HelioPhilaBot: A Bio-Inspired Origami Robot that Mimics a Sunflower

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Abstract— **This paper presents HelioPhilaBot, which is a robotic creation aimed at emulating the sunflower's movement and heliotropic behavior. The challenge lay in devising a stem structure that could flexibly mimic the sunflower's lateral movements while maintaining stability and rigidity. To achieve this, an origami-inspired design, termed the "twisted tower," was identified as a suitable actuator capable of executing twisting and bending motions. Actuation was facilitated using threads controlled by two geared DC motors. The robot was able to detect the presence of a light source with the help of light sensors and successfully demonstrated twisting and the bending motion while following the movement of the light source. The structure of the robot, its actuation and circuit integration have been discussed in the paper. Forward kinematics and control scheme for the robot were also explored and the analyses for the same have been laid out in detail.**

Keywords—bio-inspired robotics, origami actuators, soft actuator

I. Introduction

Nature is a rich source of inspiration in the field of robotics. The motion patterns, movement mechanisms and behaviour of natural organisms to different stimuli have inspired scientists to draw parallelism and employ similar methodologies to solve problems in the real world. One such organism of fascination in the nature is the sunflower. Sunflowers are tall and have stems that are flexible and allow them certain degrees of freedom for movement. More interestingly, they exhibit heliotropic behaviour, that is, they track the sun's movement across the sky through the duration of the day.

Origami describes a method of paper-folding that creates three dimensional structures from two dimensional paper sheets [1], [2], [3]. The implementation of origami structures in robotics has been on a constant rise because of their unique properties that blend flexibility with rigidity allowing smooth movement and space reduction. Origami designs have been used as actuators [5], [6], springs [7], and printable robotics [4].

The aim of this research project was to create a robot that emulates the movement of a sunflower as well as its heliotropic behaviour. In this paper, we present our sunflower mimicking origami robot, called the HelioPhilaBot. The stem structure of the sunflower robot had to be an actuator that would be flexible enough to mimic the sideways movement in a sunflower while holding its position by the virtue of its own stiffness and rigidity. An origami inspired design called the "twisted tower" was found suitable for the purpose and implemented as the actuator. The actuator is capable of performing 2 types of movements: twisting motion and bending motion. The actuation has been done carried out using threads. The design of the actuator, forward kinematics and the control scheme of the robot have been discussed in detail.

II. Design of the Robot

A. Twisted tower

Many origami structures were analysed for the making the actuator. Finally, an origami design called the "twisted tower" by Mihiko Tachibana was selected [9].

The twisted tower is a modular origami design and is constructed layer wise. All the layers are identical and are octagonal in shape. These layers are stacked one on top of another to form the tower structure. There are two types of origami pieces that are required to make the twisted tower: Type 1 and Type 2 (Fig. 1 (a)). The base layer requires 24 origami pieces, while the top layer 16 origami pieces. All the layers in between require 16 origami pieces each. So, for a n layer twisted tower,

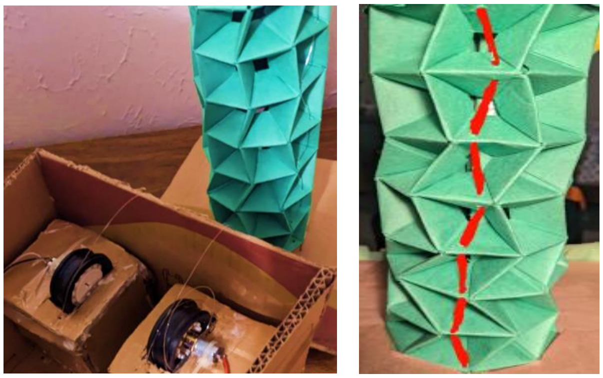
$$\text{No. of origami pieces required} = 8(2n + 1)$$

The twisted tower in the paper has 7 layers. In total, 120 pieces of origami were folded and assembled (Fig. 1 (b)). Each piece was made of a rectangular piece of construction paper of dimension 10 x 5 cm^2. Construction paper was used instead of normal origami paper because of its higher stiffness. The diameter of the circle circumscribing the octagonal pattern is 7.5 cm. Height of each layer is 3 cm. Total height of the tower is 21 cm.

