A Hardware and Software Testbed for Underactuated Self-Assembling Robots

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Abstract— **We present the implementation and characterization of an affordable testbed for underactuated multi-agent, self-assembling systems. There has been recent interest into the control of nano- and micro-scale active particle systems, but these systems are often difficult to manufacture and observe, hindering control research. Our testbed offers an accessible way to experiment with different design and control approaches. The testbed is composed of an off-the-shelf rolling *weaselball* toy and a 3D printed external hub that modifies the agent's dynamics. The software toolbox includes simulations and code for data extraction and analysis of the weaselballs. The advantage of our testbed for studying distributed robotic systems is that these robots can be made quickly and cheaply, are relatively small, and do not require complex or expensive environments. The software in our toolbox includes a high fidelity Gazebo simulation, and Python code for collecting trajectories and other data from both simulation and overhead video of the system. Using this toolbox, we present useful computed properties of the system with regards to object clustering.**

I. INTRODUCTION

Cell scaffolds, immune systems, drifting jellyfish: many natural systems achieve collective organized behavior by harnessing Brownian or seemingly random movement, breaking symmetries enough to create useful dynamical structures. We are particularly inspired by *active particles*, self-propelling micro- or nano-particles which have recently been the subject of great interest in materials science, micro-machining, and for medical and environmental applications [1] [2].

In robotics, systems leveraging physical agent-agent and agent-environment interactions are beginning to be explored [7], [8], sometimes termed embodied computation [3]. Our system is similar to some other macro-scale testbeds that use fluid or air currents, or a powered environment, to propel minimal self-assembling or swarming agents [4], [5], [6]. However, these also require relatively expensive infrastructure, a challenge our project hopes to help address (a goal we share with the Robotarium project [9]).

The Motion Strategy Lab has worked with *weaselballs* for years as a model of minimally controllable agents. In the multi-agent setting, they have been used to develop equilibrium density control algorithms based on environment geometry and discrete sensing and control [10], [11]. We extend this work by creating a hardware platform and related software library that lay the foundation toward developing control algorithms for tasks such as self-assembly and collective manipulation.

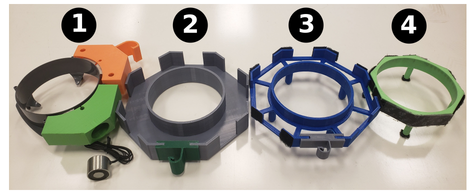


Fig. 1: Past iterations (1,2,3) and current hub design (4)

II. PLATFORM DESCRIPTION

A. Hardware

The hub was designed to enable self-assembly of a collection of weaselballs. Earlier designs emphasized attaching sensors and other components. However, the initial iterations were quite heavy; with heavy hubs, the motion of the weaselball is constrained and the system moves very slowly. Our current design is lighter and less complex, allowing for higher mobility of the robots.

The enclosure consists of whiteboard flooring, to minimize friction, and brick walls, though cardboard or similar materials may be used for walls isntead (the agents do not exert significant force on environment boundaries). All CAD models for hardware designs, and software described in Section II-B, are available on Github[1].

B. Software

We have implemented a Gazebo simulation of our platform, for flexible and scalable data collection. Amazingly, Taylor and Drumwright [12] developed and validated a simulation of a weaselball in Gazebo and made the models public. We added our hub design to the simulator as well as utility scripts for generating specific assembly configurations, and AWS integration. We have also implemented a Python toolbox for analyzing simulator logs and extracting trajectories and other quantities from overhead video data of the physical robots with openCV. From this information, we can compute quantities such as time to collision, displacement, velocity, and frequency of synchronization.

III. CHARACTERIZATION AND EXPERIMENTS

Compliance with Environment: We observed that the agents tend to spend more time interacting with the environment than in the free space. Data was recorded of a singleton agent in an octagonal hub moving autonomously with resulting distributions of agent position and orientation shown in figures 4 and 5 respectively. The weaselballs tend

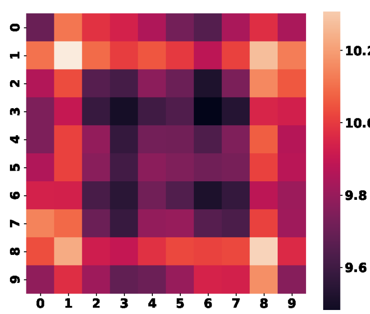
[1] https://github.com/alexandroid000/self-assembly

to position themselves near the walls of the enclosure with sides of the hubs aligned with the wall. A large subset of possible agent movements near the boundary will keep the agent trapped at the boundary, while movements in the free space do not favor any particular position or orientation, opening up discussion as to how environment design can guide dynamics.

