The Flipping Robot - Salto

Course project for EMAE488

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***Abstract*—Over the past few years, origami robots have been gaining popularity because of their versatile nature and robustness. The purpose of this paper is to provide a detailed description of one such autonomous origami robot named Salto, which moves by flipping 180° about a horizontal axis for every step – resembling the motion of a slinky. It aims to explain how the structure is controlled to bring about a shift in the center of gravity causing the flipping motion of the robot. The mechanical design as well as the control electronics of the robot is described. The body of the robot is made up of an origami spring structure which allows the robot to bend forward and backward depending on the direction of motion. A feedback control loop is implemented with the use of gyroscopes and infrared emitters and receivers to provide sensor data on the robot's state which is relayed to and processed by an Arduino microcontroller chip which in turn is programmed to timely control the actuators – stepper motors, to bring about the flipping motion.**

Keywords—origami structure; flipping robot; hardware and software design

I. INTRODUCTION

A. Literature Review - Origami

Origami refers to the traditional Japanese art of paper folding. The goal is to transform a flat, 2-D sheet of paper into a 3-D structure by various folding techniques. Making cuts to achieve the final shape is generally discouraged and if it does involves cuts, it falls under the category of kirigami – which refers to designs that use cuts and removal of material.

Origami has paved its way into several fields including engineering, mathematics, architecture and the medical field.

In mathematics for instance, the problem of flat-foldability which deals with the question whether a crease pattern can be folded into a 2-dimensional model has been a topic of considerable interest.

Several engineering applications have employed origami for innovative designs. The problem of rigid origami has great practical importance. It deals with the question whether the model would still be foldable if paper is replaced with sheet has great practical importance.

In fact, the applications of origami is so vast and versatile that computer programs have been developed to aid origami design such as TreeMaker and Oripa. Treemaker allows new origami bases to be designed for special purposes and Oripa tries to calculate the folded shape from the crease pattern.

In the field of robotics, origami has been gaining popularity over the years. It offers several characteristics and properties to engineering materials which are desirable for various applications. For example, it is possible to achieve properties of flexibility and rigidity at the same time using certain folding patterns. This property can be especially useful when the robot's working environment might involve several unknown factors or extreme conditions as it enables the robot to be more adaptable and perform a wide variety of functions which may or may not be specified.

Another major advantage of using origami in robotics is that it aids in the prediction of movement of a morphing structure. It is possible to have prior information on how a structure will move by analyzing the folds and creases. The movement of origami based morphing structures can be estimated accurately even when the deformations are large and hence enables the design for movement of the whole structure.

Also, with use of materials like paper and plastic sheets, origami designs aid to reduce the weight and the material cost. Shape Memory Alloy (SMA) is one of the most commonly materials used for self-folding origami robots which assemble themselves through deformation of the material with the application of heat. This makes external actuators like motors unnecessary which allows for miniaturization of robots like never before.

Taking into account the cost considerations, origami structures used as mechanical parts aid in the reduction of cost, time and difficulty in the fabrication process. Also, since the number of parts are reduced considerably by replacing components with origami structures, the risks involved with improper assembly also reduced.

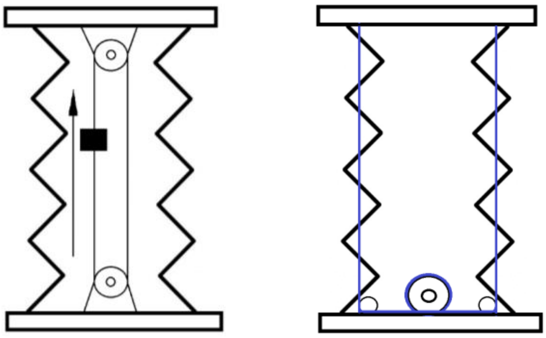
Previous work done in the field of origami robotics include, a deformable wheeled robot with wheels folded into an origami structure that enabled them to increase and decrease in diameter depending on the terrain that it was moving on. Another team of researchers designed an origami inspired worm robot with a folded structure for a body that can undergo worm-like peristaltic locomotion. Researchers from Case Western Reserve University have created a thread-actuated origami robot which uses a twisted tower origami design for manipulation and locomotion.

