A large-scale, light-weight, and soft braided robot manipulator with rapid expansion capabilities

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Abstract— **A key challenge in soft robotics is how to design self-supported large-scale soft robots. In order to address this we have created a braided manipulator. The manipulator consists of a biaxially braided cylinder made from twelve glass-fiber enforced rods. The manipulator measures 1.38m in height in its equilibrium state and has a diameter of 8.5cm at the top and 20.0cm at the base and only weighs 35g. The manipulator is fixed to a base which weighs 1.9kg in which three stepper motor driven winches are embedded at 120° intervals. From each winch a string is braided vertically through the braided manipulator and is fixed to the top. In experiments we find that the manipulator can be compressed to 51cm corresponding to 38%. The manipulator compresses in 54s which is determined by stepper speed and winch diameter and expands when the actuators are turned off in 105ms. We also find that the force required to compress the manipulator is constant at 2.6N for most of actuation range. The force generated by the manipulator corresponds to a payload of 265g which is an order of magnitude more then the weight of the manipulator itself. The limitations of the current work is that the actuation, processing, and power is externalized to the manipulator and modelling and control are unaddressed. However, overall we find that the braided manipulator is evidence that braiding holds potential as a construction paradigm for soft robotics as we have demonstrated that it allows for large-scale and light-weight soft robots.**

I. INTRODUCTION

Conventional rigid robots, built from metals and plastics, are not particularly well suited for applications that require tight interaction with humans. This is in part because, through their mass alone, they represent a safety issue [15]. Soft robots, typically built from silicone rubbers, reduce this issue by being compliant. However, with compliance, comes the challenge of creating large, self-supported robots as soft robots remain heavy. Another less technical issue of both types of robots (silicone based and traditional rigid robots) is that human acceptance is lacking, which is a limitation of increasing importance as robots move out of factories and into our everyday lives.

As an alternative, we propose light-weight soft robots created using the textile technique of braiding. In its most basic form, a braid is formed by the interlacing of three strands of materials. Braids have been used in traditional crafts most likely since before recorded history. Additionally, engineering applications of braids are also thought to be more than 17,000 years old and continue to be used today. For example, in ancient times, braiding was used to combine small, weak, natural fibers into longer and stronger ropes. In more recent times braiding, together with weaving, has found new applications in the creation of composites. Composites are used in highly engineered applications where control of material performance is crucial. For the interested reader, Branscomb et al. provides an informative account of braiding and its history in engineering [4].

For robotics, braids are an attractive construction paradigm because both soft and hard components can emerge from the same braiding process by changing braiding patterns during fabrication. The braiding pattern influences the material performance of the braided components. E.g., densely, intertwined braided structures are strong and rigid, while sparse, non-intertwined braided structures are weak and compliant (Braid patterns are further detailed in a technical report [10]). If one further considers the possibility of changing or mixing materials in the form of strands of different materials during the braiding process, the possibility of controlling the structural performance across a robot body

Fig. 1: The braided manipulator.

This work was supported through the project 'Flora Robotica', which received funding from the European Union´s Horizon 2020 research and innovation program under the FET grant agreement no. 640959 and the DFF Sapere Aude Grant for project INNATE

