Sliding-layer laminates: a robotic material enabling robust and adaptable undulatory locomotion

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***Abstract*— Continuum robots that move through undulatory actuation must be composed of body materials that can enable flexible movement yet also provide resistive forces to the surrounding fluid, granular, or solid environments. This need for "flexible-yet-stiff" materials is notably important in robot designs that use passive propulsive elements such as tails and wings. Here we explore a laminate design paradigm for "flexible-yet-stiff" robotic materials through sliding layer laminates (SLLs). We present design principles motivated by theory and experiment and illustrate a taxonomy of SLL enabled morphable materials capable of up to 7 fold change in stiffness. Lastly, we demonstrate the applicability of SLLs to undulatory continuum robots we developed a swimming robot with a passive tail. We target two desired robot locomotor behaviors: fast open water swimming, and steady swimming through narrow channels emulating underwater caverns and pipes. We demonstrate how tuning the stiffness of the robot tail maximizes thrust generation in these two locomotion modes. Soft tails are optimal in confined swimming because they generate short amplitude high wavenumber oscillations, while stiff tails in confined environments either collide with the walls or do not generate sufficient thrust. However, stiff tails are far better in unconfined environments which enable large stroke amplitudes requiring high stiffness. Through this demonstration we show that stiff or soft tail designs alone are incapable of effective locomotion in complex underwater environments challenge.**

I. INTRODUCTION

Advances in robotics will be made through development of active, nonlinear, and unorthodox materials as building blocks [1], [2], [3]. Traditional robot materials have included rigid metals and plastics to compose the chassis, actuators, and manipulators [4], [5], [6]. Rigid systems thrive in industrial scenarios where precision is critical, however these robots present safety concerns in human-robot interactions and are limited in their adaptability and robustness in unstructured environments [7]. More recently soft-bodied robots have been developed with robot bodies and actuators composed of soft, flexible polymers [8], [9], [10]. Yet despite massive efforts in soft-robot design we still lack materials that are capable of rapid, repeatable, non-hysteretic, and low-energy variable compliance [11], [12], [13]. Tunable compliance materials may enable completely new functionalities to mobile robots and manipulation systems. For instance variable stiffness robot legs can enhance running robot performance [14].

Compliance modulation in robotics has been studied based on three main approaches, granular jamming effects, linear and non-linear spring designs, and through active material properties. The jamming phenomena can enable volumes or surfaces to increase in stiffness due to high internal friction forces generated by a controllable confining pressure. Two main approaches to jamming have been demonstrated. Granular jamming utilizes a membrane filled with frictional particles that when put under vacuum pressure generate internal friction and solidify [15]. Layer jamming uses layers of paper of other flat material which when put under pressure resist internal shear and thus resist bending [16]. Jamming systems have been used to develop variable stiffness medical devices [12], robotic grippers, and morphable structures [17]. While jamming is a versatile and impressive means of stiffness variation it is slow and requires cumbersome vacuum equipment. A more classic approach to stiffness variation is through machine design implementing linear and non-linear spring arrangements. Variable stiffness actuators, serial-elastic actuators, and other mechanisms that use kinematic linkages to make controllable stiffness systems [18], [19]. Lastly, there are many methods for compliance modulation that rely on active material properties such as dielectric-elastic polymers [20], [21].

A new and exciting direction for variable compliance in robot materials is through laminate and kirigami manufacturing methods [2], [22], [23], [24]. Recent work on the material properties of foldable and origami laminate systems has demonstrated a wide range of material behavior [25], [26]. In this paper we study a flat, variable compliance material fabricated through layer lamination with stiffness control

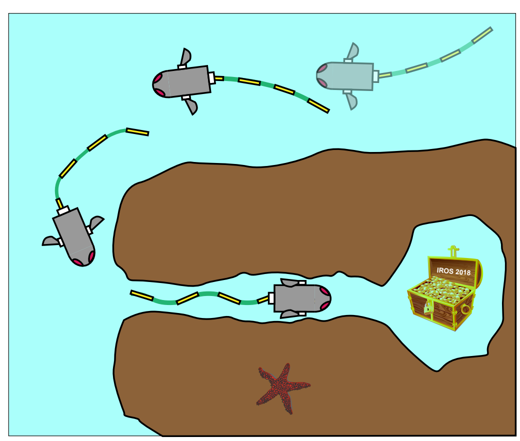

Fig. 1. Concept of a variable stiffness tail for an autonomous underwater vehicle capable of efficient propulsion in both open-water and confined environments.

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enabled by layer sliding. These sliding layer laminates are inspired by a previous study of overlapping structured laminate layers which demonstrated the feasibility of the concept [27]. A goal of this is to implement the variable compliance into a bio-inspired swimming robot's tail which is then capable of safely and efficiently exploring through complex and changeable aquatic environments (Fig. 1).

