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Peer Review File

A Fabrication Strategy for Millimeter-Scale, Self-Sensing Soft-Rigid Hybrid Robots

REVIEWER COMMENTS

Reviewer #2 (Remarks to the Author):

The paper presents a novel methodology for intricate miniature actuators with embedded resistive sensing which shows a promising solution for miniature soft robots with closed loop control.

Key results

The paper shows a novel fabrication process and some experiments to test the actuation performance in terms of force and displacement. The results show an actuation task with good agreement between the predicted tip position using the ionic fluid sensor data and the measured position of the actuator. This is shown for the 3 actuation modes as well as an actuator comprising one of each type of unit. It is unclear whether the calculated value of resistivity (P.13) was verified experimentally. On P. 10, the maximum error is given but it is not clear what parameter this error applies to (angle, displacement etc?). On P. 14 it is not clear how is K computed and where it is used. For example, the author's should give the modified version of Pouillet's Law, showing how K is used. While K is shown in Figure 6a, it's not clear how the product of K and A is used. This parameter also seems to be measured in unit of area but appears to be a distance from how it is represented in Figure 6a, and this should be corrected. It's not clear from Supplementary Table 3 which parameter the SD applies to? Is it the sensitivity? Please clarify.

Validity

The mechanism by which the actuator can be 'constrained at a more expanded state' is unclear (P.12), and so the significance of the argument around virtual work is difficult to understand. Perhaps a diagram showing what is meant by this could help to communicate this result.

P.6 A diagram should be used to illustrate what is meant by the chord length and if this refers to the Sarrus linkage or actuator as a whole

Significance

The authors compare performance with five studies on similar actuators, however, the significance of the results could be better communicated by normalising the performance metric, for example, to size, input power/flow rate of each actuator, rather than stating the absolute speed of actuation achieved by each study.

Data and methodology

The paper shows a novel fabrication process and some clearly explained experiments to test the actuation performance. The novel fabrication process is one of the main contributions, however the process could be better communicated throughout the paper, therefore this should be a point of major revision.

Specifically, in Figure 1b, colour coding should be taken advantage of to generate a key to annotate the different layers as it is difficult to see which layer each arrow indicates.

The meaning of a Sirrus linkage should be explained, for example by annotating this part on Figure 1e.

Figure 1e should also show the 'circular arms' in plan view as it is currently difficult to see their circular shape, and these should be annotated in Figure 1e to show which component the arms are.

Figure 1f is totally unclear and needs major revision to make the overlaid figure discernible. Somewhere in the paper the authors should also explain how the attachment points of the 2D layers lead to the 3D shape when inflated as this is a key part of the design, but is not explained anywhere.

The process shown in Figure 2 could also be improved, perhaps by arranging figures to show steps that happen in parallel and step that either combine the outputs of multiple previous steps or are a direct follow on from the previous step. A flow diagram / tree diagram could be an effective way to show this.

Figure 3a should also be improved by addition of annotations to fully describe the process happening. This should include labels labelling the arrows showing: bonds breaking; combination with fluorine atoms; zig-zag arrows (it's not evident what these show).

In the empirical part of the study, one actuator geometry is investigated. The authors should give detail of this actuator: how many pouches/layers are combined to achieve the performance described, and what are the fluid chamber?

Figure 7a - It's important to clarify what's being shown here. The photo of the real robot is confusing sit is shown in a different position to the modelled robot. This should be moved to outside of the axes. The significance of i-vi ishould be given in the figure caption rather than the body text as it is difficult to tell from looking at the figure alone wether this is a sequence, or else what is the difference between the different subfigures is. The use of the figure alone makes to difficult to assess how well the real system matches the model, due to perspective (in particular Figure 7ai). The authors should include the coordinates of the tip of the predicted and real system to that this can be quantifiably compared.

The grasper fabrication and methodology of pick and place task are very briefly described and more detail should be given here for example a schematic to show the gripper construction and a description of the distances through which the object was translated during the pick and place task and how the robot was controlled (e.g. open loop).

Analytical approach

The paper analyses the performance of the actuator and embedded sensor in displacement and comments on observed features such as hysteresis, elastic material relaxation over multiple cycles of use (repeatability) and physical limits of the systems (e.g. displacement plateau reached during bending). As only one geometry is investigated, it would be useful to analyse the scalability of the design to actuators comprising more laminated layers or different geometries. Ideally this should also be validated using empirical data.

Suggested improvements

On page P.17 length is shown with position error. It would be useful to see this for the individual units (extension, bending, roto-translation) as well as the combined actuator, so see how the performance of these individual actuation modes compare in terms of sensor error.

Clarity and context

In general the writing is clear and accessible.

P.12 Equation 2 (d theta should be defined).

References

A comprehensive list of relevant and up-to-date literature.

Reviewer #3 (Remarks to the Author):

The authors proposed a fabrication method for building small-scale soft-rigid hybrid robots with sensing self-sensing ability. The actuator is hydraulic driven bellow structure which can unfold and fold when inject or eject the liquids. The sensor is based on the resistive behavior of the ionic fluid. The claimed major advance is the layer-by-layer lamination-based process. In general, the layer-by-layer lamination-based fabrication process have been shown in multiple works from Wood group ([36]) and the author's group ([6][7]). The demonstration of a steerable soft robot with ability of sensing itself provides one fabrication example of the fabrication method. It seems that the fabrication method introduced is very specific which somehow reduce the enthusiasm of the proposed method.

Overview

1. Overall, I find the introduction a little confusing with the logics. The need of “self-sensing” for more information for feedback control and the need of “physical intelligence” for allowing less control seems contradicted to each other. My understanding is that the motivation of proposing the layer-by-layer fabrication method for integrating sensor and actuator seems in that such a method could result in smaller and more precise compared with manual assembly process.

2. Significance. Every robotic device comes with a fabrication process, but the question is whether the fabrication process associated is general and provide best performance. Regarding the advance of the fabrication method, how do you compare with state-of-art fabrication method to make the similar robots? For example, compared with manual assembly and other method different from lamination-based method, what are the fabrication time, fabrication accuracy, overall device size, and device capability? Without these direct and quantitative comparison in key fabrication performance, it is hard to see the advantage and impact of the proposed method.

Major comments

3. What is bandwidth of the ionic fluid-based sensing? Are there any capacitive effects associated with the fluid? In the paper, the resister is modeled as a resister only which may not be true.

4. For each module, it seems manual process must be involved for merging the tubing and wiring. Can this manual process be further eliminated? When targeting at a larger reachability, more modules are needed. How could be tubing and wiring be handled when scaling up the number of modules in the fabrication process?

5. Please comment on the biocompatibility of the material and device.

6. References. It is suggested to include more fabrication methods as a comparison. The H2 plasma etching for PTFE is not new suggesting a reference should be provided (e.g. https://www.mdpi.com/2073-4360/12/12/2855).

7. Some main figures could be combined such as Fig. 4 and Fig. 5 as they are both quantifying the actuation/motion performance.

8. Fig. 7 needs to be supported with more data as a main figure, which may be combined with Fig. 6 to show the sensor performance. The tracking error in Fig. 7b may be better represented in relative errors.

Other points

9. What is the liquid droplet in Fig. 3c? Is it water?

10. The variables in Fig. 1f should be explained in the caption.

11. “k*A” in Fig. 6a is not explained in the caption.

12. Are the layers in grey in Fig. 2e,f,g conductive film or adhesive film? What is the layer in light grey? It is not explained.

13. The fatigue test could be moved to SI.

Response to the reviewers

Paper title: A Fabrication Strategy for Millimeter-Scale, Self-Sensing Soft-Rigid Hybrid Robots
Authors: Hun Chan Lee, Nash Elder, Matthew Leal, Sarah Stantial, Elenis Vergara Martinez, Sneha Jos, Hyunje Cho, and Sheila Russo.

Introduction

We are pleased to submit the revised version of our manuscript entitled "A Fabrication Strategy for Millimeter-Scale, Self-Sensing Soft-Rigid Hybrid Robots" for consideration in the journal *Nature Communications*. The authors would like to greatly thank the editor and the reviewers for their valuable and insightful comments, which have helped us improve our work.

