Flexonics

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Abstract. We introduce a new approach to design and fabrication of mechatronic systems called flexonics. Flexonics integrates structural, mechanical and electronic elements based on 3D printing techniques, in particular inkjet printing. This paper outlines some principles for flexonic design, which is based on flexion rather than sliding or rolling motion as in traditional mechanics. It describes our preliminary explorations of materials and processes. And it describes a kinematic approach to joint design that has so far led to one promising new design. Finally, we give a brief prospectus of future applications of flexonics.

1 Introduction

In this paper, we describe a new class of mechatronic devices, and propose methods for their fabrication and design. Our overall goal is to build fully functional mechatronic devices without assembly. These devices will integrate structural, mechanical, and electronic components during fabrication using an all inkjet printing process. In order to achieve the above goal, we intend to develop a complete 3D printer, and create a vocabulary of flexonic components (both mechanical and electronic).

Flexonics are radically different from traditional electromechanical systems in both form and manner of construction. The term "flexonics" derives from the fact that the proposed mechatronic systems achieve motion through flexion (bending). There will be no traditional sliding or rolling movements in actuators, sensors, or joints. Thus, flexonic devices will not utilize or need gears, bearings, or any sliding surface. This limits traditional design drawbacks such as friction, backlash, and mechanical wear. However, new issues arise when designing with flexures: material fatigue, inherent elastic energy storage, limited range of motion, and undesirable degrees-of-freedom require a different design strategy.

Flexonic devices will be fabricated using an inkjet printing technique. Through selective material deposition, a mechanism can be built layer by layer with a high level of complexity and integration. A necessary component of inkjet polymer printing will be a diverse set of printable materials. These include solution-based polymers and oligomers, nanoparticle suspensions, and other polymers that flow when heated. The range of current polymer-oligomer-nanoparticle capabilities includes electro-mechanical sensing and actuation, specialized structural support, and electrical conduction. Our goal is to utilize this diversity to construct both active and passive mechanical components, as well as driver and control electronics.

This paper is organized as follows: In Sect. 2, we give some background work relevant to flexonics including 3D printing, integrated manufacturing, polymer actuation, and flexure-based design. In Sect. 3, we describe the printing technology we are currently exploring, along with several materials under study. Sect. 4 contains a discussion of our current work with organic electronics, as well as proposed work to meet the requirements imposed by flexonic design and fabrication. In Sect. 5, we describe our work so far on flexonic design: design of joints which are compositions of simple elements like rectangular plates. We include a promising new joint design we derived through this process. Later in that section, we also describe higher order mechanisms, actuators, and bulk volumes. We provide some example devices to demonstrate the design possibilities within the flexonics environment. Finally, in Sect. 6 we suggest several candidate applications for flexonics. We believe flexonic devices would be appropriate for human-machine interfaces, biomimetic robots, and functional prototyping.

2 Related Work

Various methods of 3D printing have emerged in recent years [8,9]. They are used for rapid prototyping during design and for building molds for manufacturing. Various systems use materials and layering processes ranging from fragile photo-cured resins (Stereolithography or SLA), to powders melted by a powerful laser (Selective Laser Sintering or SLS), to extruded thin thermoplastic filaments (Fused Deposition Modeling or FDM – Stratasys, Inc.). With FDM, fully functional devices can be made from either rigid ABS plastic or flexible elastomer. Complex parts with regions of overhang and irregular surfaces can be easily built using a system that integrates build material and sacrificial support material. We have built several flexure-based designs using FDM. These devices are shown in subsequent figures as a demonstration of flexonic components (Sect. 4). However, FDM has disadvantages when applied to the problem of fabricating a broad range of flexonic devices, including dielectric elastomer actuators. Few materials are available, resolution is relatively poor, part strength and properties are influenced by build orientation, and electronic components are not realizable.

Shape Deposition Manufacturing (SDM) [1] has similar goals to flexonics manufacturing: integrating functional components with a 3D manufacturing process so that complex devices can be built without assembly. The difference is that SDM employs several traditional technologies – electronics or mechanical components are built separately and then “dropped in” during the build. SDM does not employ one, but a large family of manufacturing processes. By contrast, our goal is to build complete, fully functional electromechanical systems using a 3D inkjet printing process.

Inkjet printing is currently being investigated as a tool for manufacturing in several areas including MEMS, organic displays, and biological assays [6,14]. In fact, commercially available systems exist (MicroFab Technologies, Inc.) for printing a variety of materials. We have targeted these systems to provide the basis for the proposed 3D printing station described in Sect. 3. Solders, adhesives, optical polymers, and bioactive molecules have all been printed using piezoelectric, drop-on-demand techniques. Demonstration of printed solution-based polymers is of particular interest for flexonic manufacturing.

