**1. Are there factual errors in the reviews? (approx. 400 words)  
Comment on facts only, not opinions. For example, if the reviewer  
says that your assumptions are too restrictive, this is an  
opinion. However, if the reviewer says that your algorithm is  
exponential when it is cubic, this is a factual error.**

We thank the three reviewers for their constructive comments. They understood the work, its significance, and suggested avenues for future work.

[minor point] In all algorithms, global inputs apply over the entire workspace.  The “build zone” and “staging zone” are names for regions, but global inputs apply according to the same rules in each space. The algorithms are designed so that with global inputs only one robot is moved from the staging zone to the build zone each iteration.

[minor point] A reviewer recommended discussing what will happen if friction is not infinite, suggesting: "This may be discussed in the future work as well."  Our future work does *briefly* mention this: "The algorithms require retooling to handle small μ\_f friction coefficients".  Given the chance, we will elaborate on this point.

**2. Is there any serious misunderstanding in reviewer's "Explanation of the Overall Recommendation" that the area chairs and program chair should attend to? (approx. 400 words)**

No serious misunderstandings. We did neglect to include the video of two kilobot robots being positioned using friction.

**3. Please use up to 400 words to address any other points you wish.**

https://ssl.gstatic.com/ui/v1/icons/mail/images/cleardot.gif

The wording in our *Introduction* was overly enthusiastic, so we will tone down the language. Our eventual goal is controlling many microrobots inside the human body. There are a host of challenges, including manufacturing such robots, designing the drugs for treatment, and dealing with flow inside the body. However, these microrobots will most likely be controlled by global control fields. This paper focuses on the basic theory of steering small particles with global forces: (1) constructive controllability proofs, (2) sufficient conditions for control, and (3) analytical results on efficient configurations that can be achieved with a single command.

We thank the reviewers for recommending additional related work – that line of work is quite relevant, and we will acknowledge their contributions. The reviewers suggested 21 small improvements that can easily be incorporated into the final submission.

[[ don’t include in reply ]]

Controlling position of all robots in a swarm given information about each robot's positions is possible with global inputs when friction is present. This is shown in our paper with complete discussion and algorithms. However; when there is noise or we do not have the information of each robot's position due to their small size, controlling position of each robot is not possible because we lack the information. In this more general case, controlling statistics of the swarm (like covariance) with friction is still possible, as shown in our paper. However, in these situations, while the moments of the swarm and not position of each one. This is the flow that may be convincing for reviewers, that the paper is looking at the same problem in different situations.

It may be also clarified why in the experiments we mostly focused on covariance control and not the n robots positioning although as a convincing result, we showed the two robot positioning with kilobots in our paper in Fig. 12. We mainly would like to control covariance of the swarm when we have a large number of robots, first because the computation time and the number of moves (Fig. 8) would significantly rise when the number of robots are more, and also as I mentioned, because of the lack of information and highly stochastic environments. -------The video is missing, should we say that we just forgot to send the video? or should we say something else? I can make the video for two robots positioning, it is easy. For covariance control it is not that easy, because the zigzag wood would not make infinite friction unfortunately, and we don't have boundary friction which makes it more challenging even.

----------------------- REVIEW 1 ---------------------  
PAPER: 66  
TITLE: Shaping a Swarm With a Shared Control Input Using Boundary Walls and Wall Friction  
AUTHORS: Shiva Shahrokhi, Arun Mahadev, Haoran Zhao and Aaron Becker  
  
  
----------- PAPER SUMMARY -----------  
This paper considers methods for swarm control using only global inputs.  The authors use boundaries to control the shape of the swarm, and consider the use of friction as a control element.  The paper is well-motivated, in that individual control of robots at microscale with current technology may best be approached with a global control technique.  The authors provide an algorithmic approach which is verified via simulation, and further supported experimentally.  The work to my knowledge is novel, although implementing it experimentally in microscale systems and/or at scale is certainly nontrivial.  
  
----------- DESCRIPTION OF A NEW SYSTEM (IN SOFTWARE OR HARDWARE) -----------  
The use of wall friction as a control element for systems with global controls as applied to a large swarm of robots is new.  Based on this concept, the authors developed a new generalized algorithm and software for controlling swarms in such a fashion.  The integration of the system is somewhat strong, **although it is limited by the extent of the experimental results, which are somewhat basic given the promise.**  
  
----------- 1-2 MOST INTERESTING ASPECTS -----------  
The central, interesting contribution of the paper is that walls can be used to shape swarms particularly when wall friction is a significant factor.  It should be noted that this is a very difficult problem when only global inputs can be considered, and that the bar is much higher for advancement in this subfield of swarm control.  
  
