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INCREASING THE LIFE SPAN OF FOLDABLE MANIPULATORS WITH FABRIC

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ABSTRACT

This paper evaluates how laminated techniques may be used to replicate the performance of more traditionally manufactured robotic manipulators. This evaluation is conducted by addressing the advantages and challenges of laminated manufacturing techniques, specifically mechanism durability. In this study, we propose a novel fabric-polyester hinge design with an improved life-span. We additionally provide an overview of the design and construction workflow for a laminated 2-DOF spherical parallel manipulator for use as a camera stabilizer. Using the proposed manipulator as a case study, we demonstrate that mechanisms fabricated with lamination techniques can achieve similar performance to devices made using conventional methods.

1 INTRODUCTION

Origami-inspired robots may be considered a branch of soft robots, distinguished by its use of flexure-based hinges and origami-inspired manufacturing techniques. These robots are affordable and fast to manufacture. One of the most popular methods of manufacturing these robots is using laminated techniques. This process involves cutting individual layers of material, stacking, aligning and fusing individual layers together into a composite, and then releasing the resulting hinged laminate with a secondary cut as in Figure 1.

Taking advantage of laminating techniques in the construction of robots can result in considerable savings with regard to fabrication cost and time, but the challenges caused by this technique must be addressed. This paper aims to demonstrate the feasibility of fabricating robotic manipulators via laminated techniques by tackling the issues of durability, an artifact of the laminate fabrication methodology itself. We propose a fabric-polyester hinge that increases the life span of laminated devices. This hinge layer consists of a polyester layer laminated between two fabric layers. Using this technique, a 2-DOF spherical parallel mechanism has been designed and built. This mechanism is both affordable and durable, with an embedded IMU sensor. While installing an IMU on mechanisms is fairly common, embedding the required circuit via easy and affordable manufacturing processes and the demonstration of using the embedded sensor can be beneficial to researchers.

Many construction methods exist for manipulators, but only a few groups investigate the use of laminate techniques for making multiple degree-of-freedom robotic manipulators, such as the delta robots presented in [1, 2]. These papers focus on high-speed manipulators at the millimeter and centimeter scale, respectively. Laminate fabrication techniques have been applied to a broad number of kinematic applications for locomotion, however. Planar four-bar mechanisms have been demonstrated in flapping-wing applications [3], and 5-bar spherical linkages have been pre-

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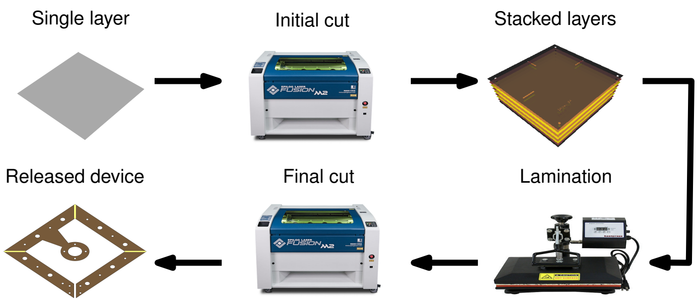

FIGURE 1. Procedure of making a laminated device using PopupCAD as design program and heat press and laser cutter as machinery.

viously used to drive 2DOF leg joints in micro-robotic walking applications [4]. A class of mechanisms known as Sarrus linkages have been used in linear actuators [5] and assembly scaffolds [6]. Numerous foldable robots use laminated techniques for different functionalities and goals by leveraging laminated techniques' advantages, i.e., scalability, affordability, weight, and agility. Among them, however, few manipulators have been implemented, especially at centimeter scales. The MilliDelta robot is a $15 \times 15 \times 20\,\mathrm{mm}^3$ robot that weighs 430 mg and is capable of moving a payload of 1.31 g [7], and can follow a periodic trajectory at frequencies up to 75Hz using piezoelectric actuators. A foldable haptic device called FOLDAWAY-Touch is being developed to be commercially introduced as a foldable, portable computer. In one version, presented in [8], a backdrivable Maxon DC motor is used with hall-effect sensors as feedback. The mechanism is attached to a HTC Vive VR interface for use in haptic applications. The most recent version can apply forces of up to 2 N at its end effector and stiffness of nearly 1.2 N/mm while tracking a user's finger [9].

In general, the mechanisms fabricated with laminated techniques can be characterized as low mass, small-scale devices for which material deformation due to payload is negligible or ignored, or devices that use exotic materials or less-accessible processes to reinforce links and eliminate the issues that accompany compliant end-effectors [1, 10]. Additionally, since this process is still used primarily within research settings, few papers focus on design issues such as mechanism lifetime or durability with a small number of exceptions [11–14].