Researchers from MIT have demonstrated an untethered miniature origami robot that self-folds, walks, swims, and degrades. The unfolded robot, which is made of a magnet and PVC sandwiched between laser-cut structural layers (polystyrene or paper), weighs just 0.31 g and measures 1.7 cm on a side. Once placed on a heating element, the PVC contracts, and where the structural layers have been cut, it creates folds.

B. Introduction of the project

The background of the flipping robot – Salto: Name is derived from the flipping move, or a "Salto" in gymnastics. As the name suggests, the robot moves by flipping 180° about a horizontal axis for every step – resembling the motion of a slinky. The overall structure is controlled to bring about a shift in the center of gravity causing the flipping motion of the robot.

The body of the robot is made out of an origami design called Miura-Ori, which has several properties of a metamaterial and imparts a spring like property to the robot body. This structure enables the robot to bend forward and backwards upon compression of one side and expansion of the other simultaneously. Strings which are passed through the Miura Ori structure and wound around a shaft which is actuated by a motor, are used cause the spring Miura Ori structure to flex in the direction of motion. Apart from this shape changing mechanism, a mass block which can be conveyed up and down the structure using a pulley system, has also been incorporated



Mass Conveyor Mechanism Shape Control Mechanism

Figure 1.1. Two main system of Salto:

in the robot design. This enables the robot to shift its center of gravity as and when needed to bring about the flipping motion of the robot. The overall control is carried out by an Arduino Microcontroller which takes sensor data from gyroscopes and infrared emitters and receivers as the feedback input and actuates the motors in a timely manner, causing the robot to flip. The gyroscopes are used to detect orientation of the robot so as to determine when the mass block is to be lifted from the bottom to the top. The infrared emitters and receivers are used to detect the mass block as it reaches the top of the structure, which is when the structure is to be bend forwards to enable flipping. Hence, the flipping motion is brought about by the combined effect of the rising mass block and the bending of the robot body.

The robot has been programmed to be operated in two different modes – the first being a fully autonomous mode and the second being a partially autonomous which provides a human interface by means of a joystick which can be used to actuate the motors manually.

II. Motion Principle and Statics Analysis

A. Motion Principles

Firstly, at the initial position, Salto should stand vertically, with mass block at the bottom side, the sensor will detect that position and will give the permission to drive it move after getting a trigger.

Secondly, active motor in mass switching system will lift the mass block to top side, which give Salto a potential energy for further flipping. Meanwhile, the infrared emitters and receivers will detect the distance between base and mass block to stop the lifting motion.

Thirdly, when the mass block has been lifted to designed position, the control chip will start the shape control system. The motor will control the strings to compress and release the origami structure at same time to control the shape. Salto will start to bend to the designed direction, and because we have already lift the mass block, whole robot will easily flip after bend.

Fourthly, in the process of third movement, the gyroscopes fixed on each base should detect the base state. When these sensors got the signal that two base both attach to the ground, it will start to drive the motor in shape control system to rotate to negative direction, which will let Salto to restore to the straight stats. As we have changed the center of mass, so the robot will lift the bottom side in initial position. Also, in the whole process, gyroscope will continuously collect state data, when it shows Salto has return to a vertical standing position, chip will send a trigger to stop motor.

These four step is a whole process for one flip. If we send the command for several series of flip, Salto will give us a continuous movement to step ahead.

B. Statics Analysis

The motors for this origami robot should be small and light, meanwhile it also should have large enough torque for lifting the mass block and compressing the origami spring. The tradeoff is reducing the output speed of the small motors. We chose the three 28BY-48 steppers, which has reduction gears inside and can provide the torque around 34.3mN.m. Due to the limit of the motor, the robot is not able to move fast but slowly. In this scenario, it should be enough for only considering the statics of the motion. Thus several moments should be considered to complete the flipping motion[1].

2.2.1 Flipping

Firstly, let's consider the robot's height and pre-load:

$$h = l_1 - \Delta l \tag{2-1}$$

while the springs should provide enough force for the pre-load:

$$\Delta l \geq \frac{(m_1 + m_2)g}{2k} \tag{2-2}$$

Let's consider the boundary condition for flipping. Assuming the mass block is attaching on the top base. So $F_1 = (m_1 + m_2)g$. And $F_2 = m_1 g$.

