

Controlling Shape of a Swarm with Global Inputs

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Abstract—Micro- and nanorobotics have the potential to revolutionize many applications including targeted material delivery, assembly, and surgery. The same properties that promise breakthrough solutions—small size and large populations—present unique challenges to generating controlled motion. We want to use large swarms of robots to perform manipulation tasks; unfortunately, human-swarm interaction studies as conducted today are limited in sample size, are difficult to reproduce, and are prone to hardware failures. We present an alternative.

This paper first examines the perils, pitfalls, and possibilities we discovered by launching SwarmControl.net, an online game where players steer swarms of up to 500 robots to complete manipulation challenges. We record statistics from thousands of players, and use the game to explore aspects of large-population robot control. We present the game framework as a new, open-source tool for large-scale user experiments. Our results have potential applications in human control of micro- and nanorobots, supply insight for automatic controllers, and provide a template for large online robotic research experiments. One surprising result was that humans completed a block-pushing task *faster* when provided with only the mean and variance of the robot swarm than with full-state feedback. Inspired by human operators, this paper next investigates controllers that use only the mean and variance of a robot swarm. We prove that the mean position is controllable, then provide conditions under which variance is controllable. We next derive automatic controllers for these and a hybrid, hysteresis-based switching control to regulate the first two moments of the robot distribution. Finally, we employ these controllers as primitives for a block-pushing task and implement all the automatic controllers on 101 kilobots, with the our vision system.

I. INTRODUCTION

Large populations of micro- and nanorobots are being produced in laboratories around the world, with diverse potential applications in drug delivery and construction [?], [?], [?]. These activities require robots that behave intelligently. Limited computation and communication rules out autonomous operation or direct control over individual units; instead we must rely on global control signals broadcast to the entire robot population. It is not always practical to gather pose information on individual robots for feedback control; the robots might be difficult or impossible to sense individually due to their size and location. However, it is often possible to sense global properties of the group, such as mean position and density. Finally, many promising applications will require direct human control, but user interfaces to thousands—or millions—of robots is a daunting human-swarm interaction (HSI) challenge.

The goal of this work is to provide a tool for investigating HSI methods through statistically significant numbers of ex-

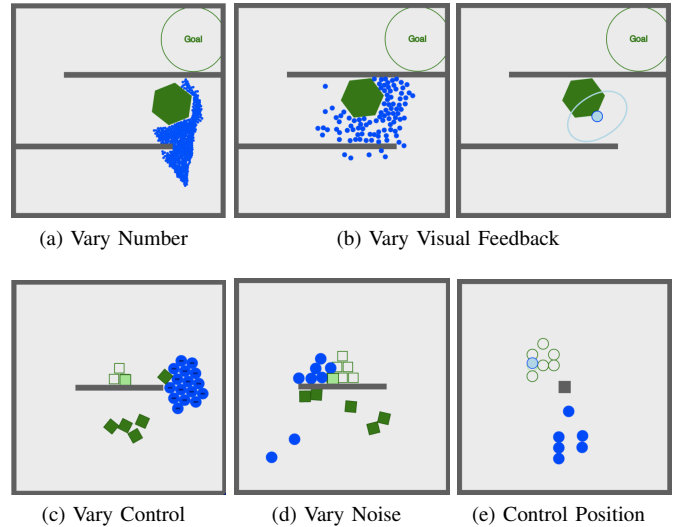


Fig. 1. Screenshots from our five online experiments controlling multi-robot systems with limited, global control. (a) Varying the number of robots from 1-500 (b) Comparing 4 levels of visual feedback (c) Comparing 3 control architectures (d) Varying noise from 0 to 200% of control authority (e) Controlling the position of 1 to 10 robots. See video overview at <http://youtu.be/HgNENj3hvEg>.

periments. There is currently no comprehensive understanding of user interfaces for controlling multi-robot systems with massive populations. We are particularly motivated by the sharp constraints in micro- and nanorobotic systems. For example, full-state feedback with 10^6 robots leads to operator overload. Similarly, the user interaction required to individually control each robot scales linearly with robot population. Instead, user interaction is often constrained to modifying a global input. This input may be nonstandard, such as the attraction/repulsion field from a scanning tunneling microscope (STM) tip.

Our previous work with over a hundred hardware robots and thousands of simulated robots [?] demonstrated that direct human control of large swarms is possible. Unfortunately, the logistical challenges of repeated experiments with over one hundred robots prevented large-scale tests.

Our goal was to test several scenarios involving large-scale human-swarm interaction (HSI), and to do so with a statistically-significant sample size. Towards this end, we created SwarmControl.net, an open-source online testing platform suitable for inexpensive deployment and data collection on a scale not yet seen in swarm robotics research. Screenshots from this platform are shown in Fig. 1. All code [?], and experimental results are posted online.

Our experiments show that numerous simple robots responding to global control inputs are directly controllable by a human operator without special training, that the visual

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feedback of the swarm state should be very simple in order to increase task performance, and that humans perform swarm-object manipulation faster using attractive control schemes than repulsive control schemes.

Our paper is organized as follows. After a discussion of related work in Section ??, we describe our experimental methods for an online human-user experiment in Section ?. We report the results of our experiments in Section ?, discuss the lessons learned in Section ?, and end with concluding remarks in Section ?.

II. CONCLUSION

The conclusion goes here.

APPENDIX A

PROOF OF THE FIRST ZONKLAR EQUATION

Appendix one text goes here.

APPENDIX B

Appendix two text goes here.

ACKNOWLEDGMENT

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Michael Shell Biography text here.

John Doe Biography text here.

Jane Doe Biography text here.