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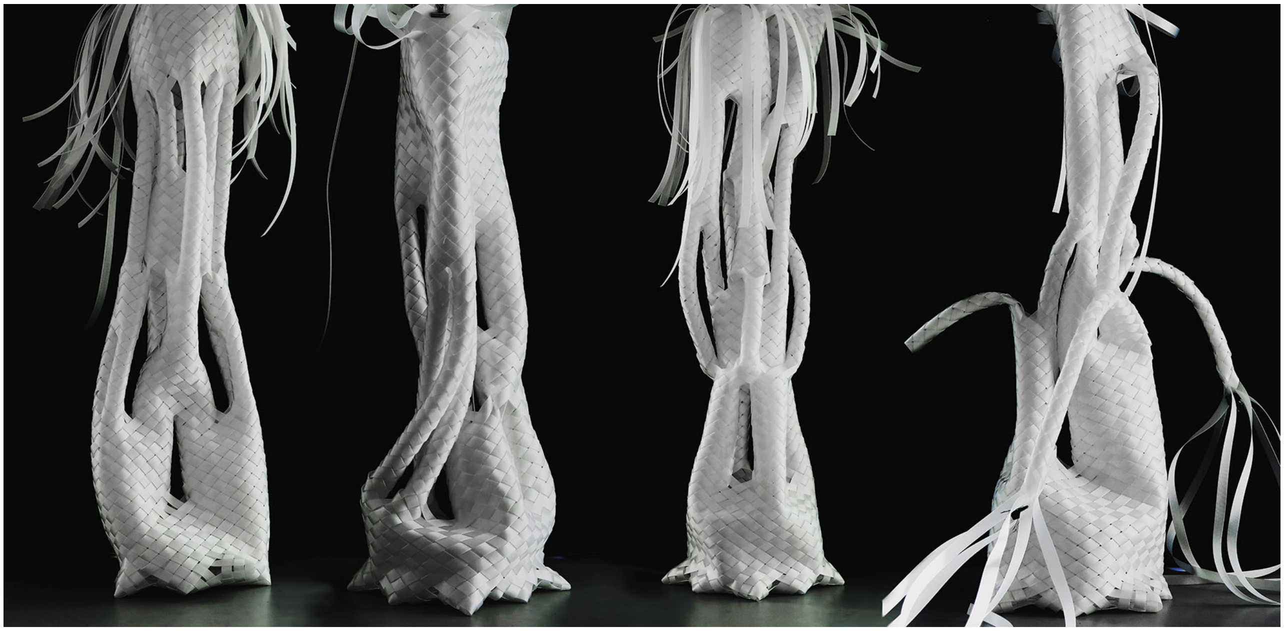

Fig. 2: Demonstration of complex of structurally stable braid morphologies. The braids are hand-braided from flat strands of fibre-reinforced plastic, measuring about 0.5 mm in thickness and 31 mm in width. The sculptures measure up to 2.3 meters in height and weigh about 12 kg.

is clear. Whilst a potential challenge of braided robots is the perceived limitation regarding the range of different morphologies, this was falsified by our early exploration into the complexity of braids shown in Figure 2. Here, for instance, multi-level bifurcation, merging and inversions were demonstrated. Another attractive aspect of braids is that they are heavily embedded in human culture and tradition. Hence, humans are accustomed to braided and woven structures and instinctively see them as aesthetically attractive - possibly due to the repetitive, geometric patterns or maybe because the production process is tangible (although not necessarily easily replicated) and recognisable as belonging to traditional crafts.

The specific contribution of this paper in the broader context of braid robotics is a large-scale, light-weight, and soft manipulator as shown in Figure 1 and its design detailed in Section III. The braided part of the robot is a cylinder created from the intertwining of glass-fiber reinforced plastic rods. This structure is self-supporting because the bent strands are under tension, held in place by the compression of the braid. Hence, there are two opposite forces cancelling out in the equilibrium state of the structure. This means that we can create large scale structures with a minimal use of material. The openness of the structure allows for an extreme degree of compression because we are not deforming material, but simply changing the angles and the curvature of the constituent members of the braided structure. The challenge of modelling and control is unaddressed in this work, however, the work on parallel continuum manipulators would be a promising starting point [19]. Another potential limitation is that in the current form the active components are outside the braided structure (i.e. the stepper driven winches), but advances in the fields of soft robotics and smart textiles may provide methods to embed the active functionality in the braided member themselves [18], [8]. However, as an intermediate step, mounting components inside a braid is also a viable and practical way forward.

In summary, we see the potential of braided robot bodies as being light-weight, having a designed heterogeneous structural performance, facilitate inclusion of multiple materials, and having a potential to be better accepted by humans. However, while we think the theoretical potential is clear, we have just started research in braided robotics and the underlying technologies. Hence, the purpose of this paper is to present the initial vision of braided robots with supporting evidence in the form of a simple braided robot manipulator.