The case study for this paper is a two degree-of-freedom(DOF) spherical parallel manipulator [15]. Parallel mechanisms leverage multiple pathways to the ground to achieve similar rigidity and precision to their serial counterparts, often with lighter components. Parallel robots are also often able to achieve higher end-effector speeds due to the fact that actuators can be proximally mounted on the fixed chassis, reducing loads on distal joints. These benefits make parallel mechanisms a rich area for research. Specific implementations include the Gough-Stewart platform [16, 17], Delta robot [18], 3RRR Parallel Planar Robot [19, 20], and the 3-Degree-of-Freedom (DOF) decoupled parallel robot [21, 22].

A number of studies have studied this mechanism's workspace for the purpose of optimization [23, 24], understanding its singularities [25], and computing its forward and inverse kinematics [15, 26] and dynamics. This mechanism has been used for applications such as camera stabilization [27] and object tracking [28]; two such manipulators have also been used in tandem in an active vision system [29]. While none of the research on this particular mechanism uses laminated fabrication techniques for construction of the manipulator, they demonstrate the general usefulness of this manipulator.

The paper is organized as follows: Section 2 describes the laminated fabrication technique and the challenges associated with it. In Section 3, we introduce solutions for increasing laminated mechanisms' stiffness and life span. A 2-DOF spherical parallel manipulator is then introduced based on the above mechanism; its design and fabrication is then discussed in Section 4. The paper concludes with some remarks and suggestions for future work indicated by obtained results in Section 5.

2 LAMINATED TECHNIQUES AND THEIR CHALLENGES

A typical laminate layup consists of material layers which each perform separate functions based on their material properties. This includes rigid materials, which can be used to form rigid kinematic links, flexible materials, which can be used used to create flexure joints at desired locations, and adhesive material, which is used to selectively join neighboring material layers into a monolithic mechanism. One commonly-used layer ordering is (rigid, adhesive, flexible, adhesive, rigid). The symmetric order of these materials with the rigid material on the outside is thought to reduce peeling and delamination between layers. The rigidity of the laminate can be tuned by adjusting the thickness of the rigid layer, switching to a stiffer material, or adjusting its planar offset from the layup's medial axis. Additionally, other material layers like copper can be added to the layup for conducting electricity.

A large number of materials including cardboard, acrylic, fiberglass, carbon fiber – even aluminum or steel – can be used as a rigid layer, as long as they are compatible with the available cutting techniques – water-jet, laser, etc – and bond well with available adhesives. The material type and thickness of the rigid material provides a vast de-

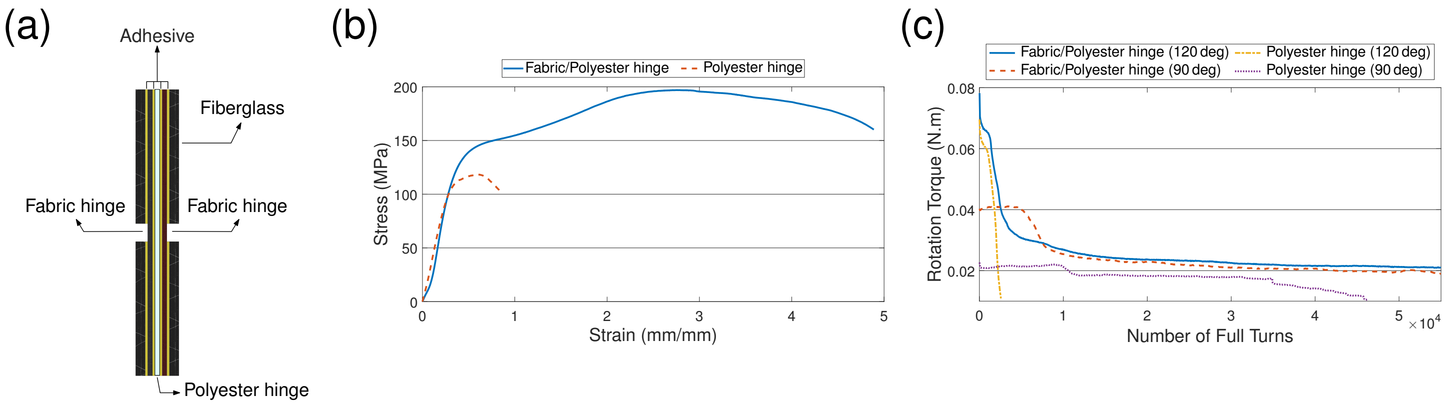

FIGURE 2. Increasing laminated hinge life span. (a) Layup of the proposed fabric-polyester hinge. (b) Tensile test data of polyester and fabric-polyester hinge. (c) Life span study on the hinges.

sign space in which one can balance rigidity, weight, cost, and durability.

