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DESIGN METHODOLOGIES FOR SOFT- MATERIAL ROBOTS THROUGH ADDITIVE MANUFACTURING , FROM PROTOTYPING TO LOCOMOTION

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ABSTRACT

Soft material robots have gained interest in recent years due to the mechanical potential of non-rigid materials and technological development in the additive manufacturing (3D printing) techniques. The incorporation of soft materials provides robots with potential for locomotion in unstructured environments due to the conformability and deformability properties of the structure. Current additive manufacturing techniques allow multi-material printing which can be utilized to build soft bodied robots with rigid-material inclusions/features in a single process, single batch (low manufacturing volumes) thus saving on both design prototype time and need for complex tools to allow multi-material manufacturing. However, design and manufacturing of such deformable robots needs to be analyzed and formalized using state of the art tools.

This work conceptualizes methodology for motor-tendon actuated soft-bodied robots capable of locomotion. The methodology relies on additive manufacturing as both a prototyping tool and a primary manufacturing tool and is categorized into body design & development, actuation and control design. This methodology is applied to design a soft caterpillar-like biomimetic robot with soft deformable body, motor-tendon actuators which utilizes finite contact points to effect locomotion. The versatility of additive manufacturing is evident in the complex designs that are possible when implementing unique actuation techniques contained in a soft body robot (Modulus discrepancy); For the given motor-tendon actuation, the hard tendons are embedded inside the soft material body which acts as both a structure and an actuator. Furthermore, the modular design of soft/hard component coupling is only possible due to this manufacturing technique and often eliminates the need for joining and fasteners. The multi-materials are also used effectively to manipulate friction by utilizing soft/hard material frictional interaction disparity.

INTRODUCTION

Biomimetic soft robots have been employing multiple manufacturing techniques which are usually beyond the traditional casting-forging-machining-fastening of metal structures [1–3]. These manufacturing techniques require specific know-how that includes mold construction, soft material casting and curing, employment of adhesives, etc. Other, more advanced, methods are being utilized as well - Shape Deposition Manufacturing (SDM), Smart Composite Microstructures (SCM), etc., but these methods are not yet available as an off-the-shelf platform [4]. The manufacturing technique of controlled layer-by-layer polymer deposition, referred to as additive manufacturing, has ability to provide solutions to soft robot manufacturing by providing flexibility of simultaneously using multi-materials. More importantly, the additive manufacturing methods of Fused Deposition Modeling (FDM) and Stereolithography (SLA) are available as off-the-shelf platforms from different companies. Fused Deposition Modeling (FDM) is a method where a solid polymer filament is liquefied by heating and deposited to form a solid layer

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of the manufactured part. In contrast, Stereolithography (SLA) employs a liquid pre-polymer that is patterned onto a surface and then cured (e.g. using UV exposure) to form a solid layer of the manufacturing part. The benefit of using SLA, in our case study is the ability to use combinations of hard and soft materials to achieve interesting properties in the soft robot body. The paper presents the design requirements for the biomimetic soft robot, conceptualizes the design methodology for soft material robots and discusses the designed robot.

DESIGN REQUIREMENTS

Roboticists have incorporated soft materials into robots with desire to mimic versatility and adaptability displayed by animals. This robot design builds on an existing work of soft-bodied robots inspired by caterpillar locomotion (*Manduca sexta*) [3, 5] which desires to build robots that can withstand impact, twist/bend and crawl by manipulating friction at finite contact points. The soft materials body is intended to provide robots with capability to adapt to variations in environments. The first versions were soft bodied and relied on actuation using shape memory alloys (SMAs) [5], but the resulting robot locomotion was slow and hard to control. The design space for caterpillar like soft-robots is very big, hence, this work augments the original design to address specific issues.

1. *Soft Deformable Body:* The original design included a soft body but the length to width ratio made the robot susceptible to rolling sideways or on its back. The requirement of the robot body is to allow a dominant axial deformation vs lateral deformation (caterpillar-like), stability of posture and elastic recovery of the body after deformation (energy storage).
2. *Locomotion:* The original design was also locomotion capable but was running fairly slow (~ 0.2 cm/sec) and the control of SMA actuators was difficult. The requirement of locomotion is to surpass the SMA-actuated robot designed previously - travel faster and with the ability to carry some load.
3. *Finite Discrete Contact Points:* The desire is to produce locomotion using manipulation of friction at finite contact points with the environment. This friction manipulation strategy is in contrast to undulatory snake-like locomotion (large area of contact) and is visible in caterpillars such as the *Manduca* genus. The design requirement is to design the robot that manipulates friction through two finite discrete points.
4. *Actuation:* The original design was SMA-actuated which are low-power, expensive and challenging to control since their performance depends on heat transfer (temperature control). Even though they are low-voltage, they provide small deformation and have been found to give unreliable performance in the original design. The design requirement is to actuate the robot with more powerful and more accurately controllable actuator. Moving to motor-tendon actuation in the proposed design allows embedding the actuators inside the robot body, large deformation, low voltage and very fine control.
5. *Body Deformation Control:* The soft actuators are typically embedded inside the deformable robot body. The manner in which actuators are placed dictates the deformation of the body. In case of motor-tendon actuator, the path of the tendons inside the was explored as part of this work. Different tendon paths induce different body deformation and thus different results of actuation and locomotion.
6. *Controlled Friction Manipulation:* As with the *Manduca* caterpillar, we require a material with grip-like properties that can be engaged/disengaged during the locomotion sequence.
7. *Quick Prototyping And Manufacturing Ability:* We require an ability to produce working prototypes and quickly that require minimal to no finishing/assembly.