II. RELATED WORK

Perhaps one of the most wide-spread uses of braiding in robotics is in McKibben artificial muscles. A common design of artificial muscles is to have a braided cylindrical mesh constraining a pneumatic bladder (e.g. [6]). Here, the braided mesh is beneficial due to its flexibility, low weight, and high tensile strength. Braiding has also found its use in worm-like robots [17], [3], [2] where the restorative force of a cylindrical braid is also exploited. It has also found its use as a way to contain internal elements in an octopus-inspired robot manipulator [11]. In relation to this work, the novelty of our braided manipulator is that it is large-scale and self-supported. Related is also the work of Connelly et al. who studied how the angle of external members of an internal soft structure could be used to control its shape, but again due to the braid we do not the need the internal soft structure [7].

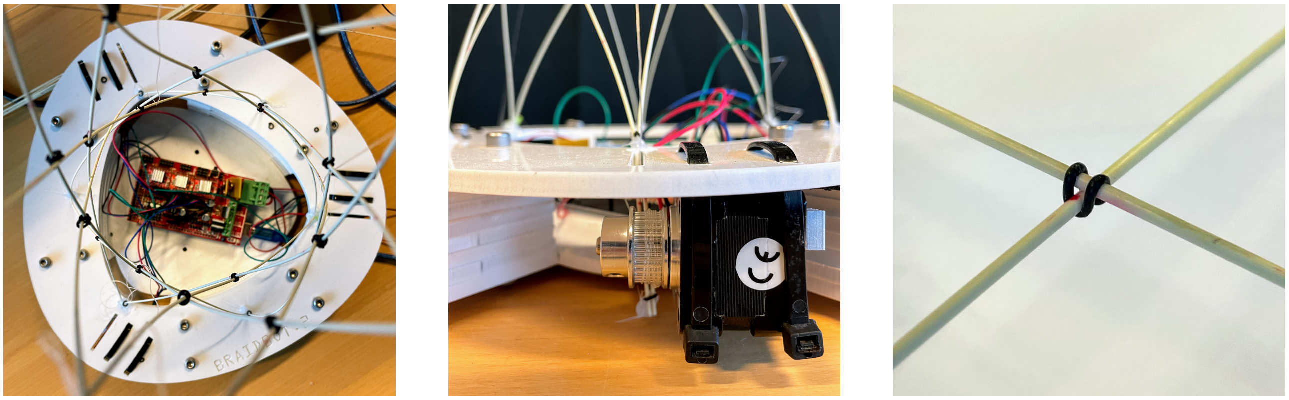

Fig. 3: The braid manipulator is mounted on a base (left) where the electronics is located and under which the winches actuating the manipulator are located (middle). The strands are fixed relative to each other using o-rings (right).

Braided robots are similar to tensegrity robots [13], [14]. Tensegrity robots also promote the idea of low weight and high strength as features that are important. However, tensegrity robots tend to be impractical to assemble and often have limited movement ranges, because displacement in one place is distributed across all members in the tensegrity. Braided robots also exploit the idea of combining tensile elements with rigid elements that together form a stable whole. However, in braided robots it is the bending of the material strands that provides an outward force while the braided structure itself provide the opposite force creating a stable whole.

The braided manipulator is also related to parallel continuum manipulators where several parallel bending rods are connected to the top and actuated by pulling or pushing the rods [5]. This essentially creates a Steward platform with flexible rods. The key difference is that in our system the bending rods are braided. This means that the rods do not buckle as easily as they are constrained by the braid and we can therefore create larger, self-supporting structures.

III. BRAIDED MANIPULATOR

As a first demonstration of the braided robot paradigm we have braided a simple 3 degrees-of-freedom (DOF) manipulator which has a height of $1.38m$ and only weighs $35g$.

The manipulator is essentially a cylinder braided from 12 strands in a simple biaxial weave where the distance between intersections is $6cm$. For the strands we have chosen $2mm$ diameter fiberglass reinforced plastic rods (Fibrolux, GRP rods 2mm x 2000mm). This choice gives us light-weight and strong strands which we have found gives us a suitable trade-off between stiffness and flexibility.

