Sailing a Boat Through a Macroscopic Smart-Fluid Composed of a Robot Swarm

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Abstract. We investigate how a physically inert vehicle, which we call a *"boat,"* can locomote through a smart fluid by communicating with the particles of a smart fluid, and thereby inducing the fluid to exert forces and moments on the boat. Our smart fluid is composed of a swarm of Kilobot robots that move on a flat surface. The boat communicates with the fluid particles through wireless messages sent from its bow and stern. By sending different pairs of messages from its bow and stern the boat directs the subsets of the smart fluid in different locations to move in different ways. This enables the boat to maneuver forward, turn left, and turn right. In experiments on a physical testbed, we evaluate how the presence and size of the boat's rudder affects motion efficacy. We find that using a small rudder provides better overall motion than using no rudder or using a large rudder.

Introduction

Smart fluids—fluids with properties which can be controlled by an artificial process—have the potential to enable amazing breakthroughs in manufacturing, medicine, and other tasks that require micro-manipulation. In this paper we demonstrate proof-of-concept that a object with no moving parts can sail through a smart fluid by altering the physical forces exerted by fluid particles on that object. The object—which we refer to stylistically as the *boat*—broadcasts infrared messages into the fluid from both its bow and stern. The fluid particles behave in different ways based on the messages they receive. Thus, the boat is able to maneuver by broadcasting different pairs of messages from its bow and stern simultaneously. The boat moves forward by asking the smart fluid to move away from the bow and toward the stern. A boat equipped with a (static) rudder turns by asking the fluid to exert a rotational moment via the boat's rudder. Meanwhile, a rudderless boat could turn by asking the smart fluid to create a clockwise or counterclockwise vortex.

In a series of hardware experiments we: (1) investigate how different rudder lengths of the boat affect the smart fluid's ability to propel and turn the boat, (2) demonstrate repeatability of both forward and turning maneuvers, and (3) demonstrate the repeatability of performing non-trivial maneuver sequences — in particular, we study the boat's ability to sail a 'Z' shaped path.

Microrobots that use magnetic fields have been studied for their potential to revolutionize medicine [1, 5] as well as their potential for micro-manipulation [11]. Some robots use a global magnetic field [14, 4] or other global field [2, 6] to achieve motion. Other work leverages *local* interactions created by a magnetic local force [3, 13]. We are inspired by this second class of methods and investigate a solution where the transported object (our boat) moves in a variety of ways by creating a local force-field gradient within the smart fluid.

Previous work has demonstrated that a robotic swarm can transport an object and/or use a robot swarm as a macroscopic fluid. For example, [6] and [2] use a homogeneous swarm control to transport an object using global commands. [15] and [7] use a swarm to move an object while passively communicating motion information from the object to the swarm. Aggregate motion is used to move an object in a direction indicated by a light source in [8]. Granular convection is used in [12] to create a pressure gradient for the purposes of object transportation; achieved by having the fluid globally repulsed from the transported object's destination. Our work differs from previous work in that the transported object (boat) creates ego-centric localized force field gradients in the smart fluid. Also, unlike [10], this work focuses mainly in the transport of an object, not in the transport of an amalgamated group of robots.

We style our work as a boat sailing through a smart fluid. The boat has no moving parts and one or more transmitters; we use two throughout this paper. The fluid used is made of particles that have the ability to run, store a program, and sense their distance from each transmitter. They are able to exert a local force on demand.

We define the *smart fluid sailing problem* that we study as follows: Given a smart fluid and a boat with a means of affecting the properties of that fluid, achieve transportation of the boat from a start location to a goal location by having the boat direct a local force-field gradient in the smart fluid.

