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UNIVERSITY OF CALIFORNIA
SANTA CRUZ

**DESIGN, MODELING, SIMULATION, AND FABRICATION OF ORIGAMI
TO IMPROVE ROTATIONAL JOINT'S PERFORMANCE**

A dissertation submitted in partial satisfaction of the
requirements for the degree of

DOCTOR OF PHILOSOPHY

in

COMPUTER SCIENCE AND ENGINEERING

by

Samira Zare

June 2023

The Dissertation of Samira Zare
is approved:

Professor Mircea Teodorescu, Chair

Professor Marco Rolandi

Professor Marcella Gomez

Professor Patrick Mantey

Peter Biehl
Vice Provost and Dean of Graduate Studies

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2023

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Abstract

Design, Modeling, Simulation, and Fabrication of Origami to Improve Rotational Joint's Performance

by

Samira Zare

The use of revolute joints in robotics is widespread, but their performance can still be improved. The goal of this research is to enhance robot joints by utilizing origami structures, which offer numerous benefits such as space efficiency, and reduced production time and costs (due to flat-foldability). In this work, we investigated various origami crease patterns, categorizing and analyzing them based on their movements. Inspired by the earwig wing and Miura-ori unit cell pattern, we designed and fabricated Four-vertex and Self-lock origami models, and analyzed their rotational motions, moments, and actuator pressure relations. The origami designs are simulated with different central angle plates, and constructed using cutting and binding and 3D-printing methods. We developed rotational manipulators and modeled transitional and modular manipulators as proof of concept.

The results of the study demonstrate that origami joints with central angles closer to 90° degrees show larger rotational motion changes compared to traditional revolute joints (equivalent to a simple fold, figure 6.7) with the same actuator. They save actuator pressure and are deployable in different sizes and weights. Moreover, the position of the central angles in the Self-lock origami affects the direction of movements. The manipulators are used with different central angle plates to illustrate the rotational and transitional movements in different

directions. The proposed Self-lock origami joints can generate bi-directional movement and increase moment in specific rotational phases. The joint is also modular and can be connected to similar or different joints to produce complex movements for various applications.

To my beloved family,

whose unwavering support has been a source of
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Chapter 1

Introduction

Deployable structures have been proposed as alternatives to rigid structures in applications where payload size is restricted (e.g., medical devices [10], spaceborne systems [11, 12], energy harvesting [13], and automotive airbags [14]). These structures, known by the Japanese name “origami,” meaning “folded paper” [15], can be folded to a compact structure and transported efficiently, and then unfolded on-site to resume operation [16, 17]. Designing robots’ bodies with origami can offer rapid, inexpensive manufacturing as well as lightweight transportation [7]. Origami robots can change their morphology to address diverse tasks [7, 18]. Flexibility results from a large number of degrees of freedom of origami help to interact smoothly and adapt to the environment [19]. Another benefit is the scalability in the fabrication of the robots from large scale [20, 21] to microscale [22] and nanoscale [23, 24].

An unlimited number of geometrical shapes can be obtained from a flat uncut sheet of paper [25, 26]. Kawasaki [27] proved that if a single-vertex origami has the sum of odd (or even) angles equal to 180° , then it is “flat foldable”. The crease patterns drawn on paper

could be tailored so the origami robot could achieve specific kinematics or actuation patterns [28, 29, 30, 31]. Additionally, origami modules could be linked and interconnected to achieve complex motion [19].

1.1 Motivation

With advancements in modern technology, devices tend to get smaller, more lightweight and more convenient to interact with. Soft robotics is one of the means of achieving these goals by using flexible and lightweight materials such as silicone and polyethylene as opposed to rigid and heavy alternatives. These qualities become especially important when humans are involved. People's interactions with heavy machinery in industrial environments, such as factories, can put their lives in jeopardy in case of any malfunction in these systems. The bigger and heavier these robots are, the safety risks that they can impose are often increased.

The benefits of soft robotics are not just limited to production lines and can be used in a variety of applications such as in the medical field. Surgical robots are becoming more extensively used every day. They help with operations that were previously too risky, either because of human error or simply because humans can not achieve the precision that robots can. Soft robotics can further improve these robots by adjusting their stiffness to the optimum level. The multi-model variable stiffness manipulator can be used instead of rigid tools for minimally invasive surgeries [32] . These materials can reduce the risks that a stiff and sharp tool could cause in a delicate surgery.

There are however cases where soft robotics may not be the best choice. Soft materials

do not have sturdy structures. They are, therefore, not a good candidate for walking robots. On the other hand, Origami structures have the advantage of being lightweight, sturdy and having the ability to change size depending on the environment they are in. They can be produced in very small sizes for delivering drugs into the human body [7] and can be easily produced in large quantities at a low cost.

Combining soft robotics with origami structures is a technique called pneumatic origami which can create sturdier robots that not only can crawl but also walk in order to pass different types of obstacles. In soft robotics, they commonly get actuated by air pressure. Making a pneumatic origami robot combines the advantages of soft robots and origami robots. In addition, pneumatic origami robots can carry loads which are many times heavier than their own weight.

Currently, a major challenge in designing origami robots with soft materials is that the usual simulation programs, such as Autodesk Inventor, Matlab, and Cosmol are not yet fully optimized for these types of structures. There are some efforts [33][34][35][36] by many researchers to overcome the challenges of modeling the nonlinear behavior of these robots, but they are mostly still works in progress. Some of the assumptions in this paper are influenced by their work [?].

The work presented in this thesis utilizes the best of both worlds of soft robotics and origami structures in an effort to create a pneumatic joint.

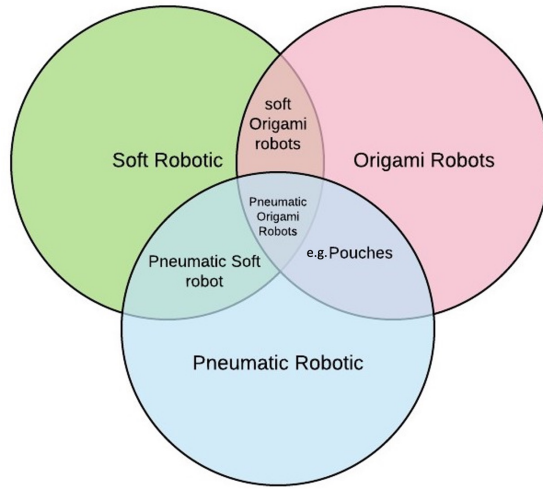


Figure 1.1: Diagram of different fields' combination to obtain Pneumatic Origami Robot.

1.2 Goals

The overarching goal of this thesis is to develop methodologies that can be used to model, design and fabricate origami robotic structures to substitute and improve the performance of the rotational joint. This can be structured into three sub-goals.

- **Designs and Fabrications**

In chapter 3, the design evolution of the models are discussed in detail. Initially, we designed the Miura-ori unit cell origami pattern with varying plate angles. Subsequently, a cutting and bonding method was developed to fabricate the design. However, during the testing phase, we encountered several issues that needed to be addressed. To overcome these issues, we implemented a new Self-lock origami design inspired by the ear-wig insect [37, 38, 39]. We utilized the wedge method and 3D printing on fabric to manufacture the origami joint. Then created pouch motor actuators to maintain the deployability property of the structure. Furthermore, we developed a Bi-directional origami using the

Self-lock structure. In order to optimize the performance of the pneumatic origami joint, we produced a variety of origamis with different materials and physical characteristics.

- **Motion Simulations and Modeling**

To investigate the feasibility of using origami joints and validate the kinematic modeling, we implemented motion simulations of origami structures with different plate angles for a Four-vertex crease pattern in chapter 4. Additionally, we simulated Self-lock joints with varying plate angle locations. Chapter 5 includes mathematical modeling. To kinematically determine the angles of the origami structures, we utilized a spherical mechanism. We also developed analyses of input and output moments for the self-lock origami and presented the pressure relations of pneumatic actuators with respect to the angles of the origami structures. A control design was developed to produce upward and downward rotational joint's movements using the pouch motors. Through these simulations and analyses, we explored origami joints' potential applications and capabilities in various engineering fields.

- **Testing and Application**

Chapter 6 discusses the two different experimental setups that were implemented to record the motions of origami structures. We utilized the motion capture system, OptiTrack, and Kinovea software to measure and analyze the movements of both designs with different plate angles. Additionally, we investigated the motion of self-lock origami with variations in fabric length, plate thickness, fabric materials, and wedge lengths. Furthermore, in chapter 7, we developed manipulators with different types of motions, including

rotational and translational movements, as a proof of concept. Also, a modular manipulator is simulated using the Self-lock origami. Lastly, we have fabricated Self-lock and Bi-directional manipulators utilizing the 3D printing method. The structures demonstrate immense potential for a multitude of robotic applications, owing to their extensive range of motion capabilities.

1.3 Contributions

This dissertation presents the design, development, experimentation, modeling, and analysis conducted to create an origami structure as a substitute for traditional rotational joints, aiming to enhance the performance of the joints. The contributions are listed below.

- Two successive generations of origami joints with different fabrication methods that are deployable, save energy, have high speed and moments in specific rotational phases.
- Motion simulations to assess feasibility of joints with different plates' angles length and positions.
- Moments, actuator's pressure, and motion modeling to determine the strength, energy consumption and speed of the joint.
- An actuator system to control the joint's upward and downward rotational movement.
- Different types of origami structured manipulators to produce various rotational and translational movements.

The dissertation concludes with a summary of potential applications for future research.

1.4 Nomenclature

S	Angle subtended by one arc-shaped side of the inflated pouch actuator.
θ_2	Angular deviation of plates 2 and 3 from coplanar.
θ_3	Angular deviation of plates 3 and 4 from coplanar.
α	Central angle of plate 1 of the origami, here set to α .
α_{12}	Central angle of plate 2 of the origami, here set to α .
α_{34}	Central angle of plate 3 of the origami, here always equal to $\frac{\pi}{2}$.
α_{41}	Central angle of plate 4 of the origami, here always equal to $\frac{\pi}{2}$.
n	Distance from the corner of the plate where the corner of the pouch actuator meets the edge of the plate.
P	Fixed pressure within the pouch actuator.
L_p	Half-length of the pouch actuator when flat, equal.

d	Height of an origami cell in its MPF state in the translational manipulator.
θ_1	Input angle, the angular deviation of plates 1 and 2 from coplanar.
M_{input}	Input moment created directly by the pouch motor.
L	Length of the inflated pouch actuator.
L_0	Length of the pouch actuator when flat, equal to $2L_p$.
L_1	Length removed from the far side of plates 1 and 2 by cutting.
m	Length of the sides of the input plate before cutting.
MPF	Maximum Possible Fold, the state where $\theta_4 = \gamma$.
MA	Mechanical advantage of the origami structure, defined as M_{output}/M_{input} .
θ_4	Output angle, the angular deviation of plates 1 and 4 from coplanar.
M_{output}	Output moment created by the pouch motor through the origami's mechanical advantage.

α_{12}	Reduced value of central angles α_{12} and α_{23} .
γ	Value of θ_4 in the MPF state.
f	Width of the horizontal components of the "zigzag" configuration of the translational manipulator.
D	Width of the pouch actuator when flat.

Chapter 2

Literature Review

This chapter provides a comprehensive review of the literature related to bio-inspired robotics and its advantages. It then delves into one of its branches called soft robotics. It addresses their issues and the potential of origami robots to bridge this gap, offering unique advantages such as flexibility, adaptability, and enhanced interaction capabilities. Additionally, the chapter explores the classification of origami structures based on their movements to identify the origami pattern with optimal rotational motion. Furthermore, it investigates the utilization of origami actuators and the application of 3D printing techniques for fabricating origami structures. By examining these topics, this chapter establishes a solid foundation for the subsequent chapters of the dissertation.

2.1 Bio-inspired Robots

Although wheeled vehicles have higher speeds and lower control complexities in flat surfaces, they may not be the best choice in rough and uneven terrains. As a minimum re-

quirement bipedal or quadrupedal locomotion is optimal to adapt to the ground irregularities and controlling their center of mass. This form demonstrates flexibility and large degrees of freedom since each leg can be controlled independently. However, these features often increase complexity in the controls compared to wheeled vehicles and result in a slower outcome.

Similar examples with low energy consumption can be found in nature. The mobility of animals is based on their attachment and detachment to the surface. Dry adhesion is an example of non-fluid attachment as represented in the movement of Geckos and the *Evarcha Arcuate* spider [40][41]. An important factor for the transfer of kinematics between points of contact for these types of biological creatures is its angle with the surface where the maximum force occurs: 30° degrees. Less than that will lead to sliding and more than that causes detachment from the surface [42][43]. These complex movements in robots require central pattern generated controllers [44], reflexive control, neural circuits and cruise control coordination of legs[45][46] to generate regulated patterns, calculating an optimal force allocation.

Ludovic Daler et al. have designed a multi-functioning robot inspired by the vampire bat (Fig. 2.1) that can fly and walk long distances. This specific robot uses DC motors as actuators and wingerons for flying. Wingerons are part of the wings that control the flight. Fiber has been used in its frame and the wings are made of Icarex which is a lightweight polyester fabric. This robot weighs just 939g with wing span of 72cm with 20m/s flight speed and 7cm/s of walking speed on a flat wooden floor[1].

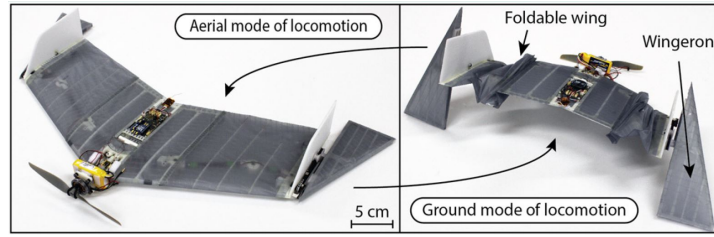


Figure 2.1: multi-modal flying and walking bat inspired robot[1].

Je-Sung Koh et al. have designed a strider robot which can jump like a water strider with only a 68-milligram weight and a high momentum transfer [47]. Later another strider robot was made which could walk on water with the cam-link method. Their cam-link mechanism is the combination of a four-link mechanism and a cam mechanism [48]. A robot called Octoroach implements independent drivers on each side and turns easier while running with the help of its tail [49]. Jianguo Zhao et al. have designed a tailbot that can make a controlled jumping motion [50]. Vidyasagar et al. have improved the design and studied the performance of this kind of locomotion and its robustness[51] by creating a locust-inspired robot which can jump high enough to pass the obstacles which are bigger than its own size. These types of robots provide a unique form of mobility which walking robots lack.[52]. Robert J. Wood has introduced a micro air vehicle inspired by insects' locomotion. Although this robot is tethered, it is extremely light-weight (60mg), and can do vertical flights and Diptera-like wing trajectories [53]. Following the importance of learning the locomotion of animals, many studies have been conducted on animals such as the spider.

Spiders are fascinating creatures where their movement is not limited to one or two forms: jumping, walking, flying, climbing and even swimming. Other unique features of spiders

include their grasp of prey, leg autonomy, and extrusion of silk with the help of their hydraulic system [2]. The mobility of spiders also allows for ease of exploration that outperforms most other natural beings. Spiders are lightweight, structurally-hybrid systems that contain both hard and soft anatomical pieces. These characteristics give them more structural stability and sturdiness while not being limited to a crawling gait similar to slugs. Even though their body is not completely soft, they still have the advantages of a hydraulic mechanism in their legs' joints. Therefore, they bend their legs using their muscles and extend it by pushing fluid into their joints. This is why they are called semi-hydraulic machines [54]. The fluid they use in this mechanism is hemolymph, which is not blood, and is why spiders are in the category of cold-blooded creatures [55].

The spider's heart is in charge of generating the necessary pressure to pump hemolymph, and the muscles in Opisthosoma and prosomal are responsible for boosting this pressure, although the exact location of these muscles is still unknown[2]. This coordination between the muscles and the pumping of the fluid results in locomotion[56][57][58]. This mechanism has many advantages over solely using muscle or hemolymph pumping which include energy efficiency, small weight, and scalability. Hydraulic systems can also carry loads many times heavier than their weight[59]. Soft robotics use a similar mechanism.

2.2 Soft Robotics

In soft robotics, materials such as gels, fluids and soft polymers can deform with minimal force. This gives them the ability to change their shape and rigidity and adapt to the

environment. They can be used in exploratory missions, surgeries, and wearable assistive tools. In exploratory missions, when the terrain is made of sand, mud or soil, a rigid robot will get stuck in the field while soft robots can easily traverse the environment. With their ability to deform, they can also be implemented in very constrained environments.

In the medical field, soft robotics can help surgeons reduce the risks of delicate procedures. Since softer materials eliminate the stress concentration and distribute the force evenly, the tissue or the substrate they are in contact with will be less likely to tear apart [60]. Wearable products such as an exo-suit can help patients with disabilities in locomotion. Brian Byunghyun Kang et al. have designed a soft tendon-driven exo-glove from silicone [61]. Later they also developed a customizable pneumatic hand [62]. The Elastic Modulus of these robots makes them a perfect bio-compatible material as they feel more like a real bio-tissue or an organ.

Elastic Modulus or Young Modulus (Fig. 2.2) is the ratio of the force to the percent elongation of a regular bar that has been stretched along its principle axis [63]. Although this property does not apply to irregular bars, non-homogeneous or materials with large deformation it can show the amount of the rigidity of the material. Rigid materials usually have a Elastic Modulus of more than 10^9 Pa as opposed to organs or tissues in which that number is 10^2 - 10^6 Pa. This means that organs and tissues have a rigidity in 3-10 orders of magnitude smaller [63].