The braided cylinder alone is sufficient to make a self-supporting structure. However, in a highly open braid like the one we created, we found that during actuation, the strands displace resulting in inconsistent behavior. We have therefore fixed the intersections with nitrile o-rings having an inner diameter of $2mm$ as shown in Fig. 3. In addition to fixing the intersection, the o-rings also provide a spring effect to the intersection such that they are in equilibrium when the strands are at $90°$ to each other. Note that, while the o-rings provide the functionality we want, we have have found that they become stretched beyond their elasticity range when the manipulator is fully contracted and thus tend to fail after some use (100+ cycles). This can be prevented by not compressing the manipulator to extremes, but a more robust solution would be desirable.

At the top of the braid the strands are fixed to a $1mm$ thick piece of polyoxymethylene which has six holes distributed evenly around a circle with a diameter $8.5cm$. We refer to this as the crown. In each of the holes two strands are hot glued in place at the point where they naturally intersect. The crown functions to hold the braid at a fixed diameter, preventing it from collapsing. In addition, the crown is also a suitable place to mount an end-effector at a later stage.

The braid is fixed at the bottom to a base which weighs $1.9kg$. Here the holes are evenly distributed around a circle with a diameter of $20cm$. The constraints provided by the crown and the base result in the braid measuring $8.5cm$ in diameter for most of its height. However, at $20.5cm$ from the base the braid widens gradually to reach a diameter of $20cm$ at the base. The base also contains the actuators and electronics as shown in Fig. 3. The actuators are three NEMA-14 motors on which we have mounted a simple pulley to work as a winch. The actuators are mounted under the base with $120°$ between them and are oriented perpendicular compared to the braid (see Fig. 3). From the winches, a $0.45mm$ nylon string goes through a slit in the base and is braided through the main manipulator as a vertical strand and connected to the crown with a knot. We can thus bend the manipulator by pulling one of the nylon strings and we can straighten the manipulator by loosing the string; allowing the manipulator to return to its natural equilibrium. The electronics is also located in the base and consists of an Arduino Mega with a Ramps 1.4 motor shield. The electronics and motors are powered from an external power supply and when the robot is moving the whole system consumes $28.9W$ ($2.41A$ at $12V$).

IV. FABRICATION

While in theory braiding is simple, we found it to represent a practical challenge and hence we describe our simple fabrication procedure. We start by marking the strands with a pen every $6cm$. These marks represent the planned intersection between two filaments. Note, that for a biaxial braid the distance between the marks represent the side length of the rhombus limited by four intersections and four filaments. In general, a similar process can be used also for other more complicated braiding patterns and coloring of the filaments can be used to indicate which strand goes under and which goes over.

We now hot glue the strands pair-wise into the holes of the base. The idea is that one strand will go clock-wise around the structure and the other counter clock-wise. We then take two strands at a time, interlace them and fasten the connection with an o-ring. This means the intersection and the strands below this point are held in place and the braiding can proceed in a controlled fashion. We then work from the bottom and up. After the braid has reached the desired height we insert the strands pair-wise into the holes in the crown and hot glue them in place and cut-off the remainder of the strand.

Currently, the manipulator is braided by hand which is practical given the simplicity of the structure, but in the future it would useful to integrated with textile automation technologies [4].

V. EXPERIMENTS

A. *Work space and ability to compress*

We conducted an experiment to document the work space of the manipulator in a two-dimensional plane parallel to one of the actuators. We let the end-effector (the crown) go through the extreme positions by controlling the length of the three actuator strings: 1) fully expanded with no tension on any of the actuation strings, 2) fully contracted with all three strings equal in length, 3) maximum horizontal reach in which two strings have no tension and one is retracted until the crown touches the ground. This is visualized in Figure 4. In the fully expanded state the manipulator is $1.35m$ high (all heights reported excluding the base which is $5.75cm$ high). It is contracted to $0.51m$ which is 38% of the fully expanded height. It touches the ground at $0.65m$ from the center of the base.