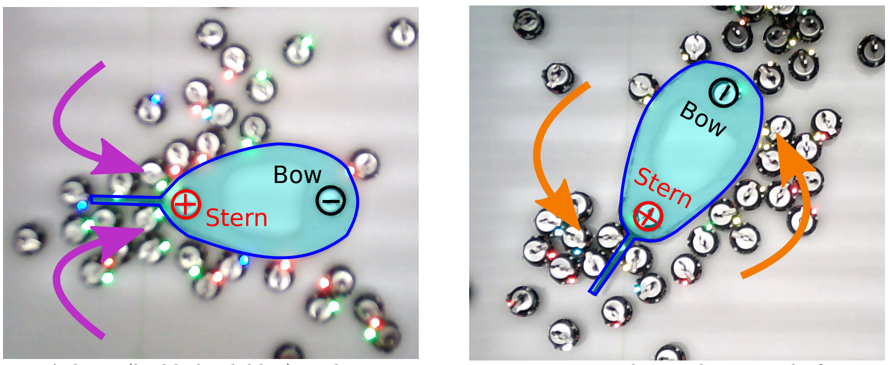


Fig. 1: A boat (highlighted blue) with no moving parts maneuvers by sending signals from two transponders (highlighted red/black and labeled +/-, - in the bow and + in the stern) to a smart fluid composed of Kilobot robot fluid particles. Forward (towards the - pole) and turning motion (left and right sub-figures) are achieved by causing a local asymmetry in physical fluid forces (purple/orange arrows).

Technical Approach

The boat has two transmitters, one each in the front and rear of the boat. It is convenient to think of the two transmitters as creating oppositely charged "poles." We refer to the front (the "bow") and rear transmitters (and their poles) as negative b_- and positive b_+, respectfully. The boat maneuvers with 3 *actions*: forward a_F, turns right a_R, and turns left $a_L$by sending messages to the smart fluid from its transmitters.

Each smart fluid particle r_i has seven *states*. The default state is *random motion* (s_R). States *move towards* (s_T) and *move away* (s_A) involve movement to or from the transmitters, respectively. Four turning-related states are named for each combination of turning direction (left, right) and boat end (front/negative, rear/positive). For example, a bot that is near b_- (the *negative* or forward most or bow transmitter) and has received the a_L (turn left action) command would be in state *left turn negative* (s_{L-}). Depending on a particle's state, its interaction with the two poles may be that of attraction, repulsion, or orbital motion around the pole (clockwise and/or counterclockwise).

Each smart fluid particle uses Algorithm 1 to determine its (non-random) action each time a message is received from the boat. A particle changes state based on a combination of which transmitter b_i it last received a message from (lines 2 and 11), the distance to that transmitter (lines 1, 5, 14, 20), and the particle's previous state (lines 2 and 11). If a particle has not received a message after a set period of time, its state is reset to s_R, the *r.turnDirection* is reassigned randomly, and *r.turnFlag* is reset (not shown in an algorithm here). Thus, most smart-fluid particles in the environment move randomly, but those near to the boat have their state temporarily altered by the boat's transmitted messages.

Forces exerted on different sides of the boat will cause it to move in a direction or rotate in a manner directly related to the force vectors applied to it. If the boat desires to move forward (in the direction of b_-), then an accumulation of particles (and forces) at b_+ is sufficient. For a turn, opposed forces on the sides of the boat at front/rear are sufficient (see Figures 1 and 2).

Algorithm 2 is used by particles interacting with boats that have a static rudder. From the boat's point of view, particles at both the positive and negative poles of the boat orbit towards the same side of the boat. Particles hitting the rudder create a torque that turns the boat, while particles in front of the boat move to the outside of the intended rotation to create additional torque near the front of the boat (Figure 2-C). If a particle receives a message from b_i requesting a turning state, then the particle moves towards the boat until its distance d is less than *r.orbitDist* from b_i (lines 1 and 5). A flag *r.turnFlag* indicates that a turning state is happening (lines 1 and 3), and the particle orbits the transmitter at radius *r.orbitDist* (lines 1-14).