Decorative pieces of sunflower origami were folded to be attached to the top layer of the twisted tower as shown in Fig. 1 (c).

(a) (b) (c)

Fig. 1. Twisted Tower a) origami piece b) assembled 7-layer tower c) sunflower origami



(a) (b)

Fig. 2. Actuation with threads a) setup showing how the threads are coonected to the motors b) routing of the thread

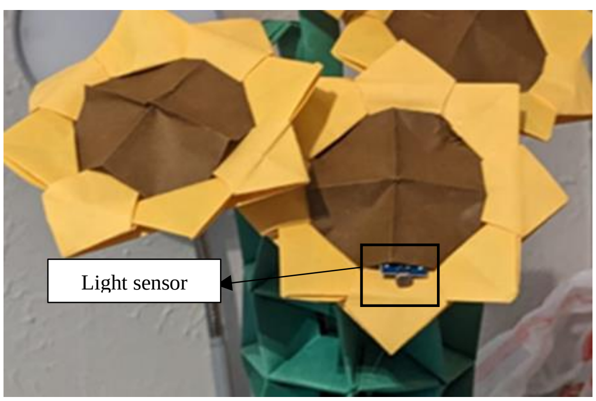


Fig. 3. Light sensor on the sunflower origami

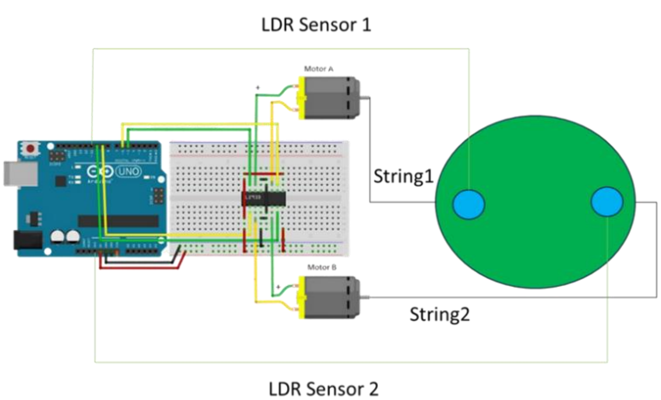


Fig. 4. Circuit diagram

B. *Actuation and Circuit Integration*

The twisted tower is actuated with the help of threads routed on either side of the twisted tower and controlled by two geared DC motors as shown in Fig. 2 (a). Fig. 2 (b) shows the routing of the thread on one side of the tower .Two light sensors are placed on 2 different sunflower origamis. Fig. 3 shows the placement of the light sensor on one of the sunflower origamis.

The aim is to keep the light source between the two sensors mounted on the sunflower origamis. Arduino code and circuit are integrated to achieve this desired goal. The circuit diagram is shown in Fig. 4.

Whenever the light source moves to the left side of the sunflower head, the left sensor detects the sunlight, and the left motor wraps the thread to bend the twisted tower until the light comes in the centre of two sensors. When light moves back towards the right, the left motor runs until the origami structure come back to the initial upright position. After this right motor actuates and bends the structure in the opposite direction. If no light is detected, both the motors actuate and contract the twisted tower back to its original position.

III. Mathematical Analysis

A. *Forward Kinematics*

The possible motions in the twisted tower are twisting about its vertical axis and bending towards one of the edgees of the octagon. Since the structure has rigid body like motions, it is assumed that the traditional rigid body dynamics hold for this particular case.