B. *Force response is constant over a large range*

In this experiment we are interested in measuring the force response as a function of compression. We start the manipulator in the equilibrium state where it rests with the crown at a height of $1.35m$. We then compress the manipulator $0.05m$ at a time and, at each increment, measure the restoration force of the manipulator using a force-meter. We continue to do this until the manipulator is compressed by $1.05m$, the point at which all segments of the manipulator are collapsed except the first and last which are attached to the crown and base respectively. We repeat this experiment five times. The results can be seen in Figure 5.

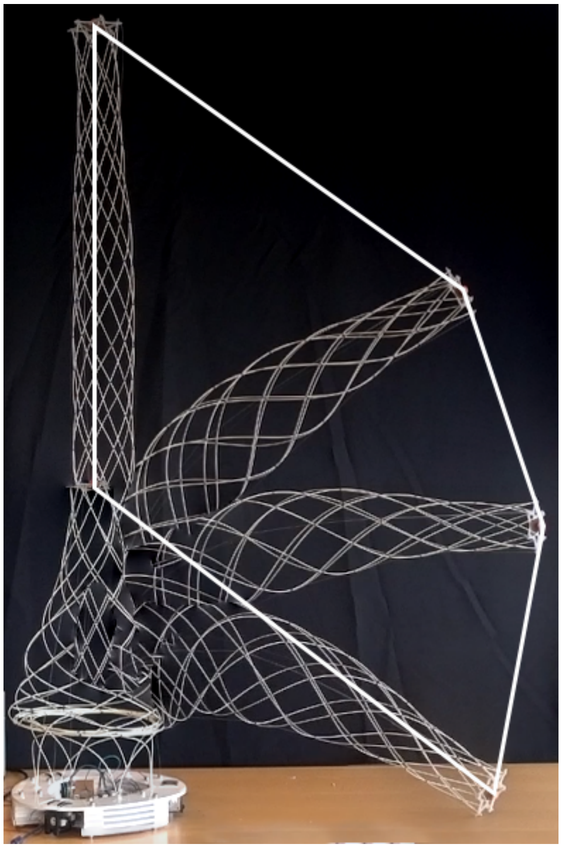

Fig. 4: Two dimensional visualization of the boundary of the work space of the braid manipulator.

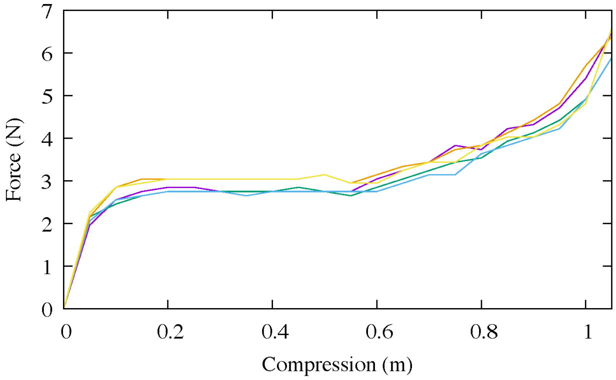

Fig. 5: The restoration force of the manipulator as a function of compression distance (five measurements shown).

While one may have expected a linear restoration force with the underlying assumption that the manipulator acts like a spring, the results show a different picture. The force grows until the manipulator reaches a comparably small compression of $0.1m$. It then has a constant restoration force of on average $2,6N$ with a standard deviation of $0.17N$ over a large range ($0.1m$-$0.6m$) and, for the remaining interval, ($0.6m$-$1.05m$) a super-linear response. From observation it seems that initially the increasing curvature of the members provides the restoration force. In the constant phase the structure works more as a scissor mechanism and thus does not change the restoration force. Finally, in the last phase the segments start to collapse from a cylinder to a circle. This means that the strands in the last and first layer, which are vertically glued to the crown and base, dominate the force response as they are prevented from collapsing.