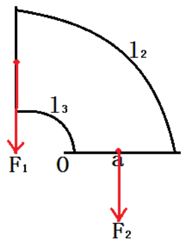


Figure 2.1

The boundary condition for flipping:

$$F_1 \frac{2l_3}{\pi} \geq F_2 \frac{a}{2}$$

which means the total torque around O should be equal to 0.

Or

$$4(m_1+m_2)l_3 - \pi m_1 a \geq 0 \tag{2-3}$$

So we can get one constraint for the length of the robot:

$$a \leq \frac{4(m_1+m_2)l_3}{\pi m_1} \tag{2-4}$$

In figure 2.1, there is no force from the load onto the springs. For the compressed one,

$$l_3 = l_1 - \frac{F}{k} \tag{2-5}$$

Note that the equality comes with two assumptions. One is that they are linear springs. While in practice the elastic coefficient is becoming smaller when compressing. That leads to the realistic minimum length after compressing is smaller than l_3, which benefits flipping. The other assumption is the bend of the spring can be ignored when calculating its elastic force.

In figure 2.1, the maximum length of spring with load:

$$l_2 = l_1$$

While notice that this is just the boundary condition, in practice the maximum length of the spring with load should be no shorter than it:

$$l_2 = l_1 \geq \frac{\pi}{2}\left(\frac{2l_3}{\pi} + a\right) \tag{2-6}$$

Substituting Eq.(2-4) into Eq.(2-5), we can get the robot's width:

$$a \leq \frac{2F}{\pi k} \tag{2-7}$$

While it is unwise to get a when F is not given, we would use below formula for geometric convenience:

$$a \leq \frac{2(l_1 - l_3)}{\pi} \tag{2-8}$$

This is derived from Eq.(2-5). This formula is better because in practice, l_3 can be easily gotten by testing.

2.2.2 Compressing Lateral Spring

The width of the robot plays an important role of deciding elastic coefficient of spring. The lateral spring can be decomposed as many small parallel springs. So if the width of the robot is extended, more parallel springs are added. Then the elastic coefficient becomes greater.

The elastic density coefficient is defined as:

$$h = \frac{k_i}{b_i} \tag{2-9}$$

which can be tested out by experiment in lab. Then arbitrary elastic coefficient with the same material and same origami structure is:

$$k = \int_b h dx = bh \tag{2-10}$$

2.2.3 Lifting the Base

The boundary condition for lifting:

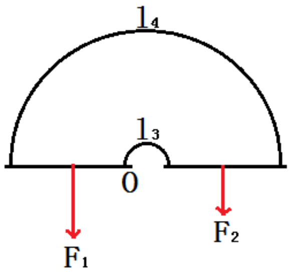


Figure 2.2

$$F_1 \frac{a}{2} \geq F_2\left(\frac{a}{2} + \frac{2l_3}{\pi}\right) \tag{2-11}$$

which means the total torque around O should be equal to 0.

Or

$$a \geq \frac{4m_1}{m_2}\frac{l_3}{\pi} \tag{2-12}$$

Let's in order consider the force for lifting.

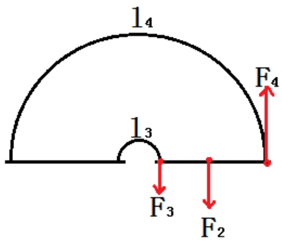


Figure 2.3

$$F_4 = F + k'(l_4 - l_1) \tag{2-13}$$

where k' can be gotten from the same method as what does to k above.

[1] See the Appendix I for the nomenclature.

$$F_3 = k(l_1 - l_3) \qquad (2\text{-}14)$$

Thus we can get:

$$F_4 \geq F_2 + F_3 \qquad (2\text{-}15)$$

Substituting Eq.(2-13) and Eq.(2-14) into Eq.(2-15)

$$F + k'(l_4 - l_1) \geq m_1 g + k(l_1 - l_3)$$

Or

$$F \geq m_1 g + k(l_1 - l_3) - k'(l_4 - l_1) \qquad (2\text{-}16)$$

From the geometry: $l_4 = l_3 + a\pi$

From Eq.(2-7), we can get:

$$F \geq \frac{\pi a k}{2} \qquad (2\text{-}17)$$

2.2.4 Practical Consideration

For our two driving structures, there exists one underlying constraint that the decreased length on one side should be equal to the increased length on the other side.

