

METHOD AND SETUP FOR EMBEDDING ONE OR MORE FIBERS

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of priority of Singapore application No. 10201903303P filed April 12, 2019, the contents of it being hereby incorporated by reference in its entirety for all purposes.

TECHNICAL FIELD

[0002] Various aspects of this disclosure relate to a method of embedding one or more fibers. Various aspects of this disclosure relate to a setup for embedding one or more fibers.

BACKGROUND

[0003] Integrated automation of additive manufacturing processes in a single platform for multi-material printing can be of great impact in soft robotics and soft mechatronics since components often require multi-material compositions to enable functionality. However, current fabrication techniques commonly used for soft robot components, such as Fused Deposition Modelling (FDM) of flexible thermoplastics, Direct Ink writing (DIW) of polymers, stereo-lithography (SLA) and digital light processing (DLP) of ultraviolet (UV) curable soft polymers have limited options to incorporate additive materials to create composites. Embedding of flexible and solid fibers, tubes, and wires to create composite structures, as well as tailoring of their performance in soft robot components (e.g. PneuNet actuators) have great potential due to the wide range of material properties and functionalities of these additives.

[0004] Commonly used techniques involve manually embedding or stitching fibers into desired positions within a component by using commercially available embroidery machines, followed by molding elastomers over the component. Other groups have used sewing machines and modified three-dimensional (3D) printers to incorporate wires and tubes into silicone components. The use of conductive fibers in soft robots by embedding them into a silicone matrix has also been previously described. Further, embedding of shape memory actuators and shape memory polymers for wearable devices has been discussed. In addition, embedding of twisted nylon fiber for actuation and tubes for cooling in a robotic skin has also been previously proposed.

One group has also experimented with string and fiber sewing onto layered additive manufacturing using commercial embroidery machines. Another group has demonstrated a sew-and-transfer method for rapid fabrication of low cost stretchable interconnects. Yet another group has validated the 3D printing of soft interactive objects using fibers by entangling and compressing sheets of fibers.

[0005] The embedding of micro tubes for transferring fluids in wearable applications has also been demonstrated. One group has developed an automated fiber installation on robot components for sensing and actuation. 3D printing of mechanical and electrical contacts using conductive steel wires and textile integrated circuits has also been studied by another group. Other developments include the demonstration of a fiber reinforced actuator exhibiting twisting, extension, and bending by exploiting the stretch and strain properties of fabrics, the demonstration of the use of fibrous materials in 3D printing to create multi-material objects, and the use of conductive stretchable fabrics for dielectric elastomer and electro-adhesive actuators.

[0006] However, current processes and their work-flows are still too intrusive and limit rapid prototyping time, material handling, and automation.

SUMMARY

[0007] Various embodiments may relate to a method of embedding one or more fibers in a matrix. The method may include forming the one or more fibers using a fiber extruding tool of an apparatus. The method may also include arranging the one or more fibers using one or more physical guides and/or anchors. The method may further include depositing matrix material over the one or more fibers using a matrix material extruding tool of the apparatus, thereby embedding the one or more fibers in the matrix formed from the matrix material.

[0008] Various embodiments may relate to a setup. The setup may include an apparatus including a fiber extruding tool configured to form the one or more fibers. The setup may also include one or more physical guides and/or anchors used for arranging the one or more fibers. The apparatus may further include a matrix material extruding tool configured to deposit matrix material over the one or more fibers, thereby embedding the one or more fibers in the matrix formed from the matrix material.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The invention will be better understood with reference to the detailed description when considered in conjunction with the non-limiting examples and the accompanying drawings, in which:

FIG. 1 is a general illustration of a method of embedding one or more fibers in a matrix according to various embodiments.

FIG. 2 is a general illustration of a setup according to various embodiments.

FIG. 3A shows (left) a schematic of a setup including a three dimensional (3D) printer, a weaving template and a bottom mold according to various embodiments; and (right) a photograph of the setup shown on the left according to various embodiments.

FIG. 3B shows a schematic of a matrix material such as silicone being deposited into the mold by a pressure controlled dispenser, i.e. the silicone extruding tool (also referred to as matrix material extruding tool), to form a first mold part according to various embodiments.

FIG. 3C shows (top) a schematic of a fiber being loaded onto the fiber extruding tool of the three-dimensional (3D) printer according to various embodiments; and (bottom) a photograph showing the fiber being weaved over the template according to various embodiments.

FIG. 3D is a schematic showing a top mold being printed directly over the first mold part according to various embodiments.

FIG. 3E is a schematic showing the extrusion of elastomer onto the cavity of the top mold according to various embodiments.

FIG. 3F is a schematic illustrating the oven curing of the mold contents, followed by laser cutting to form a workpiece or sample with the desired shape according to various embodiments.

FIG. 3G is a photograph of the fabricated fiber embedded dog bone sample formed by methods shown in FIGS. 3A-F according to various embodiments.

FIG. 4 shows a top view of a wave pattern template according to various embodiments.

FIG. 5 shows a computer-aided design (CAD) model of the fiber extruding tool of the printer according to various embodiments.

FIG. 6 is a schematic illustrating the fabrication process steps according to various embodiments.

FIG. 7A shows images of dog bone samples with embedded cotton fibers (samples 1 – 3), and embedded polyester fibers formed using methods illustrated by FIGS. 3A – F according to various embodiments.

FIG. 7B shows time lapse images of a dog bone sample formed according to various embodiments during tensile tests.

FIG. 7C is a plot of stress (in mega Pascals or MPa) as a function of strain (in percent or %) showing the stress-strain behaviour of cotton fiber embedded silicone samples according to various embodiments.

FIG. 7D is a plot of stress (in mega Pascals or MPa) as a function of strain (in percent or %) showing the stress-strain behaviour of polyester fiber embedded silicone samples according to various embodiments.

FIG. 8A shows a microscope image of polyester fiber embedded elastomer according to various embodiments.

FIG. 8B shows a microscope image of cotton fiber embedded elastomer according to various embodiments.

FIG. 8C shows a microscope image of conductive fiber embedded elastomer according to various embodiments.

FIG. 9 shows the color changes of a thermochromic pigmented silicone sample with embedded conductive fibers according to various embodiments.

FIG. 10 shows the color change of the sample according to various embodiments by applying a direct current (DC) voltage of 9V and a current of 1.5A. Full color transition was achieved at 45s (35°C).

FIG. 11A shows a schematic of a setup including a three dimensional (3D) printer with a fiber extruding tool and a weaving template according to various embodiments.

FIG. 11B shows a schematic of the fiber embedding process using the setup shown in FIG. 11A according to various embodiments.

FIG. 11C is a photo illustrating anchoring fibers using template poles according to various embodiments.

FIG. 11D shows (left) a photograph showing some weaving templates according to various embodiments; and (right) schematic of weaving templates with fibers anchored onto poles according to various embodiments.

FIG. 11E shows a schematic showing the silicone deposition process according to various embodiments.

FIG. 12A shows a three dimensional (3D) printer with a fiber extruding tool according to various embodiments.

FIG. 12B shows a sheet template being set up under the fiber extruding tool according to various embodiments.

FIG. 12C shows (left) photographs of some sheet templates according to various embodiments; and (right) schematics of the sheet templates according to various embodiments.

FIG. 12D is a schematic showing the fiber embedding process with fibers anchored in small cuts placed around sheet templates according to various embodiments.

