Reply to Reviewer Comments for SoRo Submission "Autonomous Object Manipulation using a Soft Planar Grasping Manipulator"

Robert Katzschmann, Andrew Marchese and Daniela Rus

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We thank both reviewers for their time and effort to provide us with thoughtful comments. We worked on each point raised by the reviewers and hope that we have a much clearer and improved manuscript. Below we detail how we addressed the reviewers concerns. The original reviewer comments are shown in italics, our answers are given underneath.

1 Reviewer 1's Comments

This paper discusses an autonomous object manipulation algorithm using a soft planar grasping manipulator.

1.1 Contribution Discussion

Several major issues with the paper hold it back. First, the contribution of the paper seems very minor. A considerable amount of the paper is already covered in the work[2] [4] [3], which involves the design of the robot, the recipe to create the robot, and the whole-arm motion planning. The contribution of this work is the grasping algorithm itself, which is a preplanned sequence of robot curvatures. In light of the whole arm motion planner in [2], this contribution seems minor when adding in a (circular) object. The algorithm itself is implemented as a state-machine method, and with 4 or 5 states and seems trivial. Only one experimental test is performed to demonstrate the algorithm, and no quantitative error metrics are provided. We thank the reviewer for pointing out that the contribution is not clear. The contribution of this paper is an autonomous system for object pick-and-place manipulation that can handle objects of unknown geometry using only soft components to build the manipulator. The gripper can pick up arbitrarily shaped objects (compatible with the size of the gripper) placed at arbitrary locations on the work space. We revised the contribution subsection within the subsection to make the main contribution clear. We also adjusted the text to highlight the extensive experiments. *For these reasons and especially for the minor contribution that this manuscript offers, I cannot recommend publication as a journal paper in SoRo. The contribution seems better suited for a conference paper submission.* We believe that the contribution of successfully and repeatedly performing object manipulation using a fully soft, multiple degree of freedom arm is a novel capability. Our feasibility study opens many avenues for soft robotic manipulation. We revised the conclusion section to better articulate these ideas.

1.2 Motion-Capture

With a motion-capture system, the problem becomes entirely well-defined. However, soft robotics are specifically designed to work in confined or constrained environments where constraints and obstacles are unknown, with often no line of sight. Discuss how one might actually implement this without a motion-capture system that picks up the entire configuration of the robot manipulator. Why does soft robotics systems need to specifically be designed for confined or constrained environments only? How is the use of motion capture systems a well-defined problem and how is it such especially in conjunction with soft robotics? Have others done it before, do you have a reference on this? We thank the reviewer for this observation. We developed an end-to-end system that can approximately locate an object placed at an a priori unknown location and move it somewhere else. The external localization system is a convenient way to approximately identify the location of the object and to track how the object is moved around. The exteroceptive tracking system has the disadvantage that the full occlusion of one or more markers can cause the tracking system to temporarily loose track of a measured arm segment. In that case, the control loop can not function properly until the occlusion disappears. The external localization system could be replaced with another method for localizing the manipulator and the object in the workspace. For example, proprioceptive sensors within the segments could solve this issue partially. A first step towards proprioceptive sensing was done for three soft fingers arranged as a hand in reference [1].

1.3 Suitable contactless/constrained motion?

Section 1.1 Last paragraph: was only suitable for contactless motion implies that your proposed method solved motion when the robot is constrained by the environment, but it is rather about gripping objects. The sentence was confusing, we clarified the manuscript.

1.4 Contribution 1

Section 1.2 Contribution 1 seems entirely described in [2] and [3]. Contribution 4 seems obvious that force sensing nor accurate positioning is required to manipulate objects. Contribution 1 is different to previous contributions: Reference [2] only presents a 6 segment soft arm that can move on a plane, not interaction or manipulation capabilities with objects are shown. The paper deals with the changing body shape of the soft arm when moving it around on a plane. Reference [3] discusses fundamental actuator morphologies and presents recipes on combining those morphologies, but how to make a 7 DOF arm controllable is not detailed in that work. In this manuscript, we plan for an enveloping grasp of an unknown object in the plane and demonstrate pick-and-place from uncertain locations. We made clarifications to the contributions sections accordingly.