This document contains a detailed response to the reviewers' comments. The three reviews are denoted as Reviewer 1, Reviewer 2, and Reviewer 3 below. For each reviewer's comment, the original review text is quoted in *italics*. The authors' response to each point is provided in normal typeface font in blue. In the revised manuscript, the revised contents are highlighted in red text.

Comments from Reviewer 1

In this manuscript, the authors present a manufacturing paradigm for millimeter-scale soft-rigid hybrid (SHY) robots, aiming to achieve monolithic integration of actuator, mechanical controller, and sensor components, minimizing the need for manual assembly and adopting a compact form factor. While the manuscript explores interesting aspects, particularly in the fabrication of small-scale soft robots, there are many major concerns that merit careful attention for potential publication in Nature Communications:

R1.1. *Clarification on Fabrication Capabilities: It would be beneficial for the authors to provide a more precise definition of the capabilities inherent in the reported fabrication strategies. Additionally, clarification on the scalability of this fabrication method, both in terms of size and batch scale, and its adaptability to fabricating various systems, would enhance the manuscript.*

Response: We thank the reviewer for the constructive feedback. In this paper, we demonstrated the versatility and adaptability of our fabrication approach by manufacturing three distinct SHY robotic modules with different degrees-freedom and a gripper (see Fig. 1 in the main manuscript). These modules can be combined to achieve different robotic architectures and degrees-of-freedom. We demonstrated how these robotic modules can be assembled to build a continuum robot (Fig. 7) and a robotic manipulator (Fig. 8) and included shape sensing functionalities (Fig. 7).

To address the reviewer's comment, we have extensively revised the *SHY Continuum Robot*

Demonstration section where the SHY continuum robot is now integrated with various end effectors, including a robotic grasper, a needle, and an optical fiber. The manuscript is now showcasing additional capabilities of our manufacturing approach and the resulting robotic systems. The integration of a robotic grasper enables robotic pick-and-place tasks of soft and hard objects of various shapes and sizes, showcasing potential applications in food handling, manufacturing, and surgery. The addition of a needle and an optical fiber demonstrates potential applicability of our robotic technology in medical procedures (e.g., tissue biopsies and laser ablation).

To showcase the scalability of our fabrication method, we miniaturized the SHY robotic modules down to a 5 mm outer diameter (OD). As described in the newly added the *Scalability* section, these miniaturized modules retain the monolithic fabrication capability and functionalities of their scaled-up counterparts (11.5 mm OD version). These miniaturized modules were fully characterized, as shown in Fig. 6.

Lastly, we highlighted the possibility of batch fabrication in the *Discussion* section [P. 23] and Supplementary Information (Section: *Batch Fabrication*). Supplementary Fig. 11 demonstrates the feasibility of batch fabrication by incorporating multiple (i.e., up to 15) modules within a single manufacturing session. Supplementary Fig. 11 shows a square laminate of 5×5 cm. Our diode-pumped solid-state (DPSS) ultraviolet (UV) laser precision micromachining system (Coherent Matrix 355 nm, 5 W) has a working area of 15×15 cm. Therefore, a total of 105 scaled-down (5 mm OD) SHY robotic modules can be manufactured in a single batch, if desired. Moreover, this setup allows for the fabrication of various types and sizes of SHY modules simultaneously as well, facilitating the construction of the SHY continuum robot.

R1.2. *Further Insight into the Operating Window: Expanding on the previous question, the manuscript could benefit from a more thorough exploration of the operating window for the fabrication process. Additional characterizations regarding the key fabrication processes would contribute to a more comprehensive understanding.*

Response: We thank the reviewer for pointing this out. To address this comment, we have revised the *SHY Robot Manufacturing* section in the main manuscript to include additional characterizations on the key steps of our fabrication process, as suggested.

PTFE film properties can be permanently altered through plasma etching with H_2 gas. This modification is highlighted by the added Zisman plot (Fig. 3d, Supplementary Fig. 3, Supplementary Table 1), which shows increased critical surface tension after plasma etching and consistent critical surface tension at two distinct time points: one hour and one week after plasma etching. Consequently, the SHY robot fabrication can be initiated at any time after film preparation. The total fabrication time after cutting films for a SHY robotic module is approximately 3 hours. This encompasses adhesive film peeling, copper thinning, film lamination, and release cutting.

Lastly, as highlighted in the Supplementary Information (Section: *Fatigue Test*), the SHY robotic modules demonstrated their durability by enduring 500 actuation cycles over a period of 16 hours without experiencing delamination.

R1.3. *Detailed Performance Comparisons: It is suggested that the authors delve into more detailed performance comparisons between devices fabricated using their methods and other actuators/sensors. Highlighting advancements in performance metrics such as force, torque, power*

density, efficiency and other possible performance would add advancements to the manuscript.
Response: We thank the reviewer for providing constructive feedback. To address this comment, we have generated Supplementary Table 3 and further expanded our *Discussion* section in the main manuscript. In Supplementary Table 3, we delve into a more detailed performance comparison between our fabrication method and similar ones (based on a layer-by-layer approach for soft actuators and sensors) by providing information on fabrication method, time, type of assembly required, actuation method used, whether or not sensing integration is reported, and scale of the devices. It is worth noting that many papers lack clear, quantitative information on fabrication metrics, especially on overall needed fabrication time. The information reported for fabrication time in Supplementary Table 3 is based on the available information in the papers cited. Lastly, we compared performance metrics such as output force and torque, speed, and power density.

R1.4. *Quantitative Energy Measurements: In Figure 3, where the plasma etching process is discussed, could the authors provide quantitative energy metrics, such as interfacial energy, to offer a more concrete perspective on the chemical modification of the PTFE film?*
Response: We thank the reviewer for this comment. To quantify the surface free energy of the film, we generated and added a Zisman plot to the manuscript, as shown in Fig. 3d. We used five different probing liquids with varying surface tension (DI water, glycerol, ethylene glycol, chlorobenzene, and isopropanol) to identify the critical surface tension of both pristine and plasma-etched PTFE films. As depicted in Fig. 3d, Supplementary Fig. 3, and Supplementary Table 1, the consistent critical surface tension was observed at two different time points after plasma etching, 1 hour and 1 week after. This indicates that the PTFE film's critical surface tension (wettability) has been permanently increased after plasma etching.

R1.5. *Demonstration Complexity/Capabilities: The demonstrations in Figure 8 seem relatively straightforward. It would be valuable if the authors could showcase additional capabilities that set their soft actuators apart from others, considering that many similar-scale robots can perform pick-and-place tasks with objects of varying shapes and sizes. To my knowledge, this demonstration cannot prove its progressiveness.*
Response: We thank the reviewer for this comment. To highlight our SHY robot's capabilities, we conducted two additional experiments using two different end effectors: a needle and an optical fiber. In these demonstrations, we showcased the precise steering capabilities of the SHY continuum robot by guiding various end effectors to pre-defined target locations.

As illustrated in Fig. 9, we utilized the SHY continuum robot to guide the needle and puncture a soft tissue simulator (i.e., tofu) at predefined locations. This material has been used in other soft surgical robotics applications as a good tissue analog (*1.* "Soft Robotic Deployable Origami Actuators for Neurosurgical Brain Retraction" by Amadeo et al. (2022), *2.*"Approach to the Development of an Abdominal Phantom with the Function of Respiratory Motion for Robotic Surgery" by Konovalov et al. (2020), and *3.*"Display of Needle Tip Contact Forces for Steering Guidance" by Bae et al. (2016)). To simulate medical biopsy and drug delivery procedures, we integrated a microtubing with a 304 μm inner diameter into the needle end effector to inject a pink dye solution, representing a drug solution, at the designated target locations. This setup can also be utilized for tissue biopsies by extracting tissue and biological fluid from the target locations.

As illustrated in Fig. 10, the SHY continuum robot can integrate an optical fiber. In this demonstration, we showcased its capability to steer and deliver light toward designated target locations, simulating scenarios akin to laser-assisted surgeries where laser light is transmitted through an optical fiber. Here, we utilized green LED light to simulate laser light. Analogous to how laser light diverges upon exiting the optical fiber, the behavior of green LED light exiting an optical fiber is similar. This dispersion diminishes the light's focus, reducing its ability to deliver concentrated power to the target. Consequently, positioning the optical fiber closer to the targets becomes necessary to achieve focused and high-power light delivery. During actual laser-assisted surgeries, a larger laser spot size can inadvertently result in photothermal energy to unintended areas, potentially damaging healthy tissues (”When the End Effector Is a Laser: A Review of Robotics in Laser Surgery” by Lee et al. (2022)). Moreover, anatomical surfaces are rarely flat, necessitating constant control over the distance between the optical fiber and the target tissue to maintain a consistent laser spot size. In this demonstration, we effectively control the light spot size by moving the robot closer to the targets, ensuring precise delivery of light energy to three distinct locations. As depicted in Fig. 10, the diameter of the light beam reduces as the optical fiber approaches the targets, indicating enhanced focus. These demonstrations highlight the potential application of the SHY continuum robot in medical contexts.