FIG. 12E show photographs illustrating the fiber embedding process with fibers anchored in small cuts placed around sheet templates according to various embodiments.

FIG. 12F is a schematic illustrating the silicone deposition process according to various embodiments.

FIG. 13A shows a three dimensional (3D) printer according to various embodiments.

FIG. 13B shows the printing of the polymer guides according to various embodiments.

FIG. 13C is a photo of a polymer guide according to various embodiments.

FIG. 13D shows the laying of the fibers between the polymer guides according to various embodiments.

FIG. 13E shows a photograph of guiding a fiber between the polymer guides according to various embodiments.

FIG. 13F shows deposition of silicone over the fiber according to various embodiments.

FIG. 14A shows a schematic of the automated fiber embedding (AFE) workflow according to various embodiments.

FIG. 14B is a schematic illustrating layer merging according to various embodiments.

FIG. 15A shows photographs of (left) top view and (right) side view of a soft bio-inspired fin including embedded high tensile strength fibers according to various embodiments.

FIG. 15B shows (left) schematics of the dog-bone samples with various embedded fiber patterns according to various embodiments; and (right) a plot of stress (in MegaPascals or MPa) as a function of strain (in percent or %) showing the behaviour of the samples according to various embodiments.

FIG. 16A shows (left) a photograph of a sting-ray-like soft silicon body with embedded thermochromic yarn according to various embodiments; and (right) the sting-ray-like soft silicon body with embedded thermochromic yarn after being heated by an external source according to various embodiments.

FIG. 16B shows (top) images of silicone components with conductive fiber embedded using direct ink writing (DIW) according to various embodiments; and (bottom) thermal images of the silicone components with embedded fibers during heating according to various embodiments.

FIG. 17 shows (left) a photograph of a silicone finger-like structure with embedded soluble yarn according to various embodiments; and (right) another the photograph of the finger-like structure after dissolving soluble yarn and using resulting channels for pneumatic actuation according to various embodiments.

FIG. 18 shows (top row) top view of inflatable disk-like structures (S1 – S4) with various fiber patterns according to various embodiments; (middle row) top view (TV) of the disk-like structures during inflation according to various embodiments; and (bottom row) side view (SV) of the disk-like structures during inflation according to various embodiments.

DETAILED DESCRIPTION

[0010] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, and logical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0011] Embodiments described in the context of one of the methods or setups/apparatuses are analogously valid for the other methods or setups/apparatuses. Similarly, embodiments described in the context of a method are analogously valid for a setup/apparatus, and vice versa.

[0012] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0013] The setup/apparatus as described herein may be operable in various orientations, and thus it should be understood that the terms “top”, “bottom”, etc., when used in the following description are used for convenience and to aid understanding of relative positions or directions, and not intended to limit the orientation of the setup/apparatus.

[0014] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0015] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance.

[0016] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0017] Various embodiments may seek to address or mitigate issues faced by existing methods.

[0018] FIG. 1 is a general illustration of a method of embedding one or more fibers in a matrix according to various embodiments. The method may include, in 102, forming the one or more fibers using a fiber extruding tool of an apparatus. The method may also include, in 104, arranging the one or more fibers using one or more physical guides and/or anchors. The method may further include, in 106, depositing matrix material over the one or more fibers using a matrix material extruding tool of the apparatus, thereby embedding the one or more fibers in the matrix formed from the matrix material.

[0019] In other words, the method may include extruding one or more fibers, which are then guided by one or more physical guides and/or anchors. A matrix material may then be deposited over the one or more fibers to embed the one or more fibers.

[0020] In the current context, “embedding one or more fibers” may refer to fixing the one or more fibers onto the matrix material, or completely enclosing the one or more fibers in the matrix material. In various embodiments, the embedded one or more fibers may be fully covered by the matrix material. In various other embodiments, the embedded one or more fibers may not be fully covered by the matrix material. In various embodiments, arranging the one or more fibers may include layering the one or more fibers.

[0021] In various embodiments, the matrix material may be an elastomer such as silicone rubber, fluorosilicone rubber, ethylene-vinyl acetate, silicone polymers, gels, waxes, resins, thermoplastics, clays, or combinations thereof.

[0022] In various embodiments, the apparatus may be a printing apparatus such as a 3D printer. The method may be referred to as automated fiber embedding (AFE). The apparatus may be coupled to a processor or a computer, which may control the apparatus, e.g. the movement of the fiber extruding tool and/or the movement of the matrix extruding tool. In various embodiments, each fiber of the one or more fibers may include a single material. In various other embodiments, each fiber of the one or more fibers may include a plurality of materials. Each fiber may include one or more organic materials (e.g. cotton) and/or one or more inorganic / synthetic materials (e.g. a polymer such as polyester, a metal such as steel) and/or active materials (e.g. nitinol wire, shape memory polymers). In various embodiments, the fiber may be thermochromic. In various other embodiments, the fiber may be luminescent or soluble.

[0023] In various embodiments, the one or more physical guides and/or anchors may be or may include a weave template with a plurality of poles.

[0024] In various embodiments, a pole of the plurality of poles may be used as an anchor point to fix an end of a fiber of the one or more fibers. Additionally or alternatively, a pole of the plurality of poles may be used as a nodal point to change a direction of a fiber of the one or more fibers.

[0025] In various embodiments, the weave template and associated poles may be formed by fused deposition modelling (FDM). The method may include forming a first mold part defined by a bottom mold before forming the one or more fibers. The one or more fibers may be arranged on the first mold part. The first mold part may be formed by the apparatus, i.e. the matrix material extruding tool of the apparatus. The matrix material extruding tool may deposit mold material into the bottom mold to form the first mold part. The weave template with the plurality of poles may

have a hole configured to accommodate the bottom mold. When the bottom mold is provided in the hole, the plurality of poles may surround the bottom mold, so that the plurality of poles also surrounds the first mold part defined by the bottom mold. The matrix may be a second mold part so that the one or more fibers are between the first mold part and the second mold part. The matrix may be defined by a top mold. The matrix material may be deposited in the top mold and over the one or more fibers and the first mold part to form the second mold part. The one or more fibers may be encapsulated or embedded within the combined structure including the first mold part and the second mold part.

[0026] In various embodiments, the one or more physical guides and/or anchors may include a sheet template with a plurality of line cuts along one or more edges and/or inside of the sheet template.

[0027] In various embodiments, a line cut of the plurality of line cuts may be used as an anchor point to fix an end of a fiber of the one or more fibers.

[0028] In various embodiments, a line cut of the plurality of line cuts may be used as an anchor point to fix an end of a fiber of the one or more fibers. Additionally or alternatively, a line cut of the plurality of line cuts may be used as a nodal point to change a direction of a fiber of the one or more fibers.

[0029] In various embodiments, the plurality of line cuts may be formed by using a laser cutter. The sheet template may alternatively or additionally include a plurality of holes.

[0030] In various embodiments, the one or more physical guides and/or anchors may include polymer guides (also referred to as guided paths) printed onto a part mold. The polymer guides may, for instance, be splines, lines, or poles. The polymer guides may be printed onto the part mold using a shear thinning polymer. The polymer guides may be formed by direct ink writing (DIW).