II. CONCEPTUAL DESIGN & MODELLING

Sliding-layer laminates (SLLs) are multi-stiffness laminated materials with stiffness modulation based on a sliding-layer mechanism. The conceptual design of SLLs is motivated by a laminate layers that have periodic stiffness variation along their length. When adjacent laminate layers are brought into or out of alignment their bending stiffness can change dramatically (Fig. 2a). The stiffness variation phenomena can be understood through a simple cartoon model of parallel and series springs of different stiffness (k_1 and k_2, with $k_1 >> k_2$). When the layers are aligned the composite stiffness of the system is dominated by the lower stiffness elements, and when the layers are anti-aligned the composite stiffness is higher due to the parallel interactions between the stiff and soft springs. However, unlike the spring analogy we can configure arrangements of layers over a continuum of overlapping states from 0% (anti-alignment) to 100% (perfect alignment) which potentially can lead to a continuum of stiffness variation in the composite beam (Fig. 2b). In this section we describe our modeling efforts to analytically design stiffness variation profiles in SLLs.

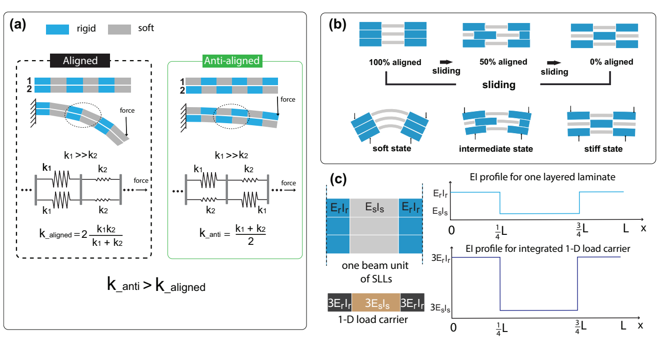

Fig. 2. Conceptual design of SLLs (a) A reconfigurable Dual-stiffness structure analogized by a corresponding spring system. (b) Multi-stiffness enabled by a tripple-layered SLL with intermediate stiffness states. (c) Modelling of SLLs variable stiffness using integrated EI profiles (based on Euler-Bernoulli beam theory)

A. Theoretical Multi-stiffness Analysis

Based on the dual-stiffness beam structure, we have developed a multi-stiffness model for SLLs. For simplicity we assume there is no relative sliding motion between layers and that deflections are small compared to the length of the beam. We focus here on SLLs that contain only three layer-laminates, with the central laminate sliding between the top and bottom laminates for alignment re-configuration. However, this concept is extendable to an indefinite number of layers with periodic patterns along different xy directions.

SLLs have multiple layered laminates each having periodic rigid and soft materials (Fig. 2b top). Based on the periodic stiffness regions on each layered laminate, a sliding-layer mechanism can be achieved to create different alignment states between the soft and rigid regions, leading to different bending performances of the whole beam (Fig. 2b bottom). To simplify the sliding-layer mechanism, we constrain the motion of both top and bottom laminates and change only the relative positions of the central laminate with regard to the outer laminates. Thus, the laminate alignment state is solely depended on the displacement of the central laminate. Due to the periodicity of the alignment states, the stiffness characterization of SLLs can be focused a single beam element with the alignment state varied from -100% (stiff) to 0% (soft) and back to 100% (stiff). We consider the $\pm 100\%$ range as opposed to the $0-100\%$ range because finite-size effects of the beams in experiment generate asymmetry between -100% to 100%. We use the alignment state as the input parameter to the modeling and assume that there is no layer sliding during beam bending, and thus the alignment state remains the same during the bending motion.

The modelling approach we have taken is based on Euler-Bernoulli beam theory and it provides a means of calculating the cantilever beam stiffness for beams with variable EI values. The Euler-Bernoulli equation describing the relationship between the beam's deflection and the applied loads is expressed as

$$\frac{d^2}{dx^2}(E(x)I(x)\frac{d^2\omega}{dx^2}) = q \tag{1}$$

where x is the horizontal position along the longitudinal direction, E is the Young's modulus (Pa), I is the second moment of area (m^4), ω is the transverse displacement of the beam at x and q is the distributed load (N/m). In this paper, we use assume a clamped-free cantilever with a point load at the free end for stiffness characterization. We used $M(x)$, the bending moment, as the load source and rewrite (1) as

$$M(x) = E(x)I(x)\frac{d^2\omega(x)}{dx^2} \tag{2}$$

Additionally, the deflection at each point along x can be integrated for a total displacement at the beam's free end, which can be expressed as

$$y = \int\int_L \frac{M(x)}{E(x)I(x)}dxdx \tag{3}$$

where y is the total tip displacement at the free end and L is the total length of the beam. The effective spring stiffness of an elastic beam can be expressed as

$$K = \frac{P}{y} \tag{4}$$

Based on the cantilever beam bending test, we have

$$M(x) = P(L-x) \tag{5}$$

By inserting (3) and (5) into (4) we have,

$$K = \frac{P}{\int\int_L \frac{P(L-x)}{E(x)I(x)dxdx}} = \frac{1}{\int\int_L \frac{(L-x)}{E(x)I(x)dxdx}} \tag{6}$$

Thus, the bending stiffness of beam with variable flexural rigidity can be expressed as (6). For SLLs with different longitudinal alignment states across multiple layered laminates in the transverse direction, the flexural rigidity can be simplified as the addition of multiple EIs at each longitudinal position x [28]. This is expressed as

$$E(x)I(x)_{int} = \sum_{i=1}^{n} E(x)_i I(x)_i \tag{7}$$

where $E(x)I(x)_{int}$ is the total flexural rigidity for all the composite beam elements at the same longitudinal position x and i stands for each composite layer. We then replace each soft and rigid region with EI values and combine them as a 1-D load carrier (Fig. 2c).