R1.6. *Manipulation Resolution Clarification: Can the authors provide more clarity on the minimum manipulation resolution achievable with the presented soft-rigid hybrid system? Additional information on this aspect would contribute to a more nuanced understanding.*
Response: We appreciate the reviewer's request for clarification. To provide further details on the grasper's specifications, we conducted a range of motion tests using an electromagnetic tracker. The results of this test are presented in Supplementary Fig. 10c. To quantify the grasper manipulation resolution, we segmented the plot into two linear regions (0-20 kPa and 20-150 kPa). In the first region, the resolution measures 0.48 °/kPa, while in the second region, it changes to 0.23 °/kPa. We have specified this in the caption of Supplementary Fig. 10. Additionally, from the object grasping demonstration, we determined that the smallest object the grasper can handle is a black rice grain, which has a width of 2 mm. We have indicated this information in the *SHY Continuum Robot Demonstration* section [P. 19].

Comments from Reviewer 2

The paper presents a novel methodology for intricate miniature actuators with embedded resistive sensing which shows a promising solution for miniature soft robots with closed loop control.

Key results
The paper shows a novel fabrication process and some experiments to test the actuation performance in terms of force and displacement. The results show an actuation task with good agreement between the predicted tip position using the ionic fluid sensor data and the measured position of the actuator. This is shown for the 3 actuation modes as well as an actuator comprising one of each type of unit.
R2.1. *It is unclear whether the calculated value of resistivity (P.13) was verified experimentally.*

Response: We thank the reviewer for asking this clarification. The resistivity of the solution underwent experimental verification through a procedure involving the measurement of voltage across a defined cylindrical volume of the solution. Tinned copper plates with known radii were positioned on the top and bottom surfaces of the cylinder. The cylindrical water resistor was integrated into a voltage-dividing circuit alongside a known resistance value, and a 1 Vpp sine wave at a frequency of 10 kHz was applied to the circuit. Subsequently, the resistivity was calculated using Pouillet's law, yielding a measured value of 180,791 Ω-mm. We have further clarified this calculation in the *Sensor Model and Characterization* section [P. 13] of the main manuscript.

R2.2. *On P. 10, the maximum error is given but it is not clear what parameter this error applies to (angle, displacement etc?).*
Response: We thank the reviewer for asking for clarification. In the *Range of Motion* section [P.11], the maximum error refers to the differences observed between the experimental and theoretical range of motion of the roto-translational module. This comparison is depicted in Supplementary Fig. 5a, which illustrates the relationship between the extension and rotation angle of the roto-translational actuator when the extension is provided as input. This has been revised in the *Range of Motion* section [Now in P. 11].

R2.3. *On P. 14 it is not clear how is K computed and where it is used. For example, the author's should give the modified version of Pouillet's Law, showing how K is used. While K is shown in Figure 6a, it's not clear how the product of K and A is used. This parameter also seems to be measured in unit of area but appears to be a distance from how it is represented in Figure 6a, and this should be corrected.*
Response: We appreciate the reviewer's insightful comment. In our model, we assumed that electrodes have variable cross-sectional areas based on the expansion of the robotic module. This assumption was made because, at the flat configuration, the robotic module features a cylindrical fluid channel connecting two electrodes, while at the expanded configuration, the soft-foldable actuator transforms its shape into a bellows, expanding the fluid channel radially. To address this, we introduced a corrective function, denoted as K. In the main text, we clarified this assumption in *Sensor Model and Characterization* section [Now in P. 13].

R2.4. *It's not clear from Supplementary Table 3 which parameter the SD applies to? Is it the sensitivity? Please clarify.*
Response: We thank the reviewer for pointing this out. The standard deviation applies to the sensitivity. We further clarified this detail in the caption of the table (now Supplementary Table 4).

Validity
R2.5. *The mechanism by which the actuator can be 'constrained at a more expanded state' is unclear (P.12), and so the significance of the argument around virtual work is difficult to understand. Perhaps a diagram showing what is meant by this could help to communicate this result.*
Response: We thank the reviewer for this comment. To further clarify, we added Supplementary Fig. 6. As shown in the figure, the actuator can be constrained at different heights due to external constraints, causing the actuator to stop expanding. Depending on this height, the output force

would vary. We clarified this in the *Output Force and Torque Performance* section.

R2.6. *P.6 A diagram should be used to illustrate what is meant by the chord length and if this refers to the Sarrus linkage or actuator as a whole*
Response: We thank the reviewer for pointing this out. We have added a top view of each SHY robotic module and labeled the circular arm and Sarrus linkages of SHY robotic modules in Fig. 1e. In addition, in the main text, we indicated that this chord length refers to the circular arm (*SHY Robot Design* section [P. 6]).

Significance
R2.7. *The authors compare performance with five studies on similar actuators, however, the significance of the results could be better communicated by normalising the performance metric, for example, to size, input power/flow rate of each actuator, rather than stating the absolute speed of actuation achieved by each study.*
Response: We thank the reviewer for providing constructive feedback. To enhance the clarity of our results and facilitate comparisons with other works, we have included Supplementary Table 3. This table provides a detailed comparison of soft robots fabricated using only lamination techniques. In this table, instead of normalizing each parameter, which would result in unconventional units, we included the size specification of each robot as a reference. This additional information aims to provide a comprehensive view of our work in relation to other works. Additionally, we further discussed the content of Supplementary Table 3 in the *Discussion* section [P. 24].

Data and methodology
The paper shows a novel fabrication process and some clearly explained experiments to test the actuation performance. The novel fabrication process is one of the main contributions, however the process could be better communicated throughout the paper, therefore this should be a point of major revision.
R2.8.*Specifically, in Figure 1b, colour coding should be taken advantage of to generate a key to annotate the different layers as it is difficult to see which layer each arrow indicates.*
Response: We thank the reviewer for pointing this out. In Fig. 1b, The color of the arrows was changed such that it follows the same color coding used on each layer. The green arrow indicates the rigid, structural layer, the yellow arrow indicates the flexible layer, the blue arrow indicates the soft, flexible layer and the grey arrow indicates the conductive layer.

R2.9. *The meaning of a Sarrus linkage should be explained, for example by annotating this part on Figure 1e. Figure 1e should also show the 'circular arms' in plan view as it is currently difficult to see their circular shape, and these should be annotated in Figure 1e to show which component the arms are.*
Response: We thank the reviewer for this comment. As the reviewer recommended, we further explained what a sarrus linkage is in the *SHY Robot Design* section [P. 6]. In addition, we included the top view of each actuator and annotated circular arms and Sarrus linkages in Fig. 1e.

R2.10. *Figure 1f is totally unclear and needs major revision to make the overlaid figure discernible.*

Somewhere in the paper the authors should also explain how the attachment points of the 2D layers lead to the 3D shape when inflated as this is a key part of the design, but is not explained anywhere.
Response: We thank the reviewer for the constructive feedback. We improved the visualization of Fig. 1f by deleting overlaid images. We also labeled the images in the figure as "actual and estimated motion" to clarify what the images are about. Additionally, we added a sentence in the *SHY Robot Design* section [P. 6], stating that the attachment points can act as hinges upon inflation.

R2.11. *The process shown in Figure 2 could also be improved, perhaps by arranging figures to show steps that happen in parallel and step that either combine the outputs of multiple previous steps or are a direct follow on from the previous step. A flow diagram / tree diagram could be an effective way to show this.*
Response: We thank the reviewer for this suggestion. To clarify which steps can be done in parallel, we added asterisk symbols next to the procedure label in Fig. 2. In addition, we added a fabrication flow diagram in Supplementary Fig. 2. As specified in Fig. 2 and Supplementary Fig. 2, "Peeling Adhesive films", "Tinning Copper Films", and "Plasma Etching PTFE Films" from the film preparation process can be done in parallel.

