MORI-A: Soft Vacuum-Actuated Module With 3D-Printable Deformation Structure

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Abstract—Many soft robots are made of polymeric materials such as silicone, urethane, and gel. These soft matter-based robots can be designed to have soft functionality by controlling the deformation, elastic modulus, and other properties of the flexible material. However, updating the shape of a soft robot once it is developed is not considered to be highly effective. It has to be redesigned whenever different functions are required. The body of a modular robot is composed of connected voxel units, and the model and behavior of the robot can be altered conveniently by recombining the module groups. This study proposes a reconfigurable and vacuum-actuated soft matter modular block: MORI-A. It can realize different behaviors of uniaxial bending, shear deformation, and non-deformation depending on the 3D-printed structure contained in a unit. In addition, MORI-A can display elastic anisotropy that depends on the density of the 3D structure it contains and the trajectory it adopts during fabrication. This study quantitatively verifies the load capacity and bendability of MORI-A. We then show that the combination of deformable shapes can improve the diversity of soft modular robot designs by simultaneously developing many curved deformations. These designs include characters. soft modular grippers, applications for underwater swimming robots using curvature, and artificial muscles for dolls made of cloth or cotton that are not supposed to move spontaneously.

Index Terms—Soft sensors and actuators, soft robot applications, soft robot materials and design.

I. INTRODUCTION

M ODULARITY in robotics can provide the reconfigurable functions and forms required for a robot to perform the tasks desired by the robotic designer [1]–[5]. Modularity has

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been observed in neural networks such as the animal brain, as well as in artificially constructed networks such as vascular networks, gene regulatory networks, protein-protein interaction networks, metabolic networks, and social networking services. That locally aggregated functionalities and topologies determine the properties of the entire system is an important concept. Modular robots are based on two approaches: the first is to integrate electronic devices such as micro-electromechanical systems into the robot to enhance the computational processing functions [6]-[8], and the second is to define the minimum elements of the robot to allow for morphological reconfiguration [9]-[12]. Both the approaches share common design challenges [13], [14] such as miniaturization of embedded devices, self-organizing control methods, and linkage to morphological simulations. In any scenario, the addition of softness to the modular robot system is essential considering the development of organisms with higher functionality.

The study of extending the embodiment of modular robots by utilizing their softness is called soft modular robotics [15]–[18]. In general, a self-reconfiguring soft modular robot [19]–[21] consists of a fluid-filled shell structure made of soft materials. The shape is generally a cubic lattice that can be connected conveniently in six axes. Soft modules should improve (1) reconfigurability, (2) various deformability, and (3) environmental adaptability, which are directly related to the functional quality of soft modular robots. Conventional soft modular robots adopt the principle of pressurized drive and use hard materials such as magnets [19]-[23] and silicon tubes for forming many microfluidic channels to ensure reconfigurability [24]. Although these methods show high controllability owing to the convenient connectivity and independent channels, the hard materials and the complexity of the connections promote inhibition of deformation and do not fully exploit the expected module deformation. To achieve various deformability, a method to achieve local hardness bias on the surface of the shell structure [25], [26]. In particular, a method of developing a soft robot driven by gluing or magnetically connecting the smallest component units of hollow silicone, defined as "voxels," has been proposed [21], [27], [28]. These studies combine uniformly deformable and non-deformable soft modules made of very simple materials, and discuss the possibility of linking them with studies that model and simulate the motion of voxels [29], which are also made of elastic materials. Although these three works [21], [27], [28] related to advanced soft-modular robots can enhance the deformability of single-modular and soft-modular robots,

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four technical issues remain unresolved. robots, four technical issues remain unresolved: (1) Weight constraint: This implies that the deformation motion of soft materials is limited severely owing to the increased voxel weight when magnets are used as connectors. (2) Uniformity of actuation: The actuation of most modular robots is limited to uniform volume contraction, and motion complexity is generated by increasing the number of connections. Therefore, complex motions result in large soft modular robots. (3) Difficulty in reconfiguration: In soft modular robots, silicone shells are connected by gluing or multiple connections of micro-silicon tubes, which cannot be reconfigured conveniently. (4) Difficulties in modeling: Among the motions between the soft-modular robot to be simulated and the actual soft-modular robot, there are motions with large deviations due to the occurrence of buckling. To reduce this deviation, a modular system that can realize more diverse motions is necessary.