Boats lacking a rudder could turn by inducing the smart-fluid to create a vortex. All robots rotate either clockwise or counterclockwise around the boat (Figure 2-B). Pseudo-code for the corresponding particle algorithm is very similar to that in Algorithm 2 for a boat with a rudder, except lines 6 and 11 read **if** $r.s \in \{s_{R+}, s_{R-}\}$, switching the direction of rotation around b_- during a turn-

Algorithm 1: `set_action`(r_i, a_i, b_i)

```
d ← estimate_distance(r_i, b_i)
if b_i = b_+ and r.s ∉ {s_A, s_R−, s_L−}
    if a_i = a_F
        r.s ← s_T
        move_towards(d)
        return
    else if a_i = a_L
        r.s ← s_L+
    else if a_i = a_R
        r.s ← s_R+
else if b_i = b_− and r.s ∉ {s_T, s_R+, s_L+}
    if a_i = a_F
        r.s ← s_A
        move_away(d)
        return
    else if a_i = a_L
        r.s ← s_L−
    else if a_i = a_R
        r.s ← s_R−
turn(d)
```

ing maneuver (compare Figure 2-B and C). We chose the algorithms for turning each style of boat (ruddered and rudderless) by selecting which method seemed most effective for each during pre-trial development.

Particle routines for moving toward or away from the boat's receivers are presented in Algorithms 3 and 4, respectively. Particles are assumed to have distance sensors but not directional sensors. Each particle moves in a circle in a direction randomly defined at startup (*r.turnDirection*), until the transmitter distance sensed is above or below a threshold $r.d_{last}$ (Algorithm 3 or 4, respectively).

Results

Our work makes three main contributions. First, using a robotic testbed we demonstrate that it is possible and repeatable to sail through a smart fluid by creating a local force gradient. Second, we show that rudder size affects mean forward and rotational motion duration, as seen in Table 1, and that a rudder allows for repeatable turning motion. Third, we demonstrate that it is possible to chain multiple maneuvers to meet a non-trivial navigation requirement. A summary of these results appears in Table 2. 'N/A' indicates that no data was collected due to inability of a design to complete the scheduled trials. The experiments themselves are described in the next section.

Algorithm 2: `turn`(d)

```
if r.turnFlag = false and d > r.orbitDist
    move_towards(d)
    r.turnFlag ← true
else
    if d < r.orbitDist
        if r.s ∈ {s_R+, s_L−}
            turn left
        else
            turn right
    else
        if r.s ∈ {s_R+, s_L−}
            turn right
        else
            turn left
```

Algorithm 3: `move_toward`(d)

```
if d ≤ r.d_last
    r.d_last ← d
    move forwards
else
    r.d_last ← weighted_ave(d, r.d_last)
    turn r.turnDirection
```

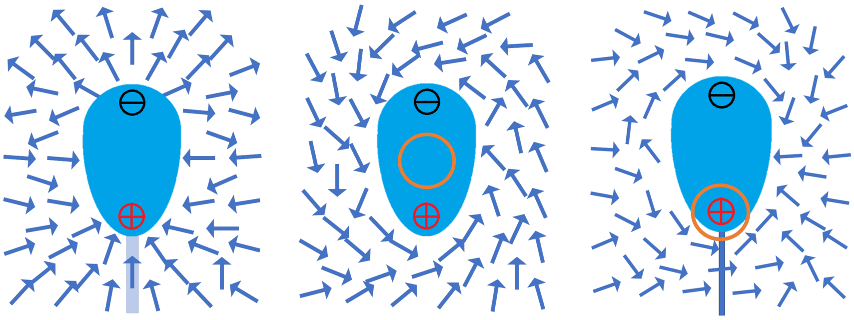
Algorithm 4: `move_away`(d)

```
if distance > r.d_last
    r.d_last ← d
    move forwards
else
    r.d_last ← weighted_ave(d, r.d_last)
    turn r.turnDirection
```