R2.12. *Figure 3a should also be improved by addition of annotations to fully describe the process happening. This should include labels labelling the arrows showing: bonds breaking; combination with fluorine atoms; zig-zag arrows (it's not evident what these show).*
Response: We thank the reviewer for pointing this out. As shown in Fig.3a, the chemical composition of pristine PTFE films changes after plasma etching with H_2 gas (illustrated by purple zig-zag arrows). During the H_2 plasma treatment, hydrogen radicals begin to combine with fluorine atoms (depicted by red arrows). Consequently, fluorine atoms detach from the carbon-fluorine bonds (indicated by green arrows), forming hydrogen fluoride (HF) and leading to changes in the chemical properties of the PTFE films. We revised Fig. 3a by labeling each arrow and further elaborated on this phenomenon in the *SHY Robot Manufacturing* section of the main text.
R2.13. *In the empirical part of the study, one actuator geometry is investigated. The authors should give detail of this actuator: how many pouches/layers are combined to achieve the performance described, and what are the fluid chamber?*
Response: We thank the reviewer for pointing this out. The fluid chamber in this work refers to the soft-foldable actuator, which holds fluid and causes the module to expand upon inflation. We further described what the fluid chamber is in the *SHY Robot Design* section [P. 5-6]. In addition, in the *Range of Motion* section [P. 10], we stated the number of balloons included within the module (five pouches for translational and bending, and six pouches for roto-translational module). The size of each pouch corresponds to 9 mm and 6.7 mm in outer diameter (OD) for 11.5 mm OD actuators and 3.8 mm in outer diameter for 5 mm OD actuators.

R2.14. *Figure 7a - It's important to clarify what's being shown here. The photo of the real robot is confusing sit is shown in a different position to the modelled robot. This should be moved to outside of the axes.*
Response: We thank the reviewer for the constructive feedback. To further clarify and improve the figure, we moved the photos of the actual robot to the side of each plot.

R2.15.*The significance of i-vi should be given in the figure caption rather than the body text as it is difficult to tell from looking at the figure alone whether this is a sequence, or else what is the difference between the different subfigures is. The use of the figure alone makes to difficult to assess how well the real system matches the model, due to perspective (in particular Figure 7ai). The authors should include the coordinates of the tip of the predicted and real system to that this can be quantifiably compared.*

Response: We thank the reviewer for pointing this out. To further clarify the results of each subfigure, we described the motion of the robot in each subfigure in the Fig. 7 caption. Additionally, we include the coordinates of the actual (written in red) and estimated (written in blue) tip position.

R2.16. *The grasper fabrication and methodology of pick and place task are very briefly described and more detail should be given here for example a schematic to show the gripper construction and a description of the distances through which the object was translated during the pick and place task and how the robot was controlled (e.g. open loop).*

Response: We thank the reviewer for the constructive feedback. The robot was controlled in open loop using syringe pumps. The average distance moved by the objects was around 20 mm. This is now stated in the *SHY Continuum Robot Demonstration* section [P. 19]. To clarify the grasper fabrication process, we included Supplementary Fig. 10a, illustrating each layer of the grasper.

Analytical approach

The paper analyses the performance of the actuator and embedded sensor in displacement and comments on observed features such as hysteresis, elastic material relaxation over multiple cycles of use (repeatability) and physical limits of the systems (e.g. displacement plateau reached during bending).

R2.16. *As only one geometry is investigated, it would be useful to analyse the scalability of the design to actuators comprising more laminated layers or different geometries. Ideally this should also be validated using empirical data.*

Response: We thank the reviewer for this comment. To further highlight the scalability aspect of our design, we scaled down the SHY robotic modules to a 5 mm outer diameter (OD). As outlined in the *Scalability* section, these 5 mm OD modules include a 3.8 mm soft-foldable actuator, a mechanical controller, and an ionic resistive sensor. As shown in Fig. 6, we conducted the range of motion, output force/ torque, and sensor calibration tests to characterize each module.

Suggested improvements

R2.17. *On page P.17 length is shown with position error. It would be useful to see this for the individual units (extension, bending, roto-translation) as well as the combined actuator, so see how the performance of these individual actuation modes compare in terms of sensor error.*

Response: We appreciate the inquiry from the reviewer. While we recognize that it would be beneficial to install an electromagnetic (EM) probe at the end of each robotic module to accurately compare the theoretical and actual tip position of each module, this is not physically possible as we cannot secure the EM probes in between the modules of the SHY continuum robot. Ideally, each EM probe should be installed at the center of each module, but this area is occupied by the spacer where the SHY robotic modules are connected in series. Therefore, we compared the theoretical and actual tip position of the SHY continuum robot instead to validate the accuracy of the sensors, as shown in Fig. 7.

Clarity and context
In general the writing is clear and accessible.
R2.18.*P.12 Equation 2 (d theta should be defined).*
Response: We thank the reviewer for pointing this out. As the reviewer pointed out, this should have been dϕ, representing the change in the rotation angle. We revised it accordingly. Please refer to the *Output Force and Torque Performance* section [P. 12].

References
R2.19.*A comprehensive list of relevant and up-to-date literature.*
Response: We thank the reviewer for their positive feedback.

Comments from Reviewer 3

The authors proposed a fabrication method for building small-scale soft-rigid hybrid robots with sensing self-sensing ability. The actuator is hydraulic driven bellow structure which can unfold and fold when inject or eject the liquids. The sensor is based on the resistive behavior of the ionic fluid. The claimed major advance is the layer-by-layer lamination-based process. In general, the layer-by-layer lamination-based fabrication process have been shown in multiple works from Wood group ([36]) and the author's group ([6][7]). The demonstration of a steerable soft robot with ability of sensing itself provides one fabrication example of the fabrication method. It seems that the fabrication method introduced is very specific which somehow reduce the enthusiasm of the proposed method.
Response: We appreciate the reviewer's comment. As the reviewer pointed out, layer-by-layer lamination-based fabrication methods have been explored by both our lab and the Harvard Microrobotics Lab.

As discussed in our *Introduction* section, paper [36] proposed to combine the pop-up book MEMS fabrication approach with techniques borrowed from soft lithography (using oxygen plasma treatment and silane coupling agents) to bond rigid components and PDMS-based soft actuators in a layer-by-layer fashion. However, this technique is sensitive to ambient conditions (i.e., temperature and humidity) and is time-dependent (i.e., the time window of the surface activation by oxygen plasma treatment is limited). These sensitivities and dependencies on environmental and procedural factors can introduce challenges in the fabrication process, necessitating careful control and management of these variables to ensure successful production. In contrast, our proposed fabrication method possesses the benefit of being independent of environmental conditions and a long operating window. Please refer to the updated *Discussion* section where we better clarify the innovations of our proposed approach to address this comment. Further, we invite the reviewer to revise our edits in the *Soft Robots Manufacturing* section where we extended the characterizations of our manufacturing method producing the Zisman plot (Fig. 3d). These results show that our approach enables time-independent permanent bonding of PTFE with adhesive films (i.e., once the film samples have been treated with H_2 plasma, they can be stored and bonded at any time).

As described in our *Introduction* section, we introduce the use of polytetrafluoroethylene (PTFE) films, which have a high melting temperature (i.e., 327°C) to create soft-foldable robots. As regards paper [6], this work focuses on the construction of thermoplastic elastomer (TPE) film-based soft actuators. TPE has a melting point of 120°C, therefore it cannot withstand high temperatures and pressures required to successfully bond with rigid and flexible materials (such as proposed in our paper). This limits the potential integration of this soft material with rigid structures in a fully monolithic approach with minimal manual assembly steps (and thus less human errors), which is part of our main innovations.

As regards paper [7], no layer-by-layer methods were used in this work. The robot described in that manuscript is an entirely soft 2.4 mm continuum robot for interventional bronchoscopy procedures. The robot body is made entirely with silicone elastomers via casting and molding into CNC-machined aluminum molds.