1.5 System Overview Figure

Section 2. System overview, Figure 2: The image is difficult to see and in its current form, and information of the physical frame surrounding the robot seems unnecessary. Thank you for this comment. We moved the labels on the figure. Also, we added to the paper in the experimental section why the physical frame is important to have a mobile presentation platform that can keep the system together, hold the tracking cameras rigidly in place, and does not require recalibration of the tracking cameras.

1.6 Fabrication Steps Detailing

Section 3.1-3.2 These sections are completely described in [3] and comes off as a recipe to make the manipulator, which is the contribution of [3], and therefore should not be reproduced in the main text. Figure 4 and Table 1. Pulled from [3] seem unnecessary. Furthermore Table 1 does not fit the column. Reference 13 includes some description of the fabrication steps, mainly to depict the more generic pleated fabrication process. The process described in that paper is not complete to allow the reader to reproduce a controllable manipulation system. We added further clarification to the text, removed unnecessary fabrication portions and set the focus on what is new. We removed Table 1.

1.7 Motion Tracker

Section 4.2 par 1., Which motion tracker was used? We used the commercially available The OptiTrack Flex 3 System by Natural Point, Inc. We revised the text in the experimental section to add this information.

1.8 Optimization Equation

Section 4.2 The optimization equation, as I eventually found hidden in Algorithm 1, is difficult to understand: what are parameters v.s. variables, and what is R in the objective function? I suggest writing the equation in the text in full. The weights are set by the matrix $\mathbf{R}$. The variables to optimize for are ϕ and κ. All parameters are introduced as inputs to the algorithm. We revised the manuscript to clarify this point and make it easier to find the optimization equation within the algorithm environment.

1.9 Algorithm Difference

I also find it difficult to see exactly the difference between the algorithm presented here and the one in [2]. While grasping is indeed is one objective, that seems to be realized by a curvature objective. We thank the reviewer for this comment. In section 4, we revised the exposition to highlight the differences between the two approaches. The algorithm in [2] is about planning the motion of a soft arm without a gripper through a maze at a centerline while taking the arms bulging shape as a trapezoidal into account. The approach does not work for approaching and grasping objects, because a tip trajectory for successfully moving towards the object is not known, but needs to be generated by posing and solving a new optimization problem. That trajectory needs to avoid pushing the object away with the manipulator trunk when approaching it with the soft gripper at its end. In this paper we present an algorithm for approaching an object by following along concentric lines, which are further and further decreasing in size until object size is achieved. The non-linear optimization is finding tangent poses along these lines using non-linear optimization and then follows down those concentric lines, which implicitly guarantees the arms pose to stay convex since the circles are convex themselves.

1.10 Optimization Constraints

Section 4.2 Is the optimization function over or under-constrained? Will you always find a solution? What happens if you dont find a solution? The optimization only becomes over-constrained if it has to find an arm pose outside of the arm's reachable workspace. That occurs if the object was user-placed outside the workspace. Before performing the optimization, a feasibility check is performed using the arm's forward kinematics.

1.11 Solver Details

Section 4.2 par 1., Provide the speed of the optimization solver as well as the solver used. The nonlinear optimization problem was implemented using Matlabs Optimization Toolbox with the function calls fmincon, which finds the minimum of a constrained nonlinear multivariable function. Sequential Quadratic Programming was used as the solver with a relative upper bound of 2×10^{-3} on the magnitude of the constraint functions. The lower bound on the size of a step was given by 1×10^{-6}. The solver takes about 1 s on a regular PC to solve for all waypoints from start to finish. We included this information in abbreviated form in the manuscript.

