robot frame
- Implementation of the state update using the robot dynamics

Practice (Testing)

- Verification of distance estimation on Lego Mindstorm robots
- Testing the combined setup of distance estimation together with motion planning on the Lego robots

4 Analyzing Natural Collective Behavior

The use of biomimetic robots to study animal social behavior has received considerable attention in recent years. Robots that mimic the appearance and behavior of conspecifics allow biologists to embody specific hypotheses regarding social interactions, perception and learning, and test them in the real world. Much time and effort can be spent on refining the robots to create increasingly realistic interactions with animals. However, we should keep in mind that the robot and its behavior only need to be realistic enough to serve the purpose of the investigation. In this tutorial we will give an introduction into biomimetic robots that interact with live animals by example of Robofish – a fish-like robot that is interacting in real-time with live guppies (*Poecilia reticulata*) thus enable us to study social interactions, social learning and perception of conspecifics. The tutorial includes an introduction to interactive biomimetic robots along with automated animal tracking. In a practical part, we will track a pre-recorded video with biotracker software. From the resulting tracks we calculate average distance between a live fish and a robofish as a measure for the robot's acceptance by the live fish.

Figure 4: **Biometric robots** for probing hypotheses about agent perception and interactions in natural settings.

Theory

- Introduction to biomimetic robots
- Biotracker software

Practice (Testing)

- Tracking video with biotracker and calculating average distances between subjects. Compare to live-live fish interaction data.

Reading Material

[9] Tim Landgraf et al. "Animal-in-the-loop: using interactive robotic conspecifics to study social behavior in animal groups". In: *Annual Review of Control, Robotics, and Autonomous Systems* 4 (2021), pp. 487–507.

[10] Donato Romano et al. "A review on animal–robot interaction: from biohybrid organisms to mixed societies". In: *Biological cybernetics* 113 (2019), pp. 201–225.

[11] Jens Krause, Alan FT Winfield, and Jean-Louis Deneubourg. "Interactive robots in experimental biology". In: *Trends in ecology & evolution* 26.7 (2011), pp. 369–375.

5 Discussion of Ethical Aspects

This assignments tightly connects the design of a synthetic multi-agent system and an experiment with live animals being confronted with a biometric robot. This robot mimics the appearance as well as the behavior of conspecifics. Clearly this raises critical questions as - *Is it dangerous for live fish putting them in tanks together with a robot fish? What are are the implications?*

When conducting experiments using live animals, it is important to consider the ethical implications of any potential harm, injury, or pain that may be caused[1]. In the case of live fish swimming with biomimetic robots, it is possible for the live animals to suffer if they perceive the robot as a threatening predator or if collision avoidance and robot force control are not appropriately managed. Our experimental paradigm does not involve predator-prey interactions, but rather the robot being accepted as a conspecific. In this setup it can be well assumed that live fish will not perceive the robot as a threat. Furthermore - from the perspective of biometric robot design, the use of animal-sized robots made of soft materials that move at low speeds (as in our case) is expected to pose a low risk of injury or collision to live animals, even without additional collision avoidance measures. On the contrary there are many examples of how the number of animal experiments can be minimized or stress for animals during experiments can be minimized by using biometric robots. More explicitely, experiments with biomimetic robots that are accepted as conspecifics help to reduce the number of live animals used by substituting animals with robots during the experiments and by allowing more standardized and less noisy experiments that require lower sample sizes for the same test power. Further, biomimetic robots can reduce handling stress for live animals by minimizing pre-training handling or other manipulations of the live animal. The videos provided were part of experiments approved by Berlin's local authorities

(LaGeSo Berlin, Reg. 0117/16 to DB). Further details on the ethical considerations of using biomimetic robots in animal research can be found in the review article by Bierbach et al.[2].

References

[1] Jerrold Tannenbaum and B Taylor Bennett. “Russell and Burch’s 3Rs then and now: the need for clarity in definition and purpose”. In: *Journal of the American association for laboratory animal science* 54.2 (2015), pp. 120–132.

[2] David Bierbach et al. “Biomimetic robots promote the 3Rs principle in animal testing”. In: *ALIFE 2022: The 2022 Conference on Artificial Life.* MIT Press. 2021.

Acknowledgements

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