

Reply to Referee #1, manuscript 1963973, by David Herrero-Pérez and Humberto Martínez Barberá

The authors are grateful to the Referee #1 for the comments which, in our opinion, have contributed to improve the manuscript. We have attempted to respond carefully to each comment. The referee's comments are highlighted in text boxes, whereas authors replies are in normal text.

(Summary/Introduction).

The manuscript was presented well. In fact, it was very nice to evaluate which was detailed really well. These are a few suggestions that would enhance certain aspects and a few clarifications which need to be taken care of before the manuscript can be accepted.

We sincerely thank the referee for his/her positive comments.

Major comment 1.

1. One aspect that would help the reader is how did the authors conclude the use of TPU 95A for soft actuator? did you try any other material. If the authors have tried other materials, it would be better share that experience.

We combine the use of flexible thermoplastic (TPU) and silicone rubbers to take advantage of the properties of both materials and fabrication processes. We can choose the Shore hardness for the TPU material. We have included the reasons of selecting the TPU 95A in the eighth paragraph of the new version of manuscript as follows

...

We have diverse commercially available TPU materials with different Shore hardnesses. We can find the characterization and comparison of 70A, 82A, 85A, 90A, 95A, and 98A TPU materials manufactured using FDM in [32]. This characterization shows the tensile test up to the point of fracture detailing the elongation at such a point and Young's modulus after the printing. This work reveals that the Shore hardness slightly decreases after the printing concerning the one provided by the supplier. **We select the TPU 95A due to the Shore hardness required for exerting the force, and the maximum elongation (262%) satisfies the application requirements.** We also take Young's modulus $E=34\text{MPa}$ obtained from such a characterization to simulate the behavior of the TPU material after printing using FDM.

[32] Georgopoulou, A.; Vanderborght, B.; Clemens, F. Fabrication of a Soft Robotic Gripper With Integrated Strain Sensing Elements Using Multi-Material Additive Manufacturing. *Front. Robot. AI* 2021, 8:615991.

Major comment 2.

2. it is very clear that the authors have used parametrized CAD model and DDM based FEA analysis for modeling. It would be better if they described what were the base geometric parameters with which they started and how did you arrive at the parameters that were presented in the paper.

In the first paragraph of section 3.1 we detail the starting point of the design and the procedure to reach the final design

The design of the soft fluidic actuator consists of finding the parameters of a parameterized geometry that allow us to bend the actuator within a given range of maximum displacements avoiding twisting. We can combine these devices to design a gripper to perform grasping operations. We show the parameterized CAD model in Figure 2 and the description of each parameter in Table 1. The actuator has multiple, separated chambers in the monolithic structure, **similar to the configuration reported by the early work of Ogura et al. [25].** ...

The parametric design allows us to explore the design space by varying the parametric variables, which modify the shape and size of the soft actuator, the shape and size of the chamber, the stiffness of the passive layer, and the maximum strain of the flexible thermoplastic. ...

We modify the parameters manually following a trial and error approach until we reach a feasible design. Ideally, we should use an optimization approach, but the computational cost of the simulation makes it unaffordable computationally.

[25] Ogura, K.; Wakimoto, S.; Suzumori, K.; Nishioka, Y. Micro pneumatic curling actuator - Nematode actuator -. In Proceedings of the IEEE Int. Conf. on Robotics and Biomimetics; , 2008; pp. 462467.

Major comment 3.

In figure 7, what do the points represent? experimental deformation?.

Right, we modified the third paragraph of the section 3.4 as follows

Figure 7 shows the **experimental** trajectory of the endpoint of the soft actuator with different internal pressures measured with the photograms of the video. We use this information in the control of the grasping maneuver to consider the delays between the pressure increase and the actuation of the soft device.

to highlight that such values are experimental data. We also modified the caption of Figure 7 to “Experimental data of the endpoint of the soft actuator with different internal pressures” to highlight that the data are not simulations.

Major comment 4.

4. Is there any way to generalize the work like if the arm diameter changes then the end-effector displacement will change but want to keep the same force, how to modify the geometric parameters of the soft actuator? This kind of work will help designers in the future.

We modify section 4.1 as follows

We use the fluidic soft actuator to develop a soft gripper to operate in underwater environments. We use the characterization of the displacement of the endpoint of the soft actuator to design the support for actuators acting together in grasping operations. The procedure consists of selecting an operative pressure of the ones characterized in Figure 7 and then using the endpoint displacement to determine the arm diameter. We also can fix an arm diameter and then selects the operative pressure for such a design parameter. In our case, we use three soft actuators operating at 400kPa for the gripper design.

to specify that we can use the information provided in Figure 7 to design the arm diameter and vice versa. In the case that the geometric parameters of the soft actuator change, we have to obtain the curves of Figure 7 again to repeat the process.

