Torque Control for Object Manipulation Using a Swarm With Global Inputs

Shiva Shahrokhi and Aaron T. Becker

***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 observing, emitting and manipulating objects. 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.**

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 significant 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. Torque control is necessary for a lot of tasks like retroreflectors, solar incinerators, targeted drug therapy, etc.

S. Shahrokhi and A. Becker are with the Department of Electrical and Computer Engineering, University of Houston, Houston, TX 77204-4005 USA {sshahrokhi2, atbecker}@uh.edu

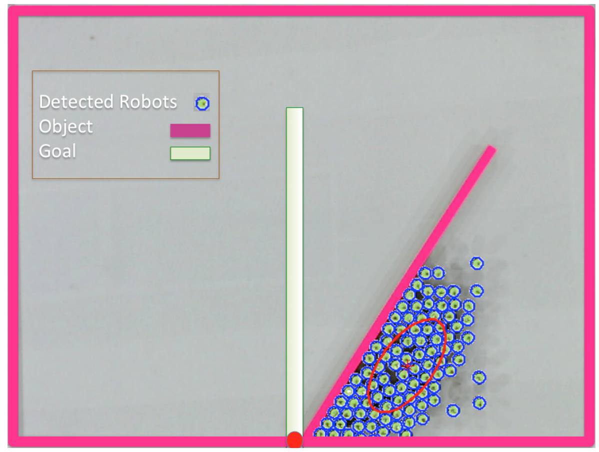

Fig. 1. Torque Control of an object is essential for manipulating objects to their goal position like when there is a narrow passageway . This paper shows how to apply force to get the required torque and force when we have a highly under-actuated system that all the robots are controlled globally with the same input. This figure shows 100 hardware robots apply torque to an object. These robots have light sensors and are programmed to go to the brightest light in the room which is their shared control input.

However, a swarm with elements' stochastic positions is not possible for precisely measuring force if the only knowledge about it is its statistics. The initial distribution of the swarm has $2n$ degrees of freedom and begins interacting with object in different times. Therefore, number of robots touching the obstacle at each time when average position of the swarm is controlled is not measurable. We are able to predict which elements hits first though, but the problem even gets harder as time runs by interacting with the object, because the swarm changes its state and distribution when it is hitting the object. The challenge is not only limited to swarm-object interaction, but also to swarm-swarm interactions when the swarm is split to some other swarms. As a result, the amount of force the swarm is making on the object is not easily measurable. Instead, this paper focuses on strategies using only the statistics of the swarm.

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 a 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.

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

Where F is the force that each touching robot make and r is the vector from that robot to the center of mass of the object.

IV. Simulation

There are four main challenges when we are doing pose and torque control of an object.

a) Pure torque control: Suppose we have a pivot that avoids the object to translate while it is still able to move and have angular velocity like a door. If there was only one robot touching the obstacle, the ending points of the obstacle was the best location due to Eq. 1 where r would be maximum and the maximum torque has been created with the same force. But, when there is a swarm of robots, because of its dynamic state it is not true. If the swarm hit the object with mean position at the top, lots of its robots is missed and will make the swarm apart, and also because there remain less robots, force is significantly decreased and torque would not maximize. In our simulation, the swarm will try to make torque as much as possible until it is passed the object, when it is passed, it will gather itself in one corner which is very time consuming. Fig. 2 illustrates how different positions of the object cause different times.

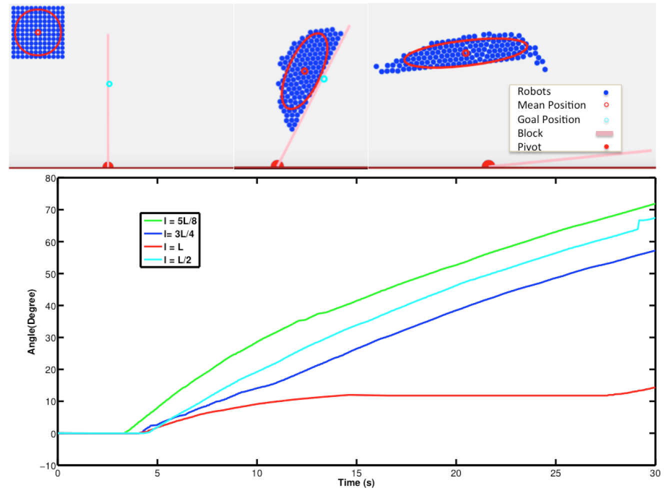

Fig. 2. Plot showing how changing the mean position of the swarm on the object may affect getting the highest torque and force with 144 robots with a standard deviation of less than $1.5m$ and the object length of $6m$.