Electroactive polymers (EAPs) are a set of materials that have received a lot of attention with regards to “artificial muscle” actuation [3]. Some EAPs, such as ionomeric polymer-metal composites (IPMC), bend when an applied voltage causes a rearrangement of ions within the material. Other types, such as dielectric elastomers, expand when a large electric field is applied across a thin sheet of the material. The latter seem to offer the most promise for flexonics. Their low weight, high energy density, and polymer construction are attractive features. They are also highly configurable: actuator designs include unimorphs, bimorphs, rolls, tubes, bellows, and diaphragms [13]. Planar actuators made from thin films of silicone and acrylic elastomers have demonstrated linear strains of 63% and 215%, respectively, and energy densities five times that of human muscle [12]. However, certain requirements must be met in order to achieve this motion. First, very large electric fields around 100 MV/m must be used: With off-the-shelf material layer thickness, voltages around 5kV are required. Second, the elastomers must be pre-strained prior to activation. Specifically, when high pre-strain is applied in one planar direction, expansion occurs primarily in the other planar direction, and at a much greater magnitude than without pre-strain. The flexonic context offers potential solutions to both difficulties. First, layer thickness of 1-10 microns are common with inkjet polymer printing, and reduce the voltage requirements with today’s materials to 100 volts or less. The loss of actuator volume per layer can be made up by laminating many layers. We expect that new material research will offer even lower working voltages in the near future. The pre-strain issue is being studied through actuator housing design (see Sect. 4) and through the deposition process itself (strains developed during solvent evaporation).

Current techniques for fabricating planar dielectric elastomer actuators are quite primitive. Dielectric elastomer is first stretched across a rigid frame. Next, closed-profile structures are attached which contain rigid constraints perpendicular to the intended direction of motion (parallel to the high pre-strain direction) and flexible expanding support parallel to the direction of motion. Compliant electrodes, usually conductive carbon grease, are applied to both surfaces of the film. Electrical contact points are attached, and the actuator is then cut from the rigid frame. This process produces inconsistent and unreliable actuators. We believe flexonic design and fabrication has the potential to greatly improve performance and longevity.

Micro Electro-Mechanical Systems (MEMS) [17] have a number of common features with flexonics. First of all, they use a single material (usually silicon) that provides both electronics and mechanical actuation functions. They allow the construction of “systems on a chip” that work as sensors with matching amplifier electronics, and occasionally as actuators (inkjet heads are in fact MEMS devices). The design principles at play in MEMS are similar in several ways to flexonics. It is usually not practical to have rolling or sliding surfaces. Therefore, movement is accomplished through flexion. Secondly, MEMS devices use a lithographic process that does not penalize device complexity. It is very desirable to use previously developed modules (e.g. the “comb drive” electro-static actuator) in new designs, and very complex designs can be built from such modules. We expect flexonic designs to have similar properties. There are also many differences. Flexonics are much more appropriate for larger scale appliances that humans use directly. Polymer materials are low cost, and are well matched to natural environments (less sensitive to impurities or surface abrasions). Finally, MEMS designs tend to be largely planar, with flexure deformation remaining within the linear range. Flexonics, however, encourages full three-dimensional devices with large nonlinear deformations.

Flexure-based devices, or compliant mechanisms, represent a substantial research area on their own. Some recent work has focused on developing systematic design methods, but most 3D compliant mechanisms are designed through ad hoc methods [7]. A significant portion of compliant mechanism design is rotating joints. Initially, most joints were designed using notches or leaf springs. However, these simple designs are not adequate for high precision, high strength joints. Part of our goals within this proposal is the development of a vocabulary of flexible joints and mechanisms. Other groups are investigating new types of joints that contain more complex geometry and three-dimensional construction [5,11]. As stated above, flexonics is perfectly suited for the task of manufacturing these devices.

3 Fabrication of flexonic devices

3.1 Process

We are developing a novel manufacturing process requiring two steps. The first step is software based and follows a procedure similar to traditional rapid prototyping methods. Initially, an appropriate 3D CAD model of the device must be created. Because flexonics integrates all components without assembly, this model can be viewed as a single part. Depending on the orientation and design of a device, there may be regions of unsupported overhang. Therefore, within this step, locations for support material should be determined and added to the model. This support material will be sacrificial; following fabrication, it will be removed either by dissolving or breaking. Continuing within the software stage, the model would be divided into horizontal layers. Each layer will represent a cross section of the part and will contain information pertaining to component type and geometry.