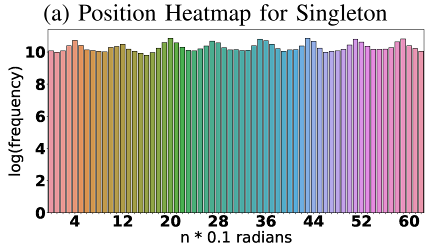
Toward Collective Manipulation: In this experiment, two lightweight rectangular cardboard boxes were placed in parallel in the center of the enclosure, either one, five, or nine inches away from each other. Four agents were then allowed to move freely in the enclosure, and push against the boxes. When the boxes start nine inches apart, the robots tended to move between the boxes, and in this case the boxes align with the walls of the enclosure without clustering. However, in the cases when boxes where initially relatively close, they clustered and aligned within a few minutes. In the 1 inch and 5 inch runs, the boxes always clustered, but in the 9 inch runs, the boxes clustered 40% of the time.

Box's Distance to Center	Average Time Until First Contact (seconds)	Average Time Until Flush (seconds)	Average Difference Between First Contact and Flush (seconds)
1 Inch	4	15.5	11.5
5 Inch	47.6	94.3	46.7
9 Inch	407	441.4	33.9
9 Inch No Max Time	118	203.5	84.75

TABLE I: Average Time for Collisions in Box Experiment



(a) Position Heatmap for Singleton



(b) Rotation Heatmap for Singleton

Fig. 2: Motion Characteristics of singleton

Effects of Assembly Size and Geometry: One observation with regards to assembly geometry is that weaselballs have a slight counterclockwise chirality, which is apparent in the assymetric rotation of larger assemblies. Second, the average displacement of an assembly over time (shown in figure 6) is related to the number of units. Third, there are instances of synchronization in weaselball assemblies of a particular size range. In both real-world assemblies and

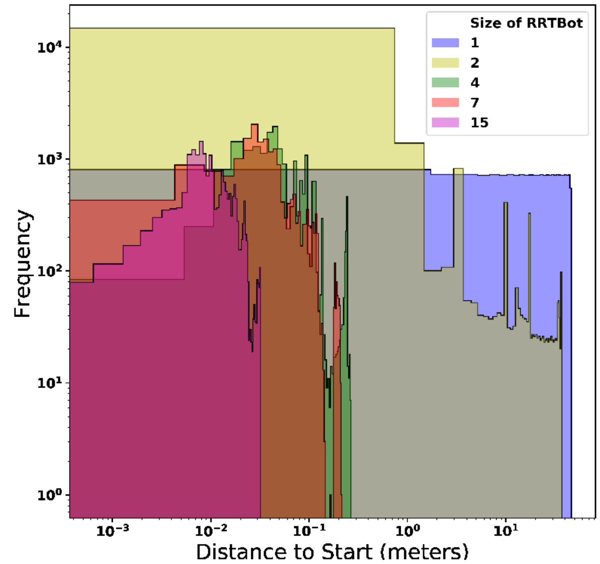


Fig. 3: Distribution of L2 displacement over two minute runs for different assembly sizes.

in simulations, when the weaselball motions aligned, the assembly was more likely to continue its current motion until an external force was applied. This synchronization was more likely in structures with between 3 and 5 weaselballs, because these assemblies had the optimal trade-off between the probability of synchronization among majority of weaselballs and the strength of inter-agent forces. These characteristics are promising for the design of minimal, distributed control systems, perhaps ones that work by "doping" the multi-agent system with a few fully-controllable mobile robots.

IV. CONCLUSION AND FUTURE WORK

The next step for this project is to use electro-permanent magnets [**?**] and minimal on-board sensing and computation. If two hubs are stacked, the top hub can be used to hold electronics, with sensors on the sides where agents attach.

We are working to extend the analysis of boundary effects, such as those in Figures 4 and 5, by modelling boundary interactions as a scattering effect and integrating related work on scattering control laws [14] [15] and robophysics [16].

We plan to tune these interactions, and eventually large-scale assembly and manipulation efficiency, through geometric design of agents such as in [19] and [20]. We are also interested in exploring switching global controls such as in [**?**], which can be emulated through tray tilting. Finally, we are developing information spaces and sensor-based approaches toward scalable state descriptions of the system that are not tied directly to the number of agents or environment complexity. Akin to recent developments in control using ergodicity metrics [13], we envision a system where the density and velocity of robots is tunable at the distribution level. This leads to opportunities to create decentralized controllers which create differential "pressure" in the robotic system, so collective manipulation can be accomplished through purely statistical, mechanical interactions.

ACKNOWLEDGMENT

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