The adhesive layer is responsible for gluing the rigid and flexible layers to each other, and should be selected based on adhesive compatibility with neighboring materials. The flexure layer is used in order to provide a rotational joint in laminated devices. Thus, it must be cuttable and robust against tearing and high forces, as well as exhibit a long lifetime. Many polymers and thin metals may be used; in our study we have selected polyester as an affordable, machinable, and flexible material.

There are, however, drawbacks to using laminate techniques for manipulator construction. One limitation is the finite range of flexure hinges, which are ultimately limited to $\pm 180°$, and even less when considering the thickness of the laminate. While using a ball bearing solves the problem in conventional mechanism designs, laminate mechanisms are not able to continuously rotate about an axis, playing an important roles in the design of laminate mechanisms. The length of the hinge region ('L' in Fig. 3) can be increased to improve range of motion to reach the theoretical $\pm 180°$ limit, but this sacrifices hinge stiffness. Shorter hinge regions result in stiffer hinges and smaller ranges of motion.

Another consideration is the torsional stiffness of hinges. Long, narrow hinges can easily twist along axes other than the intended joint axis. This condition is commonly mitigated by widening hinges or using "castellated" designs [30].

Durability of the laminated material is another important consideration, and is more often associated with low-cost materials such as cardboard and plastic. While this can be addressed in rigid links by using higher-performance materials like fiberglass or carbon fiber, the durability of flexure hinges is more challenging. For this layer we seek strong, flexible materials that go through desired deformations but do not break easily [31]. The alternative is to use material like fabric, which trades off torsional stability for lifetime. Delamination is often observed in laminate mechanisms and can have a significant impact on device life span. This occurs when torsional stresses or compressive forces exceed inter-layer pressure limits, causing laminate layers to separate or peel.

3 Laminated Mechanism Stiffness & Durability

This section addresses two important issues currently limiting laminated robot functionality, namely durability and stiffness.

3.1 Hinge Durability

As an affordable flexible material, we use polyester as the flexible layer in our laminated mechanisms. Thin polyester hinges easily tear, especially in high-stress situations. Hinge durability can be increased by using thicker material, but this adds unwanted rotational stiffness and damping.

In this paper a new hinge design is proposed to address the issues previously discussed which impact lifetime and durability. This design consists of a polyester sheet laminated between two layers of fabric using adhesive (Fig. 2(a)). Figure 2(b) demonstrates the result of a tensile test performed on a fiber-polyester hinge and a polyester hinge with the same design. The results confirm the higher fracture strength of the fiber-polyester hinge. Moreover, the similar initial slop of the plots confirms the consistency of stiffness between the two designs, meaning that the hinge stiffness is mostly affected by the polyester hinge.

A lifespan test has been carried out to show how the fabric-polyester hinge can endure more rotation before fail-

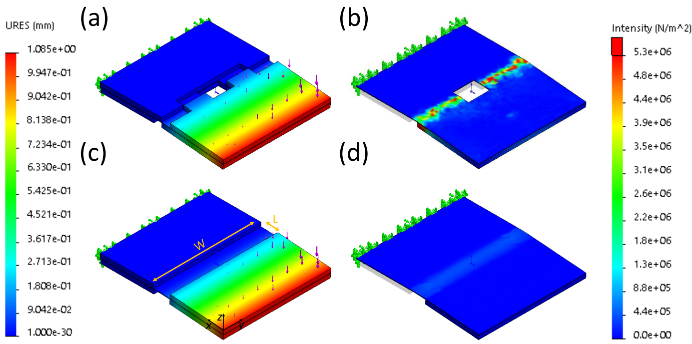

FIGURE 3. FEA study on simple and Castellated hinge for an uneven distribution of load. (a) Under load deformation of Castellated hinge. (b) Stress intensity through the flex layer for Castellated hinge. (c) Deformation of the simple hinge under uneven load. (d) Flexible layer stress density for the simple hinge.

ing. Figure 2(c) shows the torque required to rotate the hinge across a large number of rotations for both the fiber-polyester and polyester hinges. Two different cases are studied in this test. In the first case, each rotation consists of a motion between ±90°. In the second case, the rotation is increased to ±120° exposing the hinge to higher tension, as rigid parts collide with mounting attachments during this motion. The results, seen in 2(c) show that, in the presence of torsion, the polyester hinge quickly tears (2500 cycles), while the fabric-polyester hinge endures more than 50,000 cycles before failure.

This fabric-polyester hinge introduces higher strength compared to a polyester hinge. As a result, there is no need to increase polyester sheet thickness, which would result in higher joint stiffness and damping. This independence between life span and dynamic behavior is desirable, as each can thus be tuned separately.