The second step is the physical realization of the device. Here, our proposed 3D printer will produce the part by reading the layer information and selectively dispensing materials. We have begun work using an inkjet-based printer for organic electronics (detailed in Sect. 4). Our goal is to incorporate a similar set-up for flexonics, but with the capacity to print a multitude of mechanical and structural materials as well.

A flexonics 3D printer requires a specialized inkjet printing head, a high-resolution x-y-z stage, and corresponding drivers and control electronics. The number of individual print head jets on the printing head will depend on the polymer material set necessary to complete a flexonic device. Each jet will then have its own material supply and driver for individual control. The material set is dependent on the flexonic component types: actuators, joints, etc. MicroFab Technologies, Inc. manufactures specialized inkjet print heads for several applications ranging from printing optical polymers to solder bumps [6,14]. The individual jets use piezoelectric actuators to pump single drops of liquid onto a substrate surface. The jet orifice is on the order of 50 microns. The type of liquid that can be dispensed varies from solution-based polymers to molten metals. Two of their dispensing units are shown in Fig. 1. These heads should be ideal for our flexonic fabrication needs.

The print head is suspended above an x-y planar stage with a resolution on the order of 1 micron. Therefore, the limiting factor for resolution is droplet size. For a given layer of the device, the stage translates according to the geometry of the cross section. When a layer is complete, the stage is incremented downward, and the next layer is deposited. Assuming that drops forming a proceeding layer have dried before a successive layer is started, there should be no delay in the build process from layer to layer. The time to complete a given device will only be dependent on the deposited volume of material.

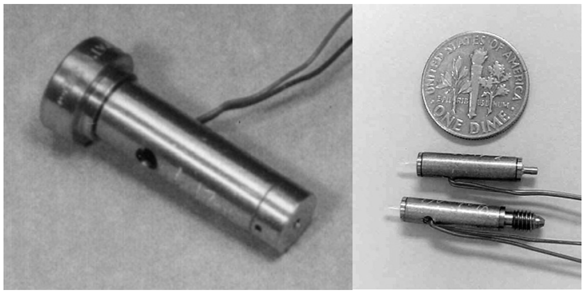

Fig. 1. MicroFab dispensers. (*left*) SolderJet high temperature dispenser. (*right*) MicroJet room temperature dispenser. Images from www.microfab.com

3.2 Materials

The 3D printing process requires materials meeting two criteria: First, the material viscosity must be low enough to allow controlled ejection from the inkjet during fabrication. Second, the material must remain a liquid for sufficient time before jetting so as not to clog the print orifice, yet solidify within a reasonable time after jetting. These requirements constrain the usable material set to those that can be dissolved into solution, or those that will flow when heated. Polymer and oligomer solutions, polymer resins, molten solders, and nanoparticle suspensions are all suitable for printing.

In Sect. 4, our current work using organic materials for electronics is discussed in greater detail. These materials include solution-based oligomers and nanoparticles. Materials for mechanical components that are being explored include thermoplastics like ABS and silicone thermoplastic and solvent-based elastomers. Flexonics integrates joints, actuators, structural volumes, and electronics. Therefore, it is necessary to match material properties to component function. Joints require both rigid and flexible regions; two polymers with high and low elastic moduli are necessary. Actuators require the properties of joints, but also need conductive and non-conductive polymers as well. Structural volumes tend to be rigid; however, the overall stiffness and anisotropy might be tuned using a selection of polymers. Flexonic manufacturing also requires a suitable sacrificial material for supporting overhanging geometry and complex forms during fabrication. Water-soluble thermoplastics are commonly used in FDM machines for sacrificial volumes and give a good starting point for our work as well.

4 Electronics

Active electronic components based on organic semiconductors are the natural choice for use as control elements in flexonics. Organic electronic devices may be fabricated using solution-based processing technologies such as inkjet deposition to produce complete electronic circuits without the use of lithography and/or vacuum processing. Such properties make organic electronic circuits ideally suited for use as integrated control elements in flexonics applications. Circuits may be fabricated on the polymer surfaces of the flexonics using inkjet-based processing facilities integrated into the flexonics manufacturing flow.

We have already initiated a program to develop inkjet-based organic semiconductor materials, device, and fabrication technology [16]. The work is targeted at developing an oligomer-based solution-processed organic semiconductor device and manufacturing technology. We are developing inkjet-based deposition protocols for formation of organic semiconductor circuits on polymer surfaces. We have developed numerous test structures to evaluate the associated materials and fabrication technologies, including FETs, conductor/semiconductor chains and organic LEDs. These may be integrated to form complete circuits for actuation and control of flexonics.