1.12 Convexity as Constraint?

Section 4.2 par 1. while its null space maintains a convex shape, bending away from the object. Is the convexity actually a hard constraint on the solver? How much does this depend on your specific task and the orientation of the arm/gripper combo? When solving for a tangent gripper pose in CCW direction along the green concentric circles, this is implicitly the constraint for convexity. The algorithm proposed is task-specific as to picking up an object on a plane without pushing it away prematurely. We also added a note to the manuscript to clarify this.

1.13 Algorithm Numbering

Section 4.3 The text describing Algorithm 1 would be well suited to have numbered sections that could help the reader understand at which location in the Algorithm the text is referring to. Thank you for this advise. The way the algorithmic environment was set up in this document, it is not trivial to add line numbering to it. Instead we clarified the description of the algorithmic steps within the manuscript better, it should not require line numbers now to understand the exposition.

1.14 Object Details

Section 5.2 What is the object weight? What is the object radius? The object has a weight of 18 g and a diameter of 3.3 cm.

1.15 Task Execution Speed

Figure 9: What is the time/speed of the task? Depending on where the object is placed, the arm takes between 17-35 s to approach it. The task of moving back to the bin takes between 10-20 s. We added this data to the paper.

1.16 Additional References

Lack of references (Some covered in DeVolder2010): De Volder, Michal, and Dominiek Reynaerts. "Pneumatic and hydraulic microactuators: a review." Journal of Micromechanics and microengineering20.4 (2010): 043001. Ikuta, Koji, Hironobu Ichikawa, and Katsuya Suzuki. "Safety-active catheter with multiple-segments driven by micro-hydraulic actuators." Medical Image Computing and Computer-Assisted InterventionMICCAI 2002. Springer Berlin Heidelberg, 2002. 182-191. J. Xiao and R. Vatcha, Real-time adaptive motion planning for a continuum manipulator, Proc. IROS 2010, pp. 59195926, Oct. 2010. J. Li and J. Xiao, A general formulation and approach to constrained, continuum manipulation, Adv. Robot., no. July 2015, pp. 111, 2015. Thank you for your comments, we added the appropriate references to the introduction section of the paper.

2 Reviewer 2's Comments

This paper covers the fabrication and integration of a new soft robot gripper with a six degree of freedom soft multi-segment arm. The paper also describes a planner for grasping using the integrated system as well as some evaluation of grasping efficacy and the gripper workspace. In general, I think the topic is very interesting and the approach valuable. There seems to be a number of practical limitations to the platform and approach that I would like to see addressed or discussed in the paper. The following are specific feedback that I have:

2.1 Uncertainty Characterization

For the third contribution listed on page 2 (line 33), I don't agree that you have characterized some of the uncertainty that is rather important. For example, you have shown for the gripper where it can grab for a single set of trials, but you do not describe repeating those trials, which would actually give you measures of uncertainty. Also, the red box used to denote the "bin" for placing the grasped object is an important measure of uncertainty. It seems like if this arm were to actually be used for manipulation, a good measure of uncertainty on positional accuracy would be important. Thank you for this comment. The capture region characterization was performed three times, always yielding to the same capture region given the grid size. The intent of this experiment was to qualitatively describe a relation between object size to gripper size to area of successful grasp. We revised the manuscript to properly phrase the contribution and provide the missing details on the experimentation.

2.2 Delicate Object Manipulation

For the fourth contribution listed on page 2 (about line 37), I don't believe that you have shown (either experimentally or analytically) that you can manipulate delicate objects. I believe it, but you haven't reported gripper forces or extensive trials with delicate objects. I would either perform those tests or rewrite this contribution. It also isn't clear what is meant by "proper manipulation." Thank you for this observation, we did not intend to draw focus on the delicate object manipulation and therefore changed that part of the experiments section to provide more details on what kind of objects have been successfully grasped. The egg is just one example.

2.3 Clearer Fabrication Process Description

I found the description of the fabrication process for the gripper to be slightly confusing. I think more annota-

tions on figure 3 (such as point 1 or c, etc) and referring to those annotations in the description could make it clearer. Especially since this is listed as a major contribution. Thank you for this comment. We adjusted the contributions section accordingly, refer to citations where necessary and shortened the hardware design/fabrication section to focus on what is new and what were challenges for the 7 dof design and fabrication.