[0031] In various embodiments, arranging the one or more fibers may include layering the one or more fibers between or inside or around the guides using a co-axial needle. The co-axial needle may be coupled to the fiber extruding tool and to the matrix material extruding tool. The co-axial needle may include an internal needle that dispenses the one or more fibers, and an outer needle that dispenses an outer polymer coat. In other words, the one or more fibers formed may be coated

by the polymer. The one or more fibers may be formed by the fiber extruding tool, while the outer polymer coat may be formed by the matrix material extruding tool.

[0032] In various embodiments, depositing the matrix material over the fibers may include pouring the matrix material over the one or more fibers after arranging the fibers or while arranging the fibers. In various other embodiments, depositing the matrix material over the fibers may include printing the matrix material layer by layer using direct ink writing (DIW).

[0033] In various embodiments, the method may further include heating the matrix material after depositing the matrix material to form the matrix. Heating the matrix material may cure the matrix material to form the matrix. The resultant workpiece may include the matrix and the embedded one or more fibers. Various embodiments may relate to the workpiece including the matrix and the embedded one or more fibers. In various embodiments, the one or more fibers may be arranged in a single layer in the workpiece. In various other embodiments, the one or more fibers may be arranged in multiple layers. The different layers of fibers may be arranged using the same process (e.g. using weave template with poles, sheet template with line cuts, or polymer guides/guided paths), or may be arranged using different processes.

[0034] In various embodiments, the method may also include using laser cutting to shape the matrix or resultant workpiece. Laser cutting may achieve the desired two dimensional (2D) profile of the matrix or resultant workpiece. In various other embodiments, a mold or direct ink writing (DIW) may be used to achieve the desired two dimensional (2D) profile of the matrix or resultant workpiece.

[0035] FIG. 2 is a general illustration of a setup according to various embodiments. The setup may include an apparatus 202 including a fiber extruding tool configured to form the one or more fibers. The setup may also include one or more physical guides and/or anchors 204 used for arranging the one or more fibers. The apparatus may further include a matrix material extruding tool configured to deposit matrix material over the one or more fibers, thereby embedding the one or more fibers in the matrix formed from the matrix material.

[0036] In other words, the set up may include an apparatus 202, i.e. a printing apparatus such as a 3D printer, which includes a fiber extruding tool and a matrix material extruding tool. The fiber extruding tool may be used to form the one or more fibers, while the matrix material extruding tool may be used to form the matrix material used for embedding the one or more fibers. One or

more physical guides and/or anchors 204 may be used to guide and arrange the one or more fibers before the one or more fibers are fixed in place by the matrix material.

[0037] For avoidance of doubt, FIG. 2 serves to illustrate some features of a setup according to various embodiments, and is not intended to limit the size, shape, orientation, arrangement etc. of the features.

[0038] In various embodiments, the one or more physical guides and/or anchors 204 may include a weave template with a plurality of poles.

[0039] In various embodiments, a pole of the plurality of poles may be used as an anchor point to fix an end of a fiber of the one or more fibers. Additionally or alternatively, a pole of the plurality of poles may be used as a nodal point to change a direction of a fiber of the one or more fibers.

[0040] In various embodiments, the weave template with the plurality of poles may be formed by fused deposition modelling (FDM).

[0041] The setup may include a bottom mold configured to define a first mold part. The first mold part may be formed before forming the one or more fibers. The one or more fibers may then be arranged on the first mold part. The first mold part may be formed by the apparatus, i.e. the matrix material extruding tool of the apparatus. The matrix material extruding tool may deposit mold material into the bottom mold to form the first mold part. The weave template with the plurality of poles may have a hole configured to accommodate the bottom mold. When the bottom mold is provided in the hole, the plurality of poles may surround the bottom mold, so that the plurality of poles also surrounds the first mold part defined by the bottom mold. The matrix may be a second mold part so that the fibers are between the first mold part and the second mold part. The second mold part may be defined by a top mold. The matrix material may be deposited in the top mold and over the one or more fibers and the first mold part to form the second mold part. The one or more fibers may be encapsulated or embedded within the combined structure including the first mold part and the second mold part.

[0042] In various embodiments, the one or more physical guides and/or anchors 204 may include a sheet template with a plurality of line cuts along one or more edges or inside of the sheet template.

[0043] In various embodiments, a line cut of the plurality of line cuts may be used as an anchor point to fix an end of a fiber of the one or more fibers.

[0044] In various embodiments, a line cut of the plurality of line cuts may be used as an anchor point to fix an end of a fiber of the one or more fibers. Additionally or alternatively, a line cut of the plurality of line cuts may be used as a nodal point to change a direction of a fiber of the one or more fibers. In various other embodiments, the sheet template may additionally or alternatively include a plurality of holes. A hole of the plurality of holes may be used as an anchor point to fix an end of a fiber of the one or more fibers. A hole of the plurality of holes may be used as a nodal point to change a direction of a fiber of the one or more fibers.

[0045] In various embodiments, the plurality of line cuts may be formed by using a laser cutter.

[0046] In various embodiments, the one or more physical guides and/or anchors 204 may include polymer guides (also referred to as guided paths) printed onto a part mold. The polymer guides may, for instance, be splines, lines, or poles. The polymer guides may be printed onto the part mold using a shear thinning polymer.

[0047] In various embodiments, arranging the one or more fibers may include layering the one or more fibers between or inside the guides using a co-axial needle. The co-axial needle may be coupled to the fiber extruding tool and to the matrix material extruding tool. The co-axial needle may include an internal needle that dispenses the one or more fibers, and an outer needle that dispenses an outer polymer coat. In other words, the one or more fibers formed may be coated by the polymer. The one or more fibers may be formed by the fiber extruding tool, while the outer polymer coat may be formed by the matrix material extruding tool.

[0048] In various embodiments, the setup may include a heater, e.g. an oven, to heat the matrix material for curing the matrix material.

[0049] In various embodiments, the setup may also include a laser cutter to shape the matrix or resultant workpiece. Laser cutting may achieve the desired two dimensional (2D) profile of the matrix or resultant workpiece. In various other embodiments, a mold or direct ink writing (DIW) may be used to achieve the desired two dimensional (2D) profile of the matrix or resultant workpiece.

[0050] Experiment 1

[0051] Fiber embedding process

[0052] In order to better incorporate fiber embedding into a multi-material fabrication process, an approach to automate the extrusion and embedding of fibers during deposition (e.g. molding)

and direct writing of elastomer components has been developed. This may be achieved using a tension based weaving method over a customized template. The approach may enable patterning of a wide variety of fiber materials and may open various opportunities for tailoring structural and functional properties in soft robot and soft mechatronic components.

[0053] FIGS. 3A – F illustrate using a wave pattern template to embed fibers in a plane within a soft robot component. FIG. 3A shows (left) a schematic of a setup including a three dimensional (3D) printer 302, a weaving temple 304 and a bottom mold 306 according to various embodiments; and (right) a photograph of the setup shown on the left according to various embodiments. The weaving template 304 and the bottom mold 306 may be formed on a 3D printer bed via FDM. The template 304 (designed in proportion to the part size) may be printed beforehand, and may be fixed around the part mold 306 prior to material deposition. FIG. 3B shows a schematic of a matrix material such as silicone being deposited into the mold by a pressure controlled dispenser, i.e. the silicone extruding tool (also referred to as matrix material extruding tool), to form a first mold part according to various embodiments.