DESIGN METHODOLOGY FOR SOFT ROBOTS

Soft robot design methodology can be conceptually categorized into *body design & development, actuation* and *control design* as illustrated in Fig. 1.

The soft robot body design and development is a two-step iterative process involving model-based exploration and prototype manufacturing. The design exploration step typically uses various simulation tools and Computer Aided Design (CAD) software (e.g. Autodesk Inventor®) and other Finite Element Analysis software (e.g. Abaqus ®). These methodologies, albeit very useful and instrumental as design tools, do not provide complete insight for cases where robot-environment interaction is difficult to model and simulate e.g. terrestrial locomotion of soft robots. This limitation can be supplemented by quick prototyping techniques (additive manufacturing) that will allow physical design variations and prototype testing.

The continuum nature of the soft deformable body contributes towards design of actuators as the robot body typically ends up performing dual function as an actuator and a structural feature. Consequently, the desire to control and design local soft material properties (e.g. stiffness) and deformation of the whole robot body leads to exploration of local (SMA-like) and global (motor-tendon-like) soft material actuators.

The soft robot control involves designing control strategies and algorithms. Fundamentally, the control strategy may involve modeling of the soft robot's body or models of the robot-environment interactions. This discussion is out of scope of this research.

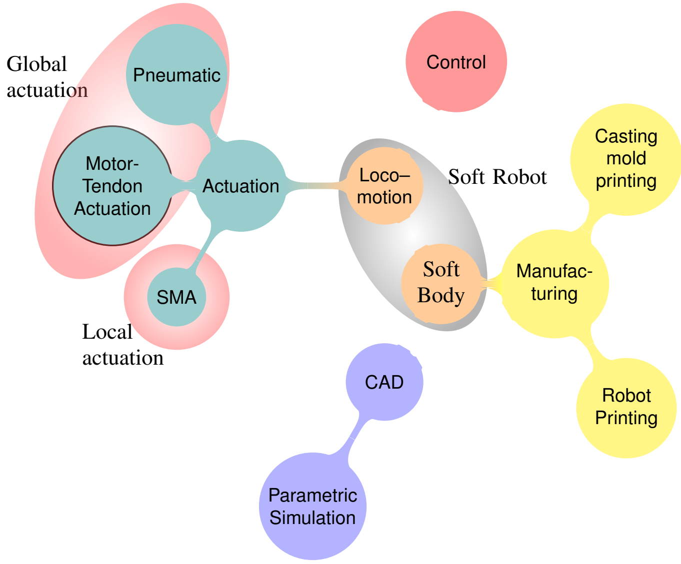

FIGURE 1. CONCEPTUALIZATION OF THE DESIGN METHODOLOGY.

Background and Design Inspiration

The design process starts with an observation of a biological locomotion system. The limb-based moving soft robots have been inspired by star-fish and caterpillar locomotion [6–8]. These give inspiration for design of body shape, desired material properties (e.g. preferred bending direction), actuators and even control. Initial robot development employed cast silicone elastomer bodies and SMA actuation [3, 5, 6]. Cast silicone elastomers are popular for soft bodied robot as resins are readily available with a wide variety of properties and silicones are known for their temperature resistance which may be a required feature with SMAs. The high strength of silicones also makes them burst resistant for pneumatic actuation methods [9].

Soft Body Design and Additive Manufacturing

The design of soft robots typically desires mixture of multiple material parts and a robot body where the materials properties change (gradient between two material polymers). Additionally, there is a desire to replicate the anisotrpy observed in nature - either through structural or material design. Additive manufacturing provides solutions for these problems but limits the selection of material.

Casting vs. Additive Manufacturing. One of the motivations of using direct additive manufacturing to make the robot body are limitations of the silicone casting process. In order to shape the body, a liquid pre-polymer is poured (sometimes injected) into an enclosed cavity (mold) and cures at room temperature or elevated temperatures, sometimes under vacuum to expel volatiles. Additionally, the use of a mold limits the flexibility in prototyping new robots as a new mold needs to be manufactured for every robot design. Even when making the mold itself via additive manufacturing to expedite prototype turnaround, we have encountered curing problems that arise from interaction between the prepolymer and the support material used in the additive manufacturing process. Additionally, multi-material manufacturing is very difficult when casting into molds and will require either insert-molding or two stage casting systems that make the tooling more complicated and the turnaround slower.