Regarding the reviewer's comment on the specificity of our fabrication process, we would like to highlight that in our paper we demonstrated the versatility and adaptability of our fabrication approach by manufacturing three distinct SHY robotic modules with different degrees-freedom and a gripper (see Fig. 1 in the main manuscript). These modules can be combined to achieve different robotic architectures and degrees-of-freedom. We believe that this will offer versatility to our method as readers interested in replicating this work could assemble the robotic modules as they prefer to build different robotic architectures. We demonstrated how these robotic modules can be assembled to build a continuum robot (Fig. 7) and a robotic manipulator (Fig. 8) and included shape sensing functionalities (Fig. 7). To address the reviewer's comment, we have extensively revised the *SHY Continuum Robot Demonstration* section where the SHY continuum robot is now integrated with various end effectors, including a robotic grasper, a needle, and an optical fiber. The manuscript is now showcasing additional capabilities of our manufacturing approach and the resulting robotic systems. The integration of a robotic grasper enables robotic pick-and-place tasks of soft and hard objects of various shapes and sizes, showcasing potential applications in food handling, manufacturing, and surgery. The addition of a needle and an optical fiber demonstrates potential applicability of our robotic technology in medical procedures (e.g., tissue biopsies and laser ablation). Lastly, to further demonstrate versatility across different dimensions, we miniaturized the SHY robotic modules down to a 5 mm outer diameter (OD). As described in the newly added *Scalability* section, these miniaturized modules retain the monolithic fabrication capability and functionalities of their scaled-up counterparts (11.5 mm OD version). These miniaturized modules were fully characterized, as shown in Fig. 6. Lastly, we highlighted the possibility of batch fabrication in the *Discussion* section [P. 23] and Supplementary Information (Section: *Batch Fabrication*). Supplementary Fig. 11 demonstrates the feasibility of batch fabrication by incorporating multiple (i.e., up to 15) modules within a single manufacturing session. Supplementary Fig. 11 shows a square laminate of 5×5 cm. Our diode-pumped solid-state (DPSS) ultraviolet (UV) laser precision micromachining system (Coherent Matrix 355 nm, 5 W) has a working area of 15×15 cm. Therefore, a total of 105 scaled-down (5 mm OD) SHY robotic modules can be manufactured in a single batch, if desired. Moreover, this setup allows for the fabrication of various types and sizes of SHY modules simultaneously as well, facilitating the construction of the SHY continuum robot.

Overview

R3.1. *Overall, I find the introduction a little confusing with the logics. The need of "self-sensing" for more information for feedback control and the need of "physical intelligence" for allowing less control seems contradicted to each other. My understanding is that the motivation of proposing the layer-by-layer fabrication method for integrating sensor and actuator seems in that such a method could result in smaller and more precise compared with manual assembly process.*

Response: We thank the reviewer for the constructive feedback and apologize for the lack of clarity. We have edited the *Introduction* section to respond to this comment and better clarify the need for sensing in soft robots and the important contribution of "physical intelligence" in soft robotics. Researchers have investigated materials selection and mechanical structural designs to provide soft robots with "physical intelligence". By combining rigid, flexible, and soft materials, both the inherent structural compliance of a soft robot and the motion controllability of a rigid robot can be maintained. As a result, the concept of a soft-rigid hybrid robot enhances the predictability of a soft robot's motion by following the rigid robot kinematics and the delivery of force toward the desired direction, while concurrently preserving its ability to safely interact with its surroundings through its inherent conformability. This approach has shown promise in capturing non-linear deformations and motions as well as hysteretic and viscoelastic behavior in soft robots. However, sensing is still an essential component in soft robotics (and in soft-rigid hybrid robots) as it provides the robots with proprioceptive and exteroceptive capabilities, which can pave the way to more accurate closed-loop control algorithms. These two components (i.e., "physical intelligence" and sensing) are therefore both important.

Lastly, as the reviewer pointed out, one of the main motivations of the proposed layer-by-layer manufacturing method is to enable the fabrication of soft robots at small scales with highly integrated sensors and actuators with minimal manual assembly steps, thus increasing accuracy and repeatability in fabrication outcomes. As we highlighted in the *Scalability* section, we miniaturized the size of the SHY robotic modules to 5 mm to further demonstrate the versatility of the proposed fabrication strategy across various scales.

R3.2. *Significance. Every robotic device comes with a fabrication process, but the question is whether the fabrication process associated is general and provide best performance. Regarding the advance of the fabrication method, how do you compare with state-of-art fabrication method to make the similar robots? For example, compared with manual assembly and other method different from lamination-based method, what are the fabrication time, fabrication accuracy, overall device size, and device capability? Without these direct and quantitative comparison in key fabrication performance, it is hard to see the advantage and impact of the proposed method.*

Response: We thank the reviewer for pointing this out. To address this comment, we have generated Supplementary Table 3 and further expanded our *Discussion* Section in the main manuscript. In Supplementary Table 3, we delve into a more detailed performance comparison between our fabrication method and similar ones (based on a layer-by-layer approach for soft actuators and sensors) by providing information on fabrication method, time, type of assembly required, actuation method used, whether or not sensing integration is reported, and scale of the devices. It is worth noting that many papers lack clear, quantitative information on fabrication metrics, especially on overall needed fabrication time. The information reported for fabrication time in Supplementary

Table 3 is based on the available information in the papers cited. Lastly, we compare performance metrics such as output force and torque, speed, and power density.

Major comments
R3.3. *What is bandwidth of the ionic fluid-based sensing? Are there any capacitive effects associated with the fluid? In the paper, the resister is modeled as a resister only which may not be true.*
Response: We thank the reviewer for pointing this out. The bandwidth of the ionic fluid-based sensing is mainly limited by the signal sampling speed of the Analog-Digital Converter. In this paper, we used USB-6210 from National Instrument to collect the sensor readings and it has a maximum sampling rate of 250 kS/s. No noticeable resonant response was noticed at the speed of operation. As mentioned in the Supplementary Information (Section: *Capacitive effect measurement test*), the capacitive effect was quantified by measuring the shift in the phase angle. However, only less than 10° phase shift was observed, and this effect drastically reduces as the actuator expands, following the inverse square law.

R3.4. *For each module, it seems manual process must be involved for merging the tubing and wiring. Can this manual process be further eliminated? When targeting at a larger reachability, more modules are needed. How could be tubing and wiring be handled when scaling up the number of modules in the fabrication process?*
Response: We appreciate the reviewer's feedback. While reducing the number of tubing by merging channels would be advantageous, this is currently beyond the scope of our paper. However, ongoing research in soft robotics is exploring these aspects and many research groups have proposed solutions to control multiple DOFs in soft robots. For example, researchers have used Quake valves and fluid logic to reduce the number of actuation lines and these solutions offer promising avenues in this field. We invite the reviewer to refer to this paper that details such approaches: *"Hardware Methods for Onboard Control of Fluidically Actuated Soft Robots" by McDonald et al. (2021)*. Integrating such solutions into our SHY robots could enhance their functionality in the future. These considerations have also been included in the *Discussion* section [P. 25] of our paper.

R3.5. *Please comment on the biocompatibility of the material and device.*
Response: We thank the reviewer for the feedback. As described in *"ePTFE functionalization for medical applications" by Roina et al. (2021)* , PTFE films are biocompatible and commonly utilized in medical applications. Additionally, as mentioned *"Toward Medical Devices With Integrated Mechanisms, Sensors, and Actuators Via Printed-Circuit MEMS" by Gafford et al (2017)*, many of the films used in this work are biocompatible except for tinned copper films. However, this biocompatibility problem can be further addressed by encapsulating the robot with a thin layer of Parylene C, which can provide a biocompatible coating (*"Parylene C and Silicone as Biocompatible Protection Encapsulants for PCBs" by Bellmann et al. (2009)*). Moreover, replacing tinned copper with gold (e.g., via sputter coating) could further enhance biocompatibility. We have revised *Discussion* section[P. 25] of the main manuscript to discuss these considerations.

R3.6. *References. It is suggested to include more fabrication methods as a comparison. The H2 plasma etching for PTFE is not new suggesting a reference should be provided*

(e.g. https://www.mdpi.com/2073-4360/12/12/2855).
Response: We thank the reviewer for the feedback. As the reviewer pointed out, H_2 plasma etching of PTFE film has been explored before in other applications (i.e., space, biotechnology, and microelectronic packages) mostly as a coating and protective layer. We addressed this point in the *Discussion* section [P. 23]. We added a reference in *Discussion* section [P. 23] and additional references related to H_2 plasma etching of PTFE are cited in the Supplementary Information (references 3-7). Yet, as discussed in the discussion section, this is the first application of plasma etching of PTFE films to create soft robotic actuators for soft robotics applications.