In this study, we develop a vacuum-actuated module named MORI-A. It combines a deformation structure and a shell structure that can be formed only with soft polymer materials. The MORI-A adds 3D-printed supporting structures with specific compression signatures inside the voxels and joins the voxels with adjustable connectors rather than glue. By using soft materials for all the components including connectors, we can significantly reduce the deformation caused by the attachment of hard metals such as magnets, which is a challenge for conventional soft modular robots. We also propose a method to dramatically reduce the number of modules required for module-to-module compatibility and robot configuration by allowing removable 3D-printable structures to generate a variety of deformability. MORI-A uses a depressurization method for the drive principle rather than the conventional pressurization method. This is to improve the controllability of the enclosed fluid and to ensure drivability that can consider mobility and buoyancy adjustment in different environments such as terrestrial and underwater environments. This study discusses how the elasticity of the Cartesian coordinate axes can vary depending on the shape of the 3D structure to be addressed. In addition, this study demonstrates that MORI-A soft modular robots can be updated conveniently to generate grasping motions of slippery, brittle, and soft object from a series of modular robot movements by altering the combination and orientation of bending, shear, and undeformed units.

II. METHODS

A. Soft-Shell and 3D-Printable Deformation Structures

This section describes the fabrication method of the soft shell structures used in MORI-A, and the parametric design of the internal deformation structures and connections. Fig. 1 shows the procedure for developing a cubic lattice shell structure with side-length of 20 mm and thickness of 2 mm, using a silicone called $Ecoflex^{TM}00-30$. A partition of laser-cut acrylic sheets assembled on a grid is used to develop a mold for molding the silicone. However, if the mold is made of a rigid material that also has the voids necessary to develop the shell structure, it would be highly difficult to remove it. In this method, thermoplastic polyurethane filaments are sculpted into molds to develop the



Fig. 1. Fabrication of MORI-A: (a) An acrylic plate and thermoplastic polyurethane (TPU) blocks are set up as a mold to develop the silicone shell. (b) In this process, silicone is poured (Ecoflex $^{\rm TM}$ 00-30), and (c) the silicone shell is released and deburred after 4 h for it to cure. (d) In the next step, the underlayment for fabricating the silicone lid on the bottom is set up, and (e) silicone pouring is repeated. (f) The final step molds the closed silicone by releasing it. 3D-printed structures can be embedded in the process in (d).

voids and air paths using a fused deposition modeling (FDM) 3D printer. After combining both the molds, silicone is injected and permitted to cure for at least 4 h at room temperature to prevent air bubbles from appearing on the surface. Subsequently, it is removed. After verifying that a cubic lattice shell with only one side open has been developed, the 3D-printed structure shown in Fig. 2 is embedded. The shell structure is completed by closing the last side again with the same silicone to enclose the 3D structure. The shell structure has a 4 mm air path in the center of each of the six sides. Furthermore, the inner structure can be attached and removed by manually pushing the air path open. This would improve the maintainability of the soft modular robot. The weight of this silicone shell is 6.5 g, which is slightly heavier than the other proposed silicone shells (1.2-4.3 g for a thickness of 1 mm in a 1.5–3.0 cm cube [27], [28]; the silicone used was Dragon Skin 10 Fast; Smooth-On, Inc.), which is slightly heavier than the others. However, the MORI-A improves the material of the connector to make it lighter. There are four types of connectors. These are formed by a 3D printer using the optical molding method. The connectors can be made of flexible resin to add softness. In addition, there are connectors with or without an air path between the modules, simple plugs, and connectors for connecting to an air compressor. The air path can be designed flexibly by combining the connectors. The specific gravity of neodymium magnets, which are often used as connectors, is 7.4 g/cm³. The MORI-A module uses resin with a specific gravity of 1.5 g/cm³. The weight of the connector is reduced by about 80% compared to connectors that use magnets. The 3D-printed internal structure and connectors are designed by parametric modeling. Therefore, the dimensions and structure can be updated conveniently using software such as OpenSCAD.

B. Deformability

In the parametric model, an important parameter that defines the deformation is the geometry of the cells. The proposed 3D-printed structure is based on the parallel cross structure [30], which is a structure of parallel rectangles orthogonal to each other in the stacking direction. By altering the intersection angle



Fig. 2. 3D-printable structures for module connector and deformation.