Materials selection and interaction. In contrast, direct additive manufacturing allows the use of multi-material manufacturing. In our case study, we employed a Stratasys®Objet500 Connex™ using TangoPlus™ (rubber-like elastomer) and VeroClear (Abs-like rigid plastic) resins as well as FullCure705 support material. The robot body was predominantly elastomeric with rigid inclusions and rigid surfaces to impart certain features (discussed further ahead). While allowing fast turnaround and complex multi-material designs, additive manufacturing limits the material choices available to the designer as most printers require proprietary resins to be used. It is possible, with the Objet500 Connex™ to create materials with properties ranging between rigid and elastomeric by blending the two resins (an out of the box software feature) but the possibilities are still within the realm of the available resins. That said, the limited material selection is a design constraint when using additive manufacturing but in the long run, can be overcome if needed by finalizing the robot design and manufacturing the tooling for *casting* the final design. Simulation, as we will discuss further ahead, can serve to conduct material selection.

Support Material. When designing the robot it is important to keep in mind how it is manufactured. The 3D model will be sliced into layers and the printer will lay one layer at a time. When a layer is deposited on top of an empty space, a sacrificial material is deposited into this space to support this layer while it is being built. The support material is, in our case, a soft polymeric hydrogel (FullCure705™). The orientation of the model while it is manufactured will determine the amount of support material used and the amount of surface area of the robot exposed to the material. The support material may have an effect on the surface of the robot. We found that in areas where the elastomeric material, TangoPlus™was in contact with the support material, removal of the sacrificial support material was more difficult. As a result, a tackier surface was obtained. This, however, may change with room temperature. Also, as discussed before, residual support material was found to interfere with curing of silicone elastomers when the latter are cast into a mold made using SLA. When introducing cavities into the soft robot, support material will fill these soft cavities for manufacturing. After manufacturing, cleaning the support material may damage the soft body due to its low strength. When possible, consider lining the soft body with a rigid layer to easily remove

TABLE 1. COMPARISON OF TRADITIONAL TOOLING TO ADDITIVE MANUFACTURING

Method	Pros	Cons
Traditional tooling (Mold)	○ Material choices ○ High volume.	○ Slow design cycle ○ Mono-material
Additive manufacturing	○ Multi-material ○ Rapid design cycle	○ Expensive ○ Limited material choices

the support material while protecting the soft robot body.

Anisotropy. Anisotropy in soft animal (caterpillar) tissues [7] is instrumental in locomotion. This anisotropic behavior exhibits increased stiffness of the caterpillar body transverse to its primary axis (circumferential stiffness) and reduced stiffness inline with the primary axis. The rise of this behavior is due to a complex tissue structure [10]. In the printer used for this work, the soft material is effectively isotropic as evident from bi-axial testing shown in Fig. 2. This challenge had to be met with a design change, as explained ahead.

Importance of Additive manufacturing to prototype design. Additive manufacturing is a very powerful tool which complements simulation by allowing quick variations in physical robot designs i.e. print multi-material robots with ease. This is very useful for the cases where the robot-environment interaction (e.g. terrestrial locomotion) or actuation process (e.g. motor-tendon actuation) is difficult to simulate.

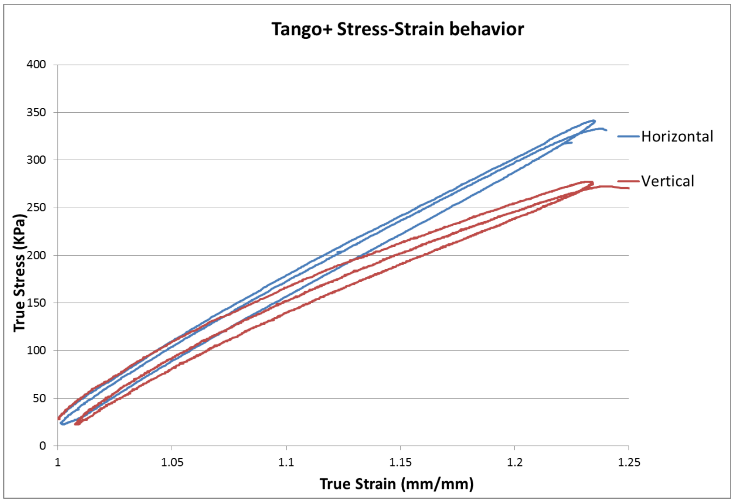

FIGURE 2. MECHANICAL PROPERTIES OF TANGO+ THROUGH STRESS-STRAIN BEHAVIOR.