The force response can also be interpreted in terms of payload capabilities and in the constant phase the manipulator would be able to support a payload of less than $265g$ without compressing, which is an order of magnitude more than the weight of the manipulator itself at $35g$.

It was surprising to find the constant force response, but this is a significant result because it means that actuators also only need to provide a constant force as the system compresses where in contrast if the system had a spring response would require linear force. This allows for weaker and hence smaller motors. Another observation is that the experiment raises a question about how best to mount the braid to the base and the crown as the boundary effects potentially could be reduced or removed. However, this requires further investigation.

C. *Contraction and rapid expansion*

In this experiment we will highlight the ability to rapidly deploy the manipulator which may be relevant in some applications. We actuate all stepper motors and compress the manipulator to $0.51m$. We then turn off the stepper motors and let the restoration force of the manipulator expand itself to its full length of $1.35m$. We record the experiment with a high-speed camera and find from the resulting video that the manipulator contracts in $54s$ and expands in $105ms$. This corresponds to an average contraction velocity of $1.6cm/s$ and an expansion velocity of $8.0m/s$. The speed of contraction is determined by the speed of the steppers and the diameter of the winches. The speed of expansion is determined by the restoration force of the braid counterbalanced by the friction in the actuation system.

VI. CHALLENGES

The braided manipulator demonstrator and the experiments above document the potential of braided robots as an alternative implementation of soft robots. In soft robotics the softness predominately arises from the softness of the materials, while in braid robotics the softness arise to some degree from the softness of the materials, but to a much higher degree from the organisation of the material. The result is a light-weight, extremely deformable, type of soft robot. Whilst many of challenges are shared with soft robotics in general, however, the braid-based implementation in some cases open up for alternative solutions to these challenges. While these challenges and outlined solutions are largely unsupported experimentally we include them because we think they will be useful to the community.

A. *Integrated soft braided robot*

In the braid manipulator the functionalities of actuation, processing, and power are externalized from the braided manipulator. One may note that the same was true for the initial generation of silicone-based soft robots e.g. see [16] for numerous examples, also [12]). This started a strong research agenda to replace the hard conventional components with soft alternatives - an endeavour that in the last years have led to the first self-contained, integrated fully soft robots (e.g. [22], [20]). Braided soft robots can also build on this development moving towards fully integrated soft braided robots. However, in the short term the openness of braided structure makes it possible to embed conventional components with a graceful degradation in the important characteristics such as weight and ability to compress. However, that the softness arises from the structural organization also means that components are not required to be soft, but just flexible. Hence, already electrical wires and flexible electronics can be integrated directly in the woven structure.

B. *Materials*

The choice of material for braiding is an important aspect of braided robots and can be chosen to support the function of the robot. At one extreme it is possible to use traditional materials common in basket making through the centuries e.g., willow or grasses. At the other extreme highly engineered materials such as fiberglass or Kevlar may also be used as we have done here. The strength of the braiding paradigm is that multiple materials can be intertwined with ease. E.g., it is possible to braid one type of material offering structural support with another that provides electrical connectivity. For actuation materials such as electro-actuated polymers and shape memory alloys are also obvious candidates for exploitation in braided robots. The exploration of materials and their benefits to braid robotics is a key research opportunity which is linked to work on composites broadly used in high-performance engineering.

C. *Braiding patterns and advanced geometries*

While the above mentioned challenges have synergies with the broader field of soft robotics. There are also challenges more narrowly related to braided robots. A key challenge is that there is a large design space in terms of braid patterns and their resulting performance characteristics. For instance, in the braid manipulator we use an open biaxial braid. This provides the manipulator with a softness in the vertical direction while being resistant to torsion. Dense braids on the other hand can create highly rigid structures. Again here an understanding of the relation between braiding patterns and materials and how they influence the performance of the resulting structure is an interesting challenge. At a higher-level the geometry of the braided structure should also be subject of investigation. In the current work we use a simple cylinder geometry, but highly complex geometries can be braided, as shown in Figure 2. This both opens up for custom-braided structures e.g. we can braid structures that buckle in specific locations to form the basis for joints as illustrated in Figure 6. It also opens up for the possibility to braid complete robot bodies and custom-designed pneumatic artificial muscles. However, again this is largely unexplored.