Reply to Referee #2, manuscript 1963973, by David Herrero-Pérez and Humberto Martínez Barberá

The authors would like to thank the Referee# 2 for his/her comments and suggestions. Such comments were relevant for improving the readability and presentation of the proposal.

(Summary/Introduction).

This paper undertakes the design and fabrication of soft gripper manipulation operable underwater. It provides design and subsequent fabrication using elastomers. The paper uses modeling and simulation techniques for designing and fabrication. The design looks simple and cost-effective easily operable. The design further validated the feasibility and ability of the proposed soft gripper.

We sincerely thank the referee for his/her positive comments.

Major comment 1.

1) The material selection for the actuator design needs more information to satisfy the users' requirements of accuracy, repeatability, durability, manufacturability, etc.

We combine the use of flexible thermoplastic (TPU) and silicone rubbers to take advantage of the properties of both materials and fabrication processes.

As we are interested in FDM additive manufacturing, the only flexible commercially available material is TPU. We have added some information regarding the Shore hardness selection for TPU

We included in the ninth paragraph of the new version of the manuscript the following text

... Anyways, these flexible thermoplastics are extremely flexible and durable. They also are easily printable with high accuracy and repeatability.

Since we can use additive manufacturing with the Fused Deposition Modeling (FDM) technique using TPU materials, the accuracy, repeatability, and manufacturability are given by the nozzle size and the techniques for 3D printing (considering material retraction and so on). Concerning durability, the shelf life of TPU material is commented on next answer.

...

We have diverse commercially available TPU materials with different Shore hardnesses. We can find the characterization and comparison of 70A, 82A, 85A, 90A, 95A, and 98A TPU materials manufactured using FDM in [32]. This characterization shows the tensile test up to the point of fracture detailing the elongation at such a point and Young's modulus after the printing. This work reveals that the Shore hardness slightly decreases after the printing concerning the one provided by the supplier. **We select the TPU 95A due to the Shore hardness required for exerting the force, and the maximum elongation (262%) satisfies the application requirements.** We also take Young's modulus $E=34\text{MPa}$ obtained from such a characterization to simulate the behavior of the TPU material after printing using FDM.

[32] Georgopoulou, A.; Vanderborght, B.; Clemens, F. Fabrication of a Soft Robotic Gripper With Integrated Strain Sensing Elements Using Multi-Material Additive Manufacturing. *Front. Robot. AI* 2021, 8:615991.

On the other hand, silicone use has no structural requisites, as its function is providing a large and deformable contact area. This does not impose large constraints on the silicone selection. As the moulding technique is very simple, we only need a soft and fluid silicone, as the selected EcoFlex 00-30 is. Any silicone with similar properties will do. We also mention other branches in the paper

...

Using two-component liquid silicone rubbers facilitates the mold-based fabrication process because we only have to mix the two liquid compounds for curing the silicone rubber in the mold. We can mention KE-1603-A-B [25], Sylgard [26], and EcoFlex 00-30 [27] from Smooth-on Inc. We can use excimer lamps to cast and bond parts fabricated in different molds by surface activation technology [25]. However, complex designs require using other techniques, such as stereo-lithography in early works for manufacturing micro-actuators of resin with shapes that are difficult to fabricate by molding [28].

Major comment 2.

2) Authors may justify the use of Thermoplastic Polyurethane (TPU) as some of the grades of TPU possess a shorter shelf life and thus become unusable after the given timeframe. Further, TPU is not as cost-effective.

Although we do have experienced a large degradation of flexible materials for resin printing, the commercial TPU filament used seems to be quite stable. We have added this sentence in the Conclusions

Although flexible thermoplastics can suffer from durability, the commercial ones used are stable enough for the application. We have kept immersed in fresh water a complete hand in our laboratory for more than 9 months and have experience no degradation (except some slight changes in coloring of the silicone). In addition, the first prototype hand has been kept in air for more than 18 months, and we have not experienced any degradation as well.

Moreover, each finger uses 35g of TPU material which can be found for around 70-80\$/Kg (which is in fact a little bit more than double the price of standard PLA). We do not think this to be an issue in the overall cost of the printed hand.

We included the following text below the ninth paragraph of the new version of the manuscript in order to highlight that the use of TPU can have a limited shelf life.

Another thing to consider is the shelf life of some properties of flexible thermoplastics. The principal mode of deterioration of polyester-based TPU material is slow hydrolysis, but polyether- and polycarbonate-based TPUs show better resistance to this problem. A secondary cause of damage is oxidation due to ozone exposure or other oxidative agents staining the material. A possible solution is to sterilize it using some coating. We also have to remark that the TPU has good resistance to radiation, which contributes to extending the service life. ...

Major comment 5.