Here we choose $l_{soft} = l_{rigid}$ such that the unit can be divided into 3 different stiffness regions. Based on (7), we integrate the flexural rigidity in the transverse (column-wise) direction to generate an effective 1D-load carrier with EIs along the longitudinal direction x. By changing α, the alignment percentage, we can achieve different rigidity matrices within the same SLL beam unit, which forms different EI topologies of the 1D-load carrier (Fig. 2c left). Finally, we extract the varying EI values from each individual laminate and integrate them as EI profiles for the 1-D load carrier (Fig. 2c right). Finally, the $E(x)I(x)$ from (6) can be determined by the transversely integrated EI profiles for calculating the effective spring stiffness at the tip end for any alignment state of the SLLs.

B. *Design Principles in Modulating Stiffness Variation*

From the above derivations, the effective bending stiffness at the SLL tip is closely related with the EI profiles under different alignment states. In this part, we introduce two design principles to discuss possible EI profiles and investigate different paths for stiffness-alignment curvatures. The design principles we focus on are: 1) material choice in SLL composition, defined as changing the flexural rigidities of the soft and rigid regions which affects the lower and upper limits of the EI profiles. 2) The aspect ratio of rigid and soft regions, defined as the ratio of the rigid region across the length of one beam unit. In our computational analysis the SLLs contain 100 beam units (EI periods) with one beam unit having a non-dimensional unit length 1.

Fig. 3 demonstrates the two different principles we explored in SLL stiffness variation. Fig. 3a and Fig. 3b demonstrate how results from changing the material choice (EI of stiffness regions), where the effective bending stiffness varies with the changing alignment percentage, with the stiff state occurring at 0% and the soft state occurring when the SLL is aligned (-100% or 100%). A symmetric stiffness variation is guaranteed for SLLs with many (>10) beam units but when we compare to experiment we will see this symmetry disappears. By increasing the young's modulus of the stiff regions (E_rI_r) while keeping constant the soft region material properties (E_sI_s), we observe that the 0% alignment state stiffness increases linearly while the $\pm100\%$ state stiffness marginally changes (Fig. 3a). The inset shows the stiffness gain of the stiff and soft alignment states with changing E_rI_r. On the other hand, increasing E_sI_s while keeping E_rI_r results in a linear increase in the $\pm100\%$ stiffness with the stiffest state stiffness remaining relatively unchanged (Fig. 3b). These calculations reveal that material selection for SLLs governs the stiffness variation range of the SLL structure.