Fig. 3. List of 3D-printable and internal structures and actual appearances of MORI-A.

of the structure, it can be made to 1) contract conveniently in the uniaxial direction if the angle is large (shrinking in Fig. 3), 2) display a behavior similar to shearing (shearing in Fig. 3), or 3) bend conveniently if the angle distribution is non-uniform (bending in Fig. 3). The filaments that enable deformation also need to be soft. Thermoplastic polyurethane is used in this study. If hard polylactic acid filaments are used, it is feasible to develop a structure that does not permit deformation or isotropic contraction if no internal structure is embedded. The deformability of the internal structure illustrated in Figs. 2 and 3 is determined by the angle of intersection. Our approach is to extend the versatility of this angle setting by designating it as a parametric design. Considering this, we set the angle gradients to 30° , 45° , 60° , 75°, and 110° in this study mainly to approximate parallel-cross structures with permutation angle gradients to a cube. Although it could be feasible to achieve bending motion with other angular settings, this angle set is a convenient approach for a MORI-A



Fig. 4. Young's modulus on the Cartesian coordinate system depend on crossing angles of 3D-printable structures.

designer to generate a parallel-cross structure for a cubic shape and realize a bending motion.

C. Physical Properties of 3D-Printed Internal Structures

Here, we discuss a more noteworthy difference in mechanical properties that results in anisotropy of elastic modulus. Fig. 4 shows the Young's modulus obtained along the Cartesian coordinate axes when the intersection angles are 30° , 45° , 60° , 75° , and 90° in the shrinking model in Figs. 2 and 3. The smaller the angle to the creation, the larger is the volume of filaments required for the cubic lattice. The Young's modulus along the z-axis, which is the stacking direction, tends to increase as the density increases. However, the structure tends to buckle and the measured Young's modulus becomes unstable at angles less than 45° . The important aspect here is the Young's modulus along the x-y axis. Where uniform squares are stacked, the Young's modulus is approximately identical, and no anisotropy can be observed at 90°. However, when the angular equilibrium is disrupted, the difference in elasticity is observable immediately. If the angle is reduced to 30° , the difference is over 70 times. The elastic anisotropy is likely to increase below 30° . However,



(a) Deformation behavior associated with the internal structure of the fabricated MORI-A



(b) View of assembled MORI-A with updated kinematic mode by modifying the local internal structure.

Fig. 5. Update of driving mode after assembly with motion by embedded 3D-printed flexible structure.

in this verification, the minimum angle at which this structure could be formed stably is 30° . By applying this anisotropy, it is feasible to develop a structure that is as hard as bone in one direction and as soft as fat in the bodies of living creatures.

III. RESULTS

A. Motion Modes Leading by 3D-Printed Flexible Structures

Fig. 5(a) shows a robot with three MORI-A modules embedded with the five proposed internal structures, connected in series. These results reveal that although the proposed module has a unified shell structure, it can realize various deformability with the internal flexible structure of the modules of compatibility. If the internal structure is limited to a flexible structures, the assembled MORI-A can have different functionalities by attaching and detaching a few of the internal structures without splitting the joints (see Fig. 5(b)). This would improve the maintainability of the soft modular robot.

B. Module Connectivity and Mechanical Properties

First, this section shows the correlation between the number of modules connected in series and the bending angle and shear angle, to verify the functionality of the modules as pneumatic actuators. The top of Fig. 6 shows the bending angle produced by connecting one–eight modules and vacuuming the air tube connected from the compressor through the ejector. Nine or more modules in series would result in a bending angle wherein it comes in contact with the silicon tube. Therefore, the verification is performed with a maximum of eight modules in terms of the kinematics of the robot. The bending angle associated with the deformation is measured by connecting a six-axis sensor that can measure the acceleration and angular velocity of the tip as shown in Fig. 7. Fig. 8 shows the verification results of the angular displacement of MORI-A. The bending angle of MORI-A is reduced from the result shown in the top of Fig. 6 owing to the weight of the sensor. However, Fig. 8(a) reveals the trend of the angle according to the number of connections. This figure shows the correlation between the number of bending modules and the bending angle (each measured 10 times). The average, maximum, and minimum values are also shown. The results show that the bending angle increases almost linearly by approximately 25° with the increase in the number of connections. Meanwhile, the angular displacement of the shearing angle between the ground plane and tip plane is measured from the image using the image analysis software ImageJ. Meanwhile, the shear behavior is shown in the bottom of Figs. 6 and 8(b). The results are validated with number-of-connections from one to eight. The quantitative results in Fig. 8(b) show that when the number of connections is more than 7, the angle starts to decrease significantly from around 25-30°. The measured shear angle has a larger dispersion than the change in the bending angle. Hence, this deformation is sensitive to the number of connections, slight misalignment of connections and internal structure, and friction.