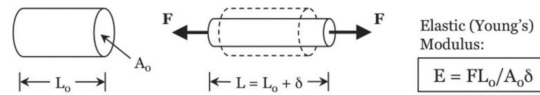


Figure 2.2: The Elastic Modulus formula and model [2]

Another benefit of soft robotics is their ability to alter their existing natural shape.

A simple mechanism that pumps air to a soft robot can change its shape and as a result create movement. Robert Shepherd et al. have made a soft quadruped robot inspired by non-skeleton animals such as starfish, in order to create crawling locomotion. They have used air pressure for actuation since it is environmental friendly, fast, and lightweight. For the fabrication, they have used lithography in order to make a pneumatic valve system which has a Pnue-net (PN) architecture [64]. The design is simple and only needs less than 10Pa to get actuated. Control is very tough with nonlinear systems like pneumatics. Currently, there exist few (or no) actual controls. This robot is composed of EcoFlex as extensible chambers of PN, which gets inflated under air pressure. The other side of it is made of PDMS (Sylgard 184, Dow Corning) for constraint which leads to the bending of the actuator. For the control part, they have used a computer valving system [3](Fig. 2.3).

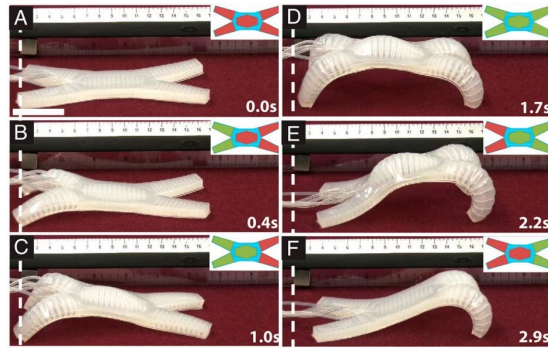


Figure 2.3: The undulation in the soft robot by compression and decompression of its PN. Red parts are inactive, and green parts are active (inflated). [3]

Soft robotics consist of compliant and low modulus materials, they are often a good candidate for medical applications such as implanting devices, drug delivery inside the body and surgery assistant. Ventricular assistive devices (VAD) have been used in the past for massaging the heart in case of heart failure. There have been some difficulties with this approach due to

bleeding and thromboembolism (forming blood clots due to the use of the non-biocompatible device). Therefore cardiac compression devices have replaced VAD. They are inflatable cuffs, and there is no direct contact with blood with these devices. Christopher Payne et al. have designed a sleeve around ventricles pressurized by air in order to simulate the heart muscle and support pumping blood to the body (Fig. 2.4). This sleeve acts as an artificial muscle and coupled with the elastic band and pressure can become a good replacement for VADs. The experiment has been done on animals and the results are accessible in the paper[65][4].

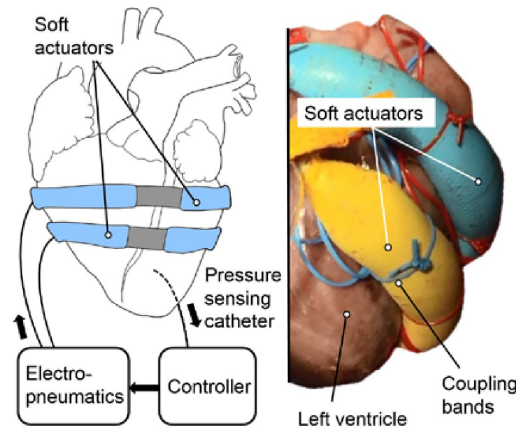


Figure 2.4: The pneumatic soft actuator supporting heart failure on the right and control schematic on the left [4]

Treadmills are often used in therapy for those recovering from spinal cord injuries. However, they are stationary and not a good option for passive gait training. Pouch motors and soft pneumatic actuators can be used in rehabilitation devices. The traditional method of therapy was only accessible on the treadmill, but now with the new devices using these lightweight, low cost and highly customizable actuators, they are able to be used as wearable assistive devices in order to help people who suffer paralysis regain voluntary movements. A team at Tokyo

University was able to use pneumatic pouch motors as a gait assistive tool on a paralyzed rat in order to help its locomotion (Fig. 2.5). Their result shows that the size of the pouch has a direct and high relationship with the force and performance of the actuator. They have also come up with a new design for pouches in order to get more significant force to help the rat. These pouches have been designed in small sizes and have been applied in series. Together they can apply a considerable force[5].

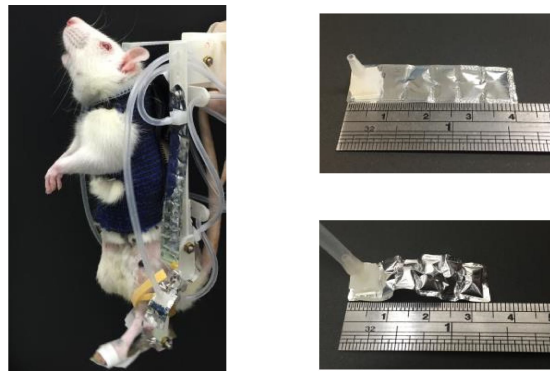


Figure 2.5: Application of pouches as a wearable assistive motor on a paralyzed rat for gait training [5]

Since rigid robots have limitations in their interaction with the environment especially in soft and cluttered surfaces, soft robots could be a good replacement. Nowadays, soft robotics play an important role in technology and their properties have attracted industry to invest in this field. Important properties of soft materials are their resiliency and compressibility. This protects them in incidents such as dropping, squishing, and hitting which enables them to continue their work without any true external damage [66][67]. Another important property is their robustness. Rebecca Kramer et al. have made a hyperelastic electronic circuit [68] [69] that opens the possibility of using electronics in soft materials[70] [71] and keep the flexibility at

the same time. This can protect the circuit in case of incidents such as bending, dropping, or hitting.

Soft materials can be ideal for pneumatic or hydraulic actuators. These two types of actuators make the robot entirely soft. However, if we take into account the pumps which push the fluid or air into the robot, it will not be an entirely soft robot, Michael Wehner et al. have made an untethered Octopus robot made of an entirely soft structure fueled by an on-board mono-propellant [72]. Pneumatic actuators can be better options in out of water environments since they are lighter, and the environment itself can become the fuel of these types of actuators. However, they do not have sturdy structures which makes their movement difficult to control and limited to crawling. In order to accomplish walking locomotion, often some sort of rigid-bodied skeleton in the structure is needed. This is where origami can play an important role.

2.3 Origami

Origami is an ancient Japanese art of folding paper. Origami has been used for many decades in architecture and engineering in order to achieve smarter structures. Robotics applications where origami has been implemented are found with cardboard boxes in space systems, small robots, and self-assembly devices. These robots are made of sturdier materials compared to soft robots [73]. However, they are still flexible due to their paper-like materials such as high or low-density polyethylene. This can give soft robots the ability to walk, swim, and climb. Another benefit of origami robots is that, like soft robots, they can change their shape. Jun Mitani

has introduced cylindrical and conical shapes and folding techniques in order to make curved origamis with a rotational-sweep kind of motion (Fig. 2.6[6]).

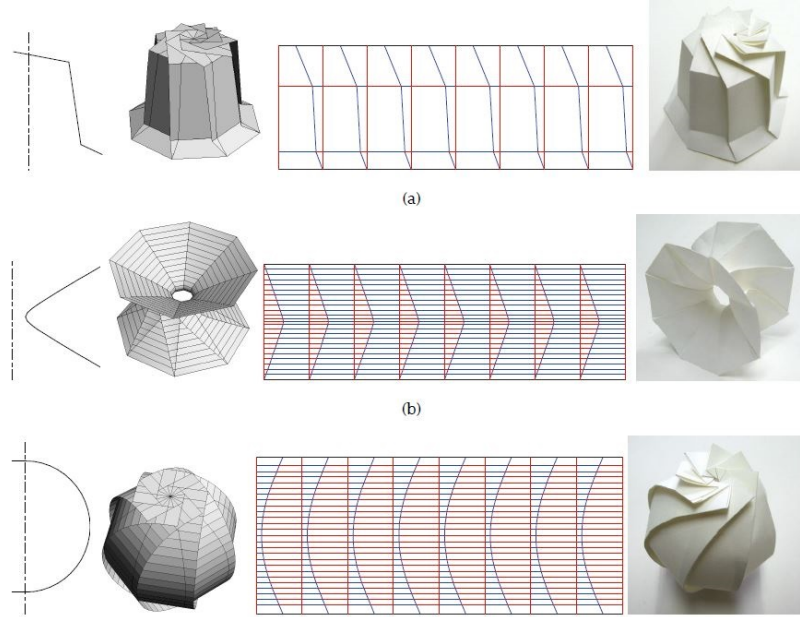


Figure 2.6: Cylindrical Origami: a) bell b) hyperboloid c) sphere. You can also see their geometrical model, crease pattern and the folded paper of them from left to right. [6]

Noy Bassik et al. researched a new multi-directional curved origami model achieving a bigger range in shapes and angles [74]. A Snake origami robot has been made based on modular snake robot technology by folding paper. However, because of the small size of the robot this snake has no actuator for controlling its movement [75].

Nowadays, smart pills have become the focus of many types of research. The ability to navigate and deliver medicine to the exact location in the body where it is needed is the main challenge in the process. There are many types of actuators which can be used in order to give robots the ability to deliver drugs including piezoelectric, ionic conducting polymer film (ICPF) and magnetic actuators. Origami can be a good solution in order to make small, lightweight and

cheap robots. Shuhei Miyashita et al. have developed an origami robot which is able to self-fold, walk, swim, and even degrade once it is inside a human body[7]. They achieve this by using shape memory polymer in order to change the shape of the robot via heat. When dealing with miniature robots of this nature it is important to use less integrated electronics while maintaining the ability of the robot to be controlled and move. The Miyashita robot is just 0.31 grams and its actuator is a remote magnetic control and since the material is polystyrene (Fig. 2.7)[76]. This robot was then further optimized to be able to deliver a drug to the wounded areas in a body. First, they put the folded robot into an ice capsule. After the capsule has been swallowed by the patient, it will melt in the stomach. The robot will get to its final shape by the heat of the environment and navigate the body to put the medicine on the wounded area [7].

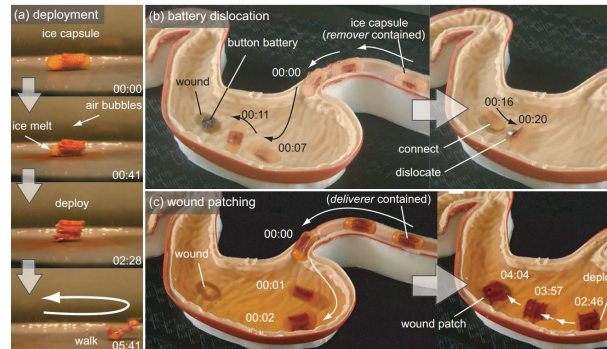


Figure 2.7: a) The capsule dissolves and robot starts to unfold due to the temperature b) It will move the battery and in c) it patches the wounded area [7]

De-Young Lee et al. have made a deformable wheeled robot using origami fabrication. The initial fabrication for the origami wheel is in two dimensions but alters formation to 3D. With the help of SMA coil spring actuator, this robot can go through a 5cm gap. This approach could be useful for big wheels [77]. The wheels can change their radius while moving. Using PVC gives them flexibility and a sturdy structure. A DC geared motor was used in

order to pull the wire and make the diameter of the wheels bigger. They have then improved the design by adding a cable-driven mechanism to give the robot a deforming capability while rotating (Fig. 2.8). Plastic bands were applied to make the diameter smaller. The maximum speed of the robot is 0.3 m/s with the total mass of 470g and the diameter can be changed from 55mm to 120mm [8].

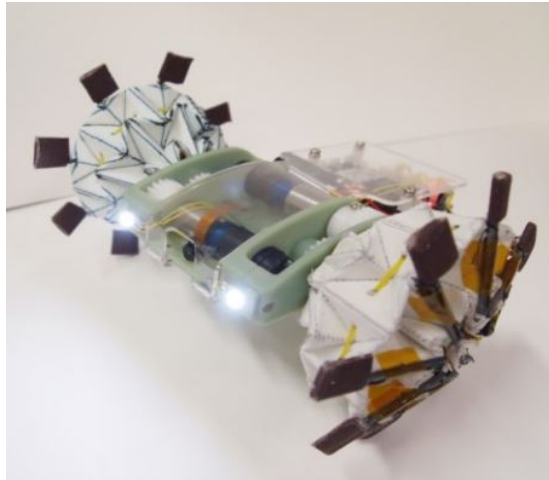


Figure 2.8: Origami Wheel Robot[8]

Tian Qiu et al. have proposed a microscopic-sized robot that can swim in liquids with a high viscous force. They have used external magnets to activate a scallop-type robot [78]. The material used is PDMS (polydimethylsiloxane), formed by a 3D printed mold. By putting micro-magnets on the shells and aligning magnetic fields with them, the shell of the scallop can close, and it can open by restoring force to the PDMS hinge[78].

2.3.1 Classification

The origami crease patterns can offer a variety of movements. To substitute the traditional robot's joints with the origami structures, we need to categorize the origami patterns based on their motions. There are some origami classifications [79][80][73][81], but these do not consider movements. Our focus is on modular patterns since they are more generalized structures for a wide range of applications. The main motions that they could generate include deployment, rotation, and translation. The rest of the origami structures' movements are composed of these main motions. Also, some of the origami patterns are application-specific [7], and their movement cannot be generalized for various actuators or robot designs. The cubic magnet [82] uses different origami patterns for various movements of walk-bot, boat-bot, glider-bot, and wheel-bot. The magnetic actuator does the majority of the movement. In these patterns, the extra length of the top and bottom of the walk-bot, the wings for the glider, and the large center of the boat-bot help the locomotion.

Deployment Many origami patterns such as Tachi–Miura [83], Miura-ori[84][85][86][87], twist-based [88] [89], waterbomb base[90][91][92], Guest et al. crease design [93], magic-ball [77], zigzag folding [94], flasher [95], kirigami (cutting paper)[96] provide a high ratio of deployed area to stowed volume in their movements. Kaori Kuribayashi[92] used waterbomb pattern to develop an origami stent graft that can change its volume and fit into a small 13 mm tube. The waterbomb pattern could be altered to take a more spherical shape rather than a long spiral and create a magic-ball pattern[97]. This could have many applications, such as vacuum-driven soft robotic grippers [98] and deformable deployable wheels[77] [99][100][101]. They

can adapt to different environmental conditions by changing their sizes based on the available spaces, objects, and surfaces.

The Eel-inspired stretchable origami [102] could expand and deploy origami patterns such as fish base, Miura (based on Miura-ori polyhedron), and Yoshimura origamis. It could produce translational and rotational movement when expanding, but the volume is large and not optimal for these movements. The stretchable and deployable kirigami designs [103][104][105] could be used in flexible electronic tools and robots. Some of the crease patterns [83][84] could provide flat-foldability property (deploy to a flat configuration). Some Kirigami composite sheets [106][107][108][109][110] use curve, folds, and pop-up motions to turn 2D sheets into 3D structures. The kirigami snake-inspired skin [111][112][113] is designed to convert from 2D into 3D skin with microornamentation. The skin adds friction and strain relief properties to improve the soft robot's locomotion. Other deployable origami applications include an adjustable energy absorption origami crash box [114], kirigami solar panels [115], kirigami biosensor [116], rotary protective system [87], and deployable cellular structure [31].

Translational Movement When crease patterns with deployment capability are connected to themselves in a way that creates a looped structure (cylindrical or semi-cylindrical shapes [117]) with zig-zag patterns, they could produce translational movement as well as flat-foldability and deployment. Some of these patterns include Twisted tower [118], magic-ball [119], Yoshimura [120][91], diagonal [91], kirigami parallel[121], triangular spring [122] patterns. Many worm-like origami robots [91][119][121][122] have been produced using these patterns. The Quadrilateral tube [123][124] is applied as pneumatic arms of micro aerial vehicle (MAV). The Kres-

ling origami tower joint [125] based on Kresling crease pattern could expand and contract to produce screw-like motion. Most of these origami joints have small rotational motion per length [125]. When they are activated (expanded), their volume increases drastically. The larger they are, the bigger their rotational motions. Since limited space is the problem that origami should solve, we only consider translational motion as their main functionality.

Rotational Movement Rotational movement is one of the main joint functionalities that could be accomplished by crease patterns such as simple fold [126][127][128], waterbomb [129], Spherical six-bar linkage [130][131][132], kirigami [133][134], reverse and accordion folds [135], castellated [136], curved folds [137][138], Hinge, Prismatic and Pivot [139], and Sacrificial [140]. A simple fold consists of two rigid or semi-rigid plates connecting with a foldline or any flexible joint. The mechanism is equivalent to the revolute joint in traditional robots. The origami joints with simple fold mechanisms include robogami [126], Helical origami gripper [127]. kirigami hand rehabilitation device [141]. Zhenishbek Zhakypov [128][18] designed a 2D pattern that could be folded and assembled into a 3D robot, Tribot. It could crawl and jump by rotating its legs using a simple fold mechanism. The legged origami robots [142][143][144][145][146] used the simple fold in their structures to walk. In addition, using the flexural element [144] could add degrees of freedom to the structure, although it jeopardizes the system's stiffness. Kirigami designs [147] could generate a similar rotational movement as well. Hiroyuki Suzuki et al. used the simple fold module to create a kirigami manipulator for microsurgery [148]. It could rotate along a remote fixed point. The design is precise and lightweight to avoid excess force in minimally invasive surgeries. These structures' function-

alities are comparable to revolute joints and could provide many origamis advantages such as saving space and flexibility in sizes and weights.