Soft Robot Actuation

Actuation of soft robots remains a challenge because most electromagnetic systems are made of hard materials [11]. Alternative systems such as dielectric elastomeric actuators (DEAs) have been explored [12, 13], but these require high voltages for actuation and, without a rigid frame, produce very low stress [1]. Other flexible actuators include pressurized liquid or air [9, 14, 15], cable-driven systems [16] and shape memory alloy (SMAs) [3, 5, 11, 16]. Table 2 compares the benefits of motor-tendon actuation with those of SMA-actuation.

Control of soft continuum structures can be performed locally or globally. Local control is defined as control of local soft structural properties e.g. stiffness. Whereas, the global control refers to control of deformation of the robot structure. The local control will typically require less powerful actuators in comparison to global control actuators. Here we discuss three actuators that work on low voltage actuation.

Pneumatic. Pneumatic actuators are powerful global control actuators that have been successfully used for design of moving soft robots [2, 9] and wearable robot technology [15]. Typically, the pressurized liquid or air is flows through intricately designed channels inside the robot body. This makes control and speed more difficult as compared to electric systems.

Motor-Tendon. Motor-tendon actuators are inspired by nature and comprise of a motor that actively shortens a Polyamide tendon (fishing line) by winding it around a pulley. The unwinding requires external force which is provided by another actuator or the intrinsic elasticity of the deformed body. They have been successfully used to control manipulator arms [1, 16–18], however, they have not been used as soft robot locomotion actuators. They are advantageous over pneumatic actuators from control and speed perspectives, however, they pose challenges due to the hardness differential between the tendons and the soft body. This global actuation mechanism involves the movement of a tendon along a constrained path (soft body deformation control) resulting from the winding and unwinding. Mechanically, the difference in hardness during the interaction between the tendon and constrained path (referred to as tendon channel) inside the soft material body can easily wear/cut down the soft material. This design challenge is addressed in the next section.

Shape Memory Alloys (SMAs). SMAs are Ni-Ti alloys that recover original shape when heated above certain temperature. This is possible due to the martensite phase transformation from the parent austenitic phase. These actuators are activated through resistive heating and have been successfully used in locomotion of small, light soft robots [3, 5]. The use of SMAs as actuators presents numerous control challenges due to the inconsistency in actuation over time. Additionally, the SMAs do not produce

TABLE 2. COMPARISON OF PROS AND CONS OF SMA AND MOTOR-TENDON ACTUATION APPROACHES

Actuation	Pros	Cons
SMA	◦ Low voltage ◦ Low power ◦ Easy to embed	◦ Inconsistent ◦ Small deformation
Motor-Tendon	◦ Consistent results ◦ Energy efficient ◦ Low voltage ◦ Body-embedded	◦ Requires path design ◦ Strength mismatch tendon-body

high strain. However, being low voltage, low power and easier to embed (compared to a motor-tendon system) makes them favorable for control of local structural properties of different soft robot body areas.

EXAMPLE CASE STUDY

The case presented here discusses a soft bodied robot manufactured on a Stratasys® Objet500 Connex™ that uses Sterolithography (SLA) additive manufacturing technology. The 3D printer facilitates multi-material printing. The soft robot is designed using CAD software (Autodesk Inventor®) and printed using soft rubber-like material (TangoPlus™ resin) alongside hard abs-like material (VeroClear™ resin). The Figure 3 illustrates a top and side view rendering of the soft robot actuated by motor-tendon actuators.

Body Design

The body was printed using rubber-like soft elastomer. The $135mm \times 60mm$ rectangular shaped body is attached to two friction manipulation mechanisms as shown in Fig. 3.

Printing. SLA printing using the 3D printer allows a choice between matte and glossy finish on the top-most layer. Hence, the orientation of the robot when printed determines if the bottom of the robot was sticky (matte) or smooth (glossy). Printing the robot "ribs-up" uses less support material and smooth finish to the ribs but printing it "ribs-down" caused a more tacky and compliant layer of TangoPlus™ / support material to form (probably due to a curing issue at the interface). As a result of this tacky, high friction surface, locomotion became unexpected since the ribs sometimes got stuck on the surface and caterpillar-like locomotion (which requires elevating the body from the surface) was not possible. To solve this tackiness effect, an addition layer was added to cap the ribs with the harder VeroClear™ resin. This provided a hard tip to the ribs while maintaining a mostly soft and compliant body. As with the case of the friction manipulation (Virtual Grip discussed later), changing the resin only at the surface can produce interesting results for locomotion.

One of the very first challenges experienced with this design was the modulus and strength mismatch between the fishing line used in the channels (the tendons) and the TangoPlus™ material used for the robot body. The strength mismatch caused the fishing line to cut into the body over time and the modulus mismatch caused a lot of energy loss at the interface between the fishing line and the robot. The solution was to internally coat the channel with segments of hard VeroClear™ resin. This allowed for both efficient energy transfer to induce body deformation as well as protection of the soft body from being cut by the tendons.