R3.7. *Some main figures could be combined such as Fig. 4 and Fig. 5 as they are both quantifying the actuation/motion performance.*
Response: We thank the reviewer for the constructive feedback. As suggested, we combined Fig. 4 and Fig. 5 (now Fig. 4) to quantify the actuation and motion performance.

R3.8. *Fig. 7 needs to be supported with more data as a main figure, which may be combined with Fig. 6 to show the sensor performance. The tracking error in Fig. 7b may be better represented in relative errors.*
Response: We appreciate the valuable feedback from the reviewer. Following the suggestion, we have revised the terminology in both Fig. 7 and the main text from “tracking error” to “relative error”. To support Fig. 7 with more data, we added the predicted and actual tip coordinates of the robot. We believe this can further support the data shown in Fig. 7b.

Other points
R3.9. *What is the liquid droplet in Fig. 3c? Is it water?*
Response: We thank the reviewer fot ths question and request of clarification. Yes, this is a DI water droplet. We specified in the caption of Fig. 3 that DI water droplets were used in Fig. 3c. To further provide a quantitative analysis of the surface free energy of the pristine and plasma-etched films, we generated a Zisman plot, depicted in Fig. 3d. As demonstrated in Fig. 3d, Supplementary Fig. 3, and Supplementary Table 1, the plasma-etched films exhibited a higher critical surface tension, leading to increased wettability.

R3.10. *The variables in Fig. 1f should be explained in the caption.*
Response: We thank the reviewer for pointing this out. We included the description of each variable in the Fig. 1 caption. As described in the caption, V_1, V_2, and V_3 refer to the voltage measured from each sensor, h_T corresponds to the extended height of a translational module, θ_b is the bending angle of a bending module, and h_R and ϕ_R are the extended height and rotation angle of a roto-translational module.

R3.11. *“k*A” in Fig. 6a is not explained in the caption.*
Response: We thank the reviewer for pointing this out. To further clarify what “$k * A$” is, we explained the details in the corresponding figure caption. As described in the figure caption, the term $k * A$ (now written in $A = k(\pi r^2)$ takes into account the variable cross-sectional area of the soft-foldable actuator. The corrective multiplicative function, k is applied to the radius of the

electrode, r. Please refer to Fig. 5.

R3.12. *Are the layers in grey in Fig. 2e,f,g conductive film or adhesive film? What is the layer in light grey? It is not explained.*
Response: We thank the reviewer for pointing this out. We revised Fig. 2 and labeled the layers in light gray, which are paper backing from adhesive films.

R3.13. *The fatigue test could be moved to SI.*
Response: We thank the reviewer for the feedback. As suggested, we moved the fatigue test information to Supplementary Information (Section: *Fatigue Test*).

REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

The author have addressed the technical concerns well in this revision. However, there is a need for further improvement in the presentation and formatting of results and data in the manuscript.

Reviewer #2 (Remarks to the Author):

What are the noteworthy results?

Actuator range of motion

Demonstration of miniaturisation to 5mm diameter

Sensor characterisation

Pick and place task demonstration

How does it compare to the established literature? If the work is not original, please provide relevant references.

The work presents a soft actor with a novel scalable layered fabrication method that exploits adhesion of acrylic sheets via heating resulting in miniaturised actuators. Another novel contribution is the combination of integrated circuitry and conductive fluid to produce a self-sensing actuator.

Does the work support the conclusions and claims, or is additional evidence needed?

Yes

Are there any flaws in the data analysis, interpretation and conclusions? Do these prohibit publication or require revision?

No

Is the methodology sound? Does the work meet the expected standards in your field?

Yes

Is there enough detail provided in the methods for the work to be reproduced?

Yes

Reviewer #3 (Remarks to the Author):

The authors have carefully addressed some of my comments. However, some responses are still not convincing and the materials in the revised paper also expose several other issues.

1. The authors spend much effort describing the H2 etching of the PTFE film which is only for bonding different layers. This is a very incremental contribution as the authors only apply the reported method for an application. Fig. 3 seems more suitable for the SI as it is very application specific. Fig. 3d is also very unclear with all the legend items including both time and materials.

2. The authors seem claim the advantage of being safe using the hybrid robot design. Is it a fully soft robot safer? There are many existing works of fully soft continuum robot e.g. Kim 2019, 2022 Sci. Robot which are much safer due to the intrinsic softness compared with a hybrid robot. In fact, the hybrid design sacrifices the degree-of-freedom of a continuum/soft robot. The self-sensing function does seem interesting in terms of providing feedback and providing safety assuming the robot can detect environment boundaries and report contact forces. However, these sensing abilities are not shown in this work.

3. I also feel the significance of the proposed fabrication method is weak as Table 3 does not show a significant advance of the robot fabricated using the proposed method over existing works in terms of size, fabrication time, output force, power density, etc.

4. For the new Fig 10, please compare with laser steering in other works such as in Kim et al. Sci. Robot. 2019.

5. The payload of the gripper and the force the robot can apply should be experimentally measured.

6. In Fig 6g,h, there is a gap between the model and experimental data. Please explain why and how to reduce the gap.

7. Fig. 4 may go to SI. The dashed lines should be marked with a value and explained clearly.

8. The quality of Fig. 7, Fig. 9 and Fig. 10 do not meet the standard of Nature Communications.

9. Fig. 9 and Fig. 10 can be combined.

The authors have made some improvements in addressing my comments, but there are still areas where their responses are not entirely convincing. Additionally, the revised paper raises several new concerns:

1. The authors dedicate significant attention to describing the H2 etching of the PTFE film, primarily for bonding different layers. While this method may be useful for specific applications, it appears to offer only an incremental contribution. Figure 3, in particular, seems more suited for Supplementary Information as it is highly application-specific. Furthermore, Figure 3d is unclear, with multiple legend items, including both time and materials, making interpretation challenging.

2. The authors appear to claim the safety advantage of the hybrid robot design. However, it is debatable whether a hybrid robot is inherently safer than a fully soft robot. Numerous existing works on fully soft continuum robots (e.g., Kim 2019, 2022 Sci. Robot) demonstrate their enhanced safety due to their intrinsic softness. Additionally, the hybrid design sacrifices the degree of freedom of a continuum/soft robot. While the self-sensing function is intriguing in terms of providing feedback and enhancing safety, the absence of evidence showcasing the sensing abilities of detecting environmental obstacles or other cues in this work is notable.

3. The significance of the proposed fabrication method appears weak, as Table 3 fails to demonstrate a significant advancement over existing works concerning robot size, fabrication time, output force, power density, etc.

4. For the new Figure 10, it would be beneficial to compare it with laser steering in other works, such as in Kim et al., Sci. Robot. 2019.

5. Experimental measurements of the gripper's payload and the robot's applied force should be included instead of only model-predicted results.

6. In Figures 6g and 6h, there is a noticeable gap between the model and experimental data. An explanation of this gap and potential strategies to reduce it would be valuable.

7. Figure 4 may be better suited for Supplementary Information. Additionally, the dashed lines should be labeled with values and explained clearly to enhance interpretability.

8. The quality of Figures 7, 9, and 10 does not meet the standard expected for Nature Communications.

9. Figures 9 and 10 could potentially be combined to streamline presentation and improve clarity.

These points highlight areas where the manuscript needs to address before being considered publication.

Response to the reviewers

Paper title: A Fabrication Strategy for Millimeter-Scale, Self-Sensing Soft-Rigid Hybrid Robots
Authors: Hun Chan Lee, Nash Elder, Matthew Leal, Sarah Stantial, Elenis Vergara Martinez, Sneha Jos, Hyunje Cho, and Sheila Russo.

Introduction

We are pleased to submit the revised version of our manuscript entitled "A Fabrication Strategy for Millimeter-Scale, Self-Sensing Soft-Rigid Hybrid Robots" for consideration in the journal *Nature Communications*. The authors would like to greatly thank the editor and the reviewers for their valuable and insightful comments, which have helped us improve our work.