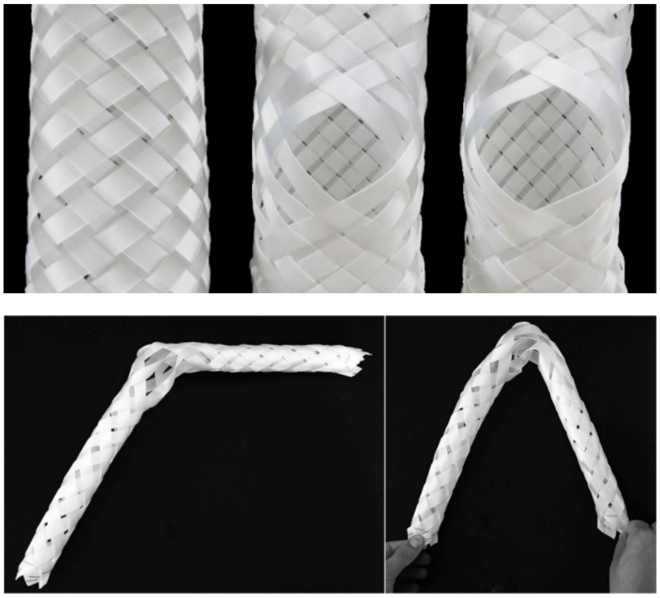

Fig. 6: Examples of braids designed to buckle in specific locations forming the basis for joints.

D. Compilation of Robot Designs

An abstract branch of mathematics deals with braid theory [1]. While it predominately has been a theory of relevance within mathematics it may find an application in braided robots [9]. In particular, it may be useful for forming the theoretical foundation for some of the compiler tools by for instance being able to make proofs of completeness. E.g., given a specific set of operations, it may be possible to show that all possible braids can be generated. At a high-level of abstraction it would be highly useful to have an automated way to go from a high-level three dimensional model to a representation of materials and the braiding steps necessary to achieve this three-dimensional model. It would further be useful to be able to assign structural performance to the structure, which then could work as input to the braiding process. This challenge is something that we are starting to address in related work [21], [23].

VII. CONCLUSION

The purpose of this paper is to introduce braid robotics as a paradigm. We acknowledge that the manipulator only represents an initial instantiation, but we think that there is mounting evidence that braid robotics has significant potential to advance robotics. Its foundation ranges from ancient humans crafts to the high-technological production of composites and it naturally integrates materials and advances in smart materials. In this paper, we demonstrated how to make a beautiful, hand-crafted robot and provided input on how to make large-scale, light-weight, self-supporting, and soft robots.

REFERENCES

[1] E. Artin. Theory of braids. *Annals of Mathematics*, 48(1):101–126, 1947.

[2] J. E. Bernth, A. Arezzo, and H. Liu. A novel robotic meshworm with segment-bending anchoring for colonoscopy. *IEEE Robotics and Automation Letters*, 2(3):1718–1724, 2017.

[3] Alexander S Boxerbaum, Kendrick M Shaw, Hillel J Chiel, and Roger D Quinn. Continuous wave peristaltic motion in a robot. *The International Journal of Robotics Research*, 31(3):302–318, 2012.

[4] D. Branscomb, D. Beale, and R. Broughton. New directions in braiding. *Journal of engineered fibers and fabrics*, 8(2):11–24, 2013.

[5] C. E. Bryson and D. C. Rucker. Toward parallel continuum manipulators. In *IEEE International Conference on Robotics and Automation (ICRA)*, pages 778–785, Hong Kong, China, 2014.

[6] D. G. Caldwell, G. A. Medrano-Cerda, and M. J. Goodwin. Braided pneumatic actuator control of a multi-jointed manipulator. In *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics*, pages 423–428, Le Touquet, 1993.