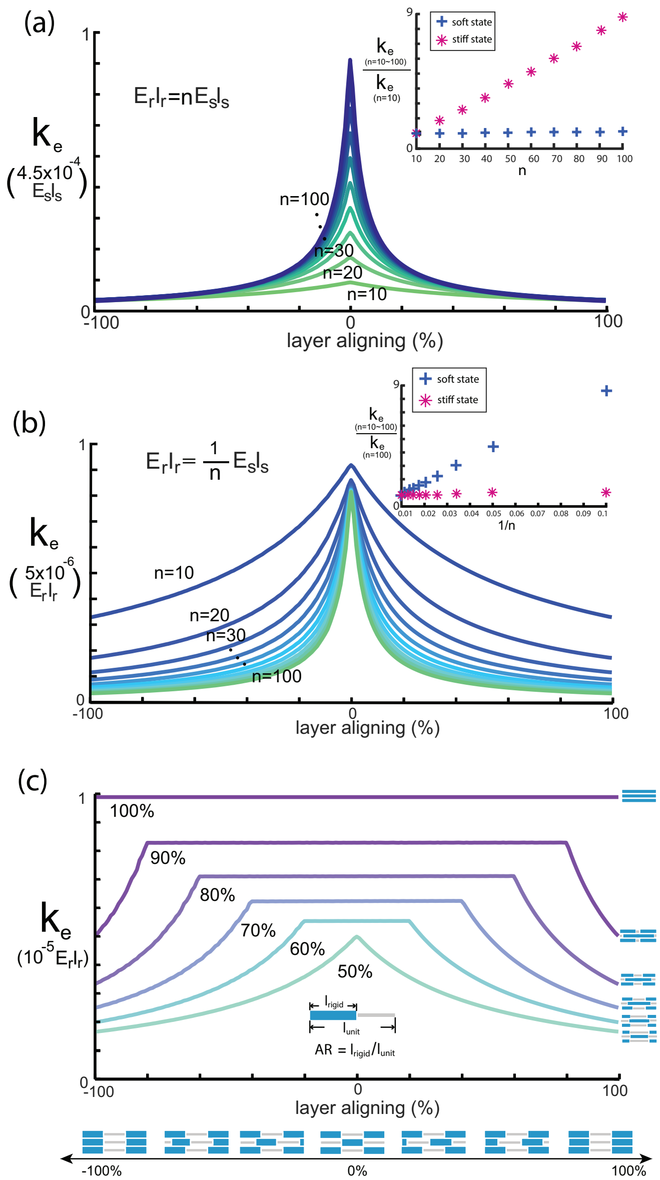

Fig. 3. Effective bending stiffness modeling from SLLs containing 100 beam units using cantilever beam test based on Euler-Bernoulli beam theory (a) Varying $E_rI_r = nE_sI_s$ (n= 10,20,...,100) (b) Varying $E_sI_s = \frac{1}{n}E_rI_r$ (n=10,20,...,100) (c) Changing beam aspect ratio from 50% to 90%.

By using different aspect ratios (ARs), we changed the overlapping areas between the inner and outer rigid regions from the adjacent layered laminates. Through control of aspect ratio we control the sensitivity of the stiffness variation with alignment state (Fig. 3c). With AR = 50% the stiffness gradually changed while at higher aspect ratio a high stiffness is maintained over a long range of inner layer displacement. The elongated rigid regions (shortened soft regions) increased the SLLs' stiffness on both ends (stiffest and softest states). Such a result reveals the fundamental role of aspect ratio in changing the sensitivity of the SLLs' stiffness-alignment curvatures, where beam stiffness could be modulated either in a graded (continuum) fashion or as a binary material property (stiff or soft).

III. FABRICATION

We use a laser cut and laminate fabrication approach to design and test SLLs. As discussed in the conceptual design section above, structural layers (FR-4, 0.12-0.50mm), compliant films (Kapton, 12-50μm), adhesive layers (double-sided pressure-sensitive-adhesive films, 3μm) and boundary layers (tape or the combination of both compliant and adhesive films) are necessary for the fabrication of multi-stiffness SLL structures. Each layer is designed with its own beam profile to achieve periodical stiffness patterning in one layered laminate (Fig. 4a).

The individual lamination for one layered laminate combines laser cutting, precision alignment with dowel pins, and pressure sensitive adhesive bonding using a hydraulic press. This process is divided into 4 consecutive steps, individual material cuts, alignment, final cuts, and SLL release (Fig. 4b). We first cut all composite layers (the structural/adhesive/compliant) with stiffness patterning and alignment holes. To form a central layer that will slide without binding we laminate this layer with compliant films on the top and bottom of the laminate. We then align all the individual layers using dowel pins and adhere the pressure sensitive adhesive in a hydraulic press. We then place the SLL back in the laser and perform the final cut of the laminated layer. This is done by alignment of the laser head with each corner of the SLL piece and we cut with a higher power density. Note that double sided compliant films might cause buckling effects and thus we used very thin Kapton (25.5μm) films where buckling does not affect the bending performance of the SLLs.

Following the same steps as the central layer, we prepared the outer laminates with same stiffness patterning. To fix the motion of the outer laminates, two layer-boundaries have to be positioned on the sides to generate a continuous bending motion. Once the outer layers are bonded we insert the central layer into the SLL with (Fig. 4c). A prototype using FR-4 and Kapton flexures is shown with different alignment state and bending performance in Fig. 4d.

IV. RESULTS & DISCUSSIONS

A. Experimental Setup

The bending stiffness of SLLs is characterized using the fixed end cantilever beam tests, shown in Fig. 5a. Instead of having a long SLL as a test specimen, here we focused on measuring the stiffness variation from a single beam unit of an SLL to have observable force readings under a small tip deflection range (Euler-Bernoulli beam theory). The effective bending stiffness of the specimen is then defined as the deflection force from a load cell (100g micro load