In addition to using simple folds in various structures, there were some efforts to create different rotational origami joints as well. Inspired by two basic folding patterns, reverse and accordion folds, the customizable three-dimensional-printed origami soft joint [135] is developed and has a rotational range of $[-60^\circ, 60^\circ]$, and 18.5Nm torque under 180kpa. This joint has significant force capability, safe and effective interaction, although the pneumatic systems tend to have large forms. Therefore, they cannot be modular to produce complex motions. Tendon-driven robogami [136] joints with adjustable stiffness using a SMP (shape memory polymer) layer could rotate along the x, y, and z axes. These joints are flat-foldable and modular. The rotational motion's range is limited and depends on the solid panels' thickness and the flexible joint between the panels. spherical six-bar joint [130][131][132] with a common spherical center creates limited rotation in different directions. A crawling robot is made using the joint. The waterbomb pattern on two parallel cross-sections is used to create cube artificial muscle [129]. It has adjustable stiffness but low rotation and is not flat-foldable. Todd G. Nelson et al. [140] designed flat-foldable Sacrificial origami joints which have motions while assembling and are rigid at their final position. Due to their specific shapes and movements, they are only suitable for structures that fit their forms. Similarly, Cynthia Sung and Daniela Rus [139] have introduced origami joint designs to substitute traditional robots' Hinge, Prismatic, and Pivot rotational joints. These Joints could be combined to achieve higher degrees of freedom and generate the expected kinematics. If a robot does not require the specific structure of the proposed joints, the simple fold takes less space and is flat-foldable.

Curved patterns could add stiffness to the origami structure [149]. The compliant rolling contact joint [150] uses the curved-folding origami technique and has $\pm 9^\circ$ degrees maximum rotation and actuation of 0.5N. The Ladybird beetle-inspired origami joint [137][138] consists of compliant facets and cross-sectional curvatures. It is a modular joint and could increase the energy storage capacity and introduces the self-locking mechanism for gliding and jumping. The moment could be improved by adding more origami layers. There are curved kirigami patterns with rotational motion as well. The Lamina Emergent joint[133] is based on a foldable mortise-tenon structure. It has a curved kirigami pattern with rotational motion in multiple directions. The maximum rotational angle is around 16.61° degrees. The bending moment is about 0.06Nm. Jihyun Ryu et al. designed a curved Kirigami rotational joint [134] that is activated by water. Curved surfaces generate a low range of rotational motion compared to simple folds. Also, fold action is impossible due to their geometrical constraints (no foldline).

Compared to a hinged like structure (Fig. 3.5, A:b) the Four-vertex origami design (Miura-ori unit cell) [151] could generate 8.4 times more rotational angle with the same actuator (ex. pouch motor). For the simple fold, this means if we attach the pouch motor on both outer edges of its plates by inflating the pouch, the length of it will decrease and result in a rotation of the fold. If we attach the same pouch on the outer edges of a four-vertex origami's input plates (plates with central angles less than 90°), the output plates (plates with central angles more than 90°) will rotate faster compared to a simple fold's plates. The pattern has three convex and one concave folds. It could be as thin as a sheet of paper and manufactured in different shapes and sizes, which gives us the capability of adjusting its weight and size based on the application. Its assembly with other origami joints will create complex movements. Connecting them might

over-constrain their movements. Using a cutting method [89] could fix this issue. Therefore, the Four-vertex origami design could be an efficient candidate to substitute for traditional rotational linkages. However, the main issue with this structure is that the origami has two configurations. The uncertainty of which foldline will be activated when the pouch motor is inflated increases the chance of failure in the joint's rotation. We discuss this problem in detail in chapter 3.

The earwig insect [37, 38, 39] has an incredible origami-like folding wing structure that provides a bi-stable mechanism for flights using rotation and extension of protein-rich joints. The wing's structure includes facets and foldlines with a common central vertex. The summation of the central angles around the common vertex is less than 360° degrees. This design provides a self-lock mechanism during the insect's flight. The Jakob Faber et al.[152] designed an earwig-inspired spring origami joint. Due to the flexibility and extensibility of the joint, it could provide programmable fast morphing, morphing tolerant geometry, and self-locking mechanism in stable configurations. Although earwig origami adds many properties to a structure, there are some issues with the design. The flat state is unstable. It reaches an energy peak to compensate for membrane extension during the transition from the flat state. The joint spring energy is low to handle heavy weights. The stretchability of the foldlines declines over time and with every use. A small missing central angle (less than 5° degrees) could cause the joint to have only one stable configuration due to low energy barriers. Depending on the number of folds, the width of flexible foldlines could be large. This results in a weaker structure.

In order to take advantage of both Miura-ori unit cell and earwig-inspired origami and solve their issues, we proposed a new rigid origami design, the Self-lock joint, that has some

combination of their properties. The earwig origami structure solves the uncertainty of Miura-ori unit cell's different possible states. To increase the earwig origami moment, we exclude the rubber band between the plates and assumed a foldline with a non-extensible material and zero gaps between them. This method also avoids wear and tear of extensible rubber joints. Unlike earwig origami, the new joint structure is created in two dimensions (flat state). Therefore, the foldlines could have the minimum possible width (gap between plates). The less space between the plates, the sturdier the structure would become. These foldlines are equivalent to revolute joints. Defining a regular revolute joint with zero gap between the solid plates would jeopardize the flat-foldability due to the missing central angles and inaccessibility of its flat state's geometry (summation of central angles $< 360^\circ$). By dividing the origami plates into pairs of input and output plates and using specific central angles for them, the joint could have a deployable structure, save energy, provide a state-lock mechanism, great moment, and downward and upward rotational movements of the structure. Also, With less than 5° missing central angle, it will still have two stable configurations.

2.4 Origami's Actuator

Self-folding [153] is one of the challenges of these structures. Achieving a large range of motion could be a solution for the deployment of the origami robots. "Active materials", which can convert electrical or thermal [73] energy into mechanical work, have been proposed as an actuation solution for origami-based mechanisms [154]. The advantage is that this actuation does not require external motors, but the disadvantage is they have slow activa-

tion [155, 77] and either require a heat influx [156] or dissipate significant amount of heat to the environment [157]. Kuribayashi et al. [92] have designed a self-deployable origami stent graft using a bio-compatible Ni-rich TiNi shape memory alloy foil. For a compact design, the stent consists of an array of squares, where each square contains a “waterbomb base” origami pattern. When inserted in an artery, the stent expands in a cylindrical shape due to the increased temperature or superelasticity in a specific location [158, 159, 160]. Dae-Young Lee et al. [77] made an origami robot with deformable origami wheels, which can adjust the shape of its wheels using SMA (Shape Memory Alloy) coil springs. Shuhei Miyashita et al. [7] designed an 1.7cm square origami robot that is capable of self-folding, walking, swimming and dissolving. This robot can be delivered to the body by a capsule and carry a drug to a specific area. It uses a Shape Memory Polymer for unfolding and magnets for actuation. S. Guitron et al. [155] developed autonomous control of these magnetically actuated robots and S. Chandra et al. investigated the possible health risks of this actuation approach [161]. Therefore, although active materials provide elegant actuation, due to slow actuation and reduced load bearing [162] they have limited application in origami robotics. The alternative solution is using pneumatic actuators [163].

Martinez et al. [9] proposed an “elastomeric origami” concept that embeds flexible (paper) elements in an elastic base (Ecoflex) and uses inflatable bladders for actuation (Fig. 2.9). This design can bend, twist, extend, and contract. The origami paper structure provides appropriate stiffness and adjustable properties, while the pneumatic bladders enable the robot to handle items about 120 times its weight. Niiyama et al. [164] proposed a self-folding and self-actuating origami robot prototype based on a “planar pneumatic system” actuated by inflatable

“pouch motors”. These are cylindrical pouches made of polyethylene which can be inflated to actuate (fold or unfold) the robot and deflated to bring the robot back to the original state. These characteristics keep the active origami flat-foldable while the speed of the motion is adjustable and depends on the rate of inflation and deflation of the pouches. The concept was extended by Wu et al. [165] to construct “An untethered self-folding locomotive paper robot using pneumatic actuators.” The main advantage of using pouch motors is that they are manufactured from very thin polyethylene, so the flat foldability of the origami structure is not jeopardized. However, each motor has a relatively small stroke. The solution proposed by Niiyama et al. [164] is to connect several motors in series to achieve a larger stroke. The advantage of the method proposed here is that they obtain much larger rotational movement with the actuator. However, the result is a bigger actuator, and it is more complex to control the actuator accurately. The proposed origami structure overcomes this issue using only one pouch motor. This is explained in detail in chapter 3.

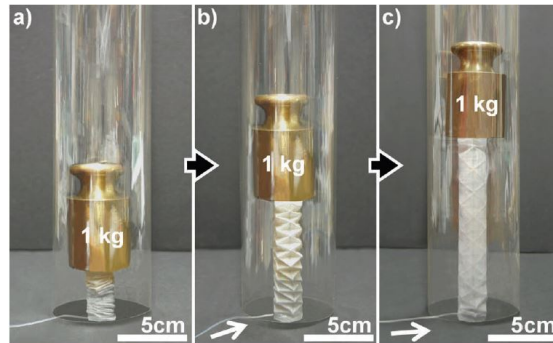


Figure 2.9: Origami extension actuator carrying 1Kg load[9]

2.5 3D Printing on Fabric

3D printing, also known as additive manufacturing, offers numerous advantages that have revolutionized various industries. One key advantage is its ability to create complex geometries and intricate designs with high precision, enabling the production of customized and personalized objects [166]. Additionally, 3D printing allows for rapid prototyping, reducing the time and cost involved in product development. It also enables on-demand manufacturing, eliminating the need for extensive storage and inventory. Furthermore, 3D printing promotes sustainability by minimizing material waste through precise layer-by-layer construction. With its versatility, speed, cost-efficiency, and design flexibility, 3D printing has emerged as an optimal method for creating origami structures.

The integration of 3D printing technology with the art of origami combines their advantages, offering an optimal structure for different applications. Fabricating origami requires manufacturing solid parts (origami plates) and soft parts (foldlines) and assembling the parts. Researchers mainly used three different methods to create the 3D printed origamis. One includes creating soft and solid parts separately and integrating them manually to create the structure. In the 3D printable Origami vacuum pneumatic artificial muscle with the fully 3D printed chamber, the rigid parts are manually inserted inside of it [167]. The actuator is powerful and capable of carrying heavy loads. However, this fabrication method requires manual labor, which increases production time, and cost, and presents challenges for fabricating small or complex structures.

The second method involves embedding rigid origami structures in a fabric skin (soft

material) using lamination [124, 168], such as the heat press method [169], or by employing an adhesive layer [170]. For example, a deformable origami wheel is fabricated using PVC segments, an adhesive layer, and fabric [170]. The use of fabric adds high flexibility, low weight and enables foldable motion in the structure. However, a limitation of this method is its difficulty in fabricating very small, delicate, or thin origami structures. The third method, which is widely employed for 3D printed origamis, involves using multimaterial 3D printers [171, 172, 173, 174, 175, 176]. In this approach, a 3D printed Kresling origami, for instance, is fabricated with a rigid core and a rubber-like frame made of visco-elastic material [171]. 3D printing both soft and solid materials simultaneously offers fast and cost-effective fabrication. However, using fabric as the soft material offers even higher flexibility, reduced thickness, and lighter weight for the soft joint. Therefore, the integration of 3D printing on fabric is an area of investigation.

By combining the versatility of 3D printing with the flexibility and functionality of fabrics, a wide range of possibilities has emerged in various fields, including fashion [177, 178, 179], medical textiles [180, 181], and wearable technology [182, 183, 184]. In the realm of wearable technology, for example, 3D printing has been used to create smart wearables by integrating push buttons directly onto fabrics [185, 186]. Furthermore, researchers like Sachith Muthukumarana et al. have leveraged the capabilities of 3D printing, combined with Shape-Memory Alloys, to develop customizable actuators [187]. Despite the numerous advantages offered by 3D printing on fabric, it has not been extensively utilized in the fabrication of origami joints. Therefore, we have chosen this method to manufacture the 3D printed Self-lock and Bi-directional origamis, exploring the novel possibilities that arise from the integration of these

technologies.

Chapter 3

Origami Patterns' Designs and Fabrication

In this chapter, we explored two distinct origami pattern designs and their implementation for creating flexible joints. By employing these origami-inspired joints, we aim to replace traditional revolute joints, which have limitations in terms of motion range and versatility. To this, we first fabricated the origami patterns using specialized techniques.

3.1 Four-vertex Origami

We propose the Four-vertex pattern for the origami joint mechanism. The pattern requires four fold-lines in order to be functional. The plates between the fold-line could have different angles, but the summation of all four plate central angles should be 360° degrees to be flat-foldable. To obtain a downward rotational motion of origami, the plates need to be vertically symmetrical. The origami consists of four, 2mm polyethylene plates bonded between two, 0.1mm sheets of flexible polyethylene adhesive tape. A 1mm gap between the edges of the 4 rigid plates generate 4 interlocking flexural joints. The mechanism is actuated by 2

pouch motors, which are gas-tight bladders made of thin sheets (0.01mm) of low-density flexible polyethylene. When inflated, the bladders change shape and apply a torque on the flexural joint between the plates, folding or unfolding the mechanism. The heat-based manufacturing technique proposed by Niiyama et al. [188] for fabricating pouch motors was adapted for the current application.

Figure 3.1 schematically shows the fabrication process used for the origami mechanism. Fabrication begins with cutting four plates of high-density polyethylene (Fig. 3.1a) and attaching them to the adhesive side of the tape with 1mm spacing between their edges. The mechanism is completed by adding the second layer of adhesive tape (Fig. 3.1b). After attaching the tapes on top and bottom of the origami plates, soft joints have been created between them. These joints can produce rotational motions. Joint 1 (rotational 1), Joint 2 (rotational 3), Joint 3 (rotational 2), Joint 4 (rotational 1) that can be seen in figure 3.2, respectively. Figure 3.1c illustrates the possible rotations of the four revolute joints. The pouches are connected to the plates using tapes at their edges. Figure 3.1d schematically shows the attachment position of the two pouch motors. Figure 3.1e is an example of a mechanism before testing. The two motors are inflated using two flexible tubes.

Figure 3.2 shows an origami mechanism during manual folding and unfolding. It can be seen that a small rotation applied to the upper two plates translates to a large folding of the lower two plates under the upper two plates (second 4 in Fig. 3.2). When the rotation applied on the upper plates is reversed, the mechanism returns to the flat position. Figure 3.3 shows a similar origami joint manufactured from cardboard, being folded and un-folded using pouch motors. Each motor is actuated by a different air tube (on the right side of each picture).

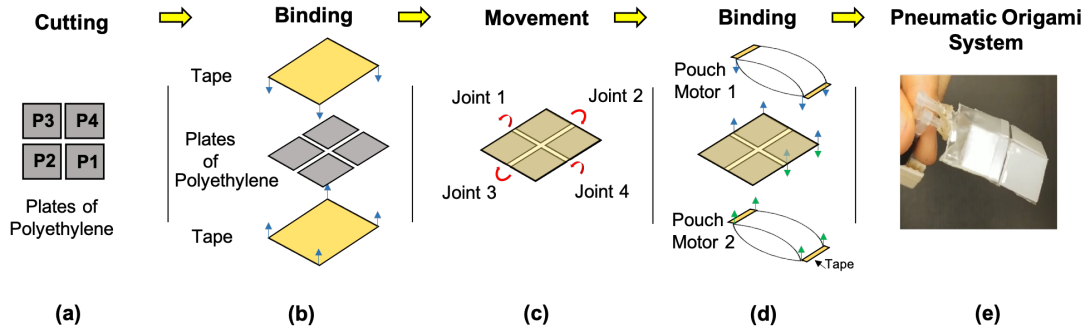


Figure 3.1: Design and the manufacturing process of the pneumatic origami joint: a) Four squares (plates) have been cut from the polyethylene sheet. b) Tapes have been attached to the top and bottom of the plates to connect them together. Space is considered between them to mimic fold-lines of origami to obtain flexibility. c) The spaces between the plates are assumed to be joints since they make the rotational movement possible for the plates. d) Pouch motors (air bags) have been attached on top and bottom of the pair of plates. e) The pouches are inflated and deflated using the attached tubes to activate the plates (rotate the joints)

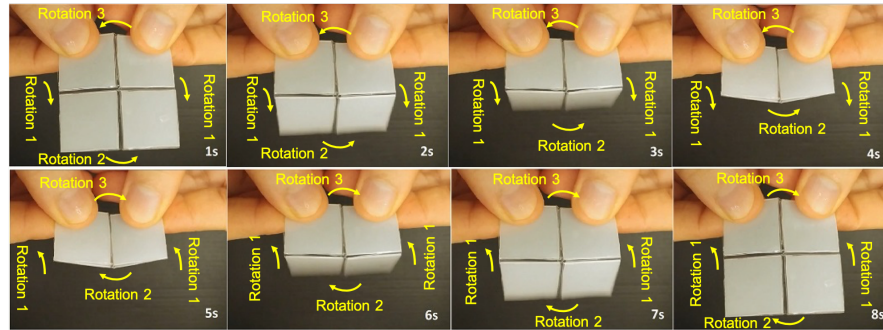


Figure 3.2: Manual folding and unfolding. Upper figures: folding, Lower figures: unfolding - Starting from the top left corner, as we move right and increase rotation 3 (joint 2, rotate the plates towards each other), rotation 2 (joint 3, rotational motion) happens equally in the opposite direction, and rotation 1 (joint 1) occurs drastically more than rotation 2 and 3 (origami folds). Starting from the bottom left corner, as we move right and apply rotation 3 in the opposite direction (rotate the plates against each other), rotation 2 (rotational motion) happens equally in the opposite direction, and rotation 1 occurs drastically more than rotation 2 and 3 (origami unfolds).