Anisotropy. In order to facilitate the required anisotropy in the soft robot, we introduced ribs (Figure 3), transverse to the primary robot axis. Introducing ribs to the structure will give the desired result but may also change the total surface area of the face the ribs are placed on. While this may not be an adverse effect, it needs to be considered for locomotion as now the surface-area interacting with the substrate has changed considerably. In our case, this was an early change that was also capitalized on by bringing the tendon channel to the face of the base of the ribs, where we may thread our tendons through. In this case, the ribs not only served as a cause for anisotropy but also as an access way to the robots internals, which were only partly sunk into the face of the base of the ribs.

Friction manipulation. Soft and hard materials interact differently when in contact with a hard surface. The friction between two hard interacting surfaces depends upon the size of irregularities. However, when a soft material interacts with a hard material surface, it possesses the capability to conform to irregularities of the hard surface to increase friction between the two surfaces, as illustrated in Fig. 4 [19]. The robot uses multiple material interaction with the surface to manipulate friction as a function of robot shape. Figure 5 shows how, during actuation, as the robot curls its far edge inwards, the contacting surface switches from soft to hard. While the contacting surface is soft, the grip will allow this side of the robot to remain stationary and the other side to drag, changing the angle of the actuated grip. The angle change allows the harder, smoother surface to come in contact with the ground and slide forward to a resting position. In the case of the virtual grip, soft and hard segments are being used as a physical switch to facilitate a grab-release effect on the substrate the robot crawls on. This has been shown to be a key effect in caterpillar (or soft body) crawling, where the substrate is used as a leverage to push the body forward [8].

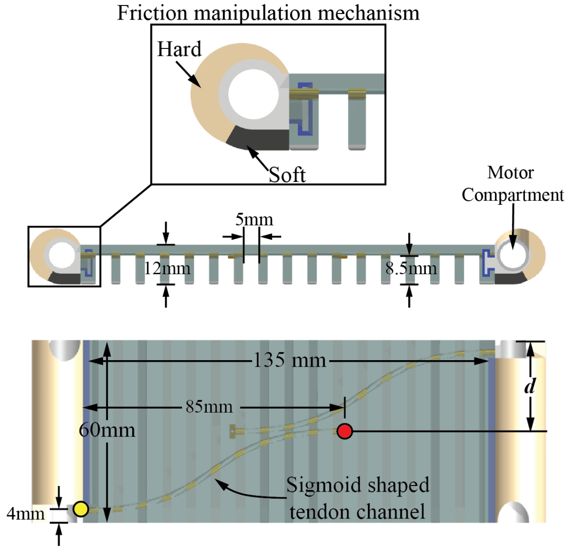

FIGURE 3. SOFT ROBOT DESIGN, DIMENSIONS AND PRIMARY COMPONENTS. THE $135MM \times 60MM$ RECTANGLE SHAPED SOFT BODY IS ATTACHED TO FRICTION MANIPULATION MECHANISMS AT EACH END OF THE ROBOT. THE $8.5MM$ DEEP GROOVES IMPART ANISOTROPY TO THE OTHERWISE ISOTROPIC MATERIAL AND FACILITATE MORE DEFORMATION ABOUT THE LENGTH OF THE ROBOT AS COMPARED TO THE WIDTH. THE FRICTION MANIPULATION MECHANISM INCLUDES A COMPARTMENT TO HOLD THE MOTOR OF THE MOTOR-TENDON ACTUATOR. THE SIGMOID SHAPED TENDON CHANNELS START AT ONE EDGE AT $4MM$ DISTANCE FROM THE EDGE (YELLOW CIRCLE). THE CHANNELS TERMINATE AT $85MM$ ALONG THE LENGTH AND DMM FROM THE OPPOSITE EDGE (RED CIRCLE).

Actuator Design

The robot is actuated using a motor-tendon actuator where the motors are enclosed inside a rigid compartment inside the virtual grip friction manipulation mechanism (Figure 3). The motors, upon actuation, wind the tendons attached at a point on the robot and deform the robot body. The tendons unwind due to intrinsic elastic forces for the deformed body. Actuation causes a mode of deformation that rotates the friction manipulation mechanism, causing the material in contact with the ground surface to switch, as seen in Fig. 5. The deformation of the robot body also determines the normal force distribution acting along the line of contact between the robot friction mechanism and the ground surface. This normal force profile affects the direction of controlled rotation of the soft robot. Hence, the soft body deformation is determined by the shape of the constrained tendon channels along the robot body. This deformation is caused by shortening of the polyamide tendon fixed on the internal end

