Torque Control for Object Manipulation Using a Swarm With Global Inputs

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***Abstract*— Micro and nano robots are suited for targeted drug delivery and micro scale manufacturing because they are small enough to navigate the passageways of the body. However, due to their small size, robots cannot contain onboard processing for autonomy nor onboard power. Instead they are controlled by external signal such as a magnetic field. Because each robot can only provide a small amount of force or transport a small amount of material, large swarms of robots are required, all controlled by the same external field. This work presents controllers and algorithms for steering such an under-actuated swarm to manipulate objects. Previous work showed that mean and variance of the swarm is controllable. This enables manipulating simple objects through a simple maze. A key remaining challenge is controlling the torque applied to an object. Torque control is necessary for navigating objects through narrow passages, for precise positioning, and for [????]. This work first proves that torque control is possible, then presents algorithms to automate the task. The paper concludes with experimental results using 100 hardware robots to manipulate rectangles with large aspect ratios.**

image 1 should be the kilobots pushing an interesting object. Current images 1 and 2 are not attractive, have the same caption, and the robots

I. Introduction

Micro- and nano-robots can be manufactured in large numbers. Our vision is for large swarms of robots remotely guided 1) through the human body, to cure disease, heal tissue, and prevent infection and 2) ex vivo to assemble structures in parallel. For each application, large numbers of micro robots are required to deliver sufficient payloads, but the small size of these robots makes it difficult to perform onboard computation. Instead, these robots are often controlled by a global, broadcast signal. The biggest barrier to this vision is a lack of control techniques that can reliably exploit large populations despite incredible under-actuation.

In previous work, we proved the mean position of a swarm is controllable and that, with an obstacle, the swarm's position variance orthogonal to rectangular boundary walls is also controllable (σ_x and σ_y for a workspace with axis-aligned walls). The usefulness of these techniques was demonstrated by several automatic controllers. One controller steered a swarm of robots to push a larger block through a 2D maze [1]. We also showed methods to control swarm's position covariance to be able to navigate the swarm through the workspaces with narrow corridors, but there is still another challenge remained. When the task is object manipulating, we need to control torque of the object also to successfully pass all the ways. This paper first discusses the ways that we can control torque of an object in Section III. Then it introduces algorithms for torque control in Section IV. We show that algorithms work in Section V on 100 kilobots.

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II. Related Work

Controlling the *shape*, or relative positions, of a swarm of robots is a key ability for a myriad of applications. Correspondingly, it has been studied from a control-theoretic perspective in both centralized, e.g. virtual leaders in [2], and decentralized approaches, e.g. control-Lyapunov functions gradient based decentralized controllers in [3]. Most approaches assume a level of intelligence and autonomy in the individual robots that exceeds the capabilities of current micro- and nano-robots [4], [5].

Instead, this paper focuses on centralized techniques that apply the same control input to each member of the swarm, as in [6].

Shear forces are unaligned forces that push one part of a body in one direction, and another part of the body in the opposite direction. These shear forces are common in fluid flow along boundaries, as described in introductory fluid dynamics textbooks [7]. Similarly, a swarm of robots under global control pushed along a boundary will experience shear forces. This is a position-dependent force, and so can be exploited to control the configuration or shape of the swarm. Physics-based swarm simulations have used these forces to disperse a swarm's spatial position for accomplishing coverage tasks [8].

More research has focused on generating artificial force-fields. Applications have included techniques to design shear forces to a single object for sensorless manipulation [9]. Vose et al. demonstrated a collection of 2D force fields generated by 6DOF vibration inputs to a rigid plate [10], [11]. This collection of force fields, including shear forces, could be used as a set of primitives for motion control for steering the formation of multiple objects.

III. Theory

A. Controlling Torque

One of the features of an object is its orientation. When a swarm is manipulating an non-symmetric object, in narrow corridors orientation matters. We can control orientation by controlling torque of the object. Equation 1 shows the parameters that we should control.

$$\tau = F \times d \tag{1}$$

where d

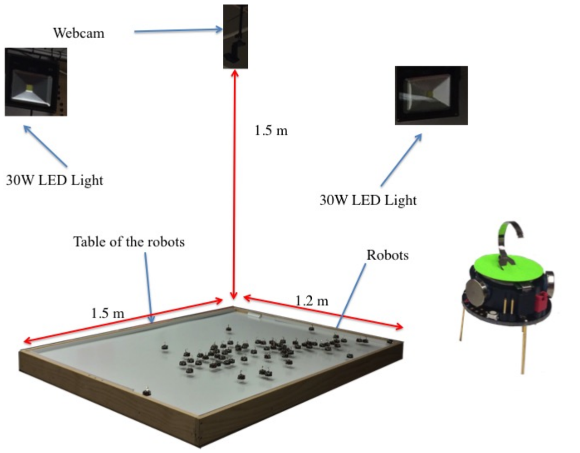


Fig. 1. Hardware platform: table with 1.5×1.2 m workspace, surrounded by eight remotely triggered 30W LED floodlights, with an overhead machine vision system.

