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Object Manipulation and Position Control Using a Swarm With Global Inputs

Dear IEEE Transactions on Automation Science and Engineering Editorial Office,

Please find attached the revised paper, *Object Manipulation and Position Control Using a Swarm With Global Inputs*, along with the document containing a response to the reviewers. We are grateful to the reviewers for helping us improve our manuscript through their comments and questions. Please let us know if further information is required.

Sincerely,

Aaron T. Becker (on behalf of all the authors)

RESPONSE TO REVIEWERS

In the following document, we have provided detailed responses to the comments and questions of the reviewers. Comments and questions by reviewers are in blue, our responses are in black.

Comments by Associate Editor

[R 0.1] "The paper is interesting and technically sound; however, a thorough revision is required before being considered for publication. The main concern to be addressed is the quality of the writing. Reviewers have provided detailed comments on how to improve the quality of this manuscript. Authors are urged to thoroughly revise the paper according to reviewers' comments and suggestions."

Comments by Reviewer #1

[R 1.1] "This paper studies the pushing effect of a robot swarm over a rectangular object. In order to study the generated torque, the authors represent the swarm as a probability distribution. Three different probability distributions are presented. The ideas in the paper are very interesting and relevant for the community. However it requires a major revision. The comments are the following."

Thank you!

[R 1.2] "At the end of Section III, What is the motivation to consider that all robots apply the same force? An intuitive efficient approach would make the farther robots apply a larger force."

[R 1.3] "Saturation is not considered. An efficient approach would be the same as using a bigger robot but a particle instead. Obviously, this approach cannot be done because of the small maximum force that each particle can generate, but it is not mentioned in the paper."

[R 1.4] "The authors claim that one of the main differences is that their robots are compliant and tend to flow over the object. However, some of the experiments present an adaptation on the object to avoid the robots flow over the object."

[R 1.5] "This "flow over the object" is not mentioned at all in the methodology (even for the triangular distribution). The authors propose static distributions, but the the distributions variate on time due to the flow."

[R 1.6] "Based on the point above, the most efficient way (and obvious) to generate the torque is just sending all robots as far as possible from the center of mass."

[R 1.7] "In contrast to the title, none of the probability distributions maximizes the torque. At least, the maximization problem is not stated in the manuscript."

[R 1.8] "The authors do not mention how to control the robots. It is one of the main points that call the attention in this type of works."

[R 1.9] "In equations (2) and (3), there is a variable n that is not defined. I suppose it is the number of the robots, but it is not explicitly denoted. In these equations, it is not clear that only the surface robots can apply force to the bar. Does F_i takes into account the force that all the robots behind F_i are applying? In this way, (2) and (10) are not consistent. Assuming that the individual forces are linear is a very strong assumption, in contrast to

, the particles move in a very unorganized way (even more when the particles flow over the object)."

[R 1.10] "I recommend to separate Fig. 2 in sub-panels to organize the caption. In the top figure, the particle is not easy to observe and it is not in all the examples. The caption says "Particulate is moving in the -y direction", but a coordinate frame is not defined (same for the x-axis). Is the particle moving with respect to the inertia frame or to the bar frame? Additionally, there is not such a gray line. Are the authors referring to the thin black line? In general, this figure is not helping to picture what the authors want."

[R 1.11] "The derivation of (4) and (5) is no shown or extending the description is required."

[R 1.12] "I like the idea of representing the swarm as a probability distribution. It is easier for the observer and the global controller to drive the swarm as a whole. Again in equations (7)-(9), the coordinate frames are not defined and not consistent. The COM $[O_x, O_y]$ is defined in the inertia frame, but the distribution of the robots is defined on the object frame (where the x-axis is parallel to the long side of the rectangle). Although these equations are intuitive, the way the authors obtained the constants (e.g. the sqrt(3) in Eq. (7), only in the next section is assumed that the length is 1) is not obvious."

[R 1.13] "In (16), the function erf is not defined. It is only defined at the end of the section."

[R 1.14] "Based on the granular effect, there is a maximum number of robots that can apply forces without flowing. What is this number? or how can you describe this final configuration?"