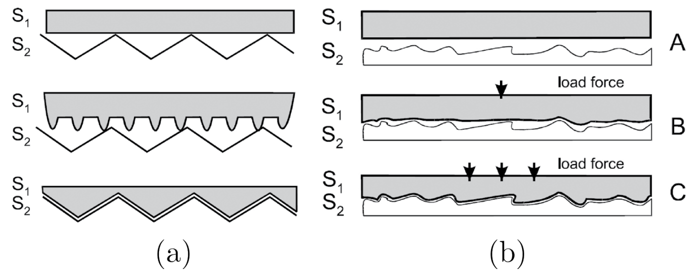

FIGURE 4. SURFACE INTERACTION COMPARISON. FRICTIONAL FORCES DEPEND ON THE INTERACTION BETWEEN THE SURFACE IRREGULARITIES (A) FRICTIONAL FORCE BETWEEN TWO INTERACTING HARD SURFACES IS MAXIMUM WHEN THE SIZE OF SURFACE IRREGULARITIES IS COMPARABLE. (B) SOFT MATERIAL CAN FLOW AND CONFORM TO IRREGULARITIES OF HARD SURFACE OF INTERACTION TO INCREASE FRICTION BETWEEN INTERACTING SOFT AND HARD SURFACES. [19]

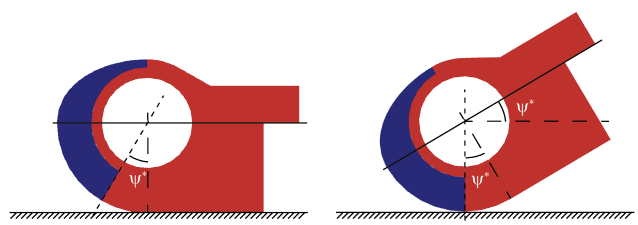

FIGURE 5. VIRTUAL GRIP FRICTION MANIPULATION DESIGN. THE DESIGN DISCRETIZES THE ROBOT-SURFACE FRICTIONAL INTERACTION AS A FUNCTION OF ROBOT SHAPE (CONTACT ANGLE ψ). THE FRICTION FORCE ACTING ON THE MECHANISM CHANGES ABOUT THE CRITICAL CONTACT ANGLE (ψ^*) RESULTING IN CHANGE IN MATERIAL OF CONTACT - SOFT (RED) OR BLUE(HARD).

of the channel with other end attached to a motor-pulley system (yellow and red circles in Fig. 3).

Simulation and tendon channel design. Using Autodesk Inventor®stress analysis module is used to explore the constraint tendon channel paths. As mentioned earlier, the tendon channel shape determines the controlled direction of rotation. This is result of the normal force gradient acting along the contact between the robot and the ground. Here, we were able to simulate the body deformation in the z-axis (ground plane) upon actuation in a fast yet pragmatically useful manner. The z-axis deformation can be assumed to be proportional to the normal force along the line of contact between the robot and the surface. To setup the simulation, the robot was reduced to the main body, motor

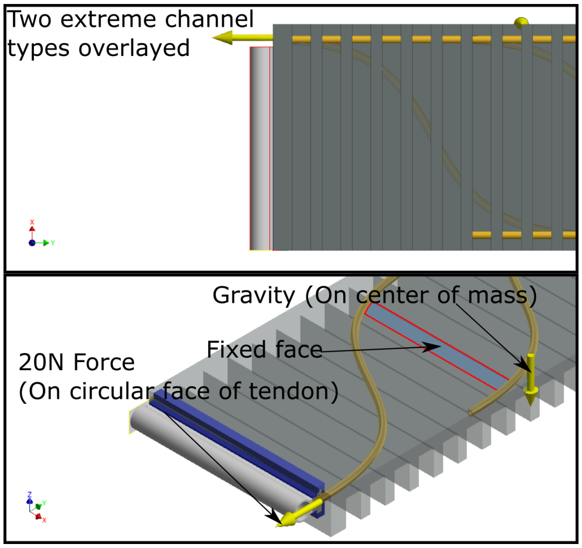

FIGURE 6. ILLUSTRATION OF SIMULATION SETUP. THE INNER MID FACE IS FIXED AND TENDONS ARE PULLED OUT THROUGH A $20N$ NORMAL FORCE ACTING ON THE CIRCULAR FACE OF THE TENDON. A RANGE OF 13 CHANNEL LAYOUTS IS SIMULATED THROUGH PARAMETRIC SIMULATION