[0054] FIG. 3C shows (top) a schematic of a fiber being loaded onto the fiber extruding tool of the three-dimensional (3D) printer 302 according to various embodiments; and (bottom) a photograph showing the fiber being weaved over the template according to various embodiments. The fiber extruding tool may be an attachment to the 3D printer. The exit needle tip of the fiber extruding tool may be changed according to the fiber diameter. The printer may include a top tensioner which is used to control fiber slack while the tool head is translating from one pole to another. The weaving template may have a pre-defined number of poles that serve as anchors for different fiber patterns. A fiber may be extruded by the fiber extruding tool and the initial fiber anchoring is done by coiling an end portion of the fiber at a selected pole (a first pole). Weaving may then continue by tensioning the fiber between the first pole and a second pole, and by coiling or partially coiling the fiber around the second pole. In various embodiments, the weaving may further continue by stretching the fiber between the second pole and a third pole, and coiling or partially coiling the fiber around the third pole. Tensioning and coiling of the fiber may be extended to further pole(s) as needed. A further end portion of the fiber may be coiled around a last pole to complete the weaving of the particular fiber. The tensioning of the fiber between poles, and the coiling or partially coiling of the fiber around the various poles may be carried out by

translating or moving the fiber extruding tool relative to the stage holding the weaving template and the mold part. In various embodiments, the movement may be carried out by moving the fiber extruding stage. In various other embodiments, the movement may be carried out by moving the stage. The fiber layering may be carried out such that the fiber is kept in tension. Fiber layering may also include more than one fiber. In various embodiments, automated fiber layering in 2D patterns may be controlled by using the 3D printer x – y stage (previously computed G-code). The resulting fiber-pole friction (capstan effect) may keep the patterns in place during fabrication. The number of poles, N , distributed around the template 304, the fiber thickness, t , and the spacing, d , between the poles may determine the density, ρ , and angles, θ_n , of the achievable fiber patterns. Templates may be designed based on the geometry of patterns to be layered or arranged. Customizing the shape may increase the range of patterns that can be programmed and layered onto the first mold part including a base matrix material.

[0055] FIG. 3D is a schematic showing a top mold being printed directly over the first mold part according to various embodiments. The top mold may be printed via FDM. In various embodiments, the top mold may be printed together with the bottom mold before the fibers are weaved. In various other embodiments, the top mold above the woven fiber plane may be prefabricated and may be attached to the bottom mold.

[0056] FIG. 3E is a schematic showing the extrusion of elastomer onto the cavity of the top mold according to various embodiments. The extrusion of the elastomer may be carried out by the silicone extruding tool. By depositing the matrix material into the top mold using the silicone extruding tool, the 2D fiber patterns may be encapsulated.

[0057] FIG. 3F is a schematic illustrating the oven curing of the mold contents, followed by laser cutting to form a workpiece or sample with the desired shape according to various embodiments. Curing may be done at any suitable temperature, e.g. 60° Celsius.

[0058] FIG. 3G is a photograph of the fabricated fiber embedded dog bone sample formed by methods shown in FIGS. 3A-F according to various embodiments.

[0059] FIG. 4 shows a top view of a wave pattern template according to various embodiments. The range of fiber pattern angles, θ_n , achievable may depend on the number of poles, N , and the spacing, d , between poles. In various embodiments, multiple patterns may be stacked on top of each other to create dense weave composites.

[0060] FIG. 5 shows a computer-aided design (CAD) model of the fiber extruding tool of the printer according to various embodiments. The fiber is loaded onto a fiber spool holder of the printer and routed through the fiber extruding tool. A top tensioner of the printer may control the fiber slack. The fiber extruding tool may have a needle top to route the fiber.

[0061] Materials and methodology

[0062] A wide variety of fibers with multiple material and functional properties are commercially available. In order to test the fabrication concept described above, experiments were performed using 2ply 100 % polyester, 3 ply 100 % cotton, and 2 ply 316L steel conductive fibers (purchased from Golden Dragon Hobby craft, Singapore) of equivalent deniers (diameters).

[0063] Matrix material deposition (e.g. volume deposited in the case of casting or paths in the case of DIW) and fiber weaving paths are obtained from a 3D object designed using CAD software which is in turn converted to G-code using a slicing software (e.g. Slic3r). The G-code paths for fiber weaving are modified further with appropriate G-code commands (e.g. tool changes, pauses, etc.). FIG. 6 is a schematic illustrating the fabrication process steps according to various embodiments. The part geometries and fiber layouts may be defined by CAD models, and process automation may use G-codes.

[0064] Silicone samples with embedded fibers were fabricated using a bench top 3D printer (e.g. HYREL SYSTEM 30M) equipped with three-axis motion control, a FDM printing head, and a pressure controlled dispenser (e.g. Nordson Ultimius V High precision). The custom designed tool head for fiber extrusion uses needle tips (e.g. Nordson EFD) matching the fibers diameters used (100 μ m to 2mm). A rectangular sample mold and weave pattern template are first 3D printed via FDM. The sample mold is first printed partially (bottom mold) and filled with EcoFlex 00-30 (matrix material) using the pressure controlled dispenser (matrix material extruding tool). Fiber is then woven in 2D patterns on a region of interest using the template anchor points. The rest of the mold (in this case referred to as top mold) is placed on the bottom mold above the woven pattern (the top mold can also be printed directly) and a further layer of matrix material is deposited using the pressure controlled dispenser (matrix material extruding tool). This process can be repeated multiple times over the height of a component. The large rectangular composite part was cured inside an oven (e.g. MEMMERT). Once cured, the composite samples are carefully de-molded.

[0065] The large rectangular composite part sample can be cut using a Laser cutter (e.g. EPILOG LASER FUSION M2) for testing in the shape of dog bones. The dog bone samples have fiber patterns embedded at different angles with respect to their principal axes: 0° (single layer, horizontal pattern), 90° (single layer, vertical pattern), $0^\circ+90^\circ$ (double layer, criss-cross pattern). The dog bone sample shape is adapted from the American Society for Testing of Materials-412-C (ASTM-412-C) standard with an effective length of 33 mm, width 25 mm and a thickness of 6 mm. The number of fibers in a sample is kept constant for all the different types of fibers used.

[0066] FIG. 7A shows images of dog bone samples with embedded cotton fibers (samples 1 – 3), and embedded polyester fibers formed using methods illustrated by FIGS. 3A – F according to various embodiments.

[0067] Results and discussion

[0068] The properties of eighteen dog bone shaped fiber embedded samples (3 vertical, 3 horizontal, and 3 criss-cross samples using cotton fiber and a similar set using polyester fiber) were characterized using tensile tests (INSTRON 5943, Instron) with a cross head speed of 50mm/min.

[0069] FIG. 7B shows time lapse images of a dog bone sample formed according to various embodiments during tensile tests. Samples are stretched to their ultimate failure and the respective stress-strain curves are recorded.

[0070] FIG. 7C is a plot of stress (in mega Pascals or MPa) as a function of strain (in percent or %) showing the stress-strain behaviour of cotton fiber embedded silicone samples according to various embodiments. The results of the sample with horizontal pattern embedded cotton fibers is denoted by “CH”, the results of the sample with vertical pattern embedded cotton fibers is denoted by “CV”, and the results of the sample with criss-cross pattern embedded cotton fibers is denoted by “CCC”. The label “exp” indicates experimental results, while the label “mod” indicates model prediction results. Stress-strain data for a pure EcoFlex 00 – 30 sample is also included as a reference (indicated by EF 00 – 30).