3.2 Delamination

Although utilizing materials or adhesives with high peel strength is one solution to reduce delamination, other strategies may be used to reduce its occurrence mechanically, via pressure applied to critical points. This is made possible by cutting holes in the laminate near the ends of each hinge and using mechanical constraints like rivets or other connectors to apply pressure to the layers. Though additional hardware can decrease the range of motion via interference, this can be mitigated by adding corresponding clearance holes so that hardware does not interfere with joint motion, as illustrated in Fig. 6(a).

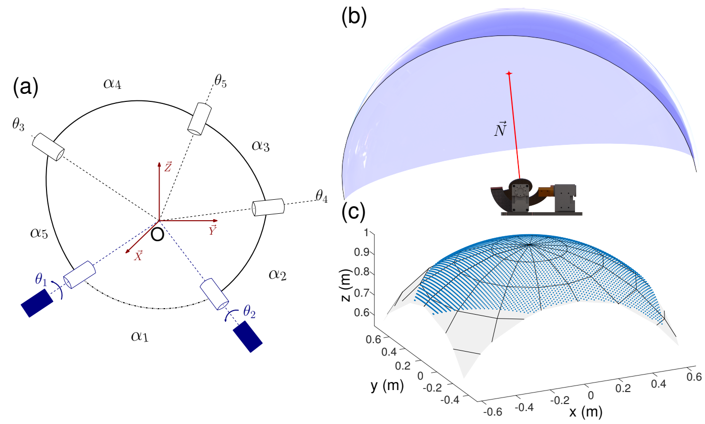

FIGURE 4. Kinematic synthesis of the 2-DOF Spherical PM. (a) The 2 DOF rotational linkage design. Dashed lines represent the rotational axes while solid lines represent rigid links. The dashed dotted line corresponding to α_1 represents fixed ground. (b) Illustration of the end-effector orientation by using projection of a virtual laser beam on a sphere. (c) Workspace of the 2-DOF Spherical PM.

3.3 Stiffness compensation

In general, using thinner sheets of material will decrease system stiffness within laminated mechanisms. While this can be mitigated several ways in rigid layers, increasing the stiffness of hinges can negatively impact the dynamic behavior of mechanisms, e.g. requiring higher torques and bigger actuators to move the joints. One of the biggest issues observed in these devices hinges are joints which twist along undesired axes under torsion. While reducing hinge length can stiffen a hinge against such torsional non-idealities, this decreases the joint's range of motion. Previously, alternative 'castellated hinge' designs have been proposed in [30]. This design reduces unwanted twist by effectively reducing the length of the flexure joint, but exhibits higher stress as well as a range of motion less than ± 180 degrees.

Figure 3 shows a Finite Element Analysis (FEA) for a simple and castellated hinge, highlighting the difference in how these two hinges resist torsional loads due to uneven force distributions on the distal end. The load is concentrated at the bottom-right corner of the hinges in Figure 3 using the following equation:

$$F(x,y,z) = (x + (5 - y)) \tag{1}$$

In this analysis the magnitude of the load ($|F|$) is adjusted between the two designs in order to make hinge rotation equal. The results show that while twist is reduced in the castellated hinge (Figs. 3(a)&(c)), the magnitude of