mounts and motors (for weight). The body material was set to an elastic, "Silicone rubber" (isotropic, Young's modulus $100MPa$). Tendon material was set as a more rigid "ABS Plastic" (isotropic, Young's modulus $2.9GPa$. The motor was set to be steel (for the high density). A parametric simulation was conducted, varying the distance of the inner end of the tendon channels from the outer walls - 13 configurations were simulated (From I shape channel layout to Simple S shape as explained in Fig. 8). All contact surfaces were set to "bonded" except for the outer face of the tendons (shown in gold in Figure 6) and the channel paths they go through that were set to a sliding contact with no separation. Gravity was turned on to allow for the motor weight to have an impact. While this simulation is only an approximation of the actual robot behavior, it was sufficient to explain why the robot deforms the way it does by simply simulating a pull on the tendons in the different configurations. The Figure 7 shows the results of the simulation for various configurations for d (the parameter varied in the simulation). From the graph and heatmaps we can see that there is a gradient in deformation in the z-direction which accounts for a gradient in normal force distribution and in friction. This, in-turn, causes a moment to induce rotation on the body. In this case, the simulation corresponds to reality and is a good example on how parametric simulation on the tendon paths can aid in predicting the robot behavior without stepping outside a familiar design environment.

However, this simulation is based on static stress analysis and does not accurately model all the terrestrial interactions. For this reason, using SLA 3D printing allows quick validation of prototypes. Figure 8 shows three different channel paths that were printed and each configuration delivers a different mode of deformation to the soft bodied robot. As a result, when experimenting with the manufactured robots, there was a difference in response to specific actuation sequences. Most importantly, while actuating a certain locomotion sequence, I-shape robot ($d = 56mm$) rotated counter-clockwise, Simple-S shape rotated in clockwise direction ($d = 4mm$) and Midline S-shape ($d = 30mm$) shows little to no rotation. The prototype testing was a very important step in the design of this soft robot as it highlighted the various design flaws missed by simulation e.g. problem arising from tendon movement along the constrained tendon channels - the hard polyamide tendons cut through the soft robot body and damaged the soft robot body. This interaction is unique to soft robot design actuated by motor tendons where the tendon is embedded inside the robot body. The problem was tackled by coating the inside the the tendon channel walls with hard material (one of the advantages of multi-material SLA). Here, simulation allows exploration of different tendon channel designs and validation by 3D printing in an iterative manner. This approach will be an important tool in unique soft robot design development as it allows exploring multiple designs in parallel (simulation) and experimental validation (rapid prototyping).

Resulting Locomotion

The resulting locomotion of the robot is dictated by the viscoelastic properties of the materials comprising the body. It is the nature of viscoelastic materials (such as the resins used here) to exhibit a modulus that is proportional to the rate of strain. The faster the rate of deformation is, the higher the modulus appears to be (analogous to non-Newtonian fluids in fluid mechanics). Moreover, viscoelastic materials will exhibit a recovery time; After a load is removed, there may be a short time period for deformation to recover. This time depends on the temperature of the material or, more precisely, the difference between the materials current temperature (assumed room temperature) and its glass transition temperature [20]. As such, given a specific torque to wind the tendons and deform the body (from the motors), the rate of body deformation limits the locomotion. In addition, after the torque ceases and the tendons unwind, the rate at which the robot's soft-body un-deforms will potentially limit how soon the next step in actuation can take place. This viscoelastic property of elastomers is important in determining the actuation sequence of the motor-tendons. Figure 9 illustrates a locomotion that actually capitalized on this property as it allows a transition at the time when the soft body was still deformed to an arch shape and elevated above the substrate. This locomotion mode allowed higher speed as less energy was required to re-deform the soft body (as it was already very close to the desired deformed state from the previous actuation). So in this case, not allowing full

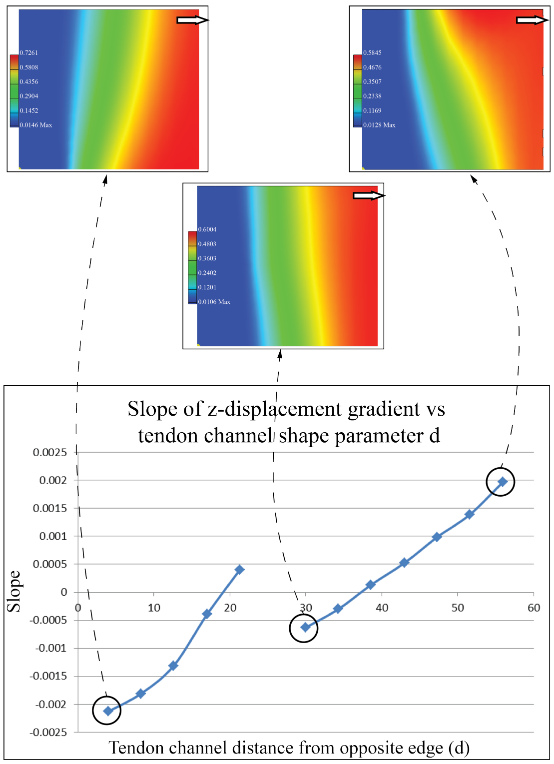

FIGURE 7. PLOT OF THE SIMULATED DEFORMATION IN THE Z-DIRECTION FOR A RANGE OF ROBOT CONFIGURATIONS. THE COLOR HEATMAPS SHOW THE DISPLACEMENT FOR THE 3 MANUFACTURED CONFIGURATIONS, FROM LEFT TO RIGHT SIMPLE-S ($4MM$) MIDLINE-S ($30MM$) AND I-SHAPE ($56MM$). HERE THE CONFIGURATIONS ARE DEFINED BY THE DISTANCE OF THE CHANNEL FROM THE OPPOSITE EDGE OF D. THE ARROW INDICATES THE END-POINT OF THE CHANNEL.

recovery of deformation actually benefits deformation.