[0071] FIG. 7D is a plot of stress (in mega Pascals or MPa) as a function of strain (in percent or %) showing the stress-strain behaviour of polyester fiber embedded silicone samples according to various embodiments. The results of the sample with horizontal pattern embedded polyester fibers is denoted by “PH”, the results of the sample with vertical pattern embedded polyester fibers

is denoted by “PV”, and the results of the sample with criss-cross pattern embedded polyester fibers is denoted by “PCC”. The label “exp” indicates experimental results, while the label “mod” indicates model prediction results. Stress-strain data for a pure EcoFlex 00 – 30 sample is also included as a reference (indicated by EF 00 – 30).

[0072] The embedded fibers were analyzed using a HIROX Digital Microscope KH-8700. Fiber images were captured by carefully illuminating the composite structure. FIG. 8A shows a microscope image of polyester fiber embedded elastomer according to various embodiments. FIG. 8B shows a microscope image of cotton fiber embedded elastomer according to various embodiments. FIG. 8C shows a microscope image of conductive fiber embedded elastomer according to various embodiments. As seen from FIG. 8B, there appears to be some loosening of cotton fibres. This may be due to a combination of the natural condition of the organic fiber and absorption of moisture within the silicone elastomer. This phenomenon is not visible in polyester fibres (FIG. 8A), which absorb less moisture than natural fibers.

[0073] As a reference, the composite behavior can be modelled using a simple rule of mixtures. Defining the volume fraction of fibers, f , to be,

$$f = V_f / (V_f + V_m) \quad (1)$$

where V_f is the total volume of fiber in a sample, and V_m is the total volume of matrix in the sample.

[0074] The composite modulus, E_c , when the loading is applied in a direction parallel to the fibers can be approximated as,

$$E_c = fE_f + (1-f)E_m \quad (2)$$

where E_f is the modulus of the fiber, and E_m is the modulus of the matrix.

[0075] The composite modulus, E_c , when the loading is applied in a direction perpendicular to the fibers can be approximated as,

$$E_c = \left(\frac{f}{E_f} + \frac{(1-f)}{E_m} \right)^{-1} \quad (3)$$

where E_f is the modulus of the fiber, and E_m is the modulus of the matrix.

[0076] Stress-strain curves based on Equation (2) can be compared to the behaviour of vertical pattern samples and curves based on Equation (3) can be compared to the behaviour of horizontal pattern samples. An average of these composite moduli is used for comparison with criss-cross samples.

[0077] Experiment results shown in FIGS. 7C-D clearly confirm that fiber placement determines the sample mechanical behaviour.

[0078] Table 1 summarizes the experimental results.

[0079] Table 1: Test Samples Mechanical Properties

<i>Sample type</i>	<i>Pattern type</i>	<i>Modulus (kPa)</i>	<i>Elongation at break (%)</i>
<i>Polyester embedded</i>	Horizontal	34 ± 2	1220 ± 0.01
	Vertical	434 ± 24	26 ± 0.2
	Criss-Cross	281 ± 29	24 ± 4.2
<i>Cotton embedded</i>	Horizontal	42 ± 5	935 ± 8
	Vertical	1336 ± 50	55 ± 9
	Criss-Cross	1430 ± 30	39 ± 0.5
<i>Pure Ecoflex 00-30</i>	No Fiber Embedded	30	1424
<i>Pure Cotton*</i>	Individual Fiber	5500	5
<i>Pure Polyester*</i>	Individual Fiber	6600	20

[0080] An increase in modulus is observed for vertical (90°) and criss-cross patterns (0°+90°). For all samples, failure begins with fiber slippage (noticeable by discontinuities in the stress strain curves) followed by a total failure of the composite. Horizontal fiber patterns do not contribute to strengthening of the axial properties of the composite (along the axis of tension), so as expected, these samples show almost the same stress strain curves as samples with pure matrix material (i.e. no embedded fibers). For cotton fibers, patterns in line with the loading axis (vertical and criss-cross) do seem to strengthen the composite. Both vertical and criss-cross pattern samples show yield strengths much higher than the control sample (pure matrix material) and steeper slopes (i.e. higher tensile modulus). For polyester fibers, failure occurs prematurely in samples with patterns aligned with the loading axis, despite the increase in modulus (steeper slopes). This may be due to the difference in contact area between the fibers and the matrix. The looseness of organic fibers may lead to larger contact areas and stronger bonds, while the smoothness of the synthetic fibers may lead to less contact area and weaker adhesion. Fibers and matrix may not react with each other and chemical bonds may not be formed. As such, the main mode of adhesion may be mechanical in nature, and as a result, total contact area may be important.

[0081] In order to study functional behaviour, a rectangular thermochromic pigmented elastomer sample (Ecoflex 00-30 + thermochromic pigments) with embedded conductive steel fibers was fabricated. The conductive fibers were connected to a direct current (DC) power supply

which provided 13.5W (9V , 1.5A) to the steel conductive fibers to heat the elastomer via joule heating.

[0082] FIG. 9 shows the color changes of a thermochromic pigmented silicone sample with embedded conductive fibers according to various embodiments.

[0083] Once the transition temperature of 31° Celsius was reached, a color change in the pigmented elastomer was triggered. The kinetics of color change may be highly dependent on elastomer thermal conductivity, and for EcoFlex 00-30, full colour change was achieved after 45s. Lower applied power lead to longer transition times. FIG. 9A and FIG. 9C show the sample color at room temperature. Different fiber patterns may enable localized heating and color changes. Color change may be localized by applying DC power only to a portion of the fiber pattern. FIG. 9B shows localized color change (power applied only to half of fibers). FIG. 9D shows a complete color transition (power applied to all fibers).

[0084] In order to demonstrate a camouflaging application, a sample in the shape of a lizard and with thermochromic pigmented silicone was fabricated via Direct Ink Writing (DIW) and conductive steel fibres were embedded. FIG. 10 shows the color change of the sample according to various embodiments by applying a direct current (DC) voltage of 9V and a current of 1.5A. Full color transition was achieved at 45s (35°C).

[0085] This study presents an automated fiber embedding fabrication process. The process may allow the weaving of complex fiber layouts with the possibility of stacking multiple layers to achieve complex and dense patterns. The approach may be combined with polymer deposition to yield soft composite structures. The process automation may have an important impact as the fabrication of soft robot components requires complex geometries that cannot be easily achieved manually.

[0086] Structural functionality was characterized using tensile tests. Preliminary experiments reveal that the nature of the fiber interface with the matrix material (i.e. adhesion) may be of great importance. Smooth polyester fibers that do not loosen during casting may easily peel off from the matrix material as stress is applied. In contrast, fibers that loosen up during casting (likely due to moisture absorption) may adhere much better to the matrix material and help increase the composite yield strength in tension. As in traditional composites, fiber alignment with the axis of loading may have a larger impact.

[0087] This study also demonstrated the use of the fiber embedding process in bio-inspired applications such as camouflage using thermochromic pigments and conductive wires. Fiber layering patterns may help control the localization of color change. Various other applications in sensing and actuation may also be possible by leveraging fiber pattern geometry and functionality. Various embodiments may also extend the approach described herein to the fabrication of more complex three dimensional fiber layouts.