The performance of organic semiconductor-based transistors today is substantially lower than the achievable performance in inorganic semiconductors. For example, the best carrier mobility achieved in an organic semiconductor is approximately two orders of magnitude below that routinely achieved in silicon. Additionally, organic semiconductor FETs typically have substantially higher operating voltage requirements – supply voltage requirements as high as 80V have been reported [10]. Therefore, most of the research work reported to date has concentrated on reducing operating voltage requirements and improving carrier mobility to achieve higher current densities.

Broadly speaking, the work can be classified into two broad categories – polymer-based electronics and small molecule / oligomer-based electronics. Of the two, the small molecule work has shown the most promise for achieving technologically viable carrier mobilities and device performance levels. Unfortunately, the best results using small molecules have all been achieved using vacuum evaporated semiconductor layers. This process is not particularly compatible with flexonics, and hence is undesirable for this application.

The Maxwell-effect based elastomer actuators used in flexonics are actually ideal interface elements for conventional organic semiconductors FETs. These elastomers typically require very low current levels to actuate, but require high voltages. It is routinely possible to fabricate ≈ 10 micron size organic FETs with operating voltages approaching 100V, but with rather low carrier mobilities of 0.1-1 cm^2/V-s. These performance levels approach those required for control of elastomer-based actuators. Well-known techniques already used in high-voltage silicon circuits may be applied to organic FET-based circuits as well. For example, the voltage across an individual FET may be reduced by using a cascade output stage, consisting of multiple transistors biased to distribute the voltage drop. Furthermore, LDMOS-type device designs may be used to minimize the peak field within individual devices, enabling high-voltage operation of lower dielectric strength materials. Note that in many cases, much of this may be unnecessary since materials design alone may enable suitably high voltage organic semiconductors, exploiting the well-known high-voltage behavior of these materials.

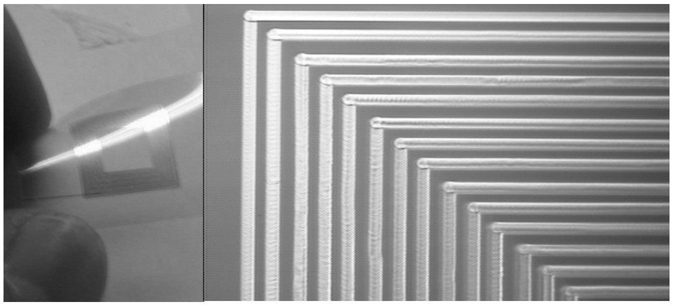

Fig. 2. Inkjet printed inductor

To achieve fully integrated control circuits in the flexonics environment, it will be necessary to develop numerous associated device and circuit technologies beyond the organic semiconductor materials technology described above. We are already developing inkjet-based conductor technologies using heavily doped aniline. While this material has a relatively high resistance, it should be adequate for use in flexonics, given the low current requirements of elastomer actuators. Current work aims to use this as the gate and interconnect material in organic FET based circuits. If higher conductivity interconnects are required, we have initiated a development program for inkjet deposited metal interconnects based on deposition of metallic nanocrystals. Numerous groups have already demonstrated fabrication of all-organic FETs, including organic conductors, insulators, and semiconductors; we are currently migrating this process to an all-inkjet flow. An example inductor is shown in Fig. 2.

5 Mechanical components

Traditional mechatronic devices require several components: structural support, mechanical joints and linkages, actuators, and control circuitry. These requirements do not change within the flexonic environment. Rather, the components take on different forms. For some, this is simply a matter of designing a suitable flexonic replacement component. For others, the discrete parts of the traditional design are replaced with one integrated, highly complex mechanism.

5.1 Simple joints

One of the requirements for most mechanical designs is some form of rotary joint. A traditional joint might employ some rolling or sliding interaction between the two connected links in the form of a hinge or bearing assembly. The flexonic counterpart moves by deflection, where elastic energy storage provides an increasing resistance to rotation. Other issues when designing flexonic joints include range of motion, axis-drift, off-axis stiffness, and stress concentrations [11]. We have identified several joint designs for possible inclusion within flexonic mechanisms; these are shown in Figs. 3, 6, and 7.