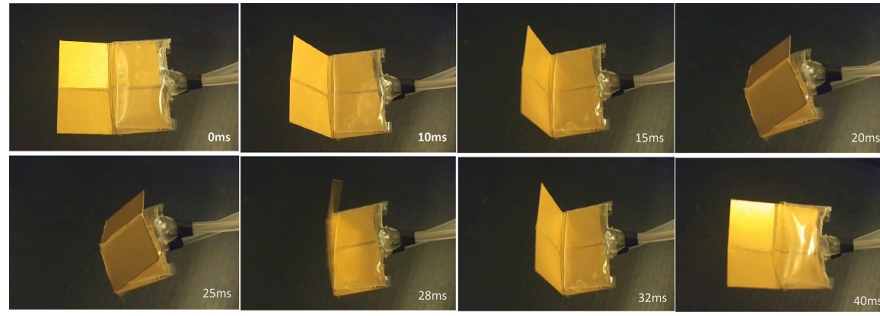


Figure 3.3: The pneumatic origami joint folded and unfolded using 2 pouch motors attached on both side of the joint. Upper figures: folding, Lower figures: unfolding - Starting from the upper left corner, as we move right, the pouch behind the two plates are inflated using tubes and pumps. By inflating the pouch, its width shrinks, and it pushes the connected plates to the pouch towards each other. This causes the other two plates to bend drastically due to the geometrical structure of the plates. Starting from the bottom left corner, as we move right, the pouch behind the plates is deflated, and the pouch on top is inflated. It results in the plates connected to the pouches to unfold and the other plates to straighten up.

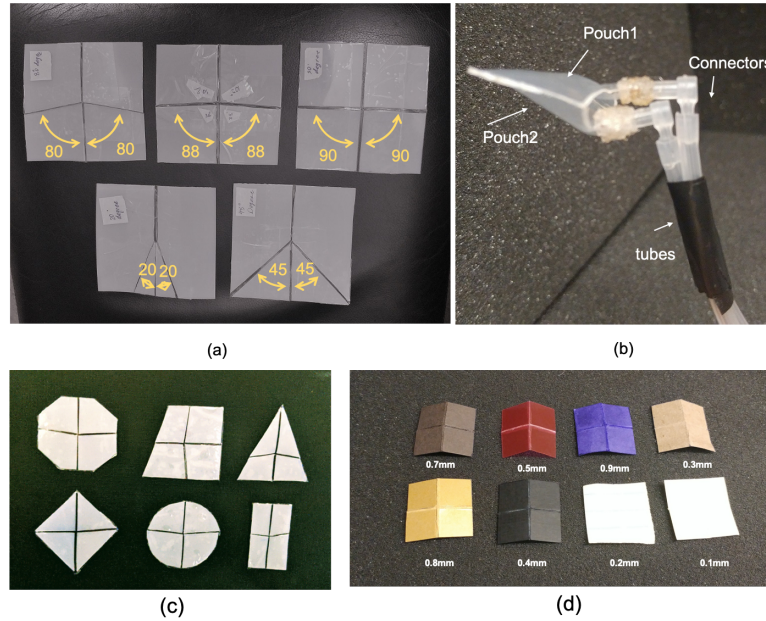


Figure 3.4: a) The origami pattern with different plate's central angles. Each will result in a different motion of the origami. b) The configuration of two pouches on the top and bottom of the origami pattern. The origami will be installed between them. c) The 89-degree Four-vertex origami pattern could have different plate shapes (different non-central angles). The plate shapes can be changed base on their applications d) Paper materials with different thicknesses have been tested on the origami pattern to find the one that results in the origami's optimal performance.

Although fabricating paper origami joints is easier and faster, in the current paper, we used polyethylene to ensure consistent operation over a longer period of time [189]. The paper-like materials tend to tear apart after several movements or over time.

The four joints of the origami mechanism are not independent. For example, folding the joint labeled “Joint 1” in figure 3.1c restricts the folding of joints 2 and 3. Understanding the correlation between the rotation of different plates considering the constraints added by their kinematic coupling will be exploited in this paper to amplify the rotation of the joint. An additional advantage of the proposed foldable design is that each 4-plate origami can be used as a separate module in a complex foldable structure constructed using this approach. We will show in chapters 5 and 6 that small changes in the vertex angle lead to significant differences in the kinematics of folding and un-folding. Therefore, an application-specific gripper (e.g., direction of folding, folding strategy, range of motion) can be designed by alternating origami modules with different vertex angles.

3.2 Self-lock Origami

The problem with the Four-vertex origami design is the possibility of having two states if we activate the origami using the pouch motor actuator on the input plates (Fig .3.5A and Fig. 5.2a). The first configuration could have a rotation along axis 1, 2, and 3, and the second possible configuration, a rotation along only axis 1. We want to avoid the second configuration since it results in a simple fold structure and would not produce a wide range of motion (a small range of rotation compared to the first configuration [151]). It also could jeopardize the

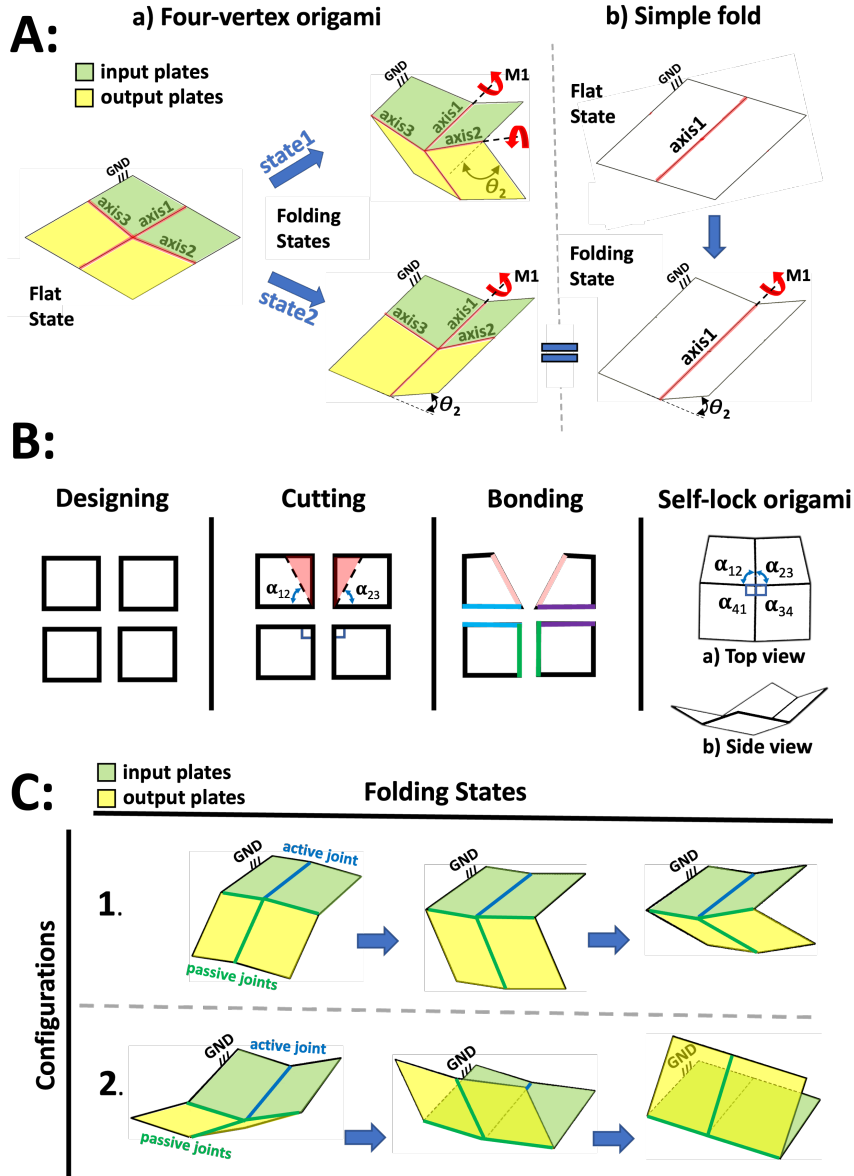


Figure 3.5: **A:** a) Transformation from the Flat state of the Four-Vortex Origami to the Folding states 1 and 2. In the Flat state, all the angles between origami plates are 180° degrees. In the Folded state, some or all the angles between origami plates are less than 180° degrees. The origami in state 1 undergoes rotation in all axes, while in state 2, only along axis 1. The input plates, covered by the pouch actuator, are colored green, while the output plates, with no actuator involvement, are colored yellow. b) Transformation from the Flat state of the Simple Fold to the Folded state. The only rotation occurs along axis 1. State 2 of the Four-Vortex origami and the Folded state of the Simple Fold are equivalent.

Figure 3.5: **B**: Design and Modeling of the Self-Lock origami. Design: drawing the square plates. Cutting: reducing the central angles on two of the plates. Bonding: defining revolute joints between the edges of plates with matching colors. Self-Lock origami: the final product in different views, with two reduced central angles α_{12} and α_{23} , and two 90° degree central angles α_{34} and α_{41} . **C**: Configurations 1 and 2: Creation of downward and upward movements, respectively. From left to right, a transition from an almost flat state to a folded state occurs. The blue active joint is a revolute joint between origami plates actuated by the pouch actuator, while the three green passive revolute joints move based on the rotation of the active joint.

integrity and performance of the robot due to the different possibilities of movements.

To solve this, we proposed a new design to cut and reduce two origami's central angles (Fig. 3.5B: Cutting phase) and then attach the updated plates together. The result is an origami whose central angles sum to less than 360° (Fig. 3.5B: Self-lock origami - cannot turn into a flat configuration). We can still retain semi-flat foldability if we cut a very small angle. It means the origami could still expand to an almost flat state (Fig. 3.5A: b)Simple fold - Flat state). This new design consists of four solid adaptable plates, one active, and three passive joints (Fig. 5.2a). The active joint is between the plates attached to an actuator (input plates), while the passive joints are between the plates without any direct connection to the actuator. The passives adapt their position based on the configuration of the active joint. Pulling two ends of the active joint towards each other (Fig. 3.5C:1) results in a downward rotation. Now, if we pull the same two ends of the joint in the opposite direction (Fig. 3.5C:2), it will produce an upward motion. Therefore, almost 360° degrees rotation is possible using the design. There is a small inaccessible motion range at the origami's flat state due to the missing central angles [152].

Figure 3.5B shows the CAD design and modeling process. First, we defined square-shaped origami plates. Thickness does not matter in the design since we assume the origami

plates are like a sheet of paper with zero thickness for the simplicity of modeling. However, for better visualization and the ability to choose the correct sides of the origami (Fig. 4.2), we designed the origami plates with 1mm thickness. Then, we cut and reduce two origami plates' central angles by drawing a line from one corner of the square (Fig. 3.5B: cutting phase) with a specified angle ($\alpha_{12} = \alpha_{23}$, different angles have been modeled and studied in chapter 6) and extend the line until it intersects with the other edge of the square. We cut that part using the extrude-cut option. All the origami plates are required to be connected on one side (in one plane of the 3D space). Revolute joints are defined at the plates' edges to make the connections (Fig. 3.5B: Bonding phase). The colored edges demonstrate which edges should be connected using the joints' relations. Depending on which origami plate we choose to reduce its central angle from 90° degrees to smaller angles (Fig. 5.2b: Input plate before cutting, and Fig. 4.2), the origami will behave differently.

3.3 3D printing Method

Using the 3D printing method to fabricate origami has many advantages, such as creating complex and intricate designs with precise and consistent foldings. It could also make possible the mass production of the design in a short amount of time. We developed two methods to fabricate Self-lock origami using 3D printers. For both of them, first, we design a CAD model for the origami plates.

Figure 3.6Aa depicts origami plates with 1mm thickness and central angles of α and 90° degrees. Mate constraint relationships are then defined between the plates to ensure that they all lie in the same plane (flat state) for 3D printing. This means that the faces of the origami plates that are in the same direction are placed in the same plane. Furthermore, a specific and consistent gap is defined between the origami plates using the constraint relationship, except for the location of the cutting angles for the Self-lock origami. In Chapter 6, different gap lengths are investigated. We conducted experiments to study the effect of varying gap lengths on the origami plates' mechanical properties and folding characteristics. Figure 3.6Ab and c show the directions of movements and configuration of Self-lock origami plates in the dynamic simulation environments.

After constraining the origami plates, the CAD model is exported to STL format for 3D printing with ABS filament. For the 3D printing phase in figure 3.6B, the PrusaSilcer software is used to program the Prusa 3D printer to pause printing to insert a fabric as the middle layer of the origami. With this method, the gaps between the plates are covered with Organza fabric to add flexibility and very small extensibility. This offers foldability of the origami while

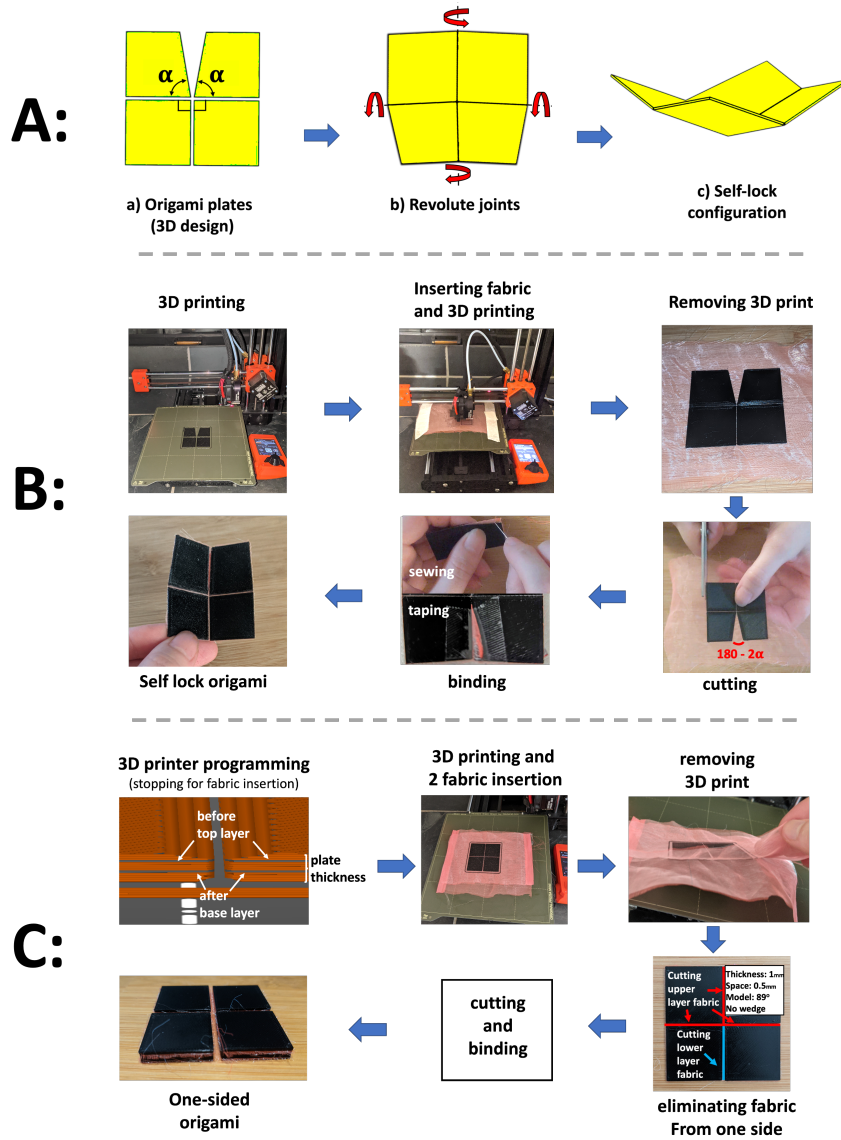


Figure 3.6: **A:** The CAD model of the Self-lock origami. a) The origami plates are constrained to a single plane and positioned at a specific distance from each other to facilitate the 3D printing process on fabric. The reduced central angles in the Self-lock origami are denoted by α . b) Revolute joints are defined in the dynamic environment of Autodesk Inventor software to simulate the movement of the origami. The directions of rotation for these joints are also specified. c) The Self-lock origami with an upward configuration. Due to its reduced central angles, it cannot maintain a flat state.