Hardware Experiments

We test our methods using a smart fluid constituted of Kilobot robots [9]. Kilobot robots measure approximately 3 cm high (disregarding the charging hook) and 3 cm in diameter and resemble a thick coin resting horizontally upon three 2 cm legs evenly spaced apart (see Figure 6). They have the ability to move forwards, turn right and left, and sense local visible light intensity. Nine-byte messages, sent by bouncing an infrared signal off of the surface a bot stands on, can be broadcast from each Kilobot to all bots within about a 20 cm radius. Kilobots are able to measure the relative distance to each other based on the signal strength of received messages.

The boat we use is an approximately 19.5×12.5 cm teardrop-shaped piece of styrofoam. The first boat design was a simple rectangle. Through informal iteration, we discovered that with the simplistic forward motion model applied, it was very difficult for the swarm to move a rectangular boat forwards. A teardrop design allows bots moving towards b_+ from anywhere in its neighborhood to exhibit forward motion on the boat, as a concentration of particles attracted to b_+ "squeeze" the boat forwards. Any left/right asymmetry in the design was unintentional.



(A) Forward (B) Turn, no rudder (C) Turn, with rudder

Fig. 2: The boat induces particles in its local area to move as indicated by the arrows, exerting local forces where a particle's motion path intersects with the boat. Forward motion (A) is the same with and without a rudder. Turing requires different smart fluid interaction without (B) and with (C) a rudder. The center of rotation is outlined with an orange circle. In this example, the intended result of the actions in (B) and (C) would be counterclockwise rotation of the boat.

Table 1: Maneuver Duration, as well as Y axis (perpendicular to the intended vector of travel) error and angle error from the intended vector of travel for the forward action tests. These values were calculated by averaging the magnitude of the measurements for the respective error for each successful test.

Rudder	**Action**	**Mean** (s)	**Std.** (s)	**Attempts**	**Success**	**Y err** (cm)	**Angle err**
None	Forward	609.57	285.56	9	7	12.55	41.23°
Short	Forward	454.40	118.79	9	5	16.39	52.10°
Long	Forward	610.00	147.60	6	5	19.33	26.46°
None	Turn	N/A	N/A	6	0	N/A	N/A
Short	Turn	378.40	153.92	6	5	N/A	N/A
Long	Turn	423.20	220.64	6	5	N/A	N/A

Table 2: "Z-Pattern" Statistics Over 5 trials (in minutes:seconds)

Mean	**Std.**	**Shortest**	**Longest**
60:59	18:33	42:59	91:56

Table 3: Boat weights, with and without embedded Kilobots

Rudder	**Empty**(g)	**With Bots**(g)
None	2.71	36.67
Short	4.44	38.43
Long	5.35	39.32

Two inert (not physically actuating) Kilobots are embedded in the boat and used as the transmitters b_+ and b_-. The transmitter bots are wedged into the boat, suspending the foam about 2 cm above the ground, with only the six legs from the two bots contacting the ground. This is far enough from the ground and the bots are close enough to the edge of the boat to not adversely effect message transmission from the boat bots to swarm bots nearest the respective poles. By altering the visual light intensity in the environment with a series of switches, a user remotely controls which action messages the boat's transmitters broadcast into the smart fluid. For example, bright, medium, and dark light indicate that

Fig. 3: Rudders: none, short (7.5 cm), long (15 cm).

the transmitters should collectively ask the smart fluid to create a forward, left turn, or right turn maneuver. The swarm itself does not exhibit behavior based on light level, only the instructions it receives from the transmitters.

Experiments are performed on a 90 cm by 120 cm whiteboard placed on top of a professionally-leveled billiards table. LED light strips suspended one meter above the whiteboard are used to control visual light intensity. A camera mounted one meter above the workspace records each experiment.