(1) The flipping

$$h - l_3 \geq l_2 - h \qquad (2\text{-}18)$$

Substituting Eq.(2-1) into Eq.(2-18):

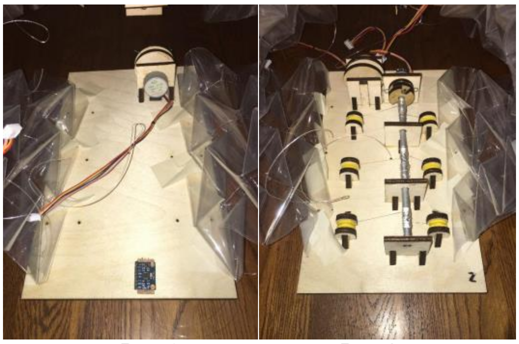
$$\Delta l \leq \frac{2l_1 - l_2 + l_3}{2} \qquad (2\text{-}19)$$

(2) The lifting

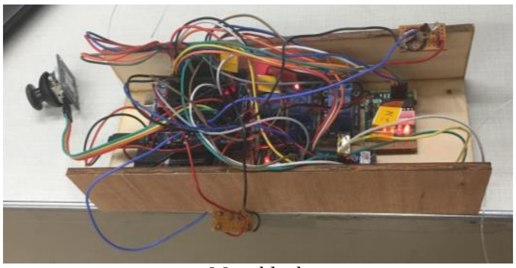
$$h - l_3 \geq l_4 - h$$

In this case, if the model could satisfy the boundary condition for lifting, we don't need to consider this constraint for this constraint makes the situation easier to lift the other side.

III. Hardware Design



Base 1 Base 2



Mass block

Origami spring

Figure 3.1 Hardware overview

The robot can be divided to several different parts: two base, the origami springs for holding structure, and the mass block for moving the mass center artificially.

Pictures shows above: base 1, base 2, origami, and mass block.

From here, we will first introduce the origami springs, then talk about the brief design of mass block whose detail information will be given later. After that, is the introduction of the main structure of two bases: the mass switching system and the shape control system.

A. *Origami spring*

Figure 3.1. Origami sheet

We choose this kind of origami structure for the body of our robot. This design can give us a spring like structure, which both has a flexible length when pressing and loosing and provide enough force to hold the whole robot which is the mass of base and the mass block, etc.

For this structure, we find that the kind of material, the side length of each segment and the number of overlapping can influence the power of spring a lot. Comparing the different materials like paper and plastic, we decide to use plastic sheets to build our origami springs because plastic one can provide much more strength. If the origami sheet has a smaller side length, the spring structure will be more powerful but more unstable, which we can get enough force but hard to control. Then we find that the number of overlapping sheets for one spring also can change the power of it. When that number goes bigger, it can significantly improve the coefficient of elasticity. So we decide to get a spring which use plastic, and has a side length for 2 inches, 2 layers of overlapping for one spring.

For the whole structure, we drill three column of holes on the origami springs which will be explained later.

B. Mass block

For the purpose to drive our robot to move, we design a mass switching system to move the mass center of robot for flipping. Here just brief introduce the inclusion inside. We put all the electrical system into the mass block, including the Arduino, electric relay, control board for motor, diode light ranger, and etc. All of this will be described later in Software design later at full length.

C. Mass switching system

As we want our robot can flip continuously, so we need a system to change the center of mass to let robot fall to the designed direction. For that, we design to use two motors to drag strings to lift the mass block which placed on each base. First, we designed a pulley like structure with a combination of motor, cylinder, shaft, and holder. Then let one side of string fixed on the cylinder, and the other side is connected to the mass block. Meanwhile, we drill some small holes for guide the strings and make sure the mass block can be moved at the center of robot. After that, when control two motors separately in different status, we can control the mass center of robot.