[7] F. Connolly, P. Polygerinos, J. W. Conor, and K. Bertoldi. Mechanical programming of soft actuators by varying fiber angle. *Soft Robotics*, 2(1):26–32, 2015.

[8] J. Forman, T. Tabb, Y. Do, M.-H. Yeh, A. Galvin, and L. Yao. Modifiber: Two-way morphing soft thread actuators for tangible interaction. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, page 1–11, New York, NY, USA, 2019.

[9] M. K. Heinrich, M. Wahby, M. D. Soorati, D. N. Hofstadler, P. Zahadat, P. Ayres, K. Støy, and H. Hamann. Self-organized construction with continuous building material: Higher flexibility based on braided structures. In *Foundations and Applications of Self* Systems, IEEE International Workshops on*, pages 154–159. IEEE, 2016.

[10] M. K. Heinrich, M. J. Zwierzycki, P. Vestartas, P. Zahadat, D. A. Leon, A. Cheheltan, H. L. Evers, P.-K. Hansson, M. Wahby, D. N. Hofstadler, M. D. Soorati, H. Hamann, T. Schmickl, and P. Ayres. Representations and design rules - Deliverable D3.1 - EU-H2020 FET project ’flora robotica’, June 2017. DOI: 10.5281/zenodo.816270.

[11] C. Laschi, M. Cianchetti, B. Mazzolai, L. Margheri, M. Follador, and P. Dario. Soft robot arm inspired by the octopus. *Advanced Robotics*, 26(7):709–727, 2012.

[12] H. Lipson. Challenges and opportunities for design, simulation, and fabrication of soft robots. *Soft Robotics*, 1(1):21–27, 2014.

[13] C. Paul, F. J. Valero-Cuevas, and H. Lipson. Design and control of tensegrity robots for locomotion. *IEEE Transactions on Robotics*, 22(5):944–957, 2006.

[14] T. Rhodes, C. Gotberg, and V. Vikas. Compact shape morphing tensegrity robots capable of locomotion. *Frontiers in Robotics and AI*, 6:111, 2019.

[15] D. Rus and M.T. Tolley. Design, fabrication and control of soft robots. *Nature*, 521(7553):467–475, 2015.

[16] Daniela Rus and Michael T Tolley. Design, fabrication and control of soft robots. *Nature*, 521(7553):467–475, 2015.

[17] S. Seok, C. D. Onal, K. Cho, R. J. Wood, D. Rus, and S. Kim. Meshworm: A peristaltic soft robot with antagonistic nickel titanium coil actuators. *IEEE/ASME Transactions on Mechatronics*, 18(5):1485–1497, 2013.

[18] M. Taghavi, T. Helps, and J. Rossiter. Electro-ribbon actuators and electro-origami robots. *Science Robotics*, 3(25), 2018.

[19] J. Till, V. Aloi, and D. Rucker. Real-time dynamics of soft and continuum robots based on cosserat-rod models. *International journal of Robotics Research*, 38(6):723–746, 2019.

[20] M.T. Tolley, R.F. Shepherd, B. Mosadegh, K.C. Galloway, M. Wehner, M. Karpelson, R. Wood, and G.M. Whitesides. A resilient, untethered soft robot. *Soft robotics*, 1(3):213–223, 2014.

[21] P. Vestartas, M. K. Heinrich, M. Zwierzycki, D. A. Leon, A. Cheheltan, R. La Magna, and P. Ayres. Design tools and workflows for braided structures. In *Humanizing Digital Reality*. Springer, 2017. (In press).

[22] M. Wehner, R.L. Truby, D.J. Fitzgerald, B. Mosadegh, G.M. Whitesides, J.A. Lewis, and R.J. Wood. An integrated design and fabrication strategy for entirely soft, autonomous robots. *Nature*, 536(7617):451–455, 2016.

[23] M. Zwierzycki, P. Vestartas, M. K. Heinrich, and P. Ayres. High resolution representation and simulation of braiding patterns. In *Acadia 2017: Disciplines and Disruption : Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture*, pages 670–670, MIT, Cambridge, USA, 2017.