As a design example, consider the use of flexible strips for creating rotary joints. The cross-flexure joint (also called the cross-axis flexural pivot) [7] consists of three or more simple beam flexures oriented at +/- 45 degrees (Fig. 3). Rotation occurs about the axis formed at the intersections of the flexures. This design exhibits a good approximation to pure rotary motion near the zero angle. To see this, consider a straight thin strip as shown on the left in Fig. 4. The thin strip has three principal bending degrees of freedom, which are T_y, R_x and R_z where T_d denotes translation in the direction d and R_d is rotation about d. The two rotation modes are obvious. The T_y translation mode is caused by S-shaped double bending around axes parallel to the x-axis. Other motions are possible, but bending

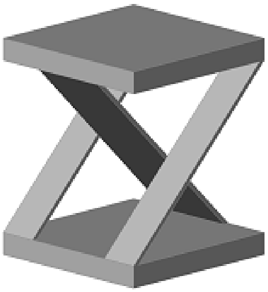

Fig. 3. Cross-flexure joint

stiffness is proportional to the cube of thickness, so a strip like the one in Fig. 4 is several orders of magnitude stiffer against motion about R_y and the other two translation modes.

If we represent the tangent space of the strip tip as (T_x, T_y, T_z, R_x, R_y, R_z), then the degrees of freedom are represented as the vector (*0, a, 0, b, 0, c*). Now, suppose we rotate such a strip by 45° CCW about the X-axis through its center. Then the tangent space becomes (*0, a, a, b, -c, c*) (we can ignore constant factors between degrees of freedom). Then we introduce a second strip with degrees of freedom (*0, a', 0, b', 0, c'*). We rotate the second strip by 45° CW, giving a new tangent space of (*0, a', -a', b', -c', c'*). The two strips are joined at their ends. Assume the lower join is rigid, and call it the "fixed" end. The upper join is also rigid; call it the "moving" end. The resulting structure is the simple X-joint shown on the right in Fig. 4. The degrees of freedom of the moving end are the intersection of degrees of freedom of the two strips, i.e. the solution to the following:

(0, a, a, b, -c, c) = (0, a′, -a′, b′, -c′, c′).

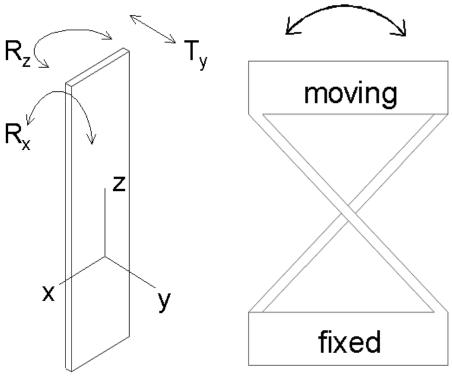

Fig. 4. Thin strip flexures. (*left*) Single strip tangent space. (*right*) Two thin strips connected at ends

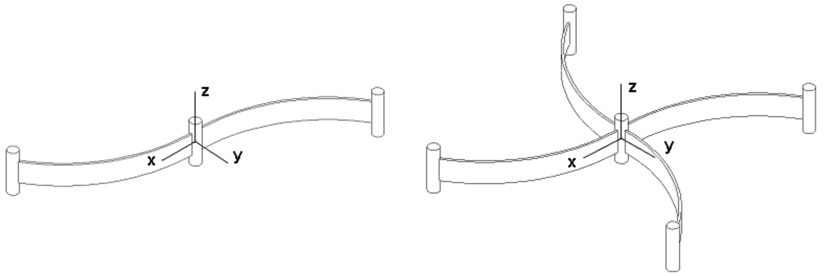

Fig. 5. Thin strip arrangement to minimize twisting during joint flexion

The solution is $a = a' = c = c' = 0$, which means no translation, and no rotation about Y- or Z-axes. The rest of the solution is $b = b'$, which means rotation about X is possible. The analysis above works when other angles (than 45°) are used to rotate the strips, so there is a family of possible X-joint designs. In summary, while a simple strip or sheet makes a poor joint, using two (or more) crossed strips gives nearly pure rotation near the zero angle.

While the basic X-joint design works well near zero flexion, at larger angles it is much less stiff in undesired directions. The problem is that while a straight strip has few degrees of freedom (three), a strip that is significantly bent and twisted is capable of motion in almost any direction. With a flexed X-joint configuration, the most problematic motion is a twisting relative to the ends of the joint. By rearranging the orientation and attachment points of the strips, it might be possible to reduce the twisting effect. Consider two flexed thin strips connected in series as shown in Fig. 5. We assume the center node is free to move in any direction, while the perimeter nodes are fixed in space. In this configuration, we can see that the center node has two rotational degrees of freedom (we will ignore the two additional translational degrees for now). The first degree of freedom is Z-axis rotation, which is the desirable rotation for this analysis. The second degree of freedom is around the X-axis. To remove this undesirable degree of freedom, we can simply add another pair of thin strips 90° from the first pair. Only Z-axis rotation is allowed in this configuration.