[0088] Various embodiments may enhance the fabrication capabilities and may enable tailoring of structural and functional features in soft robots applications.

[0089] Experiment 2

[0090] Fiber polymer interaction may be significant for the reinforcement efficiency of fibers. Fibers with high aspect ratio can be aligned to achieve high volume fraction in a composite. Automation may play a major role in robust and repeatable fabrication of complex structures and composites. In order to achieve accurate and repeatable fiber embedding, different methodologies and workflows to automate dispensing and layering have been explored. Various embodiments may relate to layer fibers using tension based anchoring over FDM printed templates, and embedding fibers with DIW guided paths. Various other embodiments may relate to embedding fibers using sheet templates. These approaches may enable patterning of a wide range of fiber materials which are useful in various applications such as tailoring structural and functional properties and fabrication of complex microchannel structures.

[0091] Placement and embedding of long fibers is a challenging process due to the mechanical properties of yarns. Long fibers may need to be secured in desired configurations during or prior to embedding within a soft material. Fiber flexural rigidity and torsional properties of the fibers may interfere with proper placement if anchoring is not in place. Therefore, proper anchoring may be required for fiber layering control.

[0092] Various embodiments may involve five steps. The steps may include: (1) anchoring fiber at the starting position; (2) autonomously guiding the fiber in the desired path(s); (3) using intermediate nodes to anchor, change, or guide the direction of fiber layering and achieve desired pattern; (4) fixing the fiber at a final anchoring position; and (5) depositing matrix material layer.

[0093] Three different approaches to achieve these steps are described below. All approaches use a fiber extruding tool specially designed to be mounted as an additional printer head in a FDM

3D printer base (e.g. HYREL System 30M). Fibers are manually loaded into the extruding tool and fitted through an exit needle tip. The custom designed tool head for fiber extrusion uses needle tips (e.g. Nordson EFD) matching the fiber diameters used (100 μ m to 2mm). The slack fiber may be tensioned above the tool-head to enable controlled fiber tool paths. The approaches can also be combined within a single component.

[0094] AFE with FDM printed wave templates

[0095] FIG. 11A shows a schematic of a setup including a three dimensional (3D) printer 1102 with a fiber extruding tool and a weaving template 1104 according to various embodiments. The fiber extruding tool may also be referred to as fiber extruder tool. The weaving template 1104 may be printed by FDM. The custom weaving template 1104 may be designed with a predefined number of poles, N, spread around the template circumference (or strategically placed within).

[0096] FIG. 11B shows a schematic of the fiber embedding process using the setup shown in FIG. 11A according to various embodiments. As shown in FIG. 11B, the printer 1102 may also include a silicone extruding tool (also referred to as silicone extruder tool or matrix material extruder tool).

[0097] FIG. 11C is a photo illustrating anchoring fibers using template poles according to various embodiments. Poles may be used as anchor points to fix fiber ends and as nodal points to change the direction of the fibers tool paths. A fiber may be extruded by the fiber extruding tool and the initial fiber anchoring is done by coiling an end portion of the fiber at a selected pole (a first pole) to form an anchor point. Weaving may include then continue by tensioning the fiber between the first pole and a second pole, by coiling or partially coiling the fiber around the second pole to form a nodal point. In various embodiments, the fiber layering may further continue by tensioning the fiber between the second pole and a third pole, coiling or partially coiling the fiber around the third pole to form a further nodal point. Tensioning and coiling or partially coiling of the fiber may be extended to further pole(s). A further end portion of the fiber may be coiled around a last pole to complete the fiber layering of the particular fiber to form another anchor point. The tensioning of the fiber between poles, and the coiling or partially coiling of the fiber around the various poles may be carried out by moving the fiber extruding tool or the stage holding the weave template. The weaving may be carried out such that the fiber is kept in tension. Weaving may also include more than one fiber.

[0098] The fiber and needle diameters (d_f , d_n) may play an important role in the arrangement and spacing d between poles. At a minimum, the spacing should allow for the needle of fiber extrusion tool to pass through. In order to establish an anchor point, fiber is coiled around a pole with a minimum of 3 full revolutions (this may depend on the fiber surface properties). The resulting fibre-pole friction forces (capstan effect) may provide the necessary resistance to anchor the fibers and keep them in place during printing. The fiber layering tool paths may be used to maintain constant tension. The tension ratio (T_1/T_2) as indicated in FIG. 11C may be provided by:

$$T_1 = T_2 e^{\mu \phi} \quad (4)$$

where ϕ represents the wrapping angle (revolutions around a pole), and μ represents the friction coefficient between the fiber and the pole material.

[0099] FIG. 11D shows (left) a photograph showing some weaving templates according to various embodiments; and (right) schematic of weaving templates with fibers anchored onto poles according to various embodiments. Weaving templates may be designed based on the target internal and external pattern geometries to be weaved. Customizing the template shape may increase the range of patterns that can be programmed and weaved within a component.

[00100] FIG. 11E shows a schematic showing the silicone deposition process according to various embodiments. Once the desired fiber layout is completed, matrix material may be poured in to achieve a desired part thickness (when template is located inside a part mold). In various other embodiments, the mold part may also be printed layer by layer using direct ink writing (DIW). The external component geometry may be achieved using the mold, DIW, or through laser cutting the desired 2D profile.

[00101] AFE with sheet based weave templates

[00102] Various embodiments may use sheet templates for fiber embedding. FIG. 12A shows a three dimensional (3D) printer 1202 with a fiber extruding tool according to various embodiments. The fiber extruding tool may also be referred to as fiber extruder tool. The printer 1202 may also include a silicone extruding tool (also referred to as silicone extruder tool or matrix material extruder tool). FIG. 12B shows a sheet template 1204 being set up under the fiber extruding tool according to various embodiments.

[00103] Sheet templates with a predefined number of short line cuts N inside and throughout their outer edges may first be fabricated using thick sheets of card stock (0.25mm) and a laser cutter. FIG. 12C shows (left) photographs of some sheet templates according to various embodiments; and (right) schematics of the sheet templates according to various embodiments. FIG. 12D is a schematic showing the fiber embedding process with fibers anchored in small cuts placed around sheet templates according to various embodiments. The line cuts may be used as anchor points to fix fiber ends and as nodal points to change the direction of the fibers tool paths. The extruding tool needle of the fiber extruding tool may pierce through a template line cut and then retract. The friction between the fiber and the template line cut edges may force a short fiber section to remain wedged at the line cut. This section of fiber wedged at the template line cut may provide the necessary resistance to anchor the fibers and may keep them in place during printing.

[00104] A fiber may be extruded by the fiber extruding tool, and the extruding tool needle of the fiber extruding tool may pierce through a first line cut to allow an end portion of the fiber to pass through the first line cut. The extruding tool needle may then retract so that the end portion of the fiber may be anchored at the first line cut to form a first anchor point. Weaving may then continue by tensioning the fiber to a second line cut by moving the fiber extruding tool with the extruding tool needle. The extruding tool needle may pierce through the second line cut before retracting, such that a further portion of the fiber (an intervening portion of the fiber between end portions of the fiber) may be anchored to the second line cut to form a nodal point. In various embodiments, the fiber may be extended to further line cuts and using further intervening portions of the fiber to form further nodal points. Another anchor point may be formed by piercing the needle through a last line cut and retracting. More than one fiber may be used in the fiber embedding process.