1. Twisting Motion

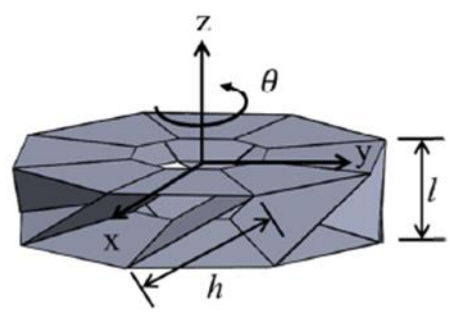


Fig. 5. Construct of a single-layered origami tower aligned with a body-fixed frame, involving dimensions such as h (the link's length), θ (the z-axis rotation), and l (the vertical displacement between two plates) [8]

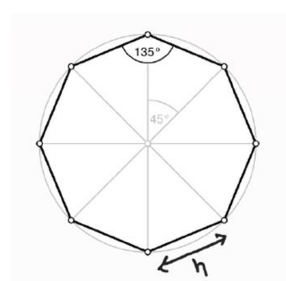


Fig. 6. Top view of the twisted tower

The twisting motion of the twisted tower can be represented by Fig. 5 and the top view of the twisted tower is shown in Fig. 6. Let r be the radius of the circle about which the edge is rotating. Assuming that the perimeter of the circumscribing circle is almost equal to the perimeter of the octagon, it can be said that

$$r \approx \frac{4h}{\pi}$$

Fig. 7. Side view of a single element in a layer and its transformation when there is a small twist of θ

Clearly,

$$a^2 + b^2 = h^2$$

$$a = r\theta \ and \ b = h - \Delta h$$

$$\Rightarrow r^2\theta^2 + h^2\left(1 - \frac{\Delta h}{h}\right)^2 = h^2$$

For low range of motion, $\frac{\Delta h}{h} \approx 0$

$$r^2\theta^2 + h^2\left(1 - \frac{2\Delta h}{h}\right) = h^2$$

$$\Rightarrow \Delta h = \frac{8h\theta^2}{\pi^2}$$

The rigid-body transformation by twisting the top plate by θ radian is given by

$$T = \begin{bmatrix} e^{\hat{w}\theta} & \left(h - \frac{8h\theta^2}{\pi^2}\right)\vec{w} \\ \vec{0}^T & 1 \end{bmatrix},$$

where $\vec{w} = [0,0,1]^T$

$\hat{w}$ = skew symmetric matrix corresponding to $\vec{w}$

If we have N such layers, then the transformation matrix is given by

$$T_0^N = \begin{bmatrix} e^{\hat{w}\theta_{1\,\ldots\ldots,N}} & \left(Nh - \frac{8h\theta^2}{\pi^2}\sum_{i=1}^{N}\theta_i^2\right)\hat{w} \\ \vec{0}^T & 1 \end{bmatrix}$$

where $\theta_{1\,\ldots\ldots,N} = \sum_{i=1}^{N}\theta_i$

In the twisting motion, alternate layers twist in opposite direction but with the same angle.

$$\theta_i = -\theta_{i+1}$$

$$\theta_{1\,\ldots\ldots,N} = \sum_{i=1}^{N}\theta_i = 0$$

As a result, the rotation matrix becomes identity and only a vertical displacement is observed.

$$\Delta h = \frac{8h}{\pi^2}N\theta^2$$

2. Bending Motion

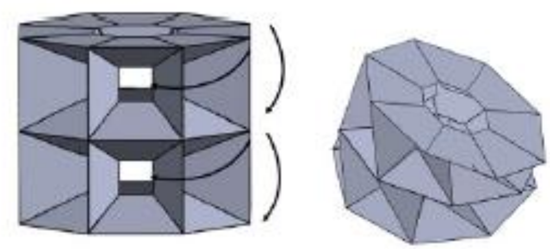


Fig. 8. Bending motion of the twisted tower [8]