Figure 3.6: **B:** The 3D printing method with a middle layer fabric. The origami is printed with half of its intended thickness. The printing process is paused to allow for the installation of Organza fabric, which is then secured with tape. Printing resumes, and once completed, the origami is removed from the printer. The external fabric surrounding the origami is cut, and in the binding phase, the internal fabric between the reduced angles of the origami plates ($180 - 2\alpha$) is taped or sewn. The result is the 3D printed Self-lock origami. **C:** The 3D printing method with dual-layer fabric. The 3D printer is programmed to pause after printing the first layer of the origami and before the final layer. The fabric installation and the cutting and binding phases are similar to the previous method. In the eliminating fabric phase, the upper layer fabric is cut along the red foldlines, while the bottom layer fabric is cut along the bluefold lines. This process yields a 3D printed Self-lock origami with rotational movement present only on one side (either downward or upward configuration).

obtaining a strong structure similar to a traditional revolute joint. Different fabric materials are investigated in chapter 6. Clips and tapes are used to hold the fabric in place on the 3D printer plate while the machine is resuming to 3D print the rest of the origami plates' layers. After the 3D printer job is finished, we take the origami out of the 3D printer plate by pulling the fabric off of it. The fabric around the external part of the origami is cut using different tools. It is necessary to make sure the gaps between the plates and the origami's reduced angles are not cut during this process. The fabric between the origami's reduced angles, $180 - 2\alpha$, could be taped or melted using heating tools or sewed with threads to connect the plates around those edges. The product is the 3D printed Self-lock origami with a summation of its plates' central angles less than 360° degrees. Due to the flexibility and minor extensibility of fabric, the Self-lock origami with α close to 90° degrees could pass the origami's flat state and offer bidirectional movement (right and left, Fig. 3.7 **B:b**) and flat-foldability property (accessing the flat state).

Figure 3.6C illustrates an alternative method for origami 3D printing using dual-layer fabric insertion. In this approach, we incorporated a two-phase pause in the PrusaSlicer software during the 3D printing process. The first phase occurs after printing the base layer of the origami

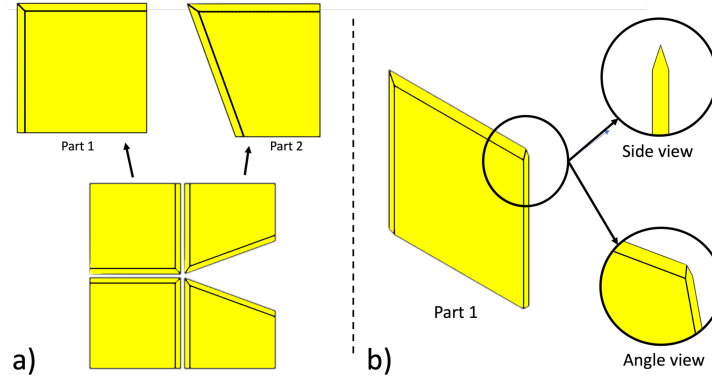
plates, while the second phase takes place prior to printing the final layer of the plates. At each phase, a sheet of Organza fabric is inserted and secured with tape. The subsequent steps involving 3D print removal, cutting, and binding are similar to the previous method described in Figure 3.6B.

However, the main distinction of this method is that the top and bottom fabrics between the plates are cut based on the configuration and movement of the origami. For the Four-vertex origami (Miura-ori cell) to exhibit downward rotation, three of the foldlines should rotate in one direction, while the remaining foldline should rotate in the opposite direction [151]. Consequently, the three top layer fabrics between the origami plates (highlighted in red in Figure 3.6C during the elimination of fabric from one side phase) and the bottom layer fabric between the remaining origami plates (shown in blue) are removed. As a result, a 3D printed origami structure with fabric foldlines is achieved, capable of rotating in a single configuration (either downward or upward) based on the cuts in the top and bottom layers of the foldlines (Fig. 3.5C).

3.3.1 Wedge Method

As the thickness of the origami plates increases and the space (fabric length) between the plates decreases, it results in a stronger structure. A detailed analysis of this phenomenon is discussed in chapter 6. However, these changes impose constraints and limitations on the movement of the 3D printed origami using the 3D printing method with a middle layer fabric. While this does not affect the movement of the origami in the second 3D printing method using dual layer fabric, bi-directional movement (Fig. 3.7Bb, two configurations) is not possible in

A: Wedge Method



B: Bi-directional rotation

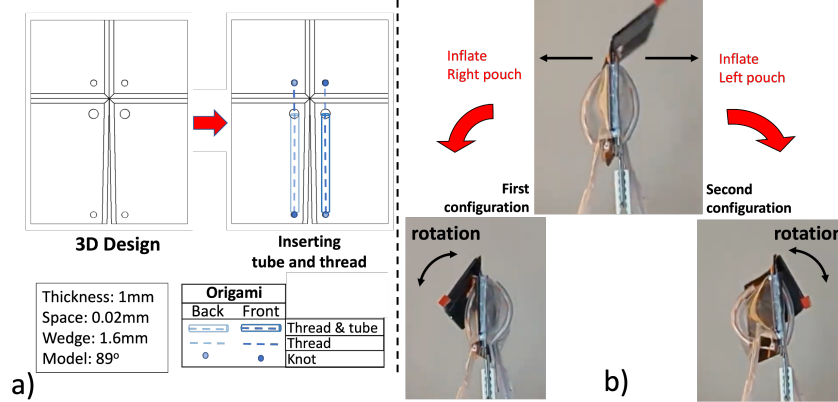


Figure 3.7: **A:** The design involves incorporating wedges along the edges of the origami plates where they come into contact with each other. a) The wedge design is implemented for all four origami plates, with two different types of plates referred to as part 1 and part 2. b) A detailed examination of the wedge design is provided in side and angle perspectives. The length of the wedge is specified in the side view. **B:** The bi-directional origami with both left and right rotational movements. a) Left: The CAD model of the self-lock origami is displayed, showcasing measurements and holes for inserting tubes and threads. Right: A map is provided to illustrate the placement of tubes and threads on the input and output origami plates. The lower section presents information regarding the origami's properties and a guide for the map. Knots are created on the threads at the top and bottom holes of the origami to induce rotation when the pouch inflates. One tube with thread is positioned at the front of the origami, and another at the back, enabling rotation in both left and right directions. Threads without tubes are inserted from the input plate to the output plate to avoid hindering the rotational motion. b) When the right pouch inflates, it pulls the thread and tube, causing the origami to transition to the first configuration (rotating left). The right rotation operates in a similar manner.

this method.

To address this issue, we have introduced wedges along the edges of the origami plates where they come into contact with each other, with a fabric joint between them. Figure 3.7A illustrates these wedges on the origami plates. Part (a) provides an overview of the wedges, while part (b) offers a closer look at one of the wedges from different viewing angles. In Chapter 6, wedges of varying lengths are studied to determine the optimal design.

3.3.2 Bi-directional Origami

Using Wedge and 3D printing in conjunction with a fabric in the middle, we can create an origami structure with two configurations: rotation to the left and rotation to the right. To achieve both configurations using the same actuator (pouch motors applied on both sides of the origami [151], Fig. 3.7Bb), we utilize tubes and threads. These components provide the necessary force to transition the origami to the first or second configuration. Figure 3.7Ba showcases the 3D design of the origami, as well as the placement of the threads and tubes.

The designed origami has a thickness of 1mm, a wedge length of 1.6mm, and a 0.02mm gap between the plates. It is vertically symmetrical, featuring output and input plates measuring 25mmx25mm and 25mmx40mm, respectively. Cuts of 1° are made on the central angle of the input plates to achieve an origami model with an angle of 89° . In the 3D CAD model, 1.5mm and 3mm holes are incorporated for the insertion of threads, tubes, and knots. Knots are utilized at the bottom and top holes of the origami to pull the threads when the pouches with 25mmx4.9mm measurements inflate. For the input plates, tubes are added to the threads since the threads alone are not thick enough to be pulled by the pouch's inflation. One tube with a

thread is attached to the front, and another to the back, creating the first and second configurations, respectively. From the input plates to the output plates, only threads are used on the opposite side of their respective tubes to facilitate configuration changes and prevent obstruction of rotational motions. It is important to install the pouches slightly loosely under the tubes to avoid locking the origami in one configuration before the threads have a chance to change it.

Figure 3.7Bb illustrates the functionality of the bi-directional origami. When the right pouch inflates, it pulls the tube and the thread, causing the origami to rotate left and transition to the first configuration. Additionally, the inflation of the pouch decreases its length [164], which leads to the input plates around it rotating toward each other, while the output plates rotate to the left. Similarly, when the left pouch inflates using the same mechanism, the origami's output plates rotate to the right. As a result, the origami is theoretically capable of achieving approximately 360° degrees of rotational motion. However, the use of knots and tubes limits the range of rotation. We have investigated and analyzed this limitation in chapter 6. Furthermore, the force generated by the tubes and threads is not sufficient to support heavy loads on the origami structure. Therefore, in applications where a strong structure is required, it is advisable to employ a second actuator instead of threads and tubes.

Chapter 4

Motion Simulation

A computer simulation of the design's motion is a suitable visualization tool to present and analyze the origami's movements. For this task, Autodesk Inventor software was selected. It predicts the mechanism's kinematics starting from the 3D Computer-Aided Design (CAD) rendering for different origami configurations. For the Four-vertex origami pattern, different simulations are implemented with different origami's central angles. For the Self-lock origami pattern, different locations in origami plates are cut for the simulations to study the structure's motion.

4.1 Four-vertex Origami

A simulation method (Fig. 4.1) has been used to compare the configuration of the origami models with different plate's angles in the 3D space. The simulation predicts the kinematics of the proposed origami plates. First, we designed the Four-vertex origamis with different angles for the plates. Like the spherical model, we assume the plates of origami consist

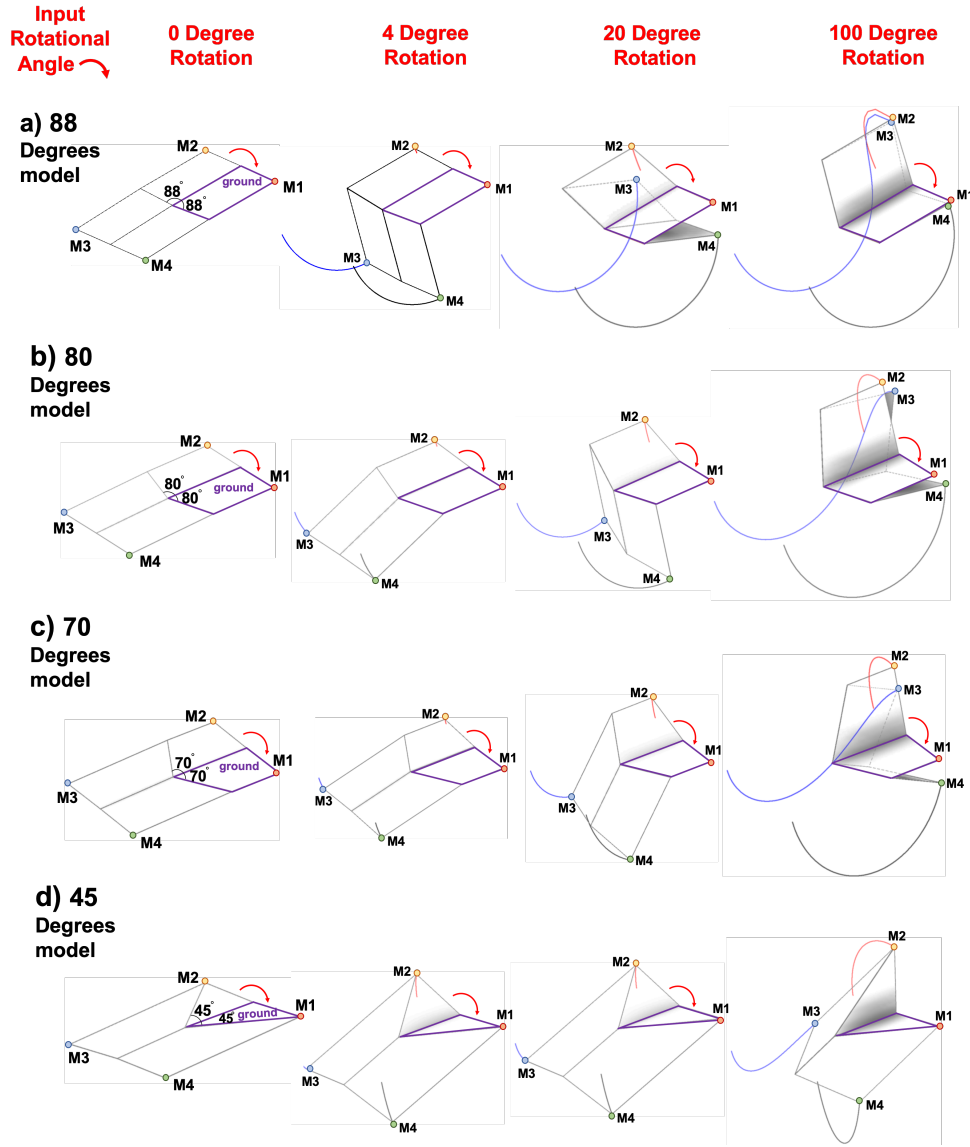


Figure 4.1: The figure represents the simulation of origami structures. The trajectories of each corner of the origami at different phases has been tracked with markers. From the left, the plates with M1 markers are grounded. All the M2 markers of the origami models have zero rotation towards M1. Therefore, the origamies are in a flat state. In the second column from the left, they start to have 4 degrees rotation from M2 towards M1. As a result, a rotational movement occurred in markers M3 and M4. As the rotation of M2 markers increases to 20 and 100 degrees in the third and fourth columns, M3 and M4 markers completely rotate and reach to M1 and M2 plates.

of rigid materials. Therefore, each origami plate can be designed as a rigid 3D plate. The revolute joints can be defined as the relation between the plates at their edges. This can create fold-line between the origami plates. One of the plates is chosen to be grounded. Then, we go to dynamical simulation to convert the relationships automatically into revolute joints. The revolute joints which contain the grounded plate are edited. An imposed angle is chosen as the input angle to simulate the origami. After running the simulation, different configuration of the origami has been recorded in figure 4.1 to compare. The Figure shows the rotational path that each of the origami designs with their markers, M1, M2, M3, and M4, takes. M1 plate has been grounded in these simulations, and M2 plate is moving as the active plate (assumed to be attached to the pouch motor). The output angle is the external angle that the M4 plate is making with the ground plate. In the initial configuration, the angle between M1 and M2 is equal to 180° , and the origami is completely flat. A decrease in the angle causes the output angle to increase. When the origami model has plate angles closer to 90° (ex. 89 Degrees Model), it produces more rotational motion than other plate's angle models (ex. 45 Degrees Model) with the same input angle (between M2-M1).

The origami simulation and spherical model have the same rotational angle changes (Fig. 6.5a). Figure 4.1 shows the asymmetrical rotational paths depending on which origami's plate is grounded. However, the angles between the plates are entirely symmetrical (Fig. 6.5b).

4.2 Self-lock Origami

The proposed "Reducing the central angle method" could be implemented in any location of the four origami plates. Analyzing the origami's movement with the cutting plates gives us a better insight into which combination (Fig. 4.2: origami type, see other origami cutting positions in Fig. A.1-A.3) is more suitable for our application (Manipulator in chapter 7). It is good to mention that the proposed cutting method only reduces the central angles of origami. Cutting in any other location of the plates would not affect the origami's movement. In fact, origami could have various shapes around its edges without compromising its motion [151]. Also, the inspection solver has been activated to find the maximum possible folding states of each origami type.

We implemented various motion simulations to find an origami that could maintain a flat configuration between its input plates (Fig. 4.2, 180° degrees angle) at its initial state and obtain the maximum rotational movement (optimal performance). Achieving a flat state by the origami's input plates offers a more simplified model and better control by the pouch motor's actuator. The pouch motor is able to maintain a zero pressure state (no inflation) and provide a known shape and dimensions at the initial state for the modeling (chapter 5). Since we assumed the origami models have zero thickness, the maximum possible folding configuration (MPF: with the angle of 36.51° degrees between the grounded plate and its connected output plate) has been defined manually for all the simulations in this paper. Some of the MPF angles might have slightly different values due to the positioning of the central angle cuts.