This document contains a detailed response to the reviewers' comments. The three reviews are denoted as Reviewer 1, Reviewer 2, and Reviewer 3 below. For each reviewer's comment, the original review text is quoted in *italics*. The authors' response to each point is provided in normal typeface font in blue. In the revised manuscript, the revised contents are highlighted in red text.

Comments from Reviewer 1

R1.1. *The author have addressed the technical concerns well in this revision. However, there is a need for further improvement in the presentation and formatting of results and data in the manuscript.*
Response: We thank the reviewer for the positive feedback. We really appreciate the time and effort they put into reviewing our paper. As the reviewer pointed out, we edited the paper to provide further improvement in the presentation and formatting of results and data. We moved the Section *Scalability* to the Supplementary Information document. In addition, we revised Figs. 6 and 8 (previously, Figs. 7, 9, and 10) to increase the clarity of the figures. In Fig. 6, we specified that the actual images are snapshots of sequence 1. In Fig. 8, we have combined the two experiments to improve clarity and readability and added gaps between each image to enhance the visibility.

Comments from Reviewer 2

R.2.1. *What are the noteworthy results?*
Actuator range of motion
Demonstration of miniaturisation to 5mm diameter
Sensor characterisation
Pick and place task demonstration

R.2.2. *How does it compare to the established literature? If the work is not original, please provide relevant references.*
The work presents a soft actor with a novel scalable layered fabrication method that exploits adhesion of acrylic sheets via heating resulting in miniaturised actuators. Another novel contribution is the combination of integrated circuitry and conductive fluid to produce a self-sensing actuator.
R.2.3. *Does the work support the conclusions and claims, or is additional evidence needed?*
Yes
R.2.4. *Are there any flaws in the data analysis, interpretation and conclusions? Do these prohibit publication or require revision?*
No
R.2.5. *Is the methodology sound? Does the work meet the expected standards in your field?*
Yes
R.2.6. *Is there enough detail provided in the methods for the work to be reproduced?*
Yes
Response: We thank the reviewer for the positive feedback on our work. We really appreciate the time and effort they put into reviewing our paper.

Comments from Reviewer 3

The authors have carefully addressed some of my comments. However, some responses are still not convincing and the materials in the revised paper also expose several other issues.
Response: We thank the reviewer for the positive feedback on our work. We really appreciate the time and effort they put into reviewing our paper.

R3.1. *The authors spend much effort describing the H2 etching of the PTFE film which is only for bonding different layers. This is a very incremental contribution as the authors only apply the reported method for an application. Fig. 3 seems more suitable for the SI as it is very application specific. Fig. 3d is also very unclear with all the legend items including both time and materials.*
Response: We thank the reviewer for this comment. In previous research, soft films such as thermoplastic films have been used as one of the methods to build soft robots. Please refer to papers:

- Ranzani, T., Russo, S., Schwab, F., Walsh, C.J., Wood, R.J.: Deployable stabilization mechanisms for endoscopic procedures. In: 2017 IEEE International Conference on Robotics and Automation (ICRA), pp. 1125–1131 (2017). IEEE
- Rogatinsky, J., Gomatam, K., Lim, Z.H., Lee, M., Kinnicutt, L., Duriez, C., Thomson, P., McDonald, K., Ranzani, T.: A collapsible soft actuator facilitates performance in constrained environments. Advanced Intelligent Systems 4(10), 2200085 (2022)

While these thermoplastic film-based soft robots offer the advantage of rapid and cost-effective fabrication, the use of thermoplastic materials poses limitations in harsh environments, such as medical sterilization, due to their lack of thermal and chemical durability. Additionally, they face challenges when integrating additional components such as mechanical reinforcement and sensors, particularly at sub-centimeter scales. Incorporating these components at a sub-centimeter scale often necessitates tedious yet difficult manual bonding by experts using glue or double-sided tape.

This manual bonding process not only yields inconsistent fabrication outcomes, but also increases the risk of delamination and failure over time.
On the other hand, the use of PTFE films presented in our paper and the proposed manufacturing approach effectively address the problems observed in thermoplastic film-based soft robots, as described in our revised Section *Discussion*. Below we summarize the main novelty points presented in our paper. These introduce potential avenues for future research that can be explored using our proposed methodology. Please also refer to our response R3.3 below.

- The introduction of PTFE films offers distinctive advantages in thermal and chemical durability that other soft films used in soft robotic applications cannot match. PTFE films can withstand temperatures exceeding 327°C and remain insoluble in most chemicals and solvents. This can pave the way for their operation within harsh environments characterized by high temperatures, humidity, and chemical exposure, such as medical sterilization.

- PTFE films exhibit biocompatibility. These properties further expand the practical applications of this methodology.

- With our proposed manufacturing approach based on laser precision micromachining, chemical surface modification via H_2 plasma, and lamination, we successfully achieved seamless integration of actuation, sensing, and mechanical control components within the robot materials, with minimal manual assembly steps. Multiple soft PTFE films can be combined to build a fully soft robotic actuator and various other films including rigid, flexible, and conductive ones can be securely and seamlessly integrated into the soft actuator to accommodate additional components like a sensor, mechanical controller, and support for integrating tools.

- We demonstrated the versatility of the proposed fabrication method by designing three distinct DOF SHY robotic modules (i.e., translational, bending, and roto-translational) and a one DOF SHY robotic end effector (i.e., a gripper). These constitute the building blocks of a robotic system. This gives flexibility in designing and building full robotic systems that a reader, interested in leveraging our approach, can tailor toward their specific applications and needs.

- Unlike bonding silicone films (e.g., PDMS bonding via oxygen plasma) and thermoplastic films, where the success of bonding is influenced by factors such as time, temperature, humidity, and cleanliness, the proposed methodology is not sensitive to these ambient conditions and time constraints. As demonstrated in the Supplementary Fig. 3b (Zisman plot), the hydrophilic property of PTFE films (provided by the H_2 plasma modification) was maintained even after one week.

- Lastly, the monolithic circuitry integration onto or within the soft-foldable actuator opens up new possibilities for sensor and actuator designs. Previously, the circuitry was primarily integrated onto the surface of soft-foldable actuators, limiting its functionality mainly to capacitive sensing (please refer to *Russo, S., Ranzani, T., Walsh, C.J., Wood, R.J.: An additive millimeter-scale fabrication method for soft biocompatible actuators and sensors. Advanced Materials Technologies 2(10), 1700135 (2017)*). However, for robots capable of large elongations with respect to their original length, capacitive sensing becomes impractical as capacitance decreases exponentially with increased electrode distance. Similarly, relying solely on pressure sensors poses challenges in accurately characterizing motion due to hysteresis effects. Previously, research has previously explored the use of inductance-based sensing (please refer to F*elt, W., Telleria, M.J., Allen, T.F., Hein, G., Pompa, J.B., Albert, K., Remy, C.D.: An inductance-based sensing system for bellows-driven continuum joints insoft robots. Autonomous robots 43, 435–448 (2019)*) to analyze the movement of centimeter and larger-scale soft-foldable actuators. Yet, the integration of such sensors into millimeter-scale soft-foldable robots remains elusive due to scaling difficulties, thus leaving sensor integration largely unexplored for millimeter-scale soft-foldable robots. The seamless integration of circuitry within the soft actuator, proposed in our approach, can also pave the way to the integration of other sensing methodologies (beyond ionic resistive sensing) and applications in the future.

As elucidated in the preceding paragraph, PTFE films play a pivotal role in our work, facilitating the integration of soft and rigid robotic components. Additionally, the PTFE plasma etching process has never been presented in the field of soft robotics. Hence, we believe that Fig. 3 aids readers in comprehending the PTFE plasma etching process and potentially replicating it for their own research purposes. We acknowledge that Fig. 3d may not have been sufficiently clear and is more suitable to be included in the Supplementary information. We apologize for the lack of clarity. We have improved our presentation by moving Fig. 3d to Supplementary Fig. 3b. Further, to enhance Supplementary Fig. 3b clarity, we have made the following adjustments: we removed time information from the legend, instead we labeled it directly on the graph.