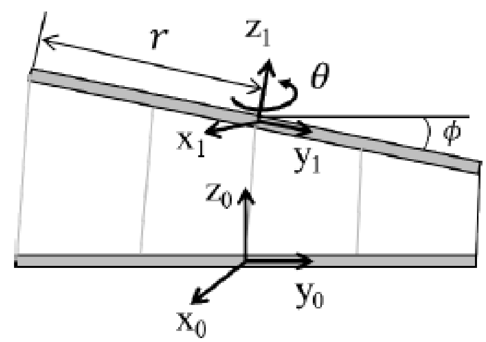


Fig. 9. Geometry of a single layer twister tower while bending [8]

Hoff et al [8] gave the transformation matrix for the bending motion of a single layer of the twisted tower.

$$T = \begin{bmatrix} c\theta & -s\theta & 0 & 0 \\ c\phi s\theta & c\phi c\theta & -s\phi & r - (r+l)s\phi \\ -s\phi s\theta & -s\phi c\theta & c\phi & lc\phi + rs\phi \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where r is the radius of the circumscribed circle of the octagon layer, l is the displacement between two plates measured along the z_0-axis, ϕ is the bending angle, and θ is the twisting angle resulted by bending.

Using that $\theta = 0$ when $\phi = 0$ and $|\theta| \approx \theta_{max}$ when $\phi = \phi_{max}$, the relationship between θ and ϕ can be approximated by

$$\theta \approx \frac{\theta_{max}}{\phi_{max}}\phi$$

where ϕ_{max} is the maximum bending angle that a single layer of twisted tower can generate and θ_{max} is the resulting torsional angle.

For a total bending of ϕ, θ can be split into N equal parts for each layer.

$$\theta \approx \frac{1}{N}\frac{\theta_{max}}{\phi_{max}}\phi$$

B. Control Scheme

The controller used for this project was an on/off controller. However, we can achieve a better control if we use a PID control. In this section we present a PID scheme which can used to improve the control of this system. In order to have a better control we assumed that dc motor can be controlled using a current controller and we have a sensor to detect the angle of impact of sunlight.

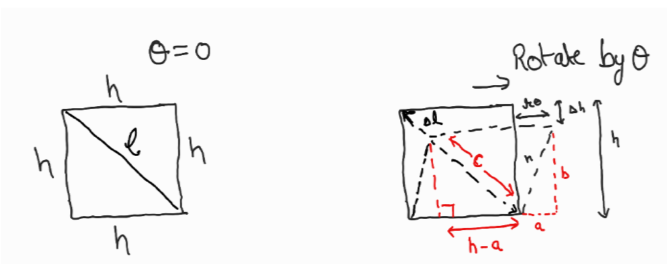


Fig. 10. Side view of the geometry of a single layer twister tower while bending showing change in l

Clearly,

$$b^2 + (h-a)^2 = c^2$$

$$(h-\Delta h)^2 + (h - r\theta)^2 = (l - \Delta l)^2$$

$$\theta \approx 0,\ \frac{\Delta h}{h} \approx 0\ \frac{\Delta l}{l} \approx 0$$

$$h^2\left(1-\frac{\Delta h}{h}\right)^2 + h^2\left(1-\frac{r\theta}{h}\right)^2 = l^2\left(1-\frac{\Delta l}{l}\right)^2$$

$$h^2\left(1-\frac{2\Delta h}{h}\right) + h^2\left(1-\frac{2r\theta}{h}\right) = l^2\left(1-\frac{2\Delta l}{l}\right)$$

$$2h^2 - 2\Delta hh - 2r\theta h = l^2 - 2\Delta ll$$

Using Pythagoras theorem,

$$h^2 + h^2 = l^2, l = \sqrt{2}h$$

$$\Delta hh + r\theta h = \Delta ll$$

$$\text{Using, } \Delta h = \frac{8h\theta^2}{\pi^2}, r = \frac{4h}{\pi}$$

$$\frac{8h\theta^2}{\pi^2}h + \frac{4h}{\pi}\theta h = \Delta l\sqrt{2}h$$

$$\Delta l = \frac{8h\theta^2}{\sqrt{2}\pi^2} + \frac{4h\theta}{\sqrt{2}\pi}$$

$$\theta \approx 0,\ \theta \gg \theta^2$$

$$\Delta l \approx \frac{2\sqrt{2}h\theta}{\pi}$$

Now, Δl here represents that if we pull the thread by Δl we will observe θ twist in the origami layer.