For origami assembly, joint constraints are necessary. Various shapes are created by

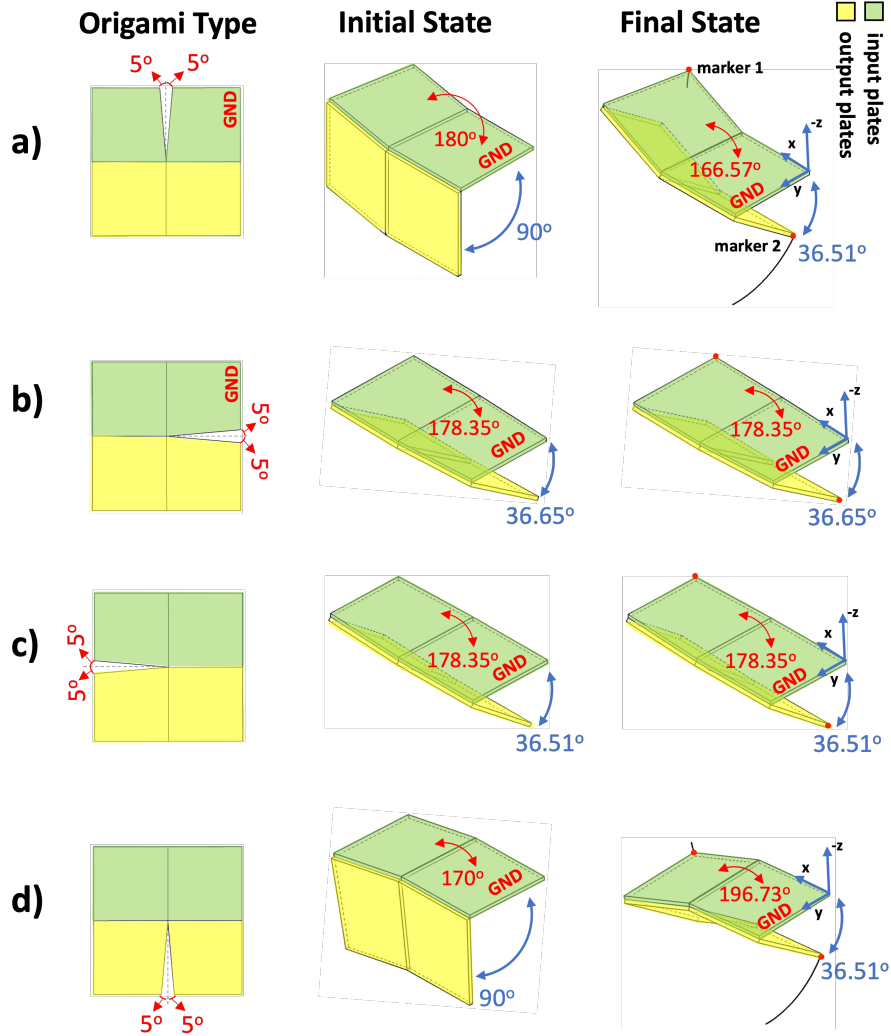


Figure 4.2: a-d) Initial and final states of Self-lock origami with a decreased central angle in different positions. Initial state: Closest possible configuration to the flat state of the input plates (180° degrees angle in between). Final state: A defined Maximum Possible Folding configuration (MPF) between the grounded and the output plate (36.51° degrees). After defining the MPF angle due to the position of the cutting angle in part b), origami's MPF angle between the grounded and output plates becomes 36.65° degrees. Origami type: Position of the origami's decreased central angle before the plates' assembly (defining revolute joints between plates). The input and output plates are highlighted with green and yellow colors, respectively. Markers 1, 2, and the reference frame is defined to trace the input and output plates' motions. The angles between the input plates and between the grounded and the output plate are measured at the initial and final states to study the origami's states. The origami type a) can achieve a flat state for the input plate, $\theta_1 = 180^\circ$.

cutting angles in different origami plates' positions. Defining revolute joints between the plates with different edges is impossible. The mate connection has been applied instead between these edges. The Inventor's simulation environment has the automatic conversion of the constraints and the part's relations into their equivalent joints to generate the desired motion. If the conversion fails, joints are required to be defined manually by selecting the revolute joint in the Joint option of the dynamic environment. Similar to the Four-vertex design, the edges between the plates should be selected as the revolute joints' axes of origami to rotate along. Gravity has not been considered for the simplicity and compatibility of the simulation with the analytical modeling. The origin is set at the outer corner of the origami's grounded plate for all the simulations (Fig. 4.2-A.3). The simulations were set to 1 second, and 100 points were recorded for a complete cycle. We activated the origamis using the imposed motion on the active joints (the foldline between the input plates) to study their movement behavior.

Figure 4.2-A.3 represent different cutting positions in the origami types. The green and yellow plates are input and output plates, respectively. After connecting the modified plates in origami type, we used the Inventor's contact solver to check each origami's ability to achieve a flat state at its input plates. The Initial state column shows the closest angle that origami's input plates could get to 180° degrees (flat form). Origami types a, i, j, m, and n could achieve that flat form since the cuts are positioned on the origamis' input plates. Even if part of the cuts is in the output plates (origami type e-h), the input plates cannot obtain 180° degrees angle. The cutting retains flexibility and a larger range of movement between its plates (more accessible states).

The Final State column shows the maximum folding ability (Fig. 4.2 and 5.2c, max-

imum angle difference between the grounded plate, 1, and plate 4 at the initial and the final states) for each origami type. Also, the motion they produce is demonstrated using markers 1 and 2 (called Traces in Inventor) at the origami's corners (one in input and one in output plate). This motion shows the movement from the initial to the final state. Whenever the cut is only on one plate out of four origami plates (i-p, Fig. A.1 and A.2), or it is only between the input plates or the output plates (a and d), the maximum rotational movement is observed. Finally, we chose a among origami types a, i, j, m, and n (origami types with input plates'). Due to its symmetrical shape, it could provide a more balanced motion for our application. Also, the data (see simulations' 3D plots in the Appendix chapter) indicates that if we do not consider the flat states of the input plates as a factor, all the origami types provide almost the same amount of rotational motions in slightly different directions. The origami's angles could be calculated using the data from markers (positions in mm) exported into a TXT or CSV file format and the algorithm 1.

Chapter 5

Modeling

Both Self-Lock and Four-vertex Origami are single-vertex origami with four fold-lines, meaning that it has a single degree of freedom [190, 191, 22]. As shown in Fig. 3.5C for Self-lock structure, the same components can be assembled into two distinct configurations whose motions are vertical mirrors of each other.

The mechanical work of the pouch motor inflation converts into the deformation of its shape and changes in its curvature length. These cause the angular motions in the simple fold (a hinged structure) that it has been attached to [188]. In this section, with the assumption of using the pouch motor as the origami's actuator, the relations between the origami's angles, output moment, input moment, and pouch's pressure has been developed.

5.1 Spherical Mechanism

The kinematics and dynamics of single-vertex rigid origami can be studied by noting that they are mechanically identical to spherical mechanisms [192, 151], for which a detailed

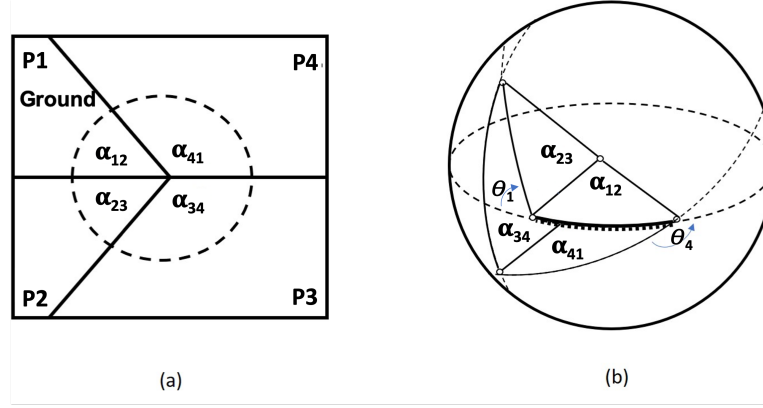


Figure 5.1: (a) The flat-foldable origami (b) The origami model with a spherical mechanism. To find input angle, θ_1 , and output angles, θ_4 , plate P3 is assumed to be grounded. A circular shape of the origami structure can be taken out and put in a spherical space.

theory exists [36]. To do this, the origami folds between the plates are treated as revolute joints regardless of material, as in the chapter 3. Then, since each plate of a single-vertex origami is assumed to be inflexible, the single vertex acts as a fixed center about which the four plates move as the bars of a spherical four-bar mechanism.

We first investigate the kinematic relationship between the input angle θ_1 and output angle θ_4 . The kinematics of a spherical four-bar mechanism are determined entirely by the angular lengths α_{12} , α_{23} , α_{34} , and α_{41} of its links. Given these quantities, the input and output angles are related by the following equation [36]:

$$\cos \alpha_{34} = \cos \alpha_{23} \cos \alpha_{41} \cos \alpha_{12} - (\sin \alpha_{23} \cos \alpha_{41} \cos \theta_4 + \cos \alpha_{23} \sin \alpha_{41} \cos \theta_1) \sin \alpha_{12} + \sin \alpha_{23} \sin \alpha_{41} (\sin \theta_1 \sin \theta_4 - \cos \theta_1 \cos \theta_4 \cos \alpha_{12}) \quad (5.1)$$

5.1.1 Four-vertex Origami

The origami design is a flat foldable structure which moves around a single vertex (in figure 4 the summation of the central angles are 360°) [193, 36, 194, 192]. Additionally,

for the origami design presented here $\hat{\alpha}_{12} = \hat{\alpha}_{23} = \alpha_{12}$, and $\hat{\alpha}_{34} = \hat{\alpha}_{41} = \pi - \alpha_{12}$. We modeled the origami as the spherical system shown in figure 5.1. The “input angle” is defined as the angle between the ground plate “1” and the input plate “2” ($\hat{\theta}_1$), the “output angle” is the angle between the ground plate “1” and the output plate “4” ($\hat{\theta}_4$). Initially the pouch is deflated, therefore, the origami has a flat rectangular shape. As the pressure increases, the pouch inflates, increasing the input angle and due to the relationship between different sections of the mechanism, the output angle as well.

The equations 5.2 and 5.3 are based on the origami structure and Chiang’s equations [36] (Please note that all angles in the equations below are in radians):

$$\sin(\theta_1)\sin(\theta_4) - \cos(\alpha_{12})(1 + \cos(\pi - \theta_1))\cos(\theta_4) - \cos(\alpha_{12})\cos(\pi - \theta_1) - \cos(\alpha_{12}) = 0 \quad (5.2)$$

Therefore:

$$\theta_4 = 2 \tan(\cos(\alpha_{12}) \tan(\frac{\theta_1}{2}))^{-1} \quad (5.3)$$

5.1.2 Self-lock origami

The structure of the Self-Lock Origami allows this equation to be simplified significantly. First, the angles α_{41} and α_{34} are both equal to 90 which zeros several terms and simplifies others. Next, we use the symmetry of the system to define $\alpha := \alpha_{12}(= \alpha_{23})$, allowing several more terms to be simplified and combined, and resulting in a simple relation between θ_1 and θ_4 . The same relation also holds for θ_2 due to symmetry.

$$\tan \theta_4 = \cos \alpha \cot \left(\frac{\theta_1}{2} \right) \quad (5.4)$$

This equation has infinitely many solutions, but up to angular equivalence there are two distinct solution curves. One curve ranges over positive angles from near zero to almost 180 corresponding to the up configuration of the Self-Lock Origami, while the curve corresponding to the down configuration ranges over positive angles from near zero to almost -180° . In computations, we use the atan2 function to ensure that the returned solution corresponds to the correct configuration.

5.2 Input and Output Moments

To model the moments that have been applied to (input moment) or generated by (output moment) the origami, we used constant air pressures on the system's pouch motor. The moments could be calculated using the origami's input angle. A range of -90° to 90° degrees has been selected for the input angle, θ_1 , due to the physical limitation of the pouch motor to produce even near 90° degrees rotational angle. Both upward and downward movements can be created by adding two pouch motors on the origami's input plates (Fig. 6.11: Drawings - pouch1 and pouch2): One on top for $\theta_1 : (0^\circ, 90^\circ)$ range of motion, and another one on the bottom for $\theta_1 : (-90^\circ, 0^\circ)$ range of motion.

In order to find the Output moment, we need to calculate the input moment first (Fig. 6.10, M_{input} , M_{output}). To estimate the input moment applied to a simple fold (a hinged structure), Ryuma Niiyama et al. developed the equation 5.5 [188]. Since the Self-lock origami's input plates (covered with a pouch) have a structure similar to a simple fold, we could use the equation to find the input moment. Based on the proposed origami structure, the equation relies

on the origami's input angle θ_1 and α_{12} . Also, given the fixed pressure P , width D , the initial length L_0 , and the central angle S of the pouch, we can find the input moment.

$$T_1(\theta_1, \alpha_{12}) = \frac{L_0(\alpha_{12})^2 D(\alpha_{12}) P}{8S(\theta_1, \alpha_{12})^2} (-1 + S(\theta_1, \alpha_{12})^2 + \cos 2S(\theta_1, \alpha_{12}) - \sqrt{2} \cos S(\theta_1, \alpha_{12}) \sqrt{-1 + 2S(\theta_1, \alpha_{12})^2 + \cos 2S(\theta_1, \alpha_{12})}) \quad (5.5)$$

The output moment depends on the origami's θ_2 and θ_3 angles (Fig. 5.2c). Based on Yang's analysis and modeling of the spatial mechanisms [195], we developed the equations 5.6-5.9 to calculate the θ_2 and θ_3 . Since $\theta_2 = \theta_4$, using equation 5.7 is not necessary. Here, angles are in degrees.

$$m_1 = \cos \theta_1 \sin \theta_4 + \cos \alpha_{12} \sin \theta_1 \cos \theta_4 \quad (5.6)$$

$$\begin{aligned} \theta_2(\theta_1, \theta_4, \alpha_{12}) &= \sin^{-1} \left(\frac{\sin \alpha_{41} m_1 + \cos \alpha_{41} \sin \alpha_{12} \sin \theta_1}{\sin \alpha_{34}} \right) \\ &= \sin^{-1} (\cos \theta_1 \sin \theta_4 + \cos \alpha_{12} \sin \theta_1 \cos \theta_4) \end{aligned} \quad (5.7)$$

$$m_2 = \cos \alpha_{34} \cos \alpha_{41} - \cos \alpha_{12} \cos \alpha_{23} \quad (5.8)$$

$$\begin{aligned} \theta_3(\theta_1, \alpha_{12}) &= \cos^{-1} \left(\frac{m_2 + \sin \alpha_{12} \sin \alpha_{23} \cos \theta_1}{\sin \alpha_{34} \sin \alpha_{41}} \right) \\ &= \sin \alpha_{12}^2 \cos \theta_1 - \cos \alpha_{12}^2 \end{aligned} \quad (5.9)$$

The mechanical advantage is the ratio of the output moment divided by the input moment. A. T. Yang et al. [196] developed an equation to calculate the mechanical advantage and the output moment of a spherical four-bar mechanism. From this, we developed the equation for the Self-lock origami system (equation 5.10). In this method, the angles are in degrees. The MA could be tuned using the α_{12} parameter based on desired motion (origami's angles).

$$\begin{aligned}
MA(\theta_2, \theta_3, \alpha_{12}) &= (T_4/T_1) \\
&= \sin \alpha_{41} \sin \theta_3 / \sin \alpha_{23} \sin \theta_2 \\
&= \frac{\sin \alpha_{12} \sin \theta_3}{\sin \theta_2}
\end{aligned} \tag{5.10}$$

5.3 Relation of Origami's Angles and its Pouch Motor's Pressure

Predicting the origami's folding behavior requires finding the relationship between the actuator's pressure and the origami's folding angles. The pouch motor is non-extensible with zero bending stiffness. Also, it has a cylinder shape [197], unlike the top part of the origami, which has trapezoid plates (Fig. 5.2a, and 5.2d) for Self-lock and a simple rectangular for Four-vertex origamis. The origami's central angle α_{12} , the width D , and the initial length L_0 of the pouch remains constant throughout the experiment. At the initial state, there is no pressure in the pouch motor (flat form), resulting in a rectangular shape of the pouch motor with D and L_0 dimensions. To find the pouch motor's measurements that could cover the Self-lock origami plates, we developed the equations 5.11-5.15. The relations include the initial length and width of the pouch motor and the origami's central angle. Figure 5.2a and 5.2b demonstrate the pouch motor and the origami's parameters. The $m = 25\text{mm}$ is the origami constant length before the cutting. The L_1 and n parameters are the cutting length and the difference of D and m , respectively.

$$L_1(\alpha_{12}) = m \cot \alpha_{12} \tag{5.11}$$

$$n(\alpha_{12}) = (m - L_1) \cot \alpha_{12} \tag{5.12}$$

$$\begin{aligned}
D(\alpha_{12}) &= (m - n) \sin \alpha_{12} \\
&= m \sin \alpha_{12} (1 - (1 - \cot \alpha_{12}) \cot \alpha_{12})
\end{aligned} \tag{5.13}$$

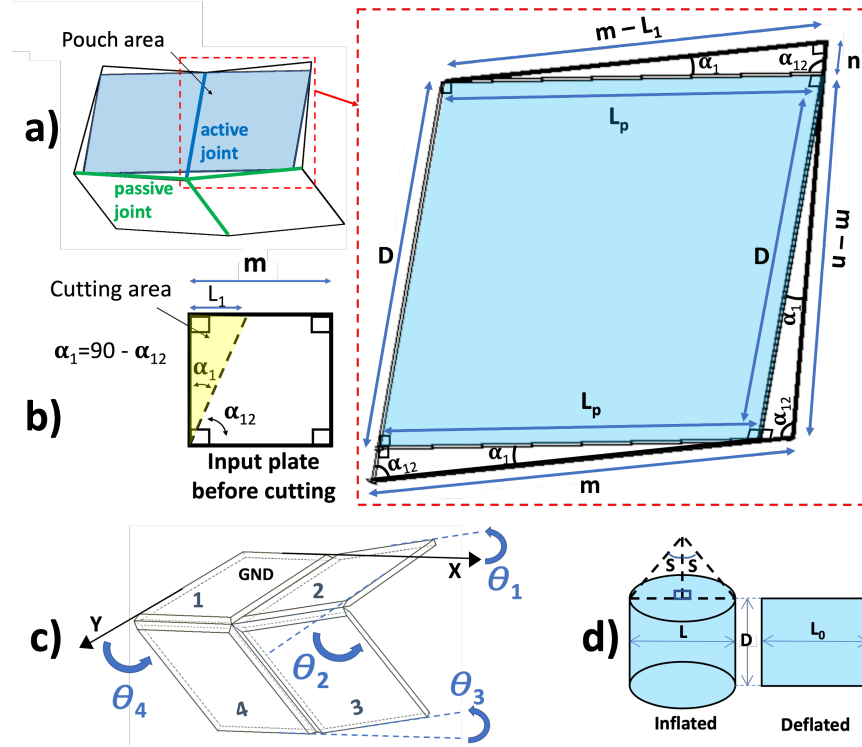


Figure 5.2: a) Schematic of the self-lock origami with attached pouch motor. The pouch has a rectangular shape before inflation and the plates covering it have a trapezoidal form when flat (input angle $\theta_1 = 180^\circ$). The pouch dimensions L_p and D are derived from the measurements of the origami plates. The active joint, marked in blue, is a revolute joint defined between the origami plates covered by the pouch actuator. The passive joints, marked in green, do not have contact with the actuator. b) Input plate before and after a reduction in the central angle. c) The Self-lock origami angles and its plates' numbers. A reference frame is established on the grounded plate to monitor the origami's movement. d) Inflated and deflated pouch actuator and its parameters.

$$L_0/2 = \sqrt{n^2 + (m - L_1)^2} \quad (5.14)$$

$$L_0(\alpha_{12}) = 2m(1 - \cot \alpha_{12}) \csc \alpha_{12} \quad (5.15)$$

As the air pressure increases, the pressure on the membrane grows, causing the pouch motor's cross-sectional area to expand. Therefore, the pouch length L decreases [188]. Since the pouch motor is attached to the origami at its input plates' edges (Fig. 5.2a), the origami folds, and its input angle increases. Due to the geometrical structure of the model, the output angle also increases drastically. This was studied further and described in Chapter 6.