R3.2. *The authors seem claim the advantage of being safe using the hybrid robot design. Is it a fully soft robot safer? There are many existing works of fully soft continuum robot e.g. Kim 2019, 2022 Sci. Robot which are much safer due to the intrinsic softness compared with a hybrid robot. In fact, the hybrid design sacrifices the degree-of-freedom of a continuum/soft robot. The self-sensing function does seem interesting in terms of providing feedback and providing safety assuming the robot can detect environment boundaries and report contact forces. However, these sensing abilities are not shown in this work.*
Response: We thank the reviewer for pointing this out and we apologize for any confusion caused by the claim regarding safety. We have edited the Sections *Introduction* and *SHY Robot Design* accordingly.

R3.3. *The significance of the proposed fabrication method appears weak, as Table 3 fails to demonstrate a significant advancement over existing works concerning robot size, fabrication time, output force, power density, etc.*
Response: We thank the reviewer for seeking clarification. As suggested, we have revised Supplementary Table 3 and the Section *Discussion* such that they better highlight the advantages of our proposed fabrication method. The key advantages of our fabrication method are listed and discussed below. Please also refer to our response R3.1 above.

1. Reduced fabrication time

2. Possibility of batch manufacturing
3. Scalability
4. Minimal manual assembly steps required (and thus, less relying on user skills and reduced possibility for human errors)
5. Thermal and chemical durability
6. Independence from ambient conditions (i.e., temperature, humidity) and time constraints (i.e., long operating window of the fabrication process)
7. Integrated fluidic lines and multiple lateral passage holes that can serve as working channels for the integration of end effectors (i.e., laser, needle)
8. Integrated sensing
9. High number of DOFs and design versatility and flexibility
10. Material biocompatibility

Our fabrication method streamlines the production, scalability, and batch fabrication of the proposed soft robots, setting the stage for their potential use in other research groups and in industrial applications.

Our approach allows for the creation of various types of degrees of freedom across different scales. We have demonstrated the versatility and flexibility of the proposed fabrication method by designing three distinct DOF SHY robotic modules (i.e., translational, bending, and roto-translational) and a one DOF SHY robotic end effector (i.e., a gripper), representing the building blocks of a robotic system. These robotic components can be batch fabricated all at once and sensing capabilities can be easily and seamlessly integrated. We therefore believe that the strengths and innovations proposed in our work, can be leveraged by anyone interested in using our approach and tailor it toward their specific applications and needs. This can have a positive impact in the soft robotics community (where design and fabrication can be a complex and time-consuming process, especially at small scales) and beyond. There is still much to be learned about how to optimize the design and fabrication process for soft robots, including how to choose the most appropriate materials and manufacturing techniques. This is particularly true for soft sensors that need to be engineered and manufactured out of soft materials to match the robot compliance. This paper presents a step forward toward this goal.

Furthermore, in terms of mechanical performance, our robots achieve comparable or better results to other fluidically actuated robots listed in the Supplementary Table 3. While our robots may exhibit slower actuation speed or lower output force compared to some other robots presented in the Table, this is attributed to the use of a hydraulic actuation method instead of pneumatic and having a smaller scale in comparison to the listed robots. Additionally, in this work, we have utilized commercially available syringe pumps with high accuracy (± 0.5 %) but a slow max flow rate (1.325 ml/min), resulting in slower actuation speed in our SHY robots. Yet, this trade-off leads to higher motion resolution in the actuation of the robotic modules. In future works, a custom actuation unit could be developed to further increase the actuation speed of the SHY robot.

R3.4. *For the new Fig 10, please compare with laser steering in other works such as in Kim et al. Sci. Robot. 2019.*
Response: We thank the reviewer for this comment. It is important to note that while the paper by Kim et al. (Sci. Robot. 2019) presented a demonstration of laser steering, similarly to one of our demonstrations, their robot was fundamentally different with respect to ours. Kim et al. fabricated their robot using 3D printing/injection molding techniques and actuated the system using magnets. In contrast, our method utilizes a layer-by-layer fabrication technique to create individual SHY robotic modules, which are then connected to form a fluidically-actuated continuum robot. Ultimately, the materials, manufacturing, scale, actuation methodologies, and conceptual design of our robot and the one proposed by Kim et al. are fundamentally different. This would not make a fair and quantitative direct comparison. Furthermore, regarding quantitative metrics for comparison, the paper by Kim et al. (Sci. Robot. 2019) does not provide specific quantitative metrics as the laser steering demonstration was primarily intended to showcase the robot concept and its potential future applications.
Finally, we would like to highlight that our approach allows embedding multiple lateral passage holes that can serve as working channels in a soft surgical robot (please refer to Section *SHY Continuum Robot Design*). This can enable the integration of additional medical/surgical tools (besides a laser and a needle), such as a micro-camera, forceps, or micro-brushes. In contrast, in the paper by Kim et al. (Sci. Robot. 2019), the laser fiber was inserted through the center of the robot with no possibility of integration of additional medical/surgical tools.

R3.5. *The payload of the gripper and the force the robot can apply should be experimentally measured.*
Response: We thank the reviewer for seeking clarification. As demonstrated in Fig. 7l, the grasper can lift up to 50 g of weight. Additionally, we have experimentally measured the gripping force using an ATI Nano force sensor and a pressure regulator. We installed two jigs, one connected to the ATI Nano force sensor and the other one connected to the ground in between two jaws of the gripper. The vacuum pressure regulator was used to control the vacuum pressure from 0 to -100 kPa and the corresponding gripper force was measured using the force sensor. With this setup, we verified that the SHY robotic grasper can exert up to 180 mN of force under a vacuum pressure of -100 kPa. We have added this information in Section *SHY Continuum Robot Demonstration*.

R3.6. *In Fig 6g,h, there is a gap between the model and experimental data. Please explain why and how to reduce the gap.*
Response: We appreciate the reviewer for pointing this out and giving us an opportunity to further investigate this. Upon closer examination of the theoretical model, we identified an error in calculating the cross-sectional area of each actuator. This miscalculation led to inaccurate predictions of the output force, as the output force is dependent on varying pressure and the constant cross-sectional area. After recalculating the cross-sectional areas accurately, the discrepancies between the model and the actual responses of the translational, bending, and roto-translational modules at

maximum input pressure were found to be 8.3 %, 0.8 %, and 5.4 %, respectively. We thank the reviewer for the opportunity to correct the mistake and we apologize for any confusion this might have caused.

R3.7. *Fig. 4 may go to SI. The dashed lines should be marked with a value and explained clearly.*
Response: We appreciate the feedback from the reviewer. In response to your suggestion regarding the dashed lines, we have included the maximum values of the dashed lines to provide further clarification. Regarding the consideration of moving Fig. 4 to the supplementary information, we respectfully believe that Fig. 4 plays a significant role in showcasing the mechanical performance of our robots. Therefore, we have opted to retain Fig. 4 in the main body of the manuscript to be more accessible to readers.

R3.8. *The quality of Fig. 7, Fig. 9 and Fig. 10 do not meet the standard of Nature Communications.*
Response: We thank the reviewer for pointing this out. To address this comment, we have made several enhancements to improve the clarity, readability, and intuitiveness of the figures. In Fig. 6 (previously Fig. 7), we have highlighted the inflation and deflation phases in the actual images of the continuum robot. Additionally, we have clarified that these actual images represent sequence 1. We have improved the quality of Fig. 8 (previously Figs. 9 and 10) and introduced gaps between the subfigures to enhance visibility. Additionally, we have added more labels to provide more clarity on each component depicted in the figures.

R3.9. *Fig. 9 and Fig. 10 can be combined.*
Response: We thank reviewer for pointing this out. As suggested, we have combined Fig. 9 and Fig. 10 (now Fig. 8).

REVIEWERS' COMMENTS

Reviewer #1 (Remarks to the Author):

The authors have effectively addressed my concerns, and therefore, I am inclined to recommend its publication.

Reviewer #3 (Remarks to the Author):

What are the noteworthy results?

A novel fabrication method to manufacture soft-rigid hybrid robots to avoid manual assembly.

Will the work be of significance to the field and related fields? How does it compare to the established literature? If the work is not original, please provide relevant references.

Yes. The bonding method using H2 plasma is firstly applied to soft robotics.

Does the work support the conclusions and claims, or is additional evidence needed?

Yes

Are there any flaws in the data analysis, interpretation and conclusions? Do these prohibit publication or require revision?

No

Is the methodology sound? Does the work meet the expected standards in your field?

Yes

Is there enough detail provided in the methods for the work to be reproduced?

Yes

I recommend publication as the authors have addressed all my concerns.