Reviewer 1 of ICRA 2016 submission 1796

Comments to the author ======================

The paper presents a strategy to exploit wall friction to break the symmetry of a global control of individuals in a swarm of nano-robots. The paper addresses an interesting topic, has an interesting approach and is well structured. There are still several possible improvements:

- **avoid superlatives** like "incredible under-actuation" (it is credible) or "myriad of applications" (mention 5 instead). This is not helping in convincing the reader, and seems not really scientific.

- using walls to differentiate the movement of several robots could be achieved by having each of them in different tubes. this could be a simplistic way of differentiating the movements using walls.

- in section II there is only one subsection, which make the whole structure a bit strange. One starts reading the sections and then finds a subsection at the same level of content that the introduction. Avoid single subsections...

- the results could be more significant and could be **better presented**: the experiments on the real system are summarized mainly by a set of pictures and the graph of figure 10 (where we do not know what is green and what is red, and we do not see the ellipse mentioned in the caption).

It could be interesting to repeat for instance the experiment of the two robots (figure 9) several times and see the precision achieved in positioning. This could be an interesting measurement of performance of the system. In general good article, thank you Comments on the Video Attachment ================================

The video is a very good illustration of the paper.

Reviewer 2 of ICRA 2016 submission 1796

Comments to the author ======================

The paper presents a strategy where a robot swarm can using their interaction with the environment to control the overall shape of the swarm as it moves through the environment. The approach leverages the friction between the individual robots and using this as an external force to help steer the overall shape of the swarm. Overall the proposed theoretical approach makes sense and the authors present simulation and experimental results validating their strategy.

The biggest weakness of this paper are the experimental results. While the authors must be commended for their experiments, I am not sure if the results validate the theory at all.

While Fig. 10 shows some correlation between the measured output and the desired input, correlation does not equal causation. What other results do you have to support this? Since the underlying system is fundamentally stochastic, I would have expected the authors to **conduct multiple trials**. The average of these trials could have been compared to the desired input. At which point, I would expect the authors to make some argument as to why the results support their theory. Rather, the experimental results are simply stated with no **analysis or discussion**. This is a significant missing component. A minor criticism is that the existing approach heavily relies on axis-aligned walls as boundaries of the workspace. What happens if you have a non-polygonal shaped workspace, how would the approach extend? **What is the computational complexity in this case if you had to approach all the workspace and obstacle boundaries with piecewise linear functions?** Lastly, the organization of the paper can be further improved. Specifically, I am not sure Figures 6 and 7 are at the end of the paper when they basically provide a graphical explanation of the approach described in Section II. And yet, Sections III and IV don't even refer to these figures. I think Section III and IV would be much easier to follow if the authors used some pictures. And since they are already provided by Figures 6 and 7, they should just refer to them. The same criticism applies for the presentation of the material presented in Section V. While Section V eventually refers to Figure 5, simple notions of the "build" and "staging" zones could have been easily understood if the authors had referred the readers to Figure 5 from the start.

Comments on the Video Attachment ================================

The order of the sequences made the material **very difficult to follow**. The most important sequence was the animation at the end showing how the approach works for 2 robots. Unfortunately, the paper did not do a very good job of using the figures to desc

Reviewer 3 of ICRA 2016 submission 1796

Comments to the author ======================

When controlling large collections of truly small robots, external and uniform control inputs are typically used as the control signal, such as electromagnetic fields. This paper takes advantage of the friction of boundaries to shape the swarm. The basic idea is to apply the uniform controller in such a way that the robots stick to the wall in a particular manner, thereby allowing for a controlled deformation of the swarm. I think this idea is really terrific and clever in that the environment provides an additional “input” that can be leveraged as a breaker of symmetries. Having said that, I do have some comments and concerns: - In the Introduction it is stated that they can “arbitrarily position a swarm of n robots”. But, what this actually entails is really the statement of algorithms without any **real justification**. To make the type of strong statements that are currently made in the paper, a much more formal approach must be taken. Without it, we are left with an algorithm and a simulation. So, what is actually assumed about the dynamics of the robots? What is assumed about the actual content forces (as opposed to the simplified forces used to generate the algorithms?) What can actually be said technically (beyond “trust us, we can do perfect position control”…)? The paper would become much stronger if the seemingly technical statements in the text were backed up by precise, mathematical, technical statements in the paper. Or, alternatively, the claims should be moderated accordingly in the paper. - The video is fun to watch but clearly exact position control is not achieved. Why is this? This, again, relates back to the question of technical assumptions made for the statements to hold. So, in summary, I really liked the basic premise and the idea of using the environment for shape control is very clever. But, the paper **oversells the contribution quite a bit and**, at the end of the day, I am very unsure as to what is actually shown as opposed to being an aspiration.

Comments on the Video Attachment ================================

The video is good and interesting. But, it does **not quite support the claims** made in the paper, i.e., there is quite a bit of mismatch here.

Reviewer 4 of ICRA 2016 submission 1796

Comments to the author ======================

The paper presents an algorithm for the positioning of an n robot swarm based on collective movements and wall friction. The authors first introduce the problem of extending their previous work, in which they controlled the x and y covariance of the swarm using walls of obstacles, to a full control of the xy covariance so that the swarm can pass through narrow corridors aligned with the x and y direction. To do so, the authors propose the introduction of walls with infinite friction. After thoroughly explaining the 2 robots positioning case, the generalization to the n case is presented. The 2 robots positioning case is shown in simulations, while some experiment is proposed with 64 kilobots. The paper seems pretty good and the presented algorithms are interesting. The idea of using wall friction in order to control some otherwise uncontrollable quantity is very clever. The biggest downfall of the paper is the fact that authors claim something but do something else. The main claim of the authors is that they will control the xy covariance. **However, the presented algorithms produce something completely different, which is complete positioning of the team**. There is no mentioned link between the final position e of the team and the controlled covariance. Also in the conclusions, the authors claims "demonstrations of efficient covariance control". This is mentioned only in the introduction, in the last paragraph of the experiment, and in the conclusions. There is no mention on how this is achieved**, no explanation at all**. It seems almost like a section is missing before the simulations to explain the covariance control. The same comment can be given about the experiments. the presented experiments are not about the presented algorithms. The experiments in the video, and in the snapshots in fig 10, are not performing positioning, at least not in the way presented in alg. 4 with an iterative structure. The same comment is applicable to the multi-robot simulations presented in the video (the 2 robot positioning is instead well tested, although only the simulations are shown in the video). My suggestion to the authors is to explain the missing connection between the multi-robot positioning and the covariance control in an additional section before the simulations. Also, the n robots experiments should be given with more details. The covariance control experiments are described in 5 lines, and as far as explained in the introduction, they should be the main goal of the paper. Additional minor issues are and improvements:

- eq (1), N is not introduced

- \epsilon-neighborhood needs to be defined formally

- Algorithm 2 should be explained with a figure or also making use of Fig 6. Providing a figure for a completely geometrical algorithm will improve enormously the effectiveness of the explanation. In current form, it is extremely hard to understand all the movements from the written description

- are there upper/lower bounds on the values wb hb ws hs?

it seems that the final configuration lowerbounds wb and hb. is it the case?

what about ws and hs?

- wb hb ws hs should be reported in fig 5

- Fig 10: the overlaid covariance ellipse are almost invisible (invisible when printing the paper)

- few typos: "bot experiences" -> "both experience"

each receive -> receives Alg.. 3

Caption of Fig 6: oculd, ocntrolled with different of profiles

Comments on the Video Attachment ================================

The video is interesting, but the authors should include also experiments of n-robot positioning (at least, that is what is explained in the paper).