[00105] FIG. 12E show photographs illustrating the fiber embedding process with fibers anchored in small cuts placed around sheet templates according to various embodiments. As described earlier, the fibers may be anchored in the line cuts (alternatively referred to as sheet grooves). The friction between the fiber and the sheet template may determine the tension ratio T_1/T_2 across a template cut.

[00106] The fiber layering tool paths may be used to maintain constant tension. The fiber and needle diameters (d_f , d_n) may also play an important role in the arrangement and dimensions of the

cuts (width w_c and length l_c) as the cut dimensions should provide an interference fit with the fiber extrusion needle and the fiber.

[00107] Similarly to AFE with FDM printed templates, sheet templates may be designed based on the target internal and external pattern geometries to be weaved. Customisation may increase the range of patterns that can be weaved.

[00108] FIG. 12F is a schematic illustrating the silicone deposition process according to various embodiments. Once the desired fiber layout is completed, matrix material may be poured in to achieve a desired part thickness (when template is located inside a part mold). In various embodiments, the mold part may be a printed layer by layer using direct ink writing (DIW). Since a flat 2D template is used, the fiber patterns may be kept at the surface of the components so that the template can be removed once the part is cured. The external component geometry can be achieved using the mold, DIW, or through laser cutting the desired 2D profile.

[00109] AFE with DIW guided paths

[00110] Various embodiments may use polymer guides (alternatively referred to as fiber guides or guided paths). The polymer guides or fiber guides may be printed using a direct ink writing (DIW) head. FIG. 13A shows a three dimensional (3D) printer 1302 according to various embodiments. As shown in the inset of FIG. 13A, the DIW head (or modified fiber extruding tool) may include a co-axial needle, a fiber extruding tool (or fiber extruder tool) coupled to the co-axial needle, and a silicone extruding tool (or matrix material extruding tool or silicone extruder tool) coupled to the co-axial needle. FIG. 13B shows the printing of the polymer guides 1304 according to various embodiments. A predetermined number of polymer guides 1304 (e.g. splines, lines or poles) may be first printed inside a part mold using a shear thinning polymer, e.g. silicone. The polymer guides 1304 may be printed using the silicone extruding tool. FIG. 13C is a photo of a polymer guide according to various embodiments. The viscosity of the polymer guides 1304 may be tuned so that self-standing features of a few millimeters can be achieved. The guides may be cured at room temperature or using the heated base of the printer 1302.

[00111] FIG. 13D shows the laying of the fibers between the polymer guides 1304 according to various embodiments. FIG. 13E shows a photograph of guiding a fiber between the polymer guides 1304 according to various embodiments. After the guides 1304 are cured, the fiber may be laid inside or in between the guides using the co-axial needle (Rame Hart Instruments). The co-axial

needle may include an internal needle and an outer needle. The internal needle may be coupled to the fiber extruding tool and may dispense the fiber or yarn, while the external needle may be coupled to the silicone extruding tool and may dispense a polymer which covers the fiber or yarn. This approach may help keep the fiber geometry fixed in the spaces between the polymer guides 1304.

[00112] The guides 1304 may be used to achieve non-rectilinear fiber paths, which may not be achievable using AFE with FDM or sheet templates. Tension may not be used to secure the fibers and the weight and viscous forces of the polymer surrounding the fiber may help balance and prevent the tendency of the fiber from bending and buckling out of plane.

[00113] Similar to AFE with FDM and sheet templates, DIW guides may be designed based on the target internal pattern geometries and external pattern geometries to be weaved. Since the DIW guides may be of any geometry, this approach may enable a higher degree of fiber layering pattern capabilities. FIG. 13F shows deposition of silicone over the fiber according to various embodiments. After the fibers are arranged according to the desired fiber layout, matrix material, e.g. silicone, may be poured over the fibers or printed layer by layer using DIW to achieve a desired part thickness. The matrix material may also be deposited over the polymer guides 1304, and may also embed the polymer guides. In various embodiments, the matrix material and the material included in the polymer guides 1304 may be the same, e.g. silicone. In such a scenario, the matrix material and the material included in the polymer guides 1304 may be indistinguishable from each other. In various other embodiments, the matrix material and the material included in the polymer guides may be different. The external component geometry may be achieved using the mold, DIW, or through laser cutting the desired 2D profile.

[00114] Tool Path Automation (G-code Generator)

[00115] Fiber weaving templates and weaving patterns may be designed in a computer aided design (CAD) package (e.g. SolidWorks, Autodesk Fusion 360, etc) and corresponding stereolithography (STL) files may then be generated. Using the STL file as a reference, fiber tool paths may be generated using customized G-code generator script programmed in Mathematica and Python. The generated G-code may then be uploaded to the 3D printer to controls tool path movements for layering the desired fiber patterns and to control matrix material deposition (e.g. filling molds, printing guide paths via DIW, etc.).

[00116] FIG. 14A shows a schematic of the automated fiber embedding (AFE) workflow according to various embodiments. A desired part configuration is first designed in CAD and a slicing software (Slic3r) is used to generate the required G-code. The code is then upload to a modified 3D printer, the required fiber is loaded into an extruding tool and the required polymer are loaded into the dispenser tools (matrix material extruding tools). The parts may be printed layer by layer. FIG. 14B is a schematic illustrating layer merging according to various embodiments. In various embodiments, different layer may be fabricated using different AFE approaches (e.g. FDM templates, sheet templates, and DIW guide paths) and combined into 3D components.

[00117] Materials and methodology

[00118] Two polymer materials were used in the examples described in this study: Ecoflex-0030 and Smooth-Sil 960 (Smooth-on). All fins and soft bodies shown use Ecoflex-0030 silicone.

[00119] Part-A and Part-B include 2 wt% percent of Slo-Jo, 1 wt% of Thivex. Slo-Jo helps increase printing times and Thivex is used as a rheology modifier. The ratios of chemicals are combined in a disposable cup and mixed thoroughly at 2000 RPM using a Planetary Mixer (ARE-310 Thinky Mixer USA) for a period of 2 minutes and subsequently defoamed in the mixer at 2200 RPM for additional 30 seconds. The mixture is then carefully transferred to a separate 30cc syringe for direct ink writing (DIW) or for casting. DIW guide patterns and tensile test samples use Smooth-Sil 960 silicone prepared by adding 10 parts of Part A to 1 part of Part B with 1 wt% of Thivex and 2 wt% of Slo-Jo. The same mixing procedure is followed and the mixture is carefully transferred to a 30cc syringe for DIW and fiber embedding. Polymer mixture colors were controlled by adding 2.5 wt% of silicone pigments. Bulk material properties of the silicones used are listed in Table 2.