In same fashion, we can write the total Δl for N such layers with equal twist θ.

$$\Delta l \approx \frac{2\sqrt{2}hN\theta}{\pi}$$

Both desired Δh and ϕ are function of θ as we discussed in the previous section. If we can control θ we can control Δh and ϕ and θ can be controlled using Δl which represents the thread pulled by the motor.

Now if we use a current controlled DC motor, its angular acceleration can written as follows:

$$H\alpha = K_I I$$

where K_I is torque constant, I is the current and H is the moment of inertia of the pulley and motor shaft and R is the radius of the pulley attached to the motor

$$\alpha R = \Delta\ddot{l}$$

$$\alpha R = \Delta\ddot{l} = \frac{K_I R I}{H} = K_I' I$$

$$K'_I I = \frac{2\sqrt{2}hN\ddot{\theta}}{\pi}$$

$$I_{command} = K_p e + K_d\dot{e} + K_i\int e\,dt$$

$$e = \theta_d - \theta$$

Our desired output is Δh_d or ϕ_d

For the desired Δh_d, we can find a desired $\Delta\theta_d$.

$$\theta_d = \sqrt{\frac{\pi^2}{8Nh}\Delta h_d} \quad \text{or} \quad \theta_d = \frac{1}{N}\frac{\theta_{max}}{\phi_{max}}\phi_d$$

Error Dynamics:

$$\Delta\ddot{l} = \frac{2\sqrt{2}Nh\ddot{\theta}}{\pi}$$

$$e = \theta_d - \theta$$

$$\Delta\ddot{l} = -\frac{2\sqrt{2}Nh\ddot{e}}{\pi} = K_I\left(K_p e + K_d\dot{e} + K_i\int e\,dt\right)$$

$$\ddot{e} + \frac{K_d K_I \pi}{2\sqrt{2}hN}\dot{e} + \frac{K_p K_I \pi}{2\sqrt{2}hN}e + \frac{K_i K_I \pi}{2\sqrt{2}hN}\int e\,dt = 0$$

Error Dynamics:

$$s^3 + \frac{K_d K_I \pi}{2\sqrt{2}hN}s^2 + \frac{K_p K_I \pi}{2\sqrt{2}hN}s + \frac{K_i K_I \pi}{2\sqrt{2}hN} = 0$$

Following conditions must be satisfied for stability:

$$\frac{K_d K_I \pi}{2\sqrt{2}hN} > 0, \Rightarrow K_d > 0$$

$$\frac{K_p K_I \pi}{2\sqrt{2}hN} > 0, \Rightarrow K_p > 0$$

$$\frac{K_p K_d K_I}{2\sqrt{2}hN} > K_i > 0$$

IV. DISCUSSION AND FUTURE WORK

In this paper, an origami robot that mimics a sunflower named HelioPhilaBot was presented. The structural design of the robot, robot actuation and circuit integration were thoroughly discussed. The two types of motion seen in the robot: twisting motion and bending motion were analysed and their rigid body kinematics were derived and studied. The control scheme of the robot was also discussed in detail.

The PID controller can be implemented if we can find the angle of impact of rays and use a motor with current controller. Frictional and inertial losses of DC motor and actuator could also be incorporated into the controller in the future.

Origami designs are being increasingly implemented in the field of soft robotics. This is because of their adaptive designs that can mimic natural motion. With the right material and design selection, innovative solutions can be developed to implement complicated motion patterns.

Furthermore, origami robots are a unique blend of art and science. Making origami robots can be a fun activity for children and inroduce them to the field of robotics.

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