3) Please refer to line no.204: “If the result does not satisfy the design requirements detailed in the next section, we test a new set of parameters until the design requirements are satisfied.” Authors have indicated that the trial and error approach consumes time and tedious replications to arrive at the required design.

We agree the current writing can be misleading. The idea is that the fabrication of different real hands in a trial-and-error approach is really very time-consuming. We replace this approach by using a trial-and-error one but with FEM calculations. We can not claim that this method is immediate, but we are talking of hours of work compared to days of physical hand fabrication: printing each finger takes around one hour, producing the silicone cover another hour plus 8-10 hours of curing. Optimizing the process we could produce a single hand in some 24 hours. In a working day we can compute the characteristics of 4-6 candidate designs in a working day.

We have worked out the last paragraph of section 3.1 as follows:

...

We then obtain the displacements of the model using non-linear finite element analysis. If the result does not satisfy the design requirements detailed in the next section, **Awe modify some parameters constraining the search space until the design requirements are satisfied. Although this process clearly consumes some time, it takes less than actually building, testing and characterizing the physical actuators. With the presented approach a single person can characterize 4-6 configurations in a working day, while it could take more than 24 hours to produce and test a single physical hand.**

and the second paragraph of the section 3.2 as follows

... We specify the requirements of the soft actuator as the bending translating the end-point of the fluidic actuator acting with a given internal force. We usually fix the parameters defining the size of the support of the actuator (h,w,l) and then initialize the other parameters shown in the Table 1 scaling the values of a known design [25] with the support volume. This approach reduces the search space, and then the trial-and-error method consists of independent variations of a reduced set of parameters to satisfy the operative requirements. ...

Major comment 3.

4) Authors may provide assumptions and limitations of the present design.

We have modified the introduction as follows:

In this work, we present the design and fabrication of a simple, low-cost, and easily deployable soft gripper for underwater manipulation , **which can be deployed in a small underwater vehicle, with little buoyancy reserve. This implies that the additional weight that can be carried from bottom to surface is relatively small. The target application is the recollection of small objects or living living organisms (coral, seaweed, mollusks, etc).**

...

Major comment 4.

5) According to Jerrams, and Bowen (1970). “Mooney-Rivlin constants that accurately predict behavior in shear over a small strain range may prove utterly inadequate for other modes of deformation and greater strain ranges.” Authors may provide more information to enhance predict accuracy.

Jerram’s, S.J. and Bowen, J., 1970. Modeling the behavior of rubber-like materials to obtain correlation with rigidity modulus tests. WIT Transactions on Modelling and Simulation.

We included in the eight paragraph of section 2 the reference to the characterization of many TPU materials as follows

...
We have diverse commercially available TPU materials with different Shore hardnesses. We can find the characterization and comparison of 70A, 82A, 85A, 90A, 95A, and 98A TPU materials manufactured using FDM in [32]. This characterization shows the tensile test up to the point of fracture detailing the elongation at such a point and Young’s modulus after the printing. This work reveals that the Shore hardness slightly decreases after the printing concerning the one provided by the supplier. **We selected the TPU 95A due to the Shore hardness required for exerting the force and the operational range of elongation (0-262%) satisfying the application requirements. We also take Young’s modulus $E=34\text{MPa}$ obtained from such a characterization to simulate the behavior of the TPU material after printing using FDM.**

We adjusted the Mooney-Rivlin constants for the parameters specified in the characterization after printing the material. The TPU chosen has a high Shore and little maximum elongation concerning other possibilities. Besides, the range of operation is far from the maximum elongation values. It is likely due to this reason we have not experimented the problems with greater strain ranges.

Major comment 5.

6) “Author may provide citations for assuming assume $\nu = 0,48$ for fitting the Mooney-Rivlin material constants.”

We included the references for assuming $\nu = 0,48$ and adjusting the constants using the characterization of the TPU material after printing in the first paragraph of section 3.2 as follows

... Since the Poisson’s ratio ν ranges from 0,48 to 0,50 for natural rubbers [37], we assume Poisson’s ratio $\nu = 0,48$ for fitting the Mooney-Rivlin material constants [29] considering the characterization of TPU material after printing presented above [32].

[29] Qi, H.J.; Boyce, M.C. Stress-strain Behavior of Thermoplastic Polyurethanes. *Mechanics of Materials* 2005, 37, 817–839.

[32] Georgopoulou, A.; Vanderborght, B.; Clemens, F. Fabrication of a Soft Robotic Gripper With Integrated Strain Sensing Elements Using Multi-Material Additive Manufacturing. *Front. Robot. AI* 2021, 8:615991.

[37] Ward, I.M.; Sweeney, J. *Mechanical Properties of Solid Polymers: Third Edition*; John Wiley & Sons, Ltd: The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United

Kingdom, 2012.