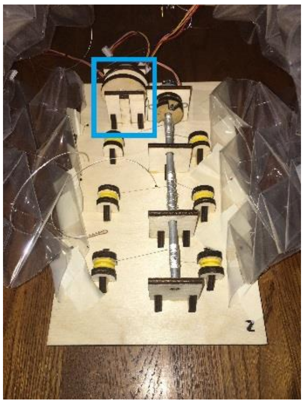


Figure 3.2

From the Fig. 3.2, it shows the combination with blue box, which contains a motor, small cylinder, shaft, and holders inside. Also there is a small hole at the center of base and a string going out of that hole which will be connected to the mass block.

D. Shape control system

To drive our robot to bend forwards, we designed a shape control system which can let robot compress one side and release the other side. We put a combination of motor, shaft and holders in the center of base 2. As we use 3 strings for driving the robot, I also put 6 pulley structure for guide the strings. Again, I made some holes to guide strings, which can match the holes on the origami plastic sheets. Finally, I wrap the strings many times on the shaft after fix them, then let them go through whole structure designed, and make a stop at the other base.

After all, when active the motor, with the rotation of main shaft, it will compress one side and release the other side at the same time.

The Fig. 3.3 below shows the shape control structure by red box, in which you can see the motor, main shaft, strings, pulleys and some holders for different purpose. You can see that the strings depart from the shaft and through pulleys, then a little detour and back through the origami springs.

Figure 3.3

IV. Software Design

We used MPU-6050 gyro to detect the orientation of the two bases, and two infrared emitters and receivers to detect the distance between the mass block and the bases. We also had three 28BY-48 steppers and three relays. With these electronics, the robot could complete the flipping automatically, though the joystick was used to manually control the robot.

We used Arduino Uno board, which has 14 pins. Four digital pins are required to control one stepper, so three steppers would occupy 12 pins. Or three relays are used to control the power of the steppers and the three steppers share the same four control pins. Thus we only need 7 pins to control three steppers.

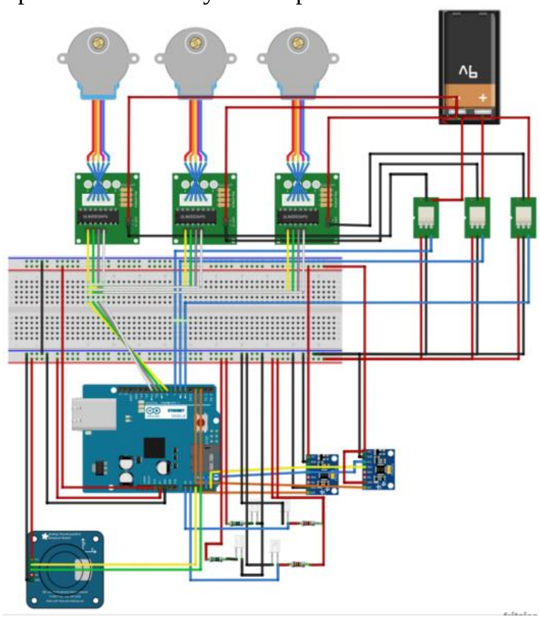


Figure 4.1

The motion of the robot can be divided into four processes: lifting mass block from base 1 to base 2, lifting mass block from base 2 to base 1, compressing the left spring, and compressing the right spring. So the joystick (see figure 4.2) can be exactly used to control these four motions.

Figure 4.2

```
void one_flipping()
{
  Serial.println("flipping automatically...");
  adjustOrientation1();
  liftTo1();
  compressLF();
  adjustOrientation2();
  liftTo2();
  compressRT();
}
```

Figure 4.3

One function can show implementation of flipping automatically:

Firstly, motor0 is actuated according to the tilt data from the gyro1 to adjust the orientation of the robot vertically. Then motor2 which is on the bottom base will release strings and motor1 which is on the top base will pull the strings on the mass block, in order to lift mass block from bottom base to top base. Then the motor0 will rotate to compress the left spring until the robot is flipped. Then the similar iteration is implemented to have another flipping.