The combination of strips in Fig. 5 will not result in a useful joint because we have assumed the perimeter nodes are fixed. In order to rotate around the Z-axis, the perimeter nodes must get closer to the center node. The original X-joint configuration allows this behavior. We can solve the problem by using two X-joints that are oriented 180° apart. We are currently analyzing a novel alternative X-joint shown in Fig. 6. We believe this design will also have the added benefit of restricting buckling from compressive loads.

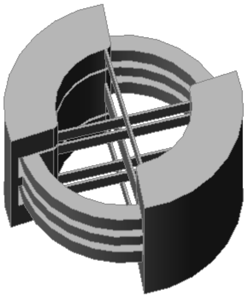

Fig. 6. Novel rotary joint using dual X-joints

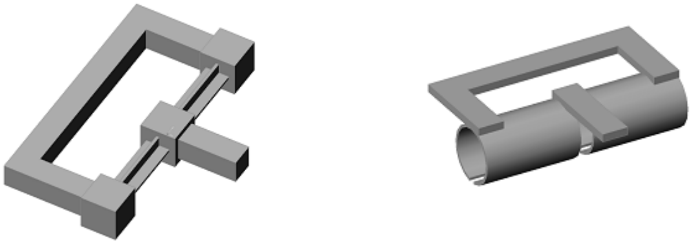

Fig. 7. Other rotary joints. (*left*) Compliant revolute (CR) joint from [11]. (*right*) Split-tube flexure from [5]

A rotary joint can also be designed by utilizing the twisting degree of freedom of a thin strip (R_z in Fig. 4). A realization of this joint is proposed and analyzed in detail in [11] and depicted in Fig. 7. Following the analysis as before, start with a thin strip oriented as shown with degrees of freedom (*0, a, 0, b, 0, c*). Next, add a second strip rotated 90 around the Z-axis with degrees of freedom (*a', 0, 0, 0, b', c'*). The intersection is simply $c = c'$, or rotation about the Z-axis. The joint utilizes perpendicular ribs along the flexure region to constrain off-axis motion. The ribs are essentially the intersection of two perpendicular thin strips. The axis of rotation is along the center of the ribbed flexure.

More complex joint designs are also feasible within the framework of flexonics. The split-tube flexure [5] is based on the principle that torsional stiffness of an open-section tube is much lower than a closed-section tube, while the remaining axial and bending stiffness remain essentially the same. The axis of rotation is along the surface of the tube, opposite from the side with the slit. Fig. 7 illustrates the split-tube design.

5.2 Complex mechanisms

While flexonics can provide a base set of simple mechanical joints, it also encourages highly complex specialized devices. Traditional motion generation mechanisms can be redesigned within the flexonics design space. As an example, consider the Peaucellier linkage illustrated in Fig. 8. The function of the linkage is to convert rotational motion into pure translation. Under traditional design methods, the links are separate parts, connected to each other via pivots at their ends. The flexonic counterpart, however, can be one continuous piece. A partial realization of this device is shown in Fig. 8 with traditional pivots being replaced by small-length flexures (also called notch flexures or "living hinges").

Mechanisms for specific functions like gripping are also relatively easy to design. One such possibility is shown in Fig. 9. Instead of discrete regions of flexion as used in the Peaucellier linkage, we implement distributed flexion along the gripper "fingers". A simple translation of the center rigid beam brings both fingers together.

Another area where complex mechanisms are useful is power transmission. One attempt at a flexonic transmission is shown in Fig. 9. This design consists of a series connection of cross-flexure joints, with additional interconnecting beam flexures. When one cross-flexure joint is rotated, each of the remaining joints exhibits rotation as well. As before, the entire device is fabricated as one continuous piece. The transmission also demonstrates another anticipated feature of flexonics: modular construction. The flexonic transmission is essentially a repeated pattern of cross-flexure joints. Although this is only a one-dimensional pattern, we

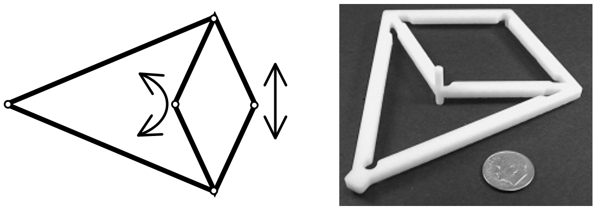

Fig. 8. Peaucellier device. (*left*) Link arrangement. (*right*) FDM partial realization

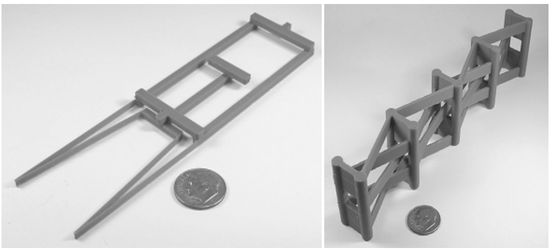

Fig. 9. Other devices. (*left*) Compliant gripper. (*right*) Power transmitting linkage

might design other devices which contain a different modular unit and employ two- or three-dimensional configurations.