By the Cosine laws [197], we can calculate L based on the input angle, θ_1 . Given $L_p(\alpha_{12})$ is the length of the origami plates that are attached to the pouch motor and the ϕ is the angle between origami's input plates (plates covered by pouch).

$$L_p(\alpha_{12}) = L_0(\alpha_{12})/2 \quad (5.16)$$

$$\phi = \pi - \theta_1 \quad (5.17)$$

$$\begin{aligned} L(\theta_1, \alpha_{12}) &= \sqrt{L_p^2 + L_p^2 - 2L_p^2 \cos(\phi)} \\ &= L_p(\alpha_{12}) \sqrt{2(1 + \cos(\theta_1))} \end{aligned} \quad (5.18)$$

For four-vertex origami, calculating L_p could be skipped due to the simple shape of origami plates and start with equation 5.17. $S(\theta_1, \alpha_{12})$ is the central angle of the circular segment of the pouch based on its cross-sectional shape (Fig. 5.2d) [197]. We obtain it using $L(\theta_1, \alpha_{12})$ and $L_0(\alpha_{12})$.

$$S(\theta_1, \alpha_{12}) = \sqrt{6(1 - L(\theta_1, \alpha_{12})/L_0(\alpha_{12}))} \quad (5.19)$$

The joint stiffness, K_s , can be obtained using the equation 5.20 [197], where $L_s = 0.3\text{e-}3$ m is the length of flexural material, $E_s = 3\text{e}9$ Pa is Young's modulus, and $t_s = 0.25\text{e-}3$ m is the spring thickness. Also, it depends on the pouch's width D.

$$K_s(\alpha_{12}) = \frac{E_s D(\alpha_{12}) t_s^3}{12 L_s} \quad (5.20)$$

$$F(\theta_1, \alpha_{12}) = \frac{K_s(\alpha_{12}) \theta_1 L(\theta_1, \alpha_{12})}{L_p(\alpha_{12})^2 \sin(\theta_1)} \quad (5.21)$$

$$P_{pouch}(\theta_1, \alpha_{12}) = \frac{F(\theta_1, \alpha_{12}) S(\theta_1, \alpha_{12})}{L_0(\alpha_{12}) D(\alpha_{12}) \cos(S(\theta_1, \alpha_{12}))} \quad (5.22)$$

The $F(\theta_1, \alpha_{12})$ and $P_{pouch}(\theta_1, \alpha_{12})$ are derived based on θ_1 and α_{12} (equations 5.21 and 5.22, [197]), where F is the actuator force, and P_{pouch} is the pressure applied to the pouch by a pump. The F parameter in equation 5.21 relies on K_s , L, and L_p as well. P_{pouch} is the function of pouch's width D, initial length L_0 , S, and F. At the beginning of the actuator's activation, due to the deformation of the pouch material and lack of folding at small pressures, the model is not accurate, and we need to add a pressure offset, P_i , based on the experimental result [197].

$$P(\theta_1, \alpha_{12}) = P_{pouch}(\theta_1, \alpha_{12}) + P_i \quad (5.23)$$

We can solve how much pressure is required to be applied on the structure by the pouch motor (actuator) [197] to generate a certain input rotational angle using equation 5.22.

5.4 Control Design for origami's motion

A bang-bang control system has been developed to activate the self-lock origami joint (Fig. 5.3) using pressure sensors (system safety) for feedback. The blue lines represent the flow of air in the system (connecting pump output to the pouches), while the red lines transmit digital signals. Each origami joint requires two pouch motors for downward and upward movements. As shown in Figure 5.3, four 3-way mini Solenoid with air gas valves (Sol 1- Sol 4) are used to activate the pouches (Fig. 5.4a and c). Sol 1 controls the miniature 5V miniature pump/vacuum device (B078H8V563) for inflating any of the pouches, while Sol 4 manages the deflation of the pouches. To prevent any potential damage to the system, a valve check and valve control (regulator) are installed between the pump and Sol 1. This setup ensures proper functioning and protection of the system. Sol 2 and Sol 3 are responsible for selecting which pouch to inflate and deflate, respectively.

Two versions of modular PCB boards with or without a pressure sensor circuit (Fig. 5.4b) have been developed. Figure 5.4c illustrates the installation of a Nano Arduino microcontroller, TIP120 transistor, 1K Ω resistor, and 1N4004 diode on the PCB board to enable the control of a solenoid. In the system, four of these PCB boards, each with its respective installation, are utilized along with a shared microcontroller to control the four solenoids. We measured the time required to fully inflate the pouch motor and utilized this information to change and

estimate the status of the pouches. The pressure sensors (Adafruit MPRLS Ported Pressure Sensor) can be utilized to verify the status of the pouches (Fig. 5.4d) before inflating or deflating them, thereby preventing any potential damage to the pouches. Additionally, a protective deflation procedure is implemented before activating any of the pouches based on user inputs to avoid issues. If the system attempts to inflate a fully inflated pouch, the pressure sensor detects it, triggering the protective deflation procedure to be executed first.

Initially, the time 't' required for the pump to fully inflate the pouch is measured (Fig. 5.4a). Then, based on the digital I/O inputs (ON/OFF switches) from the user and microcontroller programming, the values of digital pins D1-D4 change to HIGH/LOW (on/off). The corresponding status of each pouch based on the I/O switch values can be found in Table 5.1. Switch 1 input activates pouch 1. When switch 1 is turned on and switch 2 is off, pouch 1 inflates while pouch 2 deflates. The digital pins D1-D4 are set to the 'on' state. The 'off' values of pins D1 and D4 indicate that the airflow is outside of the system and would not affect the status of the pouches. After time 't', D1 and D4 are switched to the 'off' state to maintain pouch 1 in an inflated state and pouch 2 in a deflated state, respectively. Switch 2, on the other hand, corresponds to pouch 2 activation. When switch 1 is off and switch 2 is on, D1 and D4 are turned on for time 't', while D2 and D3 are turned off to inflate pouch 2 and deflate pouch 1. To continuously switch between inflating and deflating pouch 1 and pouch 2, both switch 1 and switch 2 should be turned on. Therefore, the microcontroller outputs 'on' for D1 and D4 digital pins. The values of D2 and D3 are the same and should be alternated (on/off) every 't' time. The last case occurs when both switch 1 and switch 2 are off. In this case, D1 is off, D4 is on, D3 is on for time 't', and then is off, causing both pouches to deflate. The value of D4 can

be changed at the time 't' from on to off to stop the deflation. The D2 signal is irrelevant in this case because D1 is off and the pump air is outside of the system.

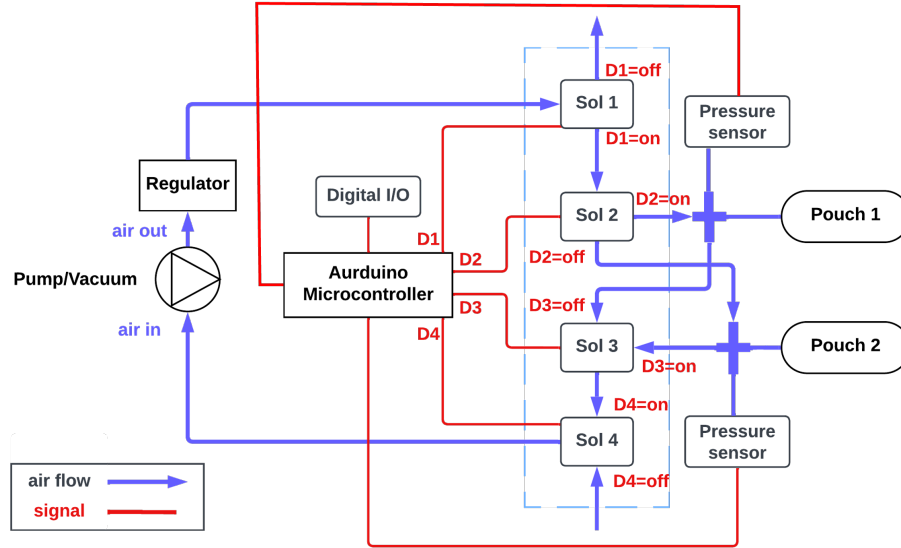


Figure 5.3: The control diagram of the system. The origami joint consists of two pouches, namely pouch 1 and pouch 2, which need to be activated. To achieve this, four solenoids (Sol1 - Sol4) along with a microcontroller are employed. A regulator is utilized to control the airflow, while a digital I/O interface receives inputs from the user to activate the pouches. Sol 1 is responsible for controlling the pump, while Sol 4 manages the vacuum. The blue arrow indicates the direction of airflow, while the red line represents the digital signal. When the Sol 1 and Sol 4 signals are off (LOW), it signifies that the airflow is outside the system, and vice versa. Similarly, Sol 2 and Sol 3 are utilized to control the inflation and deflation of the pouches, respectively. For instance, when Sol 1 receives a signal of D1 = on and Sol 2 receives a signal of D2 = on, it results in the inflation of pouch 1. Pressure sensors are integrated into the system to verify the status of the pouches and protect the system.

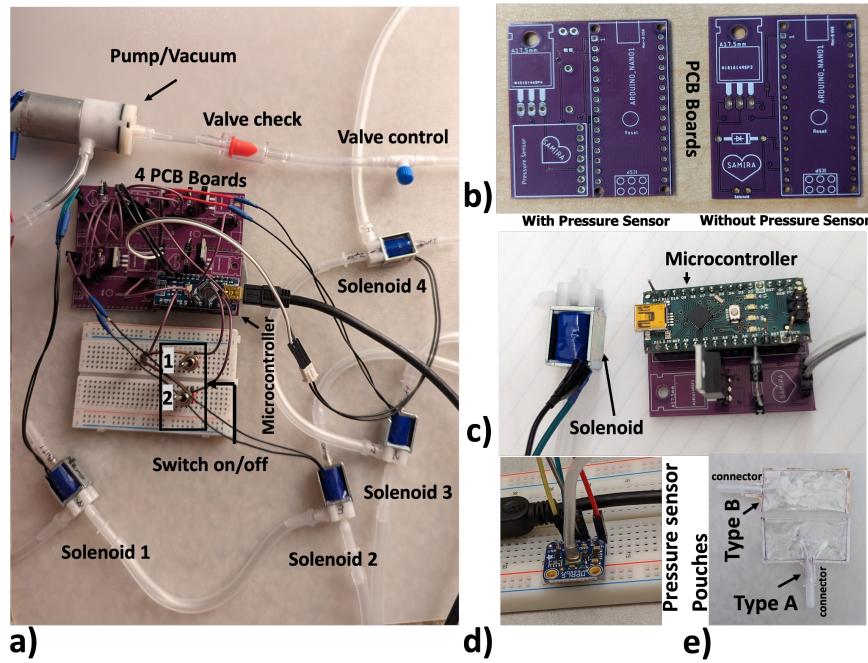


Figure 5.4: a) The devices utilized in the activation system include a pump/vacuum for pouch inflation and deflation, valve check and valve control for system protection, Switch 1 and Switch 2 as digital I/O interfaces to receive user inputs, four solenoids, their respective PCB boards, and a microcontroller for controlling pouch activation. b) Two types of PCB boards have been designed to control the solenoids: one with pressure sensor circuits and one without. c) The necessary devices, including a microcontroller, transistor, diode, and resistor, are installed on the PCB board to control a solenoid. d) A pressure sensor is employed to verify the status of the pouches. e) Type A pouches feature connectors at the bottom, while Type B pouches have connectors at the side. The development of Type B pouches aims to prevent interference between the joint's connector and tube with the rotational motion of other origami components.

Table 5.1: Pouch motors' status based on digital I/O inputs.

Digital I/O		Pouch status	
switch 1	switch 2	pouch 1	pouch 2
on	off	inflated	deflated
off	on	deflated	inflated
on	on	inflated/deflated	deflated/inflated
off	off	deflated	deflated

Chapter 6

Results

In this chapter, we explore the mechanical properties of the origami designs, and the two experimental setups designed to measure the motions of origamis. Additionally, we delve into the relationship between the origami's movements, moments, and angles concerning the pneumatic actuator. By analyzing these data, we gain valuable insights into the underlying mechanisms that govern the origami's movements and develop more advanced origami-inspired technologies in the future.

6.1 Experiment Setup

In this section, we discuss the constructed origami patterns with different physical properties, and the two methods used to measure the movements of them. Firstly, the movements of the Four-vertex origami were measured using the OptiTrack system. Secondly, the Self-lock origami's motion was recorded using smartphone cameras and Kinovea software. By using these two different methods, we were able to accurately measure the movements of both

the Four-vertex and Self-lock origami designs.

6.1.1 Four-vertex Origami with OptiTrack System

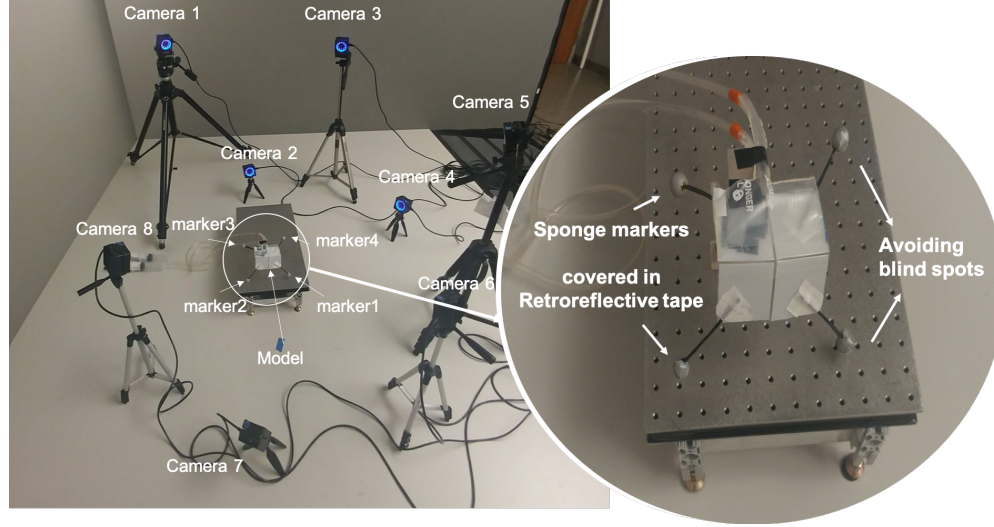


Figure 6.1: Left: The origami model with 4 markers have been activated and tracked by 6 Opti-track cameras. Right: Sponge stick markers have been used on each corner of the origami design to avoid the blind spots when tracking their movements.

The OptiTrack motion capture system shown in figure 6.1, (left) uses 8 Prime 13Ws cameras to monitor kinematics of the proposed origami joint, by tracking the position of four markers, one for each one of the origami joint's corners. To limit the unrecorded movement from blind spots on the origami, markers have been attached to extension sticks (Fig. 6.1, Right). Since commercial markers weigh more than the prototype itself, we developed sponge-like markers covered with retro-reflective materials.