[R 1.15] "The experiments section need to be extended, there granular effect need to be extensively studied. Again, it is necessary to describe how the robots are driven to maintain the distribution and to generate the torque."

[R 1.16] "According to the format guidelines, the equations are part of the text and should be punctuated. Most of them are not."

[R 1.17] "Caption in Fig 2. says "Particulate" instead of "Particle""

Comments by Reviewer #2

[R 2.1] "This paper studies the torque applied by a swarm of particles on a long aspect-ratio rod. Generally, the topic of this paper is interesting. Experiments are well designed to illustrate the theory in practice. Here are some suggestions to be considered for the possible revision. "

[R 2.2] "Please add x-y-z axes in all the experimental figures such as Figs.1 and 8."

[R 2.3] "What does cyan/white star points mean in Fig.1?"

[R 2.4] "In this paper, two different cases are considered. One is a pivoted object, the other is a free object. Differences between two experimental results are encouraged to be highlighted. "

[R 2.5] "Please highlight the material and the size of the rod used in the experiments. Contacts between robots or between robot and rod should be detailed, and their effects should be further discussed if it is possible."

[R 2.6] "The definition of 'kilobots' should be given when it is used for the first time. "

Comments by Reviewer #3

[R 3.1] "The articles discusses a variant of swarm manipulation where a large number of particle like robots are steered using a common force input. The article primarily analyses the force and torque they exert on movable objects they come in contact with; as well as the shape the particles make as they accumulate around these objects (shown to be a triangle whole apex angle is called the angle of repose. The strengths of the article are: The analysis provided for several manipulation scenarios appears to be sound The results are novel to my knowledge. Experimental results on a hardware test bed are shown. The weaknesses are: The analysis can be difficult to follow because in some cases the variables are not well defined. There are many, many grammatical and punctuation errors. (see below) The abstract is poorly written."

[R 3.2] "Question: It would seem that the angle of repose might depend on the particle size or the coefficient of friction between particles or teh object-particle. Can you explain why it doesn?t? I understand this isn?t the primary contribution of the article but it seems those parameters would play a role."

[R 3.3] "The abstract is repetitive and has a non-standard format (note to practitioners?) and should be restructured. It doesn?t make it clear that all the particles are steered with a common force (different from other swarm scenarios). It uses the term angle of repose without defining. The last paragraph about a single robot does not belong in the abstract at all."

[R 3.4] "Introduction - paragraph 1: Last sentence doesn?t flow. "

[R 3.5] "The term angle of repose should be defined earlier than the end of page 2, because it is used many times before that and while it is defined in [2] it is not a standard term in the robotics community."

[R 3.6] "Many of the equations are not properly punctuated. For example, eq 4 and 5 need periods as they end a sentence. Same with 7,8,9, 12,13, 18, 19, 20 "

[R 3.7] "The last sentence of Setcion 4 doesn?t make sense. Should the ? -? be an ?=? symbol?"

[R 3.8] "This sentence could be worded better: (page 3, col. 1) ?Given sufficient particles to pile up to the angle of repose?? also it raises an interesting point that these calculations assume a sufficient number of particles. Is there an expression that would estimate the number of particles, given the particle size?"

[R 3.9] "Page 3, col 2, top: It?s not clear what l_p and u_p are. (lower and upper bounds?). Earlier l is used to mean the length of the rod. In the first sentence you mention a variable up_p, perhaps you mean u_p?"

[R 3.10] "On page 6 you use an inconsistent style when referring to equations. At one point you use ?Eq. 16? and later on the page you use the style ?(18)?"

[R 3.11] "Caption of figure 3 needs an extra comma depending on the meaning you are trying to convey. ?For all distributions *,* pushing at $\mu = 1$ ...?"

[R 3.12] "I don?t think the subsection headings should end in ?:?"

[R 3.13] "The annotations in Figures 4-5 are small and hard to see."

[R 3.14] "Section 6 paragraph 1: The word Sections should be capitalized when referring to previous sections by number. "

[R 3.15] "Should Kilobots be capitalized? (proper noun)"

[R 3.16] "Reference section: the way you cite ICRA is inconsistent."