2.4 Distinguishing from Past Work

Although you reference past papers from your own group, I think you could do a better job distinguishing from your own past work. Can the process for making the gripper be applied to the multi-segments as well? Which is better for what and why? We revised the exposition to clarify this point. The retractable pin fabrication for uniform lateral channels, first introduced in reference [12], does not cause weakening seams to the actuator, but it also does not allow for cavities more complicated than cylindrical shapes. This is why we propose the application of lost-wax casting to the fabrication of soft fluidic actuators like a gripper. The cylindrical segments of the arm are fabricated through a retractable pin fabrication technique, which does not require lost wax cores because of their simple cylindrical cavities.

2.5 Limitations that could be Addressed

Many limitations of the hardware or approach should be addressed in the paper. I realize that they cannot all be addressed or discussed. Nor am I asking for you to solve these problems, but an effort could be made to talk about the following: See our answers below.

1. *How would the design of the gripper change if we wanted to grip in both directions? Is it even possible with the current design?* We added to the limitations discussion in the manuscript: "The experiments were only performed for picking up objects on the left quadrant of the manipulator. Grasping objects in both directions could be achieved in various ways by

   (a) increasing the reachable workspace through starting the soft arm at an extreme curvature configuration within the right quadrant,

   (b) replacing the large gripper with two smaller grippers next to each other at the end of the arm,

   (c) mounting roller supports on the top face of the manipulator and then rotating the manipulator at its root by 180°."

2. *Is using motion tracking realistic for some of the scenarios you suggest? I would guess not, but what is the future for state estimation? Existing sensors? Or are new sensors needed?* We added: "The exteroceptive tracking system has the disadvantage that a full occlusion of one or more markers can cause the tracking system to temporarily loose track of a measured arm segment. In that case, the control loop can not function properly until the occlusion disappears. Proprioceptive sensors within the segments can solve this issue. A first step towards proprioceptive sensing was done for three soft fingers arranged as a hand in reference [1]."

3. *It requires 6 degrees of freedom to achieve a reasonable reachable work space, how does this scale to a full 6 DoF task? Or does it scale? Is it limited to in-plane tasks? What is the reachable work space in the plane with 6 DoF and the + or - 60 degree joint limit?* Thank you for this observation. The focus of the paper is planar manipulation. Scaling to a 3-dimensional task is not considered in this paper. Our future work will consider the 3D case. We revised the text to clarify this point. As was shown in [13] through the characterization of various actuator morphologies, the concatenation of soft cylindrical segments is most suitable to build up a robot arm that can create high blocking forces per fluid energy inserted. Using six segments, the $\pm 60°$ joint limit does not prohibit the robot to reach its own base. Calculating the forward kinematics, see `forwKin()` procedure in Algorithm 1, for the 6 DOF arm with a segment length of 6.27 cm and an extreme curvature of $\kappa = \frac{60/180\pi}{0.0627\,\mathrm{m}} = 16.7\frac{1}{\mathrm{m}}$ shows that the tip of the robot can reach its root at a full curl.

4. *Why was a convex shape necessary for approaching a grasp? What if I wanted to approach an object with a different orientation but in the same locations you already looked at?* We added an emphasis to the manuscript to say that the shape needs not be convex. The convex shape approach is a conservative solution with minimal computation required in solving the planning problem while assuring not to collide.

5. *What is the role of the rollers in carrying your payload? Without the rollers, could the arm not move the object?* Thank you for this comment. The complete multi-segment arm is supported off the ground with two roller supports per segment. The rollers minimize frictional forces to the surface. If the arm would be moved over a non-slippery surface without rollers, the frictional effects would greatly reduce the agility of the arm and largely increase the stick-slip friction effects with the ground, rendering the arm less useful.