5.3 Actuators

We believe dielectric elastomer actuation is the most promising technology for producing flexonic motion. In order to develop practical actuators with the performance described in Sect. 2, several key issues must be addressed. First of all, actuator design should minimize the film thickness between electrodes in order to reduce high voltage requirements. This will not pose a major challenge using 3D printing techniques. Inkjetted polymer films around 1 micron are certainly feasible. To offset the reduced volume in thin layers, we plan to use laminated stacks of actuator and electrode material. As mentioned previously, there is no penalty for this type of modular construction other than the time to print the added volume. There are some challenges in uniformity of layer thickness, but low-viscosity solvent-based materials exhibit good uniformity under gravity if drying time can be made long enough.

The overall design of the actuator frame must fill two roles. First, it must have sufficient compliance to allow the elastomer to expand in the desired direction of motion. Second, the frame should contain built-in geometry necessary to produce and maintain a pre-strain perpendicular to the direction of motion. One candidate frame is shown in Fig. 10. A complete actuator would contain two frames sandwiching a dielectric elastomer film. At the left of Fig. 10, the frame is shown prior to applying pre-strain. Secondary flexures (oval-shaped) not coupled with the dielectric elastomer can be “set” into a pre-strained state. The right of Fig. 10 shows the secondary flexures extended and locked in place. The middle portion of the dielectric material (bowtie shaped) would be stretched parallel with the secondary flexures. In addition to providing pre-strain, these flexures provide the unidirectional rigid support perpendicular to the desired direction of motion. Note that the flexible ends of the bowtie remain in the same configuration following pre-strain, thereby allowing linear expansion of the dielectric elastomer.

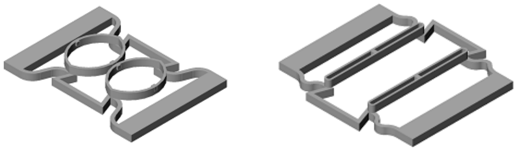

Fig. 10. Proposed actuator design. (*left*) Unstrained configuration. (*right*) Pre-strain configuration

5.4 Bulk volumes

Mechatronic devices need passive structural volumes to support and connect moving components. In traditional designs, these bulk volumes take on the form of three-dimensional solid links or, at best, two-dimensional structures like honeycombs. High strength-to-weight performance can be achieved through one-dimensional trusses, but this is usually only feasible on a large scale or through very expensive investment casting. However, with flexonic manufacturing, we can print intricate geometry to create lightweight truss and lattice volumes. One very strong, low-density lattice is the diamond lattice shown in Fig. 11. The FDM ABS plastic structure shown has approximately 1% density and weighs just over a gram, but has a theoretical yield load of over 50 kg.

The strength of these structures raises interesting design questions. Most electro-mechanical devices are quite heavy. The determining factors seem to be the weight of components such as motors, metal shafts and bearings, and heavy electrical components such as transformers or batteries. A 100% polymer device has no such constraints. Actuators are extremely light, and their weight scales down with the weight of the entire device, since the total mass of the device determines the actuators' load. Similarly, polymer electronics are extremely light, and there is no packaging or circuit boards per se. Thus, the weight of the device is primarily dictated by its strength to withstand external loads. Because of the excellent strength-to-weight performance possible with lattice structures, the structural components of flexonic devices (and the entire device) can be made very light.

For instance, consider the design of a life-size humanoid robot. Its volume will be about 80 liters (typical for a real human). With 1% density ABS polymer construction, the robot would weigh less than 1 kilogram. Assuming 10 cm diameter limbs, it could nevertheless accept total loads of several hundred kilograms. At this time, the actuators would not be able to produce the necessary torques, but their higher energy density would allow an anthropomorphic robot to (theoretically) hold or lift loads of several kilograms. This contrasts with the present Honda robot design has a hand-load capacity of about 5 kg but a weight of several hundred.