Our code repository is attached on the Appendix II.

V. PROBLEMS AND FUTURE WORK

We had encountered a number of problems during the course of this project. Some of these problems were fixed along the way however many of them persisted till the final stage of the project as they proved to be quite difficult to be overcome within the limited timeframe allotted.

A. Problem 1 and solution

The first major problem that we were faced with was that the robot failed to maintain its vertical position. The body of the robot either bulged outwards or tilted to one side thus causing it to collapse over.

The reason for this behavior of the robot can be attributed to the observation that Muira Ori structure was not stiff enough to hold up the base with the mass block attached to it. The structure was refolded several times with varying lengths and widths of the sheet but it failed to solve the problem. One possible solution to this could have been to add more number of sheets per side to make up the body of the robot. This would have increased the stiffness of the spring structure, however with the tradeoff being excessive friction between the plastic material and the s that are passed through it. Overcoming this friction would require excessive torque demand from the motor and thus, will result in it being overloaded. During our attempts at refolding the structure, different segment sizes of the spring structure were also tried out. The larger segment size proved to be two stiff to be controlled and the smaller segment sizes provided very less strength to hold up the body of the robot under load.

Another reason for the robot's inability to maintain a vertical pose is that the mass block was overweight. Since all the electronics were accommodated in the mass block, it turned out to be heavier than we had anticipated and hence weighed down the entire structure as a whole. An initial compression was provided to the spring structure to make it stand upright. However, this shortened the height of the robot considerably which made it impossible for the robot to flip.

B. Problem 2 and solution

The second problem that we were faced with was that the motors that we selected were unable to provide the torque that was required for our application. We had selected lightweight 5V stepper motors with gear reduction. However the torque demand from the motors were considerably higher than what we had anticipated and this resulted in them being overloaded and getting stuck while in operation. This problem arose due to the very high unexpected friction between the strings and the holes on the origami structure. Also, the previously mentioned problem of the overweight mass block comes into play here since the motor torque was not sufficient to lift the mass block.

As a result, the mass block kept getting stuck in between while it was being lifted. The motor driving the shaft controlling the origami structure also functioned intermittently which was not desirable for our purpose as it prevented the springs from being compressed to its full extent. This also resulted in the high and inefficient usage of the battery which caused premature draining of the battery.

C. Future work

For future work, we plan to work on solving the abovementioned problems first and to get the robot to flip as desired. For this purpose, we shall consider the possibility of changing the material used for the origami structure. One suitable material that can be used in place of the plastic film is Shape Memory Alloy (SMA). These would allow us to actuate the structure without using the motors, strings, and the pulley system. This could reduce the weight of the robot considerable and enhance efficiency by simplifying the control problem. Also, overall size of the robot needs to be reduced since the flipping motion that we desire can be achieved better at a miniature scale. With the use of SMAs, this goal of miniaturization can be also achieved since it eliminated the need for several components that are in use now.

VI. ACKNOWLEDGEMENT

We thank Dr. Kiju Lee for her insight and expertise that greatly assisted the project.

VII. REFERENCES

[1] H.C. Chiu, M.Rubenstein and W.M. Shen, "Deformable wheel-A self-recovering modular rolling track," Distributed Autonomous Robotic Systems 8, pp.429, 2009.

[2] Y. Sugiyama and S.Hirai, "Crawling and jumping by a deformable robot", The International Journal of Robotics Research, Vol.25, No.5-6, pp 603-620, 2006.

[3] C.D. Onal, R.J. Wood and D. Rus, "Towards printable robotics: Origami-inspired planar fabrication of three-dimensional mechanisms", in Proc.IEEE Int.Conf.on Robotics and Automation, pp.4608-4613, 2011.

[4] Felton Samuel M., Lee Dae-Young, Cho Kyu-Jin, Wood Robert J., "A passive, origami-inspired, continuously variable transmission", Robotics and Automation (ICRA), 2014 IEEE International Conference on, pp. 2913-2918

[5] V.H. Evan, D. Jeong and K. Lee, "OrigamiBot-I: A thread-actuated origami robot for manipulation and locomotion", Intelligent Robots and Systems (IROS 2014), 2014 IEEE/RSJ International Conference on, pp. 1421-1426

[6] D.Y. Lee, G. P. Jung, M.K. Sin, S.H. Ahn, and K.J. Cho, "Deformable wheel robot based on origami structure," in Robotics and Automation (ICRA), 2013 IEEE International Conference on, 2013, pp. 5612-5617.