IV. Simulation

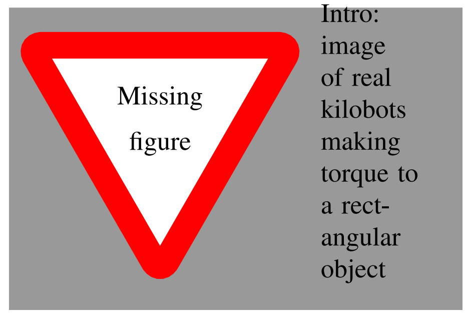
V. Experiment

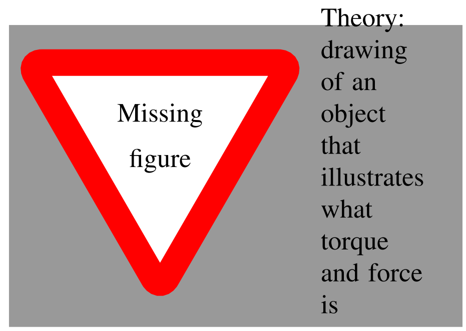
Our experiments are on centimeter-scale hardware systems called *kilobots*. These allows us to emulate a variety of dynamics, while enabling a high degree of control over robot function, the environment, and data collection. The kilobot, from [12], [13] is a low-cost robot designed for testing collective algorithms with large numbers of robots. It is available as an open source platform or commercially from [14]. Each robot is approximately 3 cm in diameter, 3 cm tall, and uses two vibration motors to move on a flat surface at speeds up to 1 cm/s. Each robot has one ambient light sensor that is used to implement *phototaxis*, moving towards a light source. In these experiments as shown in Fig. 3, we used n=97 kilobots, a 1.5 m×1.2 m whiteboard as the workspace, and eight 30W LED floodlights arranged 1.5 m above the plane of the table at the $\{N, NE, E, SE, S, SW, W, NW\}$ vertices of a 6 m square centered on the workspace. The lights were controlled using an Arduino Uno board connected to an 8-relay shield. Above the table, an overhead machine vision system tracks the position of the swarm.

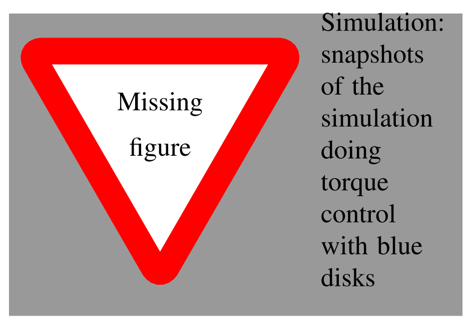
VI. Conclusion and Future Work

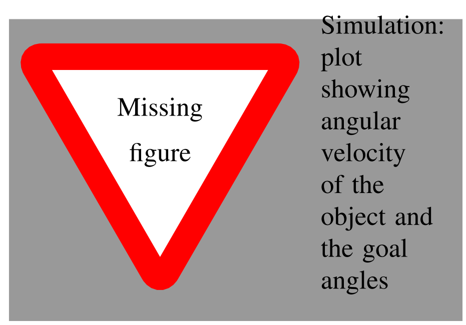
This paper presented techniques for controlling the shape of a swarm of robots using global inputs and interaction with boundary friction forces. The paper provided algorithms for precise position control, as well as demonstrations of efficient covariance control. Future efforts should be directed toward improving the technology and tailoring it to specific robot applications.

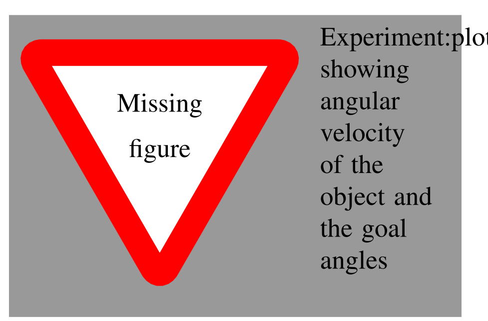
With regard to technological advances, this includes designing controllers that efficiently regulate σ_{xy}, perhaps using Lyapunov-inspired controllers as in [16], [17]. Additionally, this paper assumed that wall friction was nearly infinite. The algorithms require retooling to handle small μ_f friction coefficients. It may be possible to rank controllability as a function of friction. In hardware, friction could be modified by outfitting the kilobots with a round skirt to avoid the almost infinite friction due to the triangular leg arrangement. The wall friction can be varied by laser-cutting boundary walls with different of profiles.











Experiment: snapshots of the kilobots doing torque control of a rectangular object

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