We performed repeated trials to evaluate the forward and turning performance of three boat designs. Due to the significance of the teardrop shape, reverse was not considered, though pre-trial development testing with a teardrop-shaped boat proved reverse to be difficult. Forward motion is measured by the time duration required for the boat to cross a 30.5 cm (or one foot in standard units, which the authors chose for familiarity) region (see the top row of Fig-

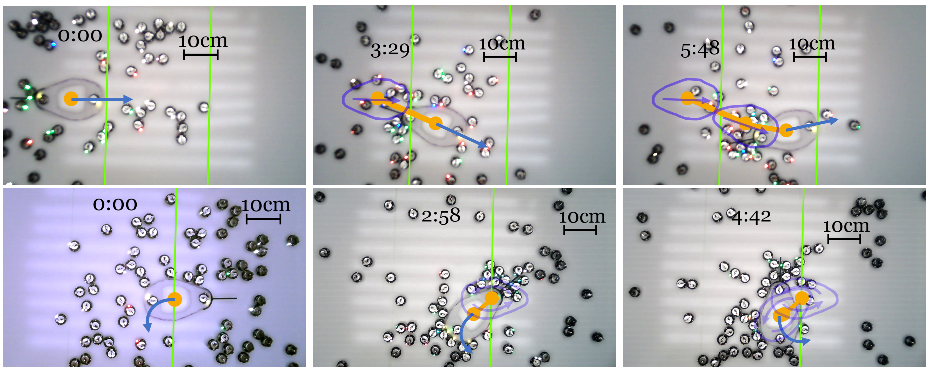


Fig. 4: **Top row:** Forward motion test. The boat starts perpendicular to and just behind the starting line; we measure the time until the bow breaks the finish line (lines are marked with dry erase during the tests, and highlighted green here). **Bottom Row:** Turning Test. The boat starts perpendicular to a straight line (green); we measure the duration of time until it rotates parallel to that line.

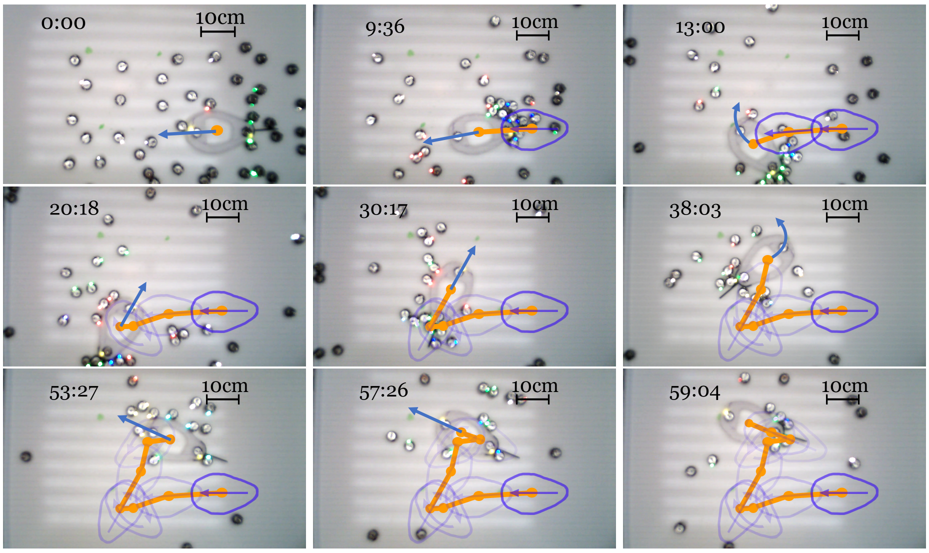


Fig. 5: In the “Z-test” trial the boat progresses through the sequence: forward, turn right, forward, turn left, forward. The boat’s progress over the course of a “Z-test” trial is highlighted in orange. Note the time intervals between steps as swarm density decreases and time increases.