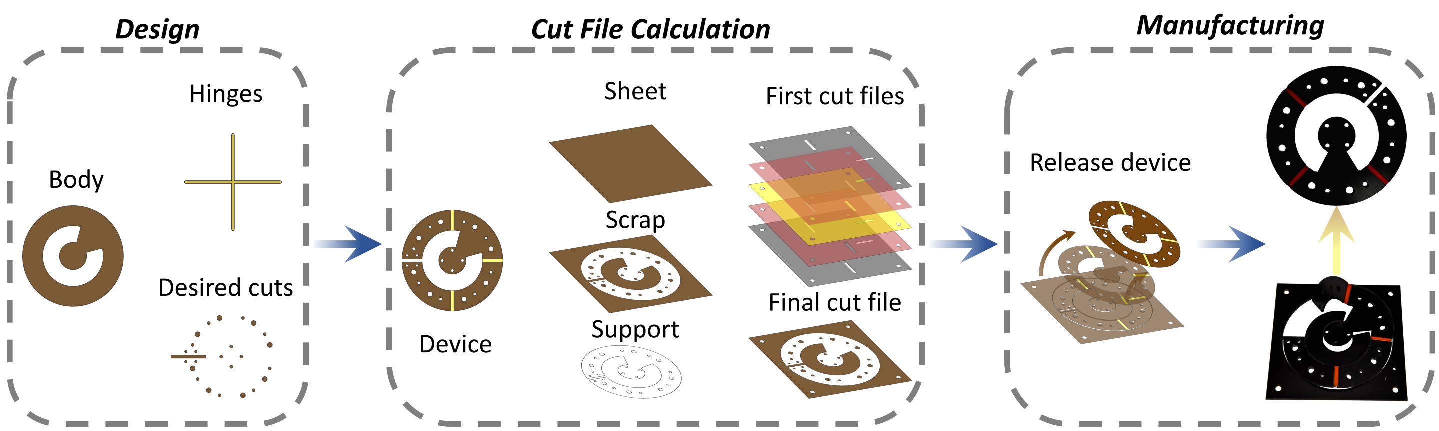

FIGURE 5. Graphical representation of the design process for 2-DOF spherical parallel manipulators using popupCAD.

the load is nearly 12 times higher than the simple hinge. In addition, the castellated hinge has higher stress on its edges (Figs. 3(b)&(d)) which can damage the hinge over time and decrease its life span.

4 CASE STUDY OF 2-DOF SPHERICAL PM

4.1 Kinematic Synthesis

The system under study, first introduced as two degree-of-freedom spherical orienting device in [32] consists of 5 rigid links connected by hinges, as shown in Fig. 4. The axes of all hinges meet at a single point (Point O) forming a spherical linkage. The loop closure between the two distal, rotational links requires three constraint equations, resulting in a two degree-of-freedom system. By co-locating the output position of the output link's (the end-effector) at the spherical mechanism's origin, the motion of the system can be considered effectively grounded, permitting the output motion of the end-effector to be represented as pure rotation.

The transmission which relates the actuator's motion to the end-effector's rotation may be computed using design parameters (α_i) and the rotation between adjacent body frames (θ_i), making the length scale of each link immaterial. Prior work by Ouerfelli et al demonstrates mathematically that the workspace of the mechanism is maximized if $\alpha_2 = \alpha_3 = \alpha_4 = \alpha_5 = \pi/2$ [23].

Based on these design parameters, the final design for the robot may be seen in Fig. 4(a). The mechanism's actuators are aligned along x and y axes of the device's chassis (considered the world frame).

Although the angle corresponding to the grounded body (α_1) does not affect the workspace of the mechanism, it impacts its singular states. If $\alpha_1 = 0$, the mechanism is singular across all inputs. Alternately, if $\alpha_1 = \pi/2$, theoretically, the mechanism has minimum singularity within its workspace [23]. Based on that knowledge, $\alpha_i = \pi/2$ has been selected for all α_i.

Though the mechanism is a 2-DOF mechanism, its end-effector experiences angular velocities in $\mathbb{R}^3$ as a function of its two actuated input velocities (even though one of those 3 dimensions is always dependent). This is also reflected in the mechanism's inverse Jacobian matrix as well:

$$\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ 0 \end{bmatrix} = \begin{bmatrix} \frac{\sin\theta_3}{\cos\theta_5 \sin\theta_3} & 0 & \frac{-\cos\theta_3}{\cos\theta_5\cos\theta_3} \\ \sin\theta_5 & -\frac{\sin\theta_4}{\sin\theta_5} & \sin\theta_5 \\ -\cos\theta_3 & 0 & \sin\theta_3 \end{bmatrix} \begin{bmatrix} \omega_X \\ \omega_Y \\ \omega_Z \end{bmatrix} \tag{2}$$

where θ_i are the hinge angles and ω_k are components of the angular velocity of the end-effector.

We have considered the potential application of a pointing task, e.g. a laser pointer, for the mechanism while formulating its kinematics (Fig. 4.b). Being a rotational mechanism, the center of its end-effector only experiences rotation and no translation. For formulating the mechanism kinematics, we consider a vector perpendicular to the plane of the end-effector link, which is co-linear with our "virtual" laser beam vector ($\vec{N}$) shown in Fig. 4.b. Based on the global axes' alignment with servos, the inverse kinematics may be written as:

$$\theta_1 = tan^{-1}(\frac{N_Y N_Z}{N_X^2 + N_Z^2}) \tag{3}$$

$$\theta_2 = tan^{-1}(\frac{N_X}{N_Z}) \tag{4}$$

where θ_i are the actuator angles and N_k are the components of the unit vector perpendicular to the end-effector body. In