----------- STRENGTHS -----------  
The main strength of the work is the support for the proposed methods for swarm control.  The authors have a compelling platform for experimental evaluation of such systems, and have developed a number of analysis as well as simulation tools.  
  
----------- WEAKNESSES -----------  
1.) [more hardware experiments]The authors have a powerful experimental platform which could be used to experimentally validate the algorithms and simulations at scale.  Some simpler experiments are performed relative to the overarching promise of the algorithms.  Naturally, one would expect experimental implementation of the described algorithms to be difficult to scale significantly, particularly since simulation assumptions such as infinite friction and build/staging zones are difficult to replicate.  
  
----------- EXPLANATION OF YOUR OVERALL RECOMMENDATION -----------  
The authors presented a strong base for their work in terms of algorithm basics and simulations.

1.) [more hardware experiments] However, it does seem that **more experimental support would add value to the work** (3, 4, 5) robots.  It's my impression that the paper would be somewhat stronger if there were less emphasis on algorithmic particulars and **more emphasis on experimental results**, particularly in terms of figure clarity and descriptions.  
  
Some minor comments in order:  
  
2.) Abstract:  
This is a general comment/suggestion concerning nomenclature.  Friction is a widely-used, generalized parameter for macroscale systems, and at a very high level it may be an appropriate parameter to consider for microscale/nanoscale systems.  However, in microscale systems, the particular form of friction becomes much more relevant (viscous boundary layers, electrostatics), and isn't often referred to as 'friction'.  I see there is some related clarification of this distinction in the Related Work section.  
  
3.) Sentence could use clarification**:  "We conclude with efficient techniques to control the covariance of a swarm not possible without wall- friction"**  
  
4.) It would be hard to argue that control techniques as examined in this paper are **the \*biggest**\* barrier to the vision as related to microscale systems.  Hardware/software in the area of robotics is still rudimentary.  
  
III. Theory  
  
**5.) Cover an area of constant volume?**  
  
**6.) Labels on Figure 2 are quite small.**

7.) It would be helpful to briefly explain the mechanism of motion of the kilobots.  This would also help explain the infinite friction assumptions for the experiments performed. (Note - I see this is explained in the experimental section.  Something like **'as explained in experimental section'** would be helpful.)  
  
**8.) Arrows in figure 5** are very difficult to discern when they coincide with the black boundary walls.  
  
9.) Build zone and staging zone should be clearly defined.  Also, this is a nice concept for simulation, but since global inputs tend to be truly global (magnetism, light), I think the authors need to qualify this approach.  
  
**10.) Procede -> proceed**  
  
IV. Simulation  
  
11.) What is the significance of the 'Shapes' section of Figure 8?  
  
12.) "In Fig. 8, the amount of clearance \*is\* eps =1"?  
  
**13.) "\*fewer\* DriftMoves are required."**  
  
V. Experiment  
  
**14.) Figure 14 caption mentions 64 kilobots, but the text refers to 97 kilobots, which seemingly conflicts.**  
  
----------------------- REVIEW 2 ---------------------  
PAPER: 66  
TITLE: Shaping a Swarm With a Shared Control Input Using Boundary Walls and Wall Friction  
AUTHORS: Shiva Shahrokhi, Arun Mahadev, Haoran Zhao and Aaron Becker  
  
  
----------- PAPER SUMMARY -----------  
This paper looked at the problem of guiding a swarm given a shared input. An addition from this work over other approaches is including the boundary and a friction component in attempting to place the swarm. It's an aspect that they leverage in altering robot's relative position to one another given the shared input. They describe controlling covariance in both a square and circular workspace and then some particulars on the friction at the wall. They then describe controlling the position of 2 robots to desired placements, utilizing the wall friction to stabilize one robot as the other  
one can move more freely. Controlling n-robots is described utilizing the DriftMove algorithm using the same concept as before. With the n-robot problem they include the idea of a build zone and a stage zone. They finish the paper with simulation results and experiments on their hardware platform consisting of kilobots.  
  
----------- 1-2 MOST INTERESTING ASPECTS -----------  
1. Guiding potentially large swarms to specific configurations using only a shared input is a very interesting concept.  
2. Applying this on a real robot platform.  
  