[7] D. J. Balkcom, and M. T. Mason, "Robotic Origami Folding,"IJRR, Vol. 27, no.5, pp.613-5627, 2008.

[8] R.M. Murry, X. Li, and S.S. Sastry, "A Mathematical Introduction to Robotic Manipulation," CRC Press.

[9] E. Hawkes, B. An, N.M. Benbernou, H. Tanaka, S. Kim , E.D. Demaine, D. Rus, and R.J. Wood, "Programmable matter by folding", *Proc. Nat. Acad. Sci.*, vol. 107--28, pp. 12441-12445, 2010

[10] C.D. Onal, R.J. Wood, and D. Rus, "An Origami-inspired approach to worm robots",*IEEE/ASME Trans. Mechatron.*, vol. 18, no. 2, pp. 430-438, 2013

[11] R. J. Lang, *Origami Design Secrets*, 2012, CRC Press, Taylor & Francis Group

[12] E. Hawkes, B. An, N. M. Benbernou, H. Tanaka, S. Kim, E. D. Demaine, D. Rus and R. J. Wood, "Programmable matter by folding", *Proceedings of the National Academy of Sciences*, vol. 107, no. 28, pp. 12441-12445

[13] M.T. Tolley, S.M. Felton, S. Miyashita, D. Aukes, D. Rus, and R.J. Wood, "Self-folding origami: shape memory composites activated by uniform heating", *The IOP Journal Smart Materials and Structures*, vol. 23, pp. 094006, 2014

[14] S. Miyashita, S. Guitron, M. Ludersdorfer, C. Sung and D. Rus, "An untethered miniature origami robot that self-folds, walks, swims, and degrades", *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, pp. 1490-1496, 2015

[15] https://en.wikipedia.org/wiki/Origami

APPENDIX

A. Appendix I

The length of free spring: l_1

The length of the pre-compression: Δl

The maximum length of spring with load: l_2

The minimum length of after being compressed: l_3

The maximum length of spring after being stretched: l_4

Elastic coefficient when compressing: k

Elastic coefficient when stretching: k'

The mass of the base (including the motor): m_1

The mass of the block: m_2

The width of the robot: b

The length of the robot: a

The loaded height of the robot: h

The maximum force of motor: F

B. Appendix II

Github: https://github.com/ZhiangChen/flipping_robot.git

C. Appendix III: Budget

Quantity	Catalog /item #	Description	unit price	total price
1		Ultimate UNO R3 Starter Kit SK#1 for Arduino Stepper Servo Motor Relay RTC (ebay)	33.98	33.98
1		Duracell Duralock 9V Alkaline Battery - Made in the USA - Uncarded Bulk (MN1604) (Battery Junction)	1.25	1.25
2	00991022	Duracell Duralock 9V Alkaline Battery - Made in the USA - Uncarded Bulk (MN1604) (Battery Junction)	2.07	4.14
1		2X set 3mm IR Receiver and Emitter Infrared LED Kit 940nm Remote Diode / Arduino (ebay)	1.99	1.99
1	28BYJ-48	Small Reduction Stepper Motor with Driver Board - 2 pack (ebay)	8.49	8.49
1	(03NPSM)	3 Mil Large Menu Size Thermal Laminating Pouches, 12" X 18", 100/box (ebay)	20.75	20.75
1		JB Weld Kwik Cold Weld Epoxy (2 oz.)	6.99	6.99
1		MEGA 2560 R3 Controller Board ATmega2560-16AU CH340G + USB Cable for Arduino (ebay.com)	13.88	13.88
2		MPU-6050 Module 3 Axis Gyroscope Accelerometer Gyro Sensor Module GY-521 Arduino (ebay.com)	6.59	13.18
2		Plywood board 12*24”	9.75	19.5
Total				124.15