6. *Why did you decide to minimize manipulator deformation for your grasp object planner? Furthermore, what if I wanted my plan to follow the shortest dis-*

tance for the end effector to travel (essentially following the black line in Figure 6), is this even possible given the possible kinematics of the arm? Minimized manipulator deformation seemed to be a feasible approach, because it is proportional to energy consumed by the cylindrical piston drives and it minimizes strain to the actuators and minimizes risk of exerting further than actuation limit of a segment. We also added this explanation to the paper.

2.6 Grammar Comments

Overall the paper is well-written, but there are some places with awkward or incorrect grammar. Examples include Thank you for pointing out these grammar mistakes. We made the following changes:

1. *pg 2 line 37 "soft robots do neither require force sensing nor accurate ...";* We changed the sentence.
2. *pg 3 line 23 "Those seams are prone to rupture ..." refers to the laminated seams, but that isn't clear from phrasing;* We fixed this sentence.
3. *pg 7 line 21 "newly registers every single time the position of the placed object." is confusing.* Sentence was changed.

2.7 Video Attachement

The paper should definitely include a video of operation of the arm. The overlaid figures are very well done, but video would be a valuable contribution to understanding the performance of the system, especially since we have no other time dependent graphs of end effector or joint position. Thank you for this suggestion, the video will be attached again to the revised version of the paper.

2.8 Table 1 Formatting

Table 1 needs to be formatted to stay in column We ended uo removing the table completely since it was not providing necessary information to bring across the key message of the paper.

2.9 Variable Definitions

I feel like many variables could be more clearly defined. Things such as L_{meas}, ϕ, g_{off} (described in algorithm, but still not clear where measured from), Thank you for pointing all this out. We added clearer descriptions to the text and more indications in figure 5 and figure 6 to clarify these variables. *w_{off}, L_N, κ (in algorithm 1, not clear if current κ or desired or ...),* We added: The end effector offset $\mathbf{w}_{\text{off}}$ describes the distance from the root of the gripper, to an offset point close to the lower end of the gripper's palm. It is visualized in the top left corner of Fig. 5. We also added to the manuscript: The arc length input to the arm's forward kinematics is the N-th element of the segment lengths $\mathbf{L}_{\text{meas}}$. We assume that it is clear κ is the variable being optimized for in $\min\limits_{\phi, \boldsymbol{\kappa}} \kappa_{off}$ *(defined in algorithm, but not clear again what it was). Some of these terms are on the diagram in Figure 6, but their definition was still not clear to me. This was especially the case since I'm not sure what the multiple green circles on each concentric circle signified. Some terms were also used but not clearly such as "minimal tip transit distance".* κ_{off} is now better defined by: "measured manipulator configuration at start". We also clarified the meaning of the circles in the text.

2.10 Value for Δd

Other items were clearly defined, but it wasn't clear how their value was set such as Δd. The amount of intermediate waypoints is determined by the variable Δd, which we found empirically to be 5 cm, around half the length of the gripper.

2.11 Object Settling

In Section 4.2, what does it mean for an "object to settle?" We consider the object to have settled if it has not moved for 2 s.

2.12 Forward Kinematics

The forwKin procedure in algorithm 1 seemed a bit odd. It is recursive and requires calculating the forward kinematics of the previous link, all the way back to the base. That is fine, but the way it is defined, this would happen every time we step forward one link. Is that correct? Why not just use a for loop to be less confusing to a reader and more efficient computationally? Yes, if only one link is changed, it is more efficient to only update the individual segment's cartesian pose and all the segments following it. In fact, our actual implementation does check for this and would then only recalculate the necessary segments. The recursive function definition nevertheless makes sense and is efficient. In practice, all curvatures are actually constantly changing, both for measuring the curvatures from the tracking system as well as when running the optimization to find a minimal curvature κ. For the system shown in the paper, this algorithmic tweak would not lead to a significant performance increase. Furthermore, in order to not complicate the math too much, we decided not to mention this detail of implementation.