----------- STRENGTHS -----------  
This paper described a very interesting problem, guiding a potentially large swarm with a shared input and utilizing the wall friction. A good deal of the motivation for the problem was also very compelling on why such strategies are needed.  
  
Many individual components of the paper were very clear. For example, the sections on moving 2 robots at a time were clear. This is true also for the section on moving n-robots, simulation, and experiments.  
  
Applying this approach on an actual robotic platform is also a nice contribution of the work. The kilobot platform they are using seems particularly well suited for the problem being studied. Since much of the motivation talked about robots in the body performing essential functions, it would be interesting to describe how this approach would or would not scale to the human body or other target applications.  
  
----------- WEAKNESSES -----------  
There are two main weaknesses of the paper in this reviewer's opinion. There's a potential issue with focus/clarity of the paper and then relying so heavily on the component of infinite friction.  
  
15.) For **the flow of the paper**, it seems odd to focus on controlling they covariance of the swarm so much and then to move on to specific robot placements. It would have helped to describe or motivate when it's necessary to control the covariance and when it's necessary to control the robot friction. These two problems almost didn't seem to go together. So after focusing on the covariance aspect, it seemed awkward to go back to specific robot positions. This caused an issue of focus in the results as well. It seemed like there was a back and forth between specific positions and covariance. It would have been nice to see the hardware platform create one of the more complex shapes shown in Fig. 8. From what I saw, the robotic platform was used in a covariance example.  
  
**16.) Relying so heavily on infinite friction seems to be unlikely** to happen in most applications. It's not clear where this would ever happen in the real world except in contrived examples (like the one used on their robotic platform). This really doesn't seem likely to happen in the human body. If this is something that isn't a big deal then it would be good to have some discussion on it. What I would think would be most beneficial would be to describe how incorporate lower friction. How would this affect the overall performance or guarantees. This may be discussed in the future work as well.  
  
----------- EXPLANATION OF YOUR OVERALL RECOMMENDATION -----------  
The main issues problems I have with the paper are listed in the weaknesses section. The paper has issues with flow because it's trying to talk about managing the swarm's covariance and then getting the robots to specific locations. This is an interesting problem and the solution (even given the problems with infinite friction) is still interesting. It just does not seem focused enough at times. It also would have been interesting to see the kilobot robots getting to specific locations rather than the covariance example.  
  
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----------------------- REVIEW 3 ---------------------  
PAPER: 66  
TITLE: Shaping a Swarm With a Shared Control Input Using Boundary Walls and Wall Friction  
  
----------- PAPER SUMMARY -----------  
This work presents a method for controlling the shape of a large swarm of robot agents under the influence of a single global control input. In this way, all robots move in the same direction at the same rate. To achieve the shaping, the authors introduce an enclosed boundary around the swarm with friction such that robots touching the boundary have a slower or stopped velocity.  
The authors show that control of two agents to arbitrary goal locations is possible, and that the covariance of a large set of robots can be controlled.  
Experimental validation for a 2-agent and 97-agent case help to validate the control.  
  
----------- DESCRIPTION OF A NEW SYSTEM (IN SOFTWARE OR HARDWARE) -----------  
The authors using an existing hardware system (kilobots) for experimental work. Simulation is done in existing physics engine software.  
  
----------- 1-2 MOST INTERESTING ASPECTS -----------  
The inclusion of wall friction is an interesting addition which increases the richness of this problem.  
  
----------- STRENGTHS -----------  
The paper presents a well-rounded research study. The theoretical basis is sound and presented convincingly. Experiments do not show much, but given the novelty of the work and the limited space available, this represents a full first study on the topic.  
Figures are excellent. The information is visually appealing and easy to access.  
The videos greatly aid in quickly understanding the algorithms presented, which are rather tedious to follow on paper alone due to their complexity.  
  
----------- WEAKNESSES -----------  
**17.) The authors fail to cite a major similar work A. Becker, E. Demaine, S. Fekete, and J. McLurkin, "Particle Computation: Designing Worlds to Control Robot Swarms with only Global Signals," in IEEE International Conference on Robotics and Automation (ICRA), Hong Kong, China, 2014.  
This work studies the same problem without wall friction**.  
  
The authors motivate this work in the realm of micro-scale robots which have limited on-board computation available, and thus are often controlled by a single global input signal. However, it is not clear that the presented scheme of relying on structured environments with wall friction is a realistic scenario for the applications of micro-robots.  
  