Fig. 9(a) shows the measured load-displacement before and after vacuum for the MORI-A robot fabricated with one-eight connected modules for the shrinking state in Fig. 5(a). The setup for this load-displacement test is based on A&D's STA-1150 tabletop material testing machine. Here, the MORI-A modules are connected in series in the direction of shrinkage, and the air inside is removed to complete the shrinkage. After this pretreatment, the plugs at both ends are attached to the chuck of the tensile testing machine. Then, tension is applied. This process is used to measure the stroke and load of MORI-A. The pressure of the compressor is set at 0 [kPa], 125 [kPa], 250 [kPa], 375 [kPa], and 500 [kPa]. Fig. 9(a) compares the results at the pressures of 500 [kPa] and 0 [kPa]. Load cpacity is a measure of the extent to which MORI-A can withstand loads acting in the direction of its connections without splitting or breaking. Here, we estimate the load capacity of MORI-A based on the maximum load and the displacement at that time. These parameters are determined by the number of connections of the shrinking modules and the driving conditions. For example, in Fig. 9(a) (number of modules (vacuum): 1), the displacement is approximately 3.4 [mm] when the maximum load is approximately 17.9 [N]. This implies that MORI-A can lift an object with a mass of approximately 1.8 [kg].

The load-displacement of the single module was the strongest before and after vacuuming. The variation trend before and after vacuuming shows that the load capacity is enhanced by three–four times by vacuum actuation. In terms of the number of connections, the variation in tensile strength does not result in a significant difference before pressure reduction. However, the displacement increases with the number of connections. It is evident that the load capacity varies among single module, two–four modules, and five–eight modules. Two–four modules are sufficiently strong to lift a plastic bottle containing 1 kg of water. The strength decreases by half when the number of modules is more than five. Fig. 9(b) and 9(c) show the result of



Fig. 6. Bending and shearing behavior of connected MORI-A modules.



Fig. 7. Schematic of MORI-A's bending and shearing angular displacement performance measurements.

the force-pressure curve and displacement-pressure curve based on the set pressure of the air compressor itself. When comparing Figs. 9(b) and 9(c) in terms of differential pressure, it is very difficult to match the conditions for each number of connected modules due to the large fluctuation of the differential pressure. Therefore, in this figure, we avoided using differential pressure and instead used the pressure value of the air compressor itself to compare the x-values in Figs. 9(b) and 9(c) under the same conditions. These results reveal that as the number of modules connected increases, the force decreases, and the displacement increases. The displacement is maximum at 125 [kPa] in these results because the silicone is still dominated by stretching at 125 [kPa] notwithstanding its contraction owing to the marginal suction from the non-driven state at 0 [kPa]. The configured soft modular robot shows maximum deformation when the number of connections is 8 or less, and is driven with maximum deformation at a differential pressure of 60-80 [kPa].

C. Soft Modular Robots and Applications

Here, we demonstrate robot applications achieved by assembling the MORI-A. The first application is a quadruped robot



Fig. 8. Angle associated with the number of MORI-A modules connected in the same orientation.

and underwater swimming mechanism shown in Fig. 10(a). In the case of a walking robot on a desk, the air path is divided into two systems to show that a pneumatic drive with different phase



(a) Comparison of load displacement of MORI-A modules under vacuuming and non-driven conditions



(b) Correlation between pressure and load capacity during vacuuming



(c) Correlation between pressure and displacement during vacuuming

Fig. 9. Load carrying capacity as a function of number of connections and vacuum pressure in MORI-A, (a)Comparison of load displacement of MORI-A modules under vacuuming and non-driven conditions. (b) Correlation between pressure and load capacity during vacuuming, (c) Correlation between pressure and displacement during vacuuming.

differences can be realized with a body system. An undeformed and hard module is placed in the spine of the body, and a shear and flexion module is combined in the legs to achieve a forward pattern gait. By altering this combination, we can ensure a renewal pattern and two-system control in the front and behind. Fig. 10(a) shows another example of a bending module connected in water. When the enclosed fluid is nitrogen gas (or ordinary air), it ascends to the surface and swims through the water similar to a fish. The buoyancy can be controlled conveniently by replacing the enclosed fluid with one that has a specific gravity higher than one and incorporating it into certain parts of the system. This indicates the feasibility of achieving a posture where the narrow, elongated area of the surface is on top and the wide surface is on the left and right, similar to a fish. These results show that MORI-A can be combined to add embodiments and can be developed directly into soft modular robots and actuators. Fig. 10(b) shows an example of the implementation of soft modular grippers that can grasp a brittle raw egg and slippery boiled egg. The grasped object can be held by combining the bending module and undeformed module. The load-displacement displays an evident tendency to decrease as the number of module connections increases. Based on this decreasing tendency, the gripping performance of the MORI-A gripper decreases when the number of linearly connected modules in the gripper is large and the load applied in the direction of the module connections is large. Meanwhile, the combination of 3D structures can realize various bending directions and enveloping gripper shapes. These can be applied to the formation of grippers for gripping complex, light, and soft objects according to the result of Fig. 10(b).