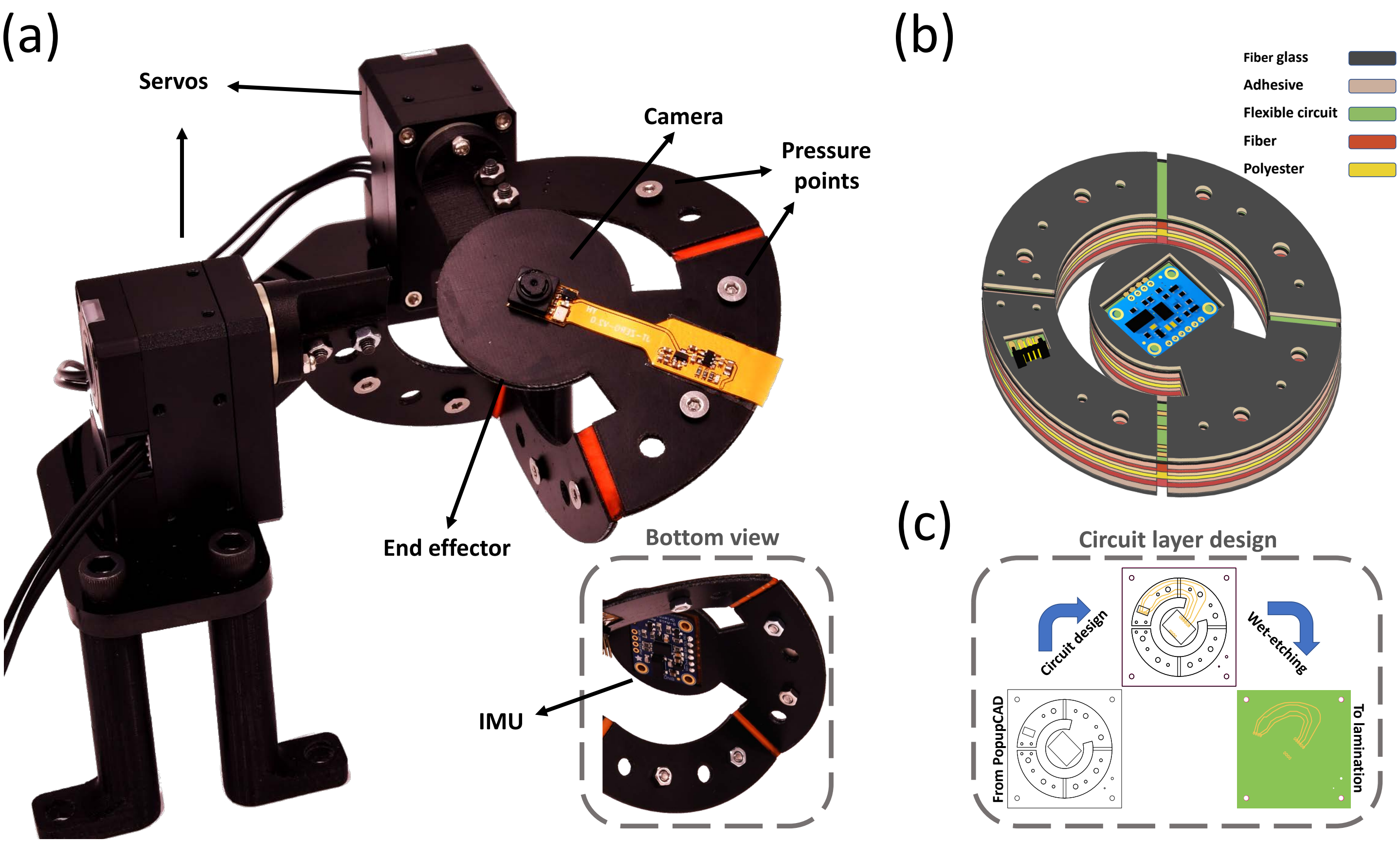

FIGURE 6. Prototyping the 2-DOF Spherical Parallel Mechanism. (a) Final prototype and its embedded IMU sensor. (b) Final Design and layers of the prototype. (c) Design of the flexible circuit using prototype design files obtained via PopupCAD.

the case of $N_Z = 0$, the values of θ_i are $\theta_1 = 0$ and $\theta_2 = \pi/2$. The forward kinematics of the robot can then be formulated as:

$$N_Z = \sqrt{\frac{1}{(t_1 + t_1 t_2)^2 + t_2^2 + 1}} \tag{5}$$

$$N_X = t_2 N_Z \tag{6}$$

$$N_Y = (t_1 + t_1 t_2) N_Z \qquad \text{where, } t_i = \tan(\theta_i)_{\{i=1,2\}} \tag{7}$$

By using the above set of equations, the workspace of the robot has been obtained and may be seen in Fig. 4(c).

4.2 Design

Figure 5 illustrates the design process in popupCAD. Based on this design tool, after designing the mechanism's main body, the hinges are placed corresponding to the above angles for α_i, along with any required attachment holes. The software then calculates the final device design, along with the initial and final cut files for each layer.