ure 4). Only the ‘forward’ command is transmitted to the smart fluid during this experiment, so trials are disregarded if the boat is unable to cross the span, e.g., due to turning sideways. Presumably, we could have used the left and right commands to keep the boat on course. However, in order to measure only effectiveness in forward motion and not contaminate these results with the a design’s turning ability, we dropped these trials. Trials alternate between moving opposite directions across the workspace to help control for surface irregularities. At least five successes were recorded for each rudder type. Turning ability is assessed by measuring the time duration required for the boat to rotate 90 degrees in a desired direction (see the bottom row of Figure 4). Trials are disregarded if the boat has not turned 90 degrees after fifteen minutes, or if the boat turns 90 degrees in the wrong direction. Trials are performed in different workspace locations and in different turning directions to help control for discrepancies in boat shape and workspace surface. Five successful trials are recorded.

The trials described above demonstrate that the short ruder configuration has the best performance of the three models we evaluate. We tested the ability of the short rudder boat to perform a sequence of maneuvers by having it sail in a ‘Z’ pattern to visit four locations, requiring forward motion and both left and right turns (Figure 5). Five trials are recorded. A human operator controlled the light levels, doing his best to guide the boat through the Z pattern as quickly as possible. Unlike the straight line tests, turning commands were allowed to correct for inconsistencies in forward motion, demonstrating the controllability of our solution.

Fig. 6: A test in progress. Note that the boat's body is suspended by the Kilobots embedded in it.

Experimental Insights

An important contribution of our work is proof of concept that 'sailing' a boat through a smart fluid, by inducing the fluid to create a local force gradient around the boat, is both possible and repeatable. The 'Z-path' trials show that single maneuvers can be chained together to enable more complex motion over a non-trivial path. They also showed that motion is possible (albeit at a slower pace) with only a few bots. Our work also shows that a smart fluid can be reconfigured on-the-fly to suit the local needs of an agent.

Our experiments demonstrate that rudder size affects both forward and turning motion ability. A short rudder has both improved straight line speed and rotation speed over no rudder and long rudder configurations (see Table 1). Both short and long rudders were found to improve turning motion, as we did not observe a rudderless boat turn at all during formal trials. While we developed a process for turning a rudderless boat design as described above (see Figure 2 B) in informal iteration before the formal trials, the results were never consistent. This prompted us to explore other options and led to experimentation on boats with rudders, which seemed more consistent in rotational motion during the pre-trial stages of this work. Therefore, we were unsurprised when the trials for rotational motion of a rudderless boat failed, either by turning 90 degrees the wrong way or failing to achieve 90 degrees of rotation in the correct direction in 15 minutes.

We note that none of the boat designs went particularly straight during the forward action tests, as seen in Table 1. However, as directional correction by the testers was disallowed during these tests, the path of the boat was highly susceptible to imperfections in the testing surface as well as the random placement of the swarm bots. While disallowing correctional commands during the forward motion tests were necessary for accurate measurements, our ability to control the boats during the Z test, where correctional commands *were* allowed for the straight portions of the pattern, assuaged our fears over the boat's inability to move in a perfectly straight line.

We believe that a rudder provides the smart fluid particles a place to physically engage with the boat during forward motion, as well as a lever that can assist rotation. We also believe that a rudderless boat was unable to achieve turning motion as, without the lever the rudder provides, our simplistic turning method was not precise enough to push on the boat in exactly the right places to rotate repeatedly or quickly.

Conclusions

We present a method for a vehicle or *boat* able to affect a surrounding smart fluid to demonstrate two-dimensional motion by inducing that fluid to exert local forces in a controlled manner. We then demonstrate this method using a micro-robotic swarming platform, the Kilobot, showing that repeatable motion and control of the boat over a complex path is possible. We also demonstrate that with our boat design, a rudder is necessary for consistent rotational motion of the boat, and that a boat with a shorter rudder results in more rapid motion compared to a boat with a longer rudder.

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