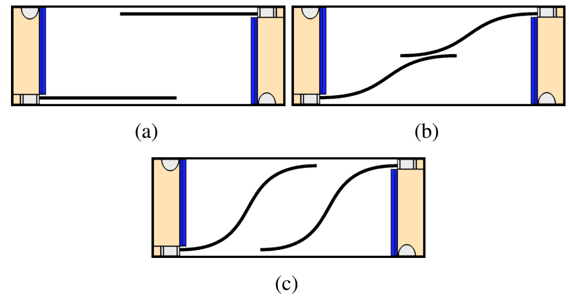

FIGURE 8. THE THREE TENDON CHANNEL SHAPES EXPERIMENTALLY EXPLORED WITH THE ROBOT. THE TWO OVERLAPPING TENDON CHANNELS DEFORM THE SOFT BODY INDEPENDENTLY. DEFINITION OF D IN FIG. 3. THE ROBOTS FOR $D = 56MM$, $30MM$, $4MM$ ARE REFERRED TO AS THE (A) I-SHAPE, (B) MIDLINE S-SHAPE AND (C) SIMPLE S-SHAPE SOFT ROBOT RESPECTIVELY.

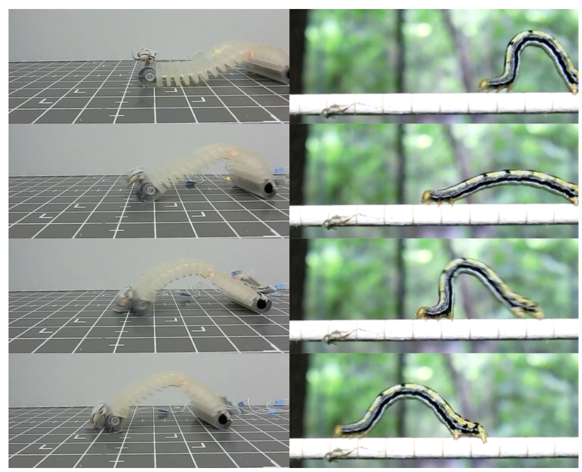

FIGURE 9. RAPID ACTUATION OF THE MOTORS, ALONG WITH THE VIRTUAL GRIP, PROMOTE A GALLOPING LOCOMOTION WHERE THE SOFT BODY IS ELEVATED ABOVE THE SUBSTRATE (ON THE LEFT) AS OCCURS IN ACTUAL CATERPILLARS (ON THE RIGHT)

CONCLUSION

Soft robots are typically designed using casting methods. However, the advancement of multi-material Stereolithography additive manufacturing technology provides advantages for iterative prototyping for exploration of soft robot design with different actuators. The research conceptualizes a design methodology for soft robot design and manufacturing. It also discusses a study case on the body and actuator design for a bio-inspired soft robot. The multi-material printing ability is utilized for design of shape dependent virtual grip friction manipulation mechanism. The virtual grip mechanism comprises of two materials and alters the material of contact with the surface (as a result, the friction force between the surfaces). The robot body is a rectangular slab comprising of ribs which impart anisotropy to the otherwise isotropic material through structural design. The motor-tendon actuators comprise of a brushless motor situated inside a compartment in the virtual grip mechanism that winds and relaxes the polyamide tendons located inside the robot body and constrained along a path (tendon channel). The shape of the tendon channels determines the deformation of the robot which influences the normal force gradient between the friction mechanism and the contact surface. The design of the tendon channels is done using a quick, simple-to-setup simulation and is supplemented by prototyping using additive manufacturing. Prototyping is essential to explore design flaws difficult to simulate. This resulted in design of hard-coated tendon channels to avoid interaction between the hard polyamide tendons and the soft robot body. Further, the simulation supplemented the possible designs of robot (I-shape, Midline S-shape and Simple S-shape) that result in different rotation behaviors. This illustrated how simulation and multi-material additive manufacturing are complementary tools for soft robot design. Additive manufacturing facilitates rapid design variation and is a powerful prototyping tool, however, constrains design exploration along the direction of material variation.

The resulting 3D printed soft robots displayed caterpillar-like locomotion and utilized the viscoelastic properties of the printed elastomer.

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