**18.) The repeatability of the experimental results is not demonstrated.**  
  
19.) It is not clear if the control algorithms presented for pairs of agents in the rectangular container would work in the case where both robots start with identical x- or y-coordinates.  
  
20.) Throughout much of the work, the authors assume that no normal force is required to maintain the friction force. This is particularly true for the driftmove algorithm. If some constant normal force is required, that algorithm would seemingly not work.  
  
21.) There are no videos for the experimental demonstrations, which is disappointing.  
  
----------- EXPLANATION OF YOUR OVERALL RECOMMENDATION -----------  
The paper has a clear novelty and advancement of the state of the art in swarm robotics control. The practical applicability to micro-scale robotic problems is not strong, which will limit the impact of the work.  
The well-written and rounded paper will be of interest to the swarm and micro-robotics communities.

**Reviews after rebuttal period**

----------------------- REVIEW 4 ---------------------  
PAPER: 66  
TITLE: Shaping a Swarm With a Shared Control Input Using Boundary Walls and Wall Friction  
AUTHORS: Shiva Shahrokhi, Arun Mahadev, Haoran Zhao and Aaron Becker  
  
  
----------- Paper Summary -----------  
The paper starts with a very interesting and grand vision: remote control a robot swarm going through the human body and cure diseases, it then quickly falls into solving an abstract, self-defined problem in an idealized world. This paper essentially proposed yet another 'force field' like approach to control a swarm robot using infinite frictional forces and covariance of the swarm shape in either a square or circular workspace.  (Both are idealized conditions that can be rarely found in practical applications.   Certainly often the internal of the human body wold be 'frictionless' and such a force field would not be applicable there.  The authors never try to connect it back to their starting motivation.)  
  
----------- 1-2 Most Interesting Aspects -----------  
The problem formulation is interesting.   And, the vision is interesting and the eventual application in medicine can be impactful \*IF IT WORKS\*.   (I don't believe it would though)  
  
----------- Strengths -----------  
- Control using shear forces (friction from the wall) and covariance  
  
----------- Weaknesses -----------  
- Idealized environments  
- impossible assumption that is not applicable to the target application within human bodies  
- no performance analysis and comparison with similar approaches  
  
----------- Explanation of Your Overall Recommendation -----------  
There is little theoretical analysis on the complexity of their control method, or performance analysis on how effective and efficient the technique is. What's the inherent complexity?  Does the robots get entrapped in local minima?  How quickly does the method converge to the desired solution (formation)?  At the minimum, the authors should show simulations of a robot swarm passing through an environment that bears some resemblance to the human body.   Again, the frictional control really does not apply here within the human body most of the time.  
  
Ironically, in the conclusion, authors stated, "Future efforts should be directed toward improving the technology and tailoring it to specific robot applications."  It sounds like the authors have forgotten why they are doing this research in the first place, indicating a detachment from real applications or realistic assumptions to start with.  
  
Incidentally there are many swarm simulation papers in applied mathematics, biology, AI, and computer graphics that address the similar problem using centralized control based on force fields.   I do not see any of such references from these areas.  Even in a problem created in abstraction with no real application in mind, the authors should compare their approach against other methods to demonstrate why this shape control mechanism is particular effective or efficient.  I would advise the authors to do a more thorough research of the literature in controlling swarm and a clear comparison against exist literature.  For a s tarter, check out the work by Andrea L. Bertozzi's group.  
  
  
-------------------------  METAREVIEW  ------------------------  
PAPER: 66  
TITLE: Shaping a Swarm With a Shared Control Input Using Boundary Walls and Wall Friction  
  
This paper considers swarm control with global inputs, using boundaries to help control the shape of the swarm. Both simulation and experimental results are included.  The problem statement of achieving covariance was not well-motivated.  The specific simulations and experiments in the paper are not well-connected to the grand vision outlined in the introduction to the paper. There is no discussion of reliability or repeatability.  
  
The paper is also missing important references to some closely related work in swarm robotics. For example:  
  
Organized Motion Control of a lot of Microorganisms Using Visual Feedback by Takahashi et al. ICRA 2006  
  
Control of Many Agents Using Few Instructions by Timothy Bretl RSS 2007 also discussed a very similar problem.  
  
Massive Uniform Manipulation: Controlling Large Populations of Simple Robots with a Common Input Signal. Becker et al. 2013 IROS.