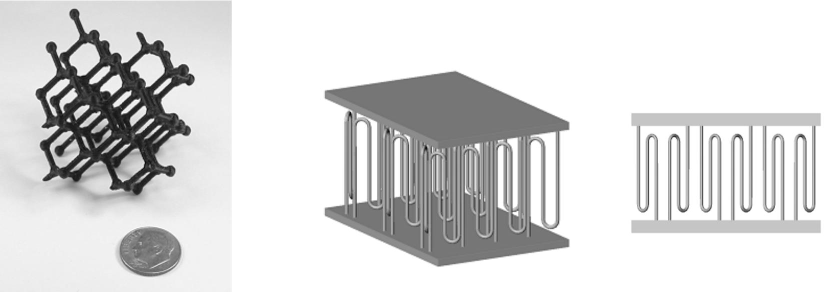

Fig. 11. Bulk volumes. (*left*) Diamond lattice. (*right*) Shearing support volume with high vertical stiffness (*isometric and side views*)

Flexonic design can produce strong, lightweight structures, with very high stiffness. However, in many cases, high stiffness may only be desirable in certain directions. The actuator frames described above are one such example of this anisotropic design. Another example would be the shearing support system shown in Fig. 11. Vertically oriented flexures resist compressive loading, but allow movement in the two planar directions.

6 Potential Application

Flexonics offers a unique set of properties not found in traditional electromechanical systems. Most notable is the ability to manufacture fully functional devices without assembly. When coupled with a diverse material set, these devices can exhibit a high level of component integration. Structures can be made lightweight, yet strong, by exploiting complex geometry and polymer construction. Flexonic devices are not intended to replace all traditional mechanical systems. For instance, systems utilizing wheels to achieve continuous and infinite travel would not be possible. However, the properties inherent to flexonic manufacturing and design are appropriate for a wide array of applications where joint range of motion is finite.

6.1 Human-machine interfaces

Flexonic design allows human-machine interfaces to be individualized according to the ergonomic needs of the user and the workspace constraints. In fact, the user can be inserted directly into the design loop. Due to the low cost of flexonic manufacturing (assuming access to a flexonic manufacturing station), a specific device design can be iterated until the user's requirements are satisfied. Flexonics also offers other attractive properties for interfaces in terms of user safety. For example, life-size humanoid robots with metal limbs pose a number of risks to the people around them. An ultra-light polymer design would have low mass, natural compliance, and low impact energy if an accidental contact with a person occurred. These "soft" characteristics are also beneficial in conveying life-like form and behaviors. Since there is no sliding or rolling motion in joints, motors or bearings, flexonic devices can be almost noiseless in operation. When designed for use as human-like representations (however abstract) in a collaborative setting, these flexonic traits may have advantages over traditional electromechanical designs in achieving social acceptance.

6.2 Biomimetic robots

Flexonics also suggests advantages in the area of biomimetic design in robotics. Biology provides an abundance of robust mechanisms for articulation and locomotion. However, these mechanisms are often highly complex and necessitate a high level of functional and structural integration. For example, consider the requirements for a biomimetic actuator. In this design space, a counterpart to natural muscle is needed. One feature of muscle is an ability to function in a variety of modalities. They can operate as motors to generate power, as dampers or brakes to absorb power, as variable springs to modulate stiffness, and as rigid struts to transmit forces [4]. These functions are all contained within a relatively compact structure. In addition to pure mechanical components, muscle also integrates all the required chemical and electrical components for power and control. With proper design, polymer actuators may fill the mechanical roles of muscle. As previously discussed, organic electronics shows promise as a technology for interfacing driver and control circuitry with polymer actuators. Flexonic mechatronic systems can combine these components in one complex, integrated package.

6.3 Functional prototypes

Even for large-volume devices that might ultimately be manufactured by some other means, such as phones, PIMs, remote controls, etc., flexonics allows fully functional prototypes to be built with extremely short turn-around. It allows more complete user testing and evaluation earlier in the design cycle. It also allows different design elements: electrical, mechanical, aesthetic, to be combined much earlier during design, because the first prototypes can incorporate all elements. It should therefore encourage shorter design times. It would also encourage shorter times between “generations” of a device, by allowing a reference design to continually evolve and be improved.

7 Conclusion

We presented a vision of a new class of mechatronic devices that integrate structural, mechanical, and electronic components in a one-piece, no assembly fabrication process. Our initial goals include the development of a complete inkjet-based 3D printing system, and the exploration of flexonic capabilities through the development of a vocabulary of mechatronic components. The basic components of an inkjet printer were described, along with the materials we are currently exploring. Methods for designing devices within the framework of flexonics were presented, along with a novel joint design. We presented several examples of joints, structures, and actuators that we have fabricated using existing 3D printing techniques. We outlined our current capabilities using organic electronics, as well as anticipated work to integrate organic electronics with a complete flexonic system. We envision flexonics as the foundation for many existing mechatronic systems, and have provided example applications including human-machine interfaces, biomimetic robots, and fully functional, prototypes.

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