We set central angles of the origami's plates as the parameter of the study (Fig. 3.4a) since it affects its movement. The none central angles of the origami plates could vary (Fig. 3.4c) without changing the motions of the structure. Therefore, the Four-vertex origami could

Algorithm 1 Finding Input and Output Angles

1: **procedure** CALCULATING NORMAL VECTOR OF STATIONARY PLANE

2: $middle \leftarrow M2_X$ at initial state/2

3: $middle2 \leftarrow M3_X$ at initial state/2

4: $ground \leftarrow (X_0, Y_0, Z_0)$

5: $middle\ ground \leftarrow (middle, Y_0, Z_0)$

6: $middle \leftarrow (middle, middle2, Z_0)$

7: $\vec{A} \leftarrow ground - middle\ ground$

8: $\vec{B} \leftarrow ground - middle$

9: $\vec{u}_i \leftarrow (\vec{A} \times \vec{B})_i$

10: $\vec{u}_j \leftarrow (\vec{A} \times \vec{B})_j$

11: $\vec{u}_k \leftarrow (\vec{A} \times \vec{B})_k$

12: **end procedure**

(Continued)

1: **procedure** CALCULATING NORMAL VECTOR OF THE MOVING PLANE

2: **for** number of experiment data points **do**

3: $M2 \leftarrow (M2_X, M2_Y, M2_Z)$

4: $\vec{C} \leftarrow M2$ - middle ground

5: $\vec{D} \leftarrow M2$ - middle

6: $\vec{v}_i \leftarrow (\vec{C} \times \vec{D})_i$

7: $\vec{v}_j \leftarrow (\vec{C} \times \vec{D})_j$

8: $\vec{v}_k \leftarrow (\vec{C} \times \vec{D})_k$

9: **procedure** CALCULATING ANGLES BETWEEN TWO PLANES

10: $Length \leftarrow (|\vec{u}|) \cdot (|\vec{v}|)$

11: $Product \leftarrow \vec{u} \cdot \vec{v}$

12: $Angle \leftarrow \text{Arccosine}(Product/Length)$

13: **end procedure**

14: **end for**

15: **end for**

16: **end procedure**

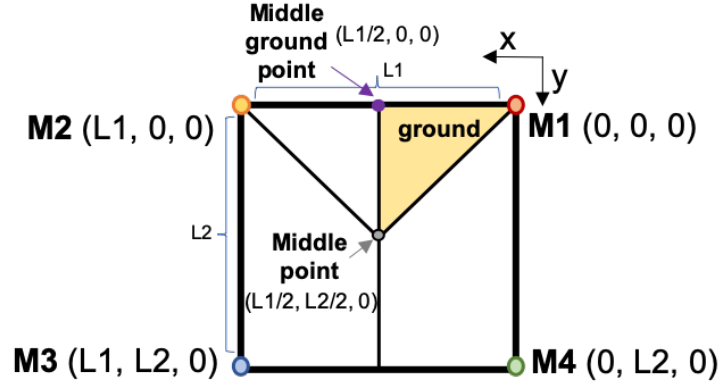


Diagram for the algorithm

Figure 6.2: The diagram represents the states of origami markers. The algorithm used them to evaluate the input and output angles. M1, M2, M3 and M4 are Marker1, Marker2, Marker3 and Marker4 on the experiment respectively.

have different shapes to fit different applications, with the same motion. Figure 3.4d shows the paper materials we have tested with different thicknesses and flexibility. As the origami plates got thicker, the structure got stronger, but it affected the flexibility of the soft joint between them. Then, we decided to make the soft joint (foldline) between them from a different material than the origami plates. Essentially, origami plates could be from any materials which are strong enough to hold the structure and the soft joints from the flexible and foldable materials. So far, the Polyethylene plates and tape as the soft joint result in enough flexibility to move the origami smoothly and a strong structure to hold very lightweight objects (figure 7.3). However, due to the flexibility of the soft joints between the plates, the torque of the structure is too small to consider. For future work, we are investigating other different methods and materials for soft joints to solve this issue.

The origami plates are 5×5 cm fabricated from 0.5mm thick high-density polyethy-

lene 0602938803236 manufactured by SIBE POLYMERS. The soft joints linking each plate use a low-density polyethylene adhesive tape (3M-3112) with the thickness of less than 0.05mm. The pouches that actuate the mechanism are also build using low-density polyethylene (ET311151). In this paper we adapted the pouch motor fabrication explained in details by Niiyama et al. [164]. To efficiently achieve a complete expansion and contraction of the joint, we placed another pouch (Fig. 3.4b) on the opposite side of the origami joint to straighten it up after bending. The coordinated actuation of the two opposing motors precisely controls the input angle.

We connected only one of the origami plates (grounded plate that is covered by the pouch motor) to a plate that is fixed by the mounting part. By attaching these plates under the pouch motor, the origami's 180° rotation was not interrupted in any direction (Fig. 6.1, 7.3, and 7.4). We tracked the rotation of three moving plates relative to one plate that is grounded (attached to the optical table) and the results were compared with the theoretical predictions (equation 5.3). "Algorithm 1" describes the steps necessary to process the experimental data. The algorithm is used to convert the marker's displacement data at each corner of the origami to angles between the origami plate. The trigonometrical formulas have been used to calculate the angles between the plates of the origami. Finally, the angles (experimental and analytical) are compared in figure 6.4. The variables middle, middle2, ground, middle ground, M2, and M3 are shown in figure 6.2. Also, A, B, C, and D are variables that have been used to calculate normal vectors of each origami plate. For each step of the algorithm, the procedure (geometrical terms) that has been used is defined separately.

6.1.2 3D printed Self-lock Origami with Kinovea Software

To study the motion of the rotational joint along its x-axis, the Kinovea software has been selected for motion analysis in the yz plane (Fig. 6.12b and 6.16b). The 3D printed origami plates are made of PLA material. In all experiments, one of the input plates is grounded, and a marker is placed at the outer corner of the output plate, which is connected to the grounded input plate. The variable ϕ represents the angle between the grounded plate and the marker's plate. A video capturing the motion of the joint is recorded, with the camera's optical axis positioned orthogonal to the yz plane of the joint. After calibrating the system using the grounded plate's edge length, the marker of interest, indicated by a small red square, can be tracked using Kinovea software. Data is collected for 20 cycles of the joint's rotational movement, including the ϕ values for both the folded and unfolded states of the joint, as well as the y and z position data. In certain studies discussed in chapter 6 section 6.4, a weight of 49 grams is applied to the marker's plate to evaluate the structural integrity and capabilities of the joint. The activation of the joint is achieved by installing pouches [164] made of a Vinyl sheet around the input plates. Two types of pouches have been developed for different applications (Fig. 5.4e). Type A pouches feature connectors at the bottom, while Type B pouches have connectors on the side. This differentiation is particularly advantageous in bi-directional origamis used in manipulators. When the Type A pouch's connector and tube obstruct the rotation of another origami, the Type B pouch can be employed to overcome this limitation.

6.2 Four-vertex Origamis' Motion with Different Central Angles

In this section, we predict and measure the output folding angles as a function of the input folding angles for origami joints with different plate angles. In figure 6.3, as the input angle changes from 0° to 180° , the output angle changes from 0° to 180° like the elbow and knee joints movements. Figure 6.3 shows the output angle change as a function of the input angle for the origami samples with $\hat{\alpha}_{12} = \hat{\alpha}_{23} = 10^\circ, 20^\circ, 45^\circ, 60^\circ, 70^\circ, 80^\circ, 89^\circ$ and $\hat{\alpha}_{34} = \hat{\alpha}_{41} = 170^\circ, 160^\circ, 135^\circ, 120^\circ, 110^\circ, 100^\circ, 91^\circ$ respectively. It should be noted that the closer the plate angles $\hat{\alpha}_{12}$ and $\hat{\alpha}_{34}$ get to 90° the faster the output angle reaches 180° . Please note that from kinematic point of view, an origami design where $\hat{\alpha}_{12} = \hat{\alpha}_{34} = 90^\circ$ is over-constrain. In that case, only moving two foldlines aligned with each other at a time would be possible. However, this only occurs when the plates and the hinges are rigid. If the origami is manufactured using soft materials the additional layer of compliance, which could allow the origami to fold. The 180° degrees model is a simple foldline with only input angle changes since $\hat{\alpha}_{34} = \hat{\alpha}_{41} = 0^\circ$ degrees. The proposed mathematical model was compared against the lab experiment, where the folding of 4 origami joints was monitored using the setup described in Section 6.1.

We monitored the displacement of four series of origami design samples with $\hat{\alpha}_{12} = \hat{\alpha}_{23} = 88^\circ, 80^\circ, 70^\circ, 45^\circ$ and $\hat{\alpha}_{34} = \hat{\alpha}_{41} = 92^\circ, 100^\circ, 110^\circ, 135^\circ$ respectively. They all have been activated by two pouch motors connected to their pair of plates. At the initial state, all the designs are flat (both pouches are deflated). As the pressure increases in one of the pouches, the plates attached to it rotate towards each other due to the shortening of the width of the pouch, and the other two plates rotate in the opposite direction. The origami is straightened by deflating

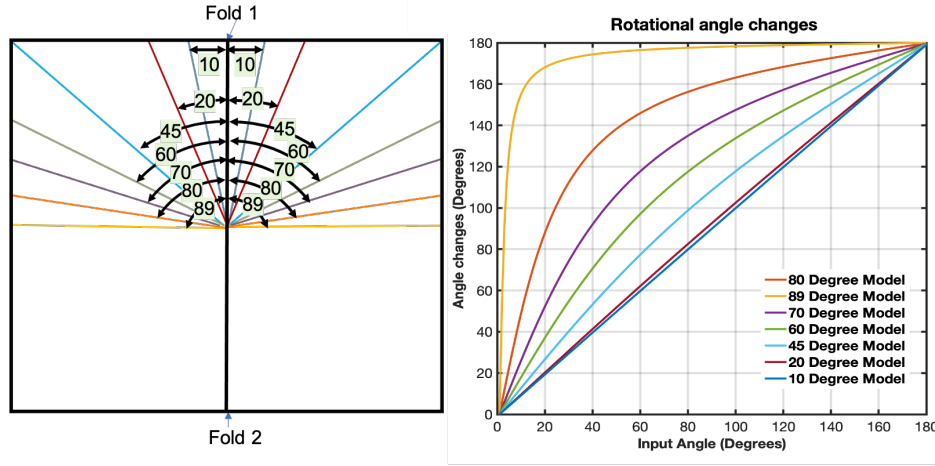


Figure 6.3: The figure on the left shows origami models with different plates' angles (α_{12} and α_{23} in figure 5.1a). The plot on the right is based on the analytical model and shows the output angle (θ_4 in figure 5.1b) as a function of the input angle (θ_1 in figure 5.1b) for origami designs with different plate angles.

the previously inflated pouch and inflating the opposite one (Fig. 3.3).

Figure 6.4 shows the predicted and measured output angles during folding and unfolding. The experiment was repeated 20 times. The average of the experimental data has been plotted. The vertical bars represent the 20 experimental data ranges. It should be noted on the right side of figure 6.4 that the experiment and the model output angles approximately follow a similar path, and the final predicted states are within 3% of the experimental ones. Also, significant errors occurred during the experiment due to the deformation of the pouch motors and the non-linear behavior of the flexible joints between the origami plate. The tracking system for the experiment regularly produces 0.1 mm errors or less. The model predictions are closer to the experimental results for origamis with larger vertex angles (e.g., 88°) where the output angles are large and therefore, the global origami behavior dominates artifacts due to fabrication imperfections (e.g., the precise plate alignment or differences in the adhesive tape's position)

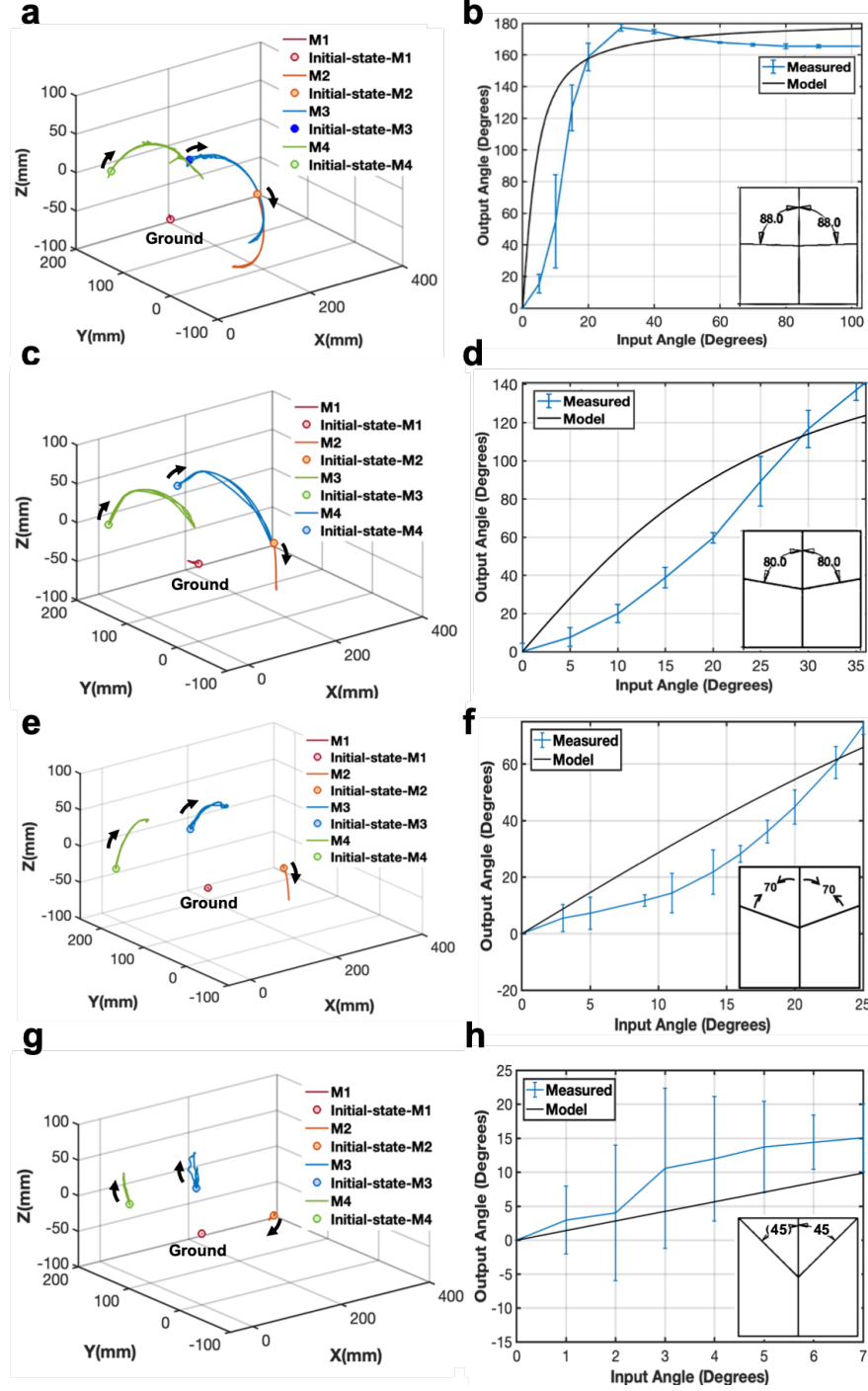


Figure 6.4: Left: The displacements of each corner of origami models with plates' angles of $\alpha_{12} = \alpha_{23} = 88^\circ$, 80° , 70° , and 45° (origami plates showed on the bottom right corners). Right: The relation between the output and input angles of origami models in the experiment and the model

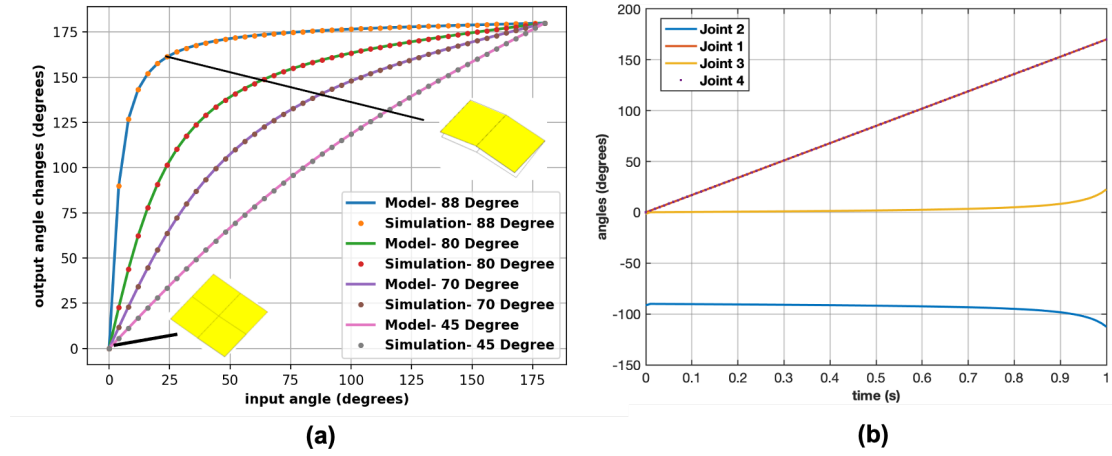


Figure 6.5: a) The plot shows the overlapping of output angle changes from the simulation of Autodesk Inventor software and the mathematical model for different origami plate angles. b) There are rotational angles of all the origami joints in the simulation. They are equivalent joints in Figure 3.1c. Joints 1 and 4 are the same, and joints 3 and 2 are symmetric.

and a local twist of the flexural joints which are not considered by the theoretical model. Due to the structure of the origami plates and the pouch motor that covers them, the closer the origami plates' central angles get to zero degrees, the rotational movement of the pouch motor decreases. Therefore, for the experiment part, we could only compare the active part of the origami models. The 88 degrees model has the complete rotational movement to compare with the analytical model. Therefore, we compared the output angle changes from the Spherical model with the simulation (figure 6.5) in Autodesk Inventor software since the experiment does not cover all the input angles of different Four-vertex origami models. The results are the same, and the simulation validates the mathematical model.

The left side of figure 6.4 shows the three-dimensional location of the corner Markers.