The 2-DOF mechanism utilizes the fabric-polyester hinge proposed in Section 3.1. An IMU is embedded on the mechanism's end-effector for rotation feedback. A flexible circuit is used to route the electrical connection from the base to the end-effector, so there are no wires affecting the mechanism's performance. The final device consists of a total of 11 layers, including two rigid fiberglass layers, two fabric layers, one flexible polyester layer, one flexible circuit layer, and five adhesive layers.

In order to design the flexible circuit, the final device design is exported from popupCAD as a vector-based DXF file and imported to DesignSpark PCB (As seen in Fig. 6(c)). Using this software, a circuit is routed along the hinge pathway. The circuit is then printed using a Xerox ColorQube 8580 Solid Ink Printer to deposit wax on copper-clad polyimide. Then, the flexible circuit layer is wet-etched and laminated with the rest of the device layers.

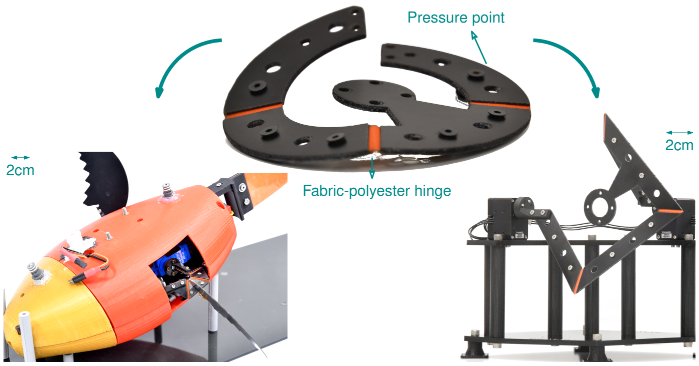

FIGURE 7. Different applications derived from the proposed mechanism.

4.3 Manufacturing

Figure 6(a) shows the final prototype with a camera attached to its end-effector. This prototype has been built using 0.03-inch fiberglass sheets as a rigid layer and 0.005-inch polyester sheet as a flexible layer. A heat-activated acrylic adhesive from Drytac[1] is used to bond layers. The flexible circuit layer is copper-coated polyimide from DuPont[2]. Two XM430 Dynamixel DC servos actuate the device. Two custom-made 3D-printed Nylon horns attach and align the mechanism hinges to the servos, as well as act as a safety coupling in the mechanism. The rest of the chassis is made with acrylic.

4.4 Manipulation

The proposed mechanism has been used at several different size scales across different projects within our research. Figure 7 shows two exemplar applications. First, this mechanism has been scaled down and used as pectoral fin in a robotic fish. The same fabric-polyester hinge with pressure-applying hardware has been responsible for increasing the lifespan of the mechanism to over 9000 runs, each consisting of the robot swimming underwater for one minute (undergoing many individual bending cycles); this demonstrates the hinge's suitability for underwater applications as well. In another study, the same mechanism has been used at a larger scale to study the performance of compliant laminated mechanisms under load. This mechanism has sustained tens of hours of tests over more than 12 months without delamination or tearing.

To further demonstrate the advantages of laminated techniques, this 2-DOF spherical mechanism has been used to stabilize a camera mounted on its end effector. This is done based on the orientation feedback from the embedded IMU (Adafruit BNO055). This demonstration is inspired by the study reported in [27], in which Safaryazdi et al. study a number of control approaches for camera stabilization based on the same 2-DOF parallel mechanism albeit manufactured using traditional machining techniques in aluminium. In order to use the mechanism for camera stabilization, a closed-loop controller is applied, using a linearized kinematic model around $N_x = N_y \simeq 0, N_z \simeq 1$. Around this point, Eqs.(5), (6), and (7) can be rewritten:

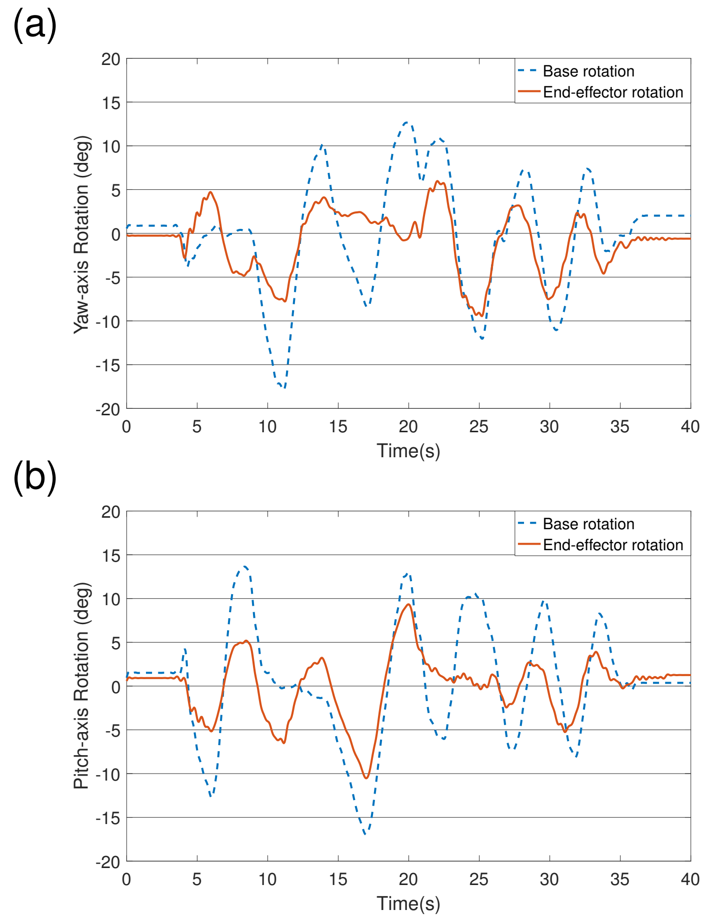

FIGURE 8. Camera Stabilization using the manufactured 2DOF spherical PM. (a) Rotations in Yaw-axis. (b) .Rotations in Pitch-axis

$$t_i = \tan(\theta_i) \simeq \theta_{i\{i=1,2\}} \quad (8)$$

$$N_Z \simeq 1 \quad (9)$$

$$N_X \simeq \theta_2 N_Z \quad \rightarrow \quad \frac{N_X}{N_Z} \simeq \theta_2 \quad (10)$$

$$N_Y \simeq (\theta_1 + \theta_1\theta_2)N_Z \simeq \theta_1 N_Z \quad \rightarrow \quad \frac{N_Y}{N_Z} \simeq \theta_1 \quad (11)$$

[1]www.drytacstore.com
[2]https://www.dupont.com

By considering small end-effector orientations about this point, Eqs. (10) and (11) can be used to describe the linearized kinematics model as:

$$\begin{bmatrix}\psi_1\\ \psi_2\end{bmatrix} = \begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}\begin{bmatrix}\theta_1\\ \theta_2\end{bmatrix}$$
$$\text{where, } \psi_1 \simeq \tan(\psi_1) = \frac{N_Y}{N_Z}, \quad \psi_2 \simeq \tan(\psi_2) = \frac{N_X}{N_Z} \tag{12}$$

In this configuration, the inverse and forward kinematics can be modeled as an identity matrix and the the orientations of the end-effector in x and y-axes become independent from each other. This simplifies the mechanism's inverse and forward kinematics significantly. In this project, we use a simple P-controller to keep the end-effector horizontal. In order to evaluate the controller, another IMU is attached to the mechanism's base and the two signals recorded.

Figure 8 shows the orientation of the end-effector vs the mechanism frame when the proposed controller is applied while the mechanism's base is moved randomly by a user[3]. It should be mentioned that the result is similar to the performance of the rigid robot reported in [27] when a similar controller and sensor mounting is used.

5 CONCLUSION AND FUTURE WORK

Laminate devices can often be manufactured faster and cheaper than conventional robots. The construction of our mechanism took less than one and a half hours and cost less than $30. Interestingly, reducing our mechanism's size not only makes it more rigid, but reduces overall cost. This contrasts with conventionally-fabricated devices, where the cost increases due to the need for tighter tolerances and more precise machining. This makes laminate techniques ideal for mass production of mechanisms at small size scales.

A novel, 2DOF, spherical, parallel manipulator made via laminate techniques has been introduced in this paper, based on a class of similar devices manufactured using more traditional approaches. The advantages and disadvantages of using laminate techniques have been discussed and several solutions have been proposed to address the non-ideal performance of this device, including both fabrication and modeling techniques. The paper subsequently describes the particular design investigated in this paper, including a description of the angles used and the specific fabrication choices made. This technique demonstrates steps towards using low cost, durable, laminate, spherical, parallel mechanisms in place of high-precision but more expensive devices. Future work will focus on manufacturing a scaled down prototype that is small, durable, and lightweight to extend the application of next generation to portable devices like gimbals, mobile robots and flying UAVs. Future work will also study control algorithms for use in precise manipulation tasks under active loads as well as study the life span of the 2-DOF mechanism under load.

[3]Shown in this video: https://youtu.be/IC7SgZzbM9w

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