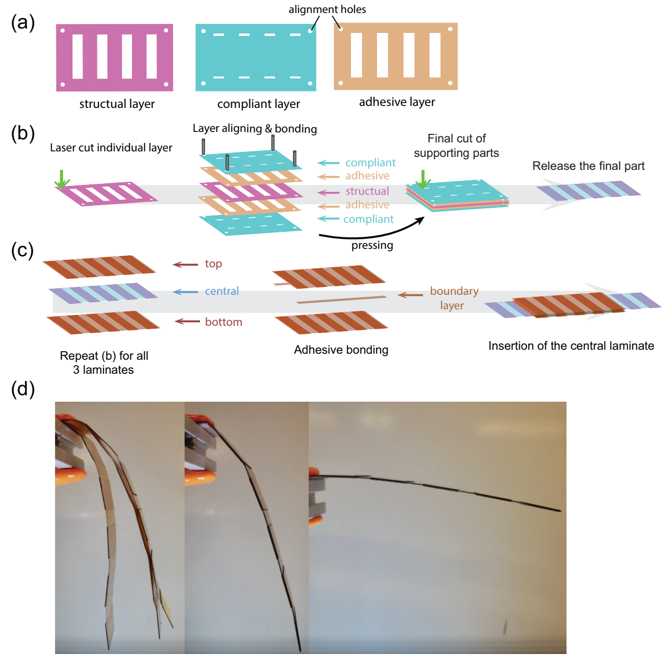

Fig. 4. The lamination process in SLLs fabrication (a) Beam profiles for each composite layer within one laminate (b) Steps for making one layered laminate (c) Steps for integrating a SLLs' beam structure (d) bending stiffness comparison of a SLLs' prototype including no boundary layers (left), with boundary layes in soft state (middle) and with boundary layers in stiff state (right).

cell, Phidgets) divided by the deflection distance controlled by a linear stage (Thorlabs). Specifically, we fix the SLL onto a stationary stage while driving the load cell against the SLL using a motorized linear stage. The linear translation is controlled by a stepper motor (Oriental Motor, PK546PMB) connected to the stage using a flexible coupling (SDP/SI) connected with a machined coupler. We measured the effective bending stiffness based on a series of laminate alignments and compared with the modelling stiffness based on two design principles.

B. Results from Changing the E_rI_r and E_sI_s

As predicted by the modelling, changing E_rI_r significantly affected the stiffness of the SLL in the stiff states with little influence on the soft states' stiffness; while changing E_sI_s changed the stiffness in the soft state with little effect on the stiff state stiffness. This test experimentally demonstrates that to separately control the stiff and soft states one can do so by changing the flexural rigidities from the stiff and soft beam regions. Furthermore, these results show excellent agreement with the predictions from our theory developed in previous sections. The theoretical predictions have no fitting parameters with equation constants solely based on material properties, thus showing excellent agreement between experiment and theory.

Changes to the SLL beam width of the rigid and soft regions will also change the effective cross-sectional moment of area, I, and thus will manipulate the flexural rigidity of the two stiffness regions. The designs we used are all

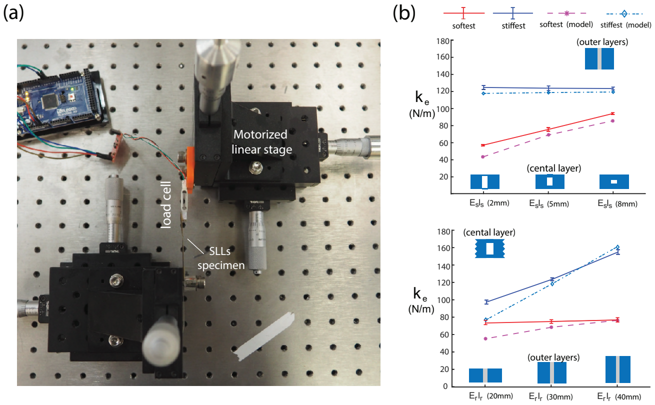

Fig. 5. Experimental testing of SLLs effective bending stiffness (a) Cantilever beam bending stiffness measured using SLLs specimen (one beam unit) fixed on a stationary stage with one load cell driven by a motorized linear stage. (b) results from changing flexural rigidities of soft and rigid regions compared with the modelling.

40 mm in length, with 2mm, 5mm and 8mm the beam width of the soft regions and 20mm, 30mm, 40mm the beam width of the rigid regions. In Fig. 5b, we observe a linearly increased bending stiffness in the soft state by keeping the E_rI_r (30mm) while changing the E_sI_s (2/5/8mm). On the other hand, by keeping E_sI_s and changing E_rI_r, we observed a linear stiffness increase in the stiff state but little variation of the soft state. The experiment results are an average over 5 independent stiffness tests and the predicted stiffness is based on the EI profile modelling, which strongly agrees with the testing results without any fitting factors.

C. Results from Changing the Aspect Ratio

The change of aspect ratios is an important design principle for changing the sensitivity of the stiffness variation. To validate the modelling, we fabricated one beam unit SLL specimens with the same material choices (FR-4 0.25mm, Kapton 25.5 μm). From aspect ratio 50% to 90%, we changed the length of the rigid regions in portion of the length of one beam unit while keeping the same values of E_rI_r and E_sI_s (Fig. 6 upper left).