2.13 Picking up Eggs

Discussion of picking up eggs in section 5.1 is a bit out of place. Was actual testing done for this? Actually reporting grip forces or pressure would be much more interesting. Picking up eggs is just as one example for a delicate manipulation the gripper actually performed. The soft manipulator picks up delicate and normal objects such as eggs, shuttlecocks or bakery items, tape rollers without squishing or breaking those. Regarding the gripping forces: It was shown in [3] that pleated grippers of similar dimensions like the one used in this work can exert a continuous spectrum of blocking force in the range of 0-2 N at a pressure range of 0-60 kPa. Grasping delicate objects should therefore be possible with the soft manipulator.

2.14 Uncertainty of User Placement

For the trial shown in Figure 7, what was the uncertainty on the user placement of the object? This seems like it could be rather large (compared to the resolution of the discrete placement locations) unless you used the motion capture system somehow. The grid paper and fine markings on all four sides of the round object ensure that the placement by the user is accurate within ± 1 mm in relation to the discrete placement locations. This test serves as a qualitative measure to show a relation between object size to gripper size to area of successful grasp.

2.15 Final Drop Off Location Size

How was an appropriate size determined for the red "bin" to determine success? It looks like the spread on placement was about 15 cm. That seems rather large and some commentary on it seems important. We added an explanation in the "Grasp Experiments" section: For these experiments, we focus on showing the capability of picking up objects at various places and moving them around, there is no emphasis set on having to drop off the object at a specific pose. To indicate that the arm can move the object after grasping, the arm was controlled to go back to the fully straight pose. When it got fairly close to that final straight pose within a large allowable delta, the gripper was set to release and drop the object. It was not ensured by the planner that the arm had to first settle to zero velocity at the final straight pose. As a consequence of this, the experimental data indicates as a red bin a relatively wide drop off area.

2.16 Discussion Section in Paper

The discussion in section 5.2 led me to have the following questions/comments:

1. *What if the object is not round?* Picking up other objects that have a similar size compared to the round test object does also work. We included the other objects we used in the experiments in the manuscript.

2. *What is the importance of the rate that way points are sent from the planner? Especially failure trials where the arm went unstable seemed to indicate that both the controller and planner may be very dependent on smoothing the desired curvature way points or sending them slowly in time. More detail would be good.* A smoothing of the complete trajectory with several intermediate waypoints was found to be necessary. The amount of intermediate waypoints is determined by the variable δd, which we found empirically to be 5 cm, around half the length of the gripper. A new waypoint is sent to the controller immediately after arriving within a small delta of the previous waypoint, the controllers for each arm segment then compensate for the new delta in curvature as quickly as possible to get to the new pose κ_i^*.

3. *The instability in general seems important and would be nice if it was determined if it was from the planner or controller.* We discuss this point now in the "Experimental Insights and Limitations" section. The instabilities observed in the unsuccessful trials could in general be fixed by loosening the constraints on the planner. The planner could allow the arm controller to have the arm pass over each intermediate waypoint without having to get to a full stop within an arbitrarily chosen delta of curvature values. The planner could take as a measure of progress a decreasing cartesian distance of the gripper to its final target pose. It is worth mentioning that the exteroceptive tracking system has the disadvantage that an occlusion of one or more markers can cause the tracking system to temporarily loose track of a measured arm segment. In that case, the control loop can not function properly until the occlusion disappears. Proprioceptive sensors within the segments can solve this issue.

2.17 High Dexterity Observation

Discussion in conclusion refers to high dexterity when handling delicate objects. However, all of your tests showed approaching the object from more or less the same direction. Do you have a kinematic model or experimental data that shows your manipulator's dexterous workspace? This is similar to a previous comment above. Thank you for this observation. We revised the conclusions to remove the high dexterity discussion; instead we describe how widely the arm can be stretched in its various poses to approach the same object. We also describe how future work could investigate the dexterity of the arm when approaching the same object pose in various ways, just by changing the constraints and cost function when optimizing for the inverse kinematics solution.

References

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