IV. DISCUSSION

We can understand the robotic behavior suitable for deformation in bending, shearing, and uniaxial shrinking by developing a soft modular robot with our proposed MORI-A. The uniaxial deformation behavior is likely to be applied to actuators such as artificial muscles that can pull linearly and strongly with conventional end-point connections such as connecting payloads. The capability to address bending and shearing behavior in an individual module can be applied to physicality that produces motions such as grippers for grasping objects and walking to capture friction. The significant difference from conventional soft robot modules is that these different functionalities can be connected by a unified shell structure and connectors, and the deformation can be controlled by parametric design. The 3D-printable structure substantially reduces the body constraint of hard materials and silicon tubes, and the structural diversity solves the problem of deformation that could only be expressed by a large number of modules. By combining 3D printable deformable structures, MORI-A achieves motions that could not be realized without buckling by conventional hollow silicone [28][29] modules. This result is expected to reduce the discrepancy between their simulation model and the real soft robot module. Without vacuuming the air, the MORI-A module would bend in the direction of its weight if it is not supported. Occasionally, a marginal air leak occurs between the silicone shell and connector. This air leakage can be remedied to a certain extent by suctioning it with a compressor. Although it can be deformed before and after being vacuumed, it is difficult to maintain the posture during movement.





(b) Soft modular grippers that can grasp a brittle raw egg and slippery boiled egg

Fig. 10. View of soft modular robots and grippers drive obtained by assembling MORI-A.

Meanwhile, the 3D deformable structure to be embedded is a nozzle with a width of 0.4 mm. Stacking is approximately 0.25 mm, which is a formative minimum. Therefore, scalability is inconvenient. When simple scalar scaling-down is applied, the filaments of the 3D-printed structure would bond to each other unexpectedly. This would result in the development of a model different from the 3D data. Because this causes the loss of deformation properties, an effective method to scale down is to trim from the current model. There is potential for producing 3D structures that can be used to construct more general-purpose systems within the framework of MORI-A. For example, the number of modules required for a deformation system such as the one shown in Fig. 10(b), which can be realized by combining current modules, is significantly less than that of conventional soft modules. However, if a twisting motion such as winding can be developed by connecting simple modules, it would be feasible to reduce the number of modules and generate more complex motions. However, the structure should be improved further to achieve this. The modules that can be improved need to be examined to determine the design space that these would require with the present 3D-printing precision. Furthermore, the dimensions of the modules may need to be scaled up.

In addition, the deformation of the internal structure can be visualized using thermoplastic polyurethane mixed with paint that reacts with UV light having a wavelength of 405 nm or 365 nm. Visualization is likely to reduce errors during assembly. The properties of the shell in direct contact with the external environment will affect the motion with deformation and contact. Water and other fluids can be selected as the working fluid. However, the pressure required to operate depends on the working fluid.

V. CONCLUSION

This study proposed a soft robot module called "MORI-A." It has wide ranges of deformability, compact body size, and complex motions. It can be used as a new type of soft robot module. Although it was demonstrated that MORI-A can add arbitrary shape and deformation diversity similar to soft robots. we are still in the process of verifying whether MORI-A modules can be developed using other silicones and whether these can work with MORI-A modules of different sizes. However, it is a soft robot module with new drive system and functions. Furthermore, MORI-A is likely to expand the range of design through linkages with elasticity simulation technology to enable further computer design. MORI-A has contributed to the removal of the shape constraint that has been a significant obstacle for conventional pneumatic actuators. Thereby, it would be feasible to develop soft modular robots with forms suitable for specified jobs, e.g., robot hands that can be used for picking in spaces with strong layout constraints in warehouses and farms. In addition, because the robot can be driven in both underwater and terrestrial environments, it is likely to be applied as robot grippers with high environmental adaptability. The next tasks in the development of MORI-A would be to 1) improve its applicability for posture control in fluid environments such as the underwater and 2) improve the connectivity of the connector, which is comparable to the magnet method. In addition, to achieve the functionality of MORI-A as an actuator, it is necessary to demonstrate its use in conjunction with other robot parts to gain knowledge that would result in the development of soft robots.

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