[00120] Table 2: Test Samples Mechanical Properties

Sample type	Pattern type	Modulus (kPa)	Elongation at break (%)	Functionality
Polyester embedded	Horizontal	34±2	1220±0.01	
	Vertical	434±24	26±0.2	
	Criss-Cross	281±29	24±4.2	
Cotton embedded	Horizontal	42±5	935±8	
	Vertical	1336±50	55±9	
	Criss-Cross	1430±30	39±0.5	
Pure Cotton	Individual Fiber	5500	5	Tailor tensile strength and flexural rigidity
Pure Polyester	Individual Fiber	6600	20	Tailor tensile strength and flexural rigidity
Steel Conductive yarn	Individual Fiber	-	-	High electrical and thermal conductivity
PVA yarn	Individual Fiber	-	-	Water soluble
Thermochromic yarn	Individual Fiber	-	-	Color change
Glow in dark yarn	Individual Fiber	-	-	Luminescent
Pure Ecoflex 00-30	No Fiber Embedded	30	1424	
Pure Smooth-Sil 960	No Fiber Embedded	XXX	XXX	

[00121] In order to test the proposed fabrication concept, experiments were performed using various types of structural and functional fibers: 2ply 100 % polyvinyl alcohol (PVA) based water soluble yarn, 3 ply 100 % cotton, and 2 ply 316L steel conductive fibers (purchased from Adafruit, USA) of equivalent deniers (diameters). The properties of the fibers are also listed in Table 2.

[00122] The rheological properties of the silicone materials used may be important as they enable proper material deposition for direct ink writing. Silicone mixtures are characterized using a controlled stress rheometer (Discovery HR-3 Hybrid Rheometer, TA Instruments). At ambient conditions, a 40 mm parallel plate geometry with 1mm gap was used to study the rheology of pigmented and non-pigmented silicones. Care was taken to obtain the measurements within 30 minutes of the silicone mixture preparations. A shear rate from 0.01 to 4000 s⁻¹ and oscillatory measurements at a frequency of 1 Hz within a stress range of 0.1 to 2000 Pa were carried out for the rheology measurements.

[00123] Application examples

[00124] One AFE application is to use embedded fibers to tailor the flexural rigidity and tensile properties of soft structural elements. FIG. 15A shows photographs of (left) top view and (right) side view of a soft bio-inspired fin including embedded high tensile strength fibers according to various embodiments. An FDM printed template was used to embed fibers at an angle with respect to the its longitudinal axis. The stiff fibers was found to increase the tensile strength and bending rigidity of the fin along the fiber layering angle while these properties were unchanged in directions perpendicular to the fibers. This type of application may be common in soft robotics to tune the

bending rigidity of pneumatic fingers in soft grippers. However, traditionally fibers may have to be secured using intermediate molds or fixtures. One key advantage of using AFE may be the ability to easily tailor the required reinforcement regions.

[00125] In order to characterise tensile strength control capabilities, six different patterns of embedded cotton fiber were tested. A dog-bone shaped sample mold and weave pattern templates were first 3D printed via FDM (ASA). The sample mold is first printed up to half its original height and filled with Smooth-Sil 960 (matrix material) using the pressure controlled dispenser. Fiber is then woven in three different 2D patterns (horizontal, vertical, and criss-cross) on a region of interest using the template anchor points. A top mold is placed above the woven pattern. This process may be repeated multiple times over the height of a component.

[00126] Two additional dog-bones were fabricated using patterns printed via DIW (zig-zag and wavy) and a pure Smooth-Sil 960 sample (no embedded fibers) was also fabricated as a benchmark. All dog-bone sample were subjected to tensile tests (MTS UTM) with a cross head speed of 50mm/min. Samples were stretched to their ultimate failure and the respective stress-strain curves were recorded.

[00127] FIG. 15B shows (left) schematics of the dog-bone samples with various embedded fiber patterns according to various embodiments; and (right) a plot of stress (in MegaPascals or MPa) as a function of strain (in percent or %) showing the behaviour of the samples according to various embodiments. “CH” denotes horizontal pattern embedded cotton fibers, “CV” denotes vertical pattern embedded cotton fibers, “CCC” denotes criss-cross pattern embedded cotton fibers. The label “exp” indicates experimental results.

[00128] The dog bone sample shape was adapted from the American Society for Testing of Materials-412-C (ASTM-412-C) standard with an effective length of 33 mm, width 25 mm and a thickness of 6 mm. The number of fibers in a sample is kept constant for all the different types of fibers used.

[00129] The dog-bone samples were cured at room temperature for 2 hours followed by 4 hours post cure at 60° Celsius inside an oven (MEMMERT). Once cured, the composite samples are carefully de-molded. The dog bone samples have fiber patterns embedded at different angles with respect to their principal axes: 0° (single layer, horizontal pattern), 90° (single layer, vertical pattern), 0°+90° (double layer, crisscross pattern).

[00130] FIG. 16A shows (left) a photograph of a sting-ray-like soft silicon body with embedded thermochromic yarn according to various embodiments; and (right) the sting-ray-like soft silicon body with embedded thermochromic yarn after being heated by an external source according to various embodiments. A FDM printed template was used to layer thermochromic fibers horizontally and vertically across both fins. When the body was heated up from room temperature to 31°C using an electric heating pad (Adafruit, USA), the thermochromic fibers were observed to change color from blue to colourless. An alternative option is to use a polymer body with thermochromic pigmentation and employ a conductive fiber layout to enable color change through local heating. A key advantage of using embedded fiber patterns may be the ability to tailor the regions that undergo a color change.

[00131] FIG. 16B shows (top) images of silicone components with conductive fiber embedded using direct ink writing (DIW) according to various embodiments; and (bottom) thermal images of the silicone components with embedded fibers during heating according to various embodiments. The DIW guide patterns were used to define the layout of the conductive fiber. The guide patterns are printed using Smooth-Sil 960 ink modified to have increased viscosity. After the guides were cured completely, a co-axial needle based extruder was used to layer conductive yarns and silicone within the guide paths followed by DIW of silicone elastomer to get a flat localized heating pattern. The conductive steel fibers were supplied with 9W (9V, 1A) using a DC power supply to heat the elastomer via joule heating. Thermal imaging was carried out using a thermal camera (FLIR ETS320). The top row of images in FIG. 16B shows the samples at room temperature and the bottom row of images shows the corresponding thermal images of the localized heat along the desired patterns. Localized heating may have many applications in soft robotics where heat is used to activate phase changes in various materials to tune rigidity or to activate motions (e.g. 4D printed components).

[00132] Water soluble yarns may be layered in various patterns using sheet based weave templates. After curing, the yarns may be dissolved in water to create micro-channels. FIG. 17 shows (left) a photograph of a silicone finger-like structure with embedded soluble yarn according to various embodiments; and (right) another photograph of the finger-like structure after curing according to various embodiments. The soluble yarn was embedded in the silicone finger-like

structure using a sheet template. After the structure was cured, the yarn was dissolved and the resulting U-shaped channel was inflated to force bending motions on the finger-like structure.

[00133] Conductive yarns may also be layered in various patterns and geometries to create fiber based printed circuit boards (PCBs).

[00134] By using one or more fibers to reinforce a circular elastomeric inflatable in defined patterns, it may be possible to generate shapes which are not possible through pure matrix material. Cotton yarn may be embedded into a Ecoflex 00-30 matrix with AFE based FDM printed template, sheet template and guided paths. FIG. 18 shows (top row) top view of inflatable disk-like structures (S1 – S4) with various fiber patterns according to various embodiments; (middle row) top view (TV) of the disk-like structures during inflation according to various embodiments; and (bottom row) side view (SV) of the disk-like structures during inflation according to various embodiments. The different fiber patterns may help to tailor the surface topology of the disk-like structures when the disk-like structures are inflated. The fiber reinforcement into composites may be used to create strain limiting layer to create programmable surface topology and morphological skin.

[00135] Various embodiments may also be used in pneumatic gripper actuators.

[00136] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.