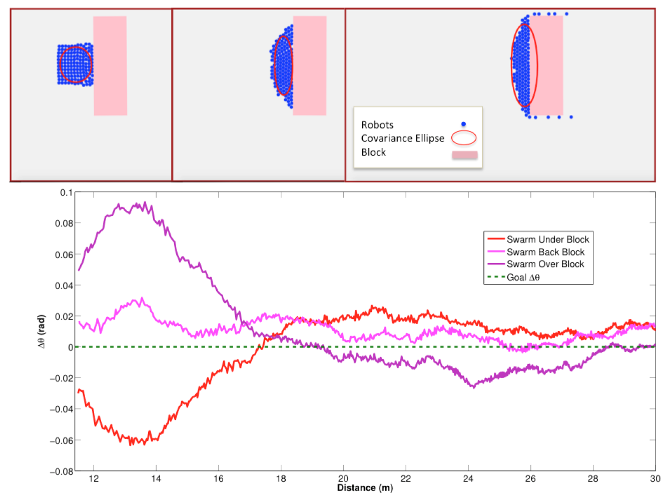

Fig. 3. The swarm can navigate the object without changing its orientation significantly if it hits in the line of COM of the object and perpendicular to it. It will correct itself if it makes some torque.

b) Pure translation of the object: In our simulations we used a big uniform density rectangle as object. If the force is applied perpendicular to the object and in line of the center of mass, according to Eq. 1 there would be no torque. We proposed the following goal position for mean position of the swarm in which uses the difference between the goal angle and the current object angle, $\Delta\theta$ to find where to apply force, C is a constant and O_x, O_y is the object COM position.

$$\begin{aligned} goal_y &= C\Delta\theta + O_y \\ goal_x &= O_x \end{aligned} \tag{2}$$

We use a PD controller to control mean position as in [1]. Fig. 3 shows how $\Delta\theta$ converges to zero with different locations of the swarm. When it is upper or downer of the object, when it hits it makes a little torque but then it tries to cancel it.

c) Orientation of the object: Using the pure torque control that we discussed, we can control the orientation of the object with applying force to it. We do not have pivot

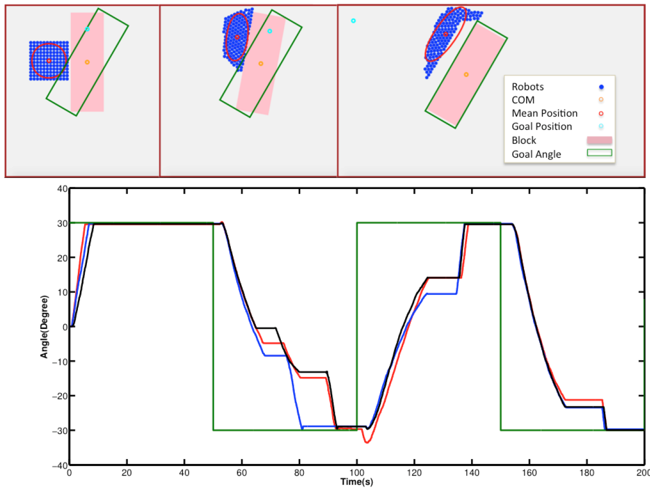

Fig. 4. This plot shows how we can control orientation of the object. The green line is the goal orientation, at the times that other lines are steady, it is because the swarm is on variance control mode.

here so the rectangle would move besides rotating. We used that data to pick up a more rational length to lead the swarm to hit that spot. However, the swarm still may split and get apart. We use our hysteresis variance control to gather the swarm together again when it is split. The goal position is related to the angle that the object has made already. It should be somewhere upper or downer the COM, inside the object. In the following equation, O_θ is the orientation of the object and w is the width of the object.

$$\begin{aligned} goal_y &= O_y + Ccos(O_\theta)w \\ goal_x &= O_x + Csin(O_\theta)w \end{aligned} \tag{3}$$

Fig. 4 illustrates this controller with different starting positions. When the lines are steady, it means that the variance had grown more and the swarm was on variance control mode.

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. 5, 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.

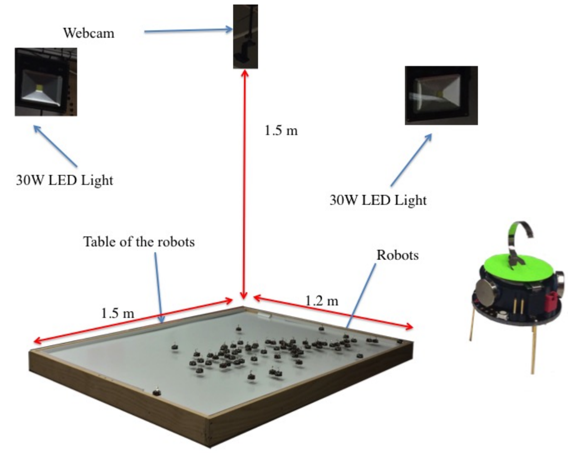

Fig. 5. Hardware platform: table with 1.5×1.2 m workspace, surrounded by eight remotely triggered 30W LED floodlights, with an overhead machine vision system.

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.

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