In Fig. 6, each figure exhibits the stiffness-alignment curvature of SLLs with different aspect ratios. With the increasing aspect ratio, the stiffness of both the stiffest and softest states rose approximately 3 times (from 50% to 90%); however, as we increase the aspect ratio the stiffness stays in the stiff for larger alignment displacements. This affects the sensitivity of the stiffness variation against the sliding motion. Such a feature can be used for designing either graded (60%) or binary SLLs ($80-90\%$) where stiffness variation and sensitivity can be tailored for different applications. For instance, the binary SLL can be used in areas where the variable stiffness is desired for an on-off pattern with the on-state stiffness as high as possible. Since the transition between the on to off state is shorter, the actuation requirements would require less displacement and thus less energy consumption; while the graded SLL can be used for cases where stiffness has to be gradually changed using continuous actuation methods. Consequently, the difficulty of the linear sliding motion will increase with the decreasing size of the SLLs' design. As a comparison, the predicted stiffness with only one SLLs' beam unit strongly agrees with the experimental results in high aspect ratios. For low aspect ratio (50%), the model overestimates the data due to the 3D design imperfections leading to a discontinuous bending curvature of the stiffest state.

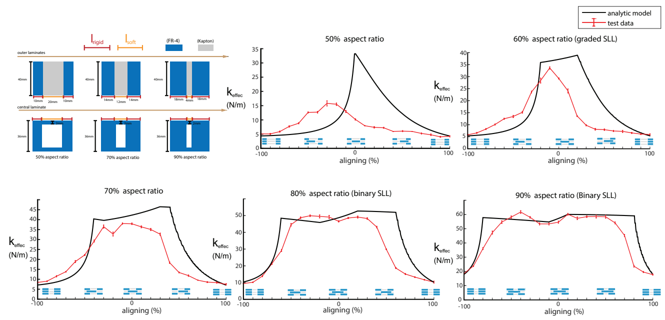

Fig. 6. Thrusts measured from SLLs flapper under two sets of driving conditions.

V. DEMONSTRATION

A. SLLs enable optimal swimming propulsion in both open and confined underwater environments

We have so far considered SLLs as an abstract material capable of stiffness variation. We now seek to use this stiffness control for a flapping tail of a autonomous underwater vehicle (AUV) concept (Fig. 1). We hypothesize that variable mechanical stiffness of a fish-inspired AUV tail will enable high functionality for exploring complex and confined underwater environments. Our bio-inspired approach is motivated by biological observations in which fish swimming performance under different driving conditions is optimized for different tail stiffness [29], [30]. In this paper, we considered SLLs as a passive tail and we target two desired robot locomotion patterns: high-frequency and amplitude open water swimming, and low-frequency, low amplitude swimming through a confined tunnel (or pipe).

We first consider SLLs with dual-compliance states flapping under two driving amplitudes (high and low) and measured the thrusts using a load cell. The thrust is measured over a range of frequency from 2-5 hz. We measure thrust using a robotic swimmer confined to move along a linear trackway. The SLLs oscillation creates thrust and drives the robot forward on the trackway eventually reaching a load cell (Fig. 7a). We used a solenoid to actuate the central layer of the SLL to dynamically control the alignment state. We performed thrust measurements over a range of frequencies and amplitudes and recorded the averaged forces from the load cell. The SLLs tails are fabricated using FR-4 (0.685mm ,0.787mm), Kaptons (0.05mm) and Mylars (0.178mm) (Fig. 7b). For the outer case (104mm x 40mm), we chose a half laminated design where only one layer of Kapton (0.05mm) and FR-4 (0.685mm) are laminated together with the Kapton facing inward for a smooth sliding interface. The central laminate (137mm x 32mm) is a full laminated design with two layers of Mylar (0.178mm, $E-0.199Gpa$) covering the FR-4 (0.787mm). Here the soft regions are cut into one strip of Mylar (beam width 3mm), such as to have both an observable stiffness change and a easy pull and push sliding motion. Here we demonstrate that by undergoing pure self-weight, the tip displacement difference of two stiffness states are about 4 folds, meaning that the effective bending stiffness from the stiff state is around 5 times the one in the soft state (Fig. 7c,d). A picture of the experimental designs is shown in Fig. 7e.

Based on all the prerequisite parameter settings, we drove the SLLs under the two extreme stiffness states and measured the thrusts using a load cell over a range of driving conditions, where the raw data displays the change in thrust generations shown in Fig. 8a. Fig. 8b shows two sets of comparisons of thrust generation between the stiff and soft state SLLs in both a low ($\pm 7.2°$) and a high driving amplitude ($\pm 14.4°$) over a range of driving frequencies (from 2 hz to 5 hz). As we measured the thrust generations under a low amplitude ($\pm 7.2°$), the stiffest state SLLs is better than the softest state SLLs in thrust generation in low frequency regimes; however, by increasing the driving frequency, the thrusts generated by the softest state SLLs are increased and comparable with the thrusts by the stiffest state SLLs (Fig. 8b top). The data is based on 5 independent tests with averaged value and standard deviations. On the other hand, as we repeated the same experiments under a higher driving amplitude ($\pm 14.4°$), two different thrust peaks are exhibited for both the stiff and soft state SLLs, where the stiff state SLLs can be effective in thrust generation around 4hz and 3hz for the soft state SLLs (Fig. 8b bottom). This indicates that an optimized swimming speed or force is related with the combination of driving conditions and the tail stiffness, and thus the variable stiffness SLL can be exploited for improved swimming performance as a response to each variable working and driving condition.

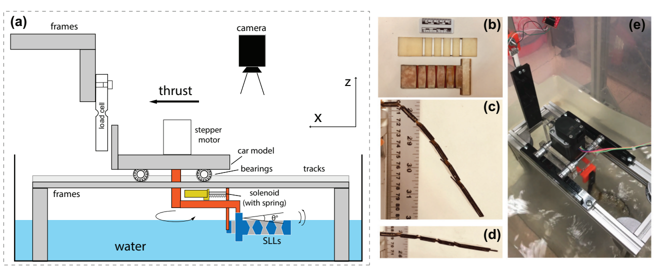

Fig. 7. Measuring thrusts from the SLLs flapping motion using a water-track system. (a) Experimental setups for thrusts measurement. (b) SLLs tail prototype (c)(d) are bending performances between stiff and soft states. (e) Isometric view of the water-track experimental system.

B. Open-water vs. Confined space undulatory swimming performances

Based on the previous measurement of the thrust generations from SLLs' passive propulsor under 2 different states, we proposed another use of variable compliance SLLs

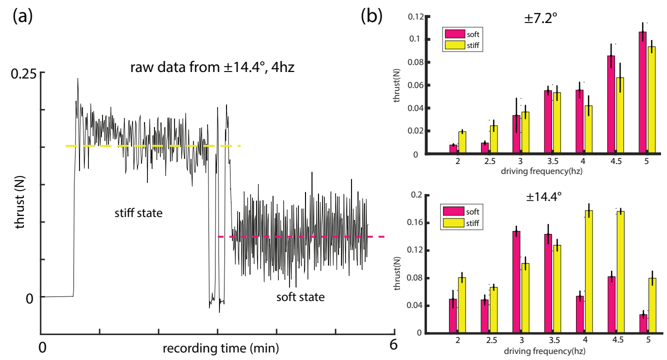

Fig. 8. Thrusts measured from SLLs flapper under two sets of driving conditions. (a) Raw data from one driving condition of one test. Here we used solenoid for changing beam stiffness and thrust generations. (b) Results from sweeping amplitudes $\pm 7.2°$ over 2-5Hz. (c) Results from sweeping amplitudes $\pm 14.4°$ 2-5Hz.

navigating through structured aquatic environments. Namely, we hypothesize that a high-frequency swimming pattern in open water would be optimized by the high-stiffness SLL state, and a slow but steady swimming pattern through a narrowed confined space would be optimized by the soft stiffness SLLs state. To demonstrate this, we exploited the same design concept by using a double-rail system with a longer SLLs as a passive propulsor (Fig. 9a). In the system, 2 sliders combined with a acrylic plate consists of the base of the swimmer, where the SLLs are connected with the stepper motor using a coupler to generate thrusts in the water. As a demonstration, we drove the swimming robot in both a open water scenario (in a water tank) and a narrowed channel space (45 x 392mm, with 2 acrylic plates sitting on the bottom of the tank as the walls) (Fig. 9b). We then tracked positions of the tails and sliders along the rail system and observed the swimming performance. Figure 10 illustrates the performances of the robotic swimmer navigating through dual-water environments. Note that a high sweeping amplitude will increase the thrust generation[29], we choose a high sweeping amplitude to maximize the thrust. In the open water, stiff state SLLs can generate powerful strokes with a high sweeping amplitude ($\pm 72°$)), which can easily navigate along the rail system (Fig. 10a); however, a soft state SLLs driven with the same condition will not be efficient enough to glide through the rail system. On the other hand, as we built the walls and restricted the flapping motion of the SLLs tail, the soft state SLLs is found useful in generating low amplitude ($\pm 21.6°$) steady motion through the channel whereas the stiff state can only pass through the first half of the channel as the tail's end is hitting onto the acrylic walls (Fig. 10b). This can be explained by the physical interference between the two objects combined with the water reaction effects caused by the stiff SLL tails pushing water to the sides. Since more water is pushed to the sides instead of backwards, the total thrust generated is worse in this case. The results from the robotic swimmer indicate a potential application for variable stiffness passive propulsors in aquatic environments. Such a result opens up opportunities for building robots to exploit new tunable compliance materials that can maintain optimal swimming performance over a range of working conditions.

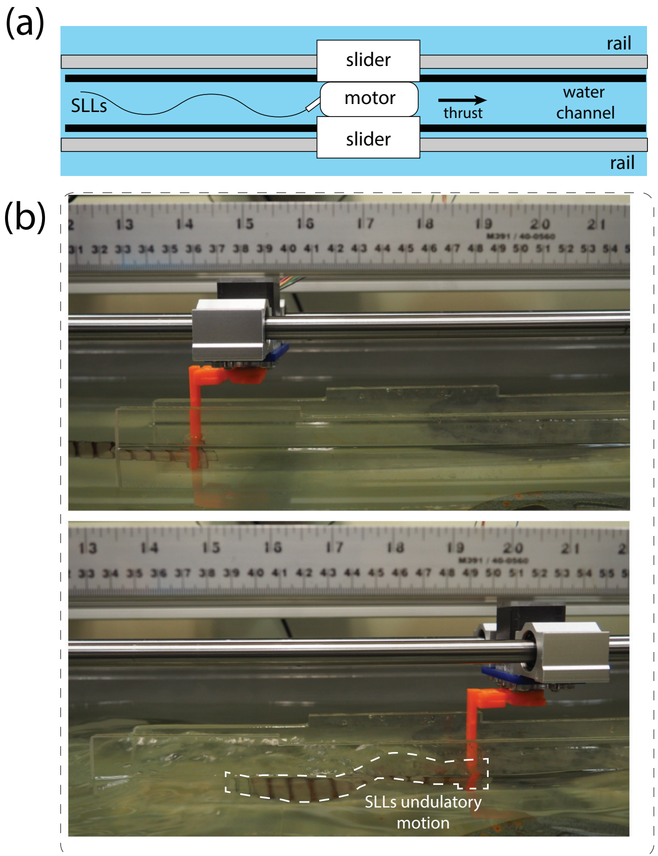

Fig. 9. Setups for rail-based SLLs robotic swimmer (a) Diagrams of robotic swimmer swimming through a confined channel using SLLs tail from top view (b) Robotic swimmer passing through a confined channel based on undulatory motion of the SLLs propulsor (driven by a stepper motor).

VI. CONCLUSION

In summary, we have demonstrated that the Sliding-layer mechanism of laminates can be exploited to create flexible and morphable materials with variable beam compliance that can be integrated into mobile robots as passive appendages achieving undulatory locomotion through multi-modal environments. Although many have proposed variable stiffness structures using spring systems (virtual spring), jamming effects, and electroactive materials in recent years, we believe that the SLL approach proposed and studied here provides a simpler, faster, and cheaper technique to create such a “flexible-yet-stiff" tunable structures. Our SLLs are simple to fabricate through lamination techniques, using laser cutting tools and adhesive bonding process.

Based on Euler-Bernoulli beam theory, we have shown that the stiffness-alignment curvatures of our SLLs can be manipulated by changing three design principles which corresponds to three aspects of the EI profiles of each composing laminate. Moreover, by conducting experimental tests using SLLs with only one beam unit, our results

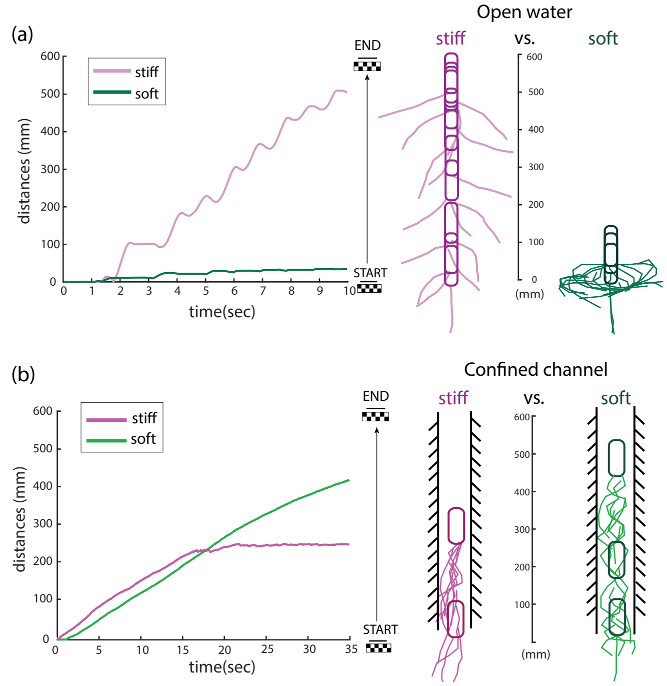

Fig. 10. Tracking of robotic swimmer under a dual aquatic environments (a) Open-water high amplitude swimming pattern (tracking every 0.67 seconds). (b) Confined space steady speed swimming pattern (tracking every 3 seconds).

strongly agrees with the theoretical modelling based on the EI profile based on 2 design principles. However, the predicted stiffness-alignment curvatures of the low aspect ratios overestimates the experimental data, indicating the stiff regions not fully engaged into the bending motion caused by spatial gaps between laminates. Although we have focused on elastic bending stiffness enabled by such a layer reconfiguration, the concept of modular materials with self-reconfiguring mechanism can also be applied to different physical properties such as ductility and visco-elasticity. In addition, since the changeable properties of the designed SLLs are primarily governed by the geometry of the structure rather than the constitutive properties of the material, the proposed principles can be applied to systems over a range of length scales and fabrication methods, such as 3D printed materials and mirco-fabrications. Hence, recent advances in top-down techniques, such as micro laser cutting and photolithography, will bring up opportunities for miniaturization of the proposed architectures. On the other hand, using thicker and stiffer blocks or sheets can be used to realize beams for larger robots such as planetary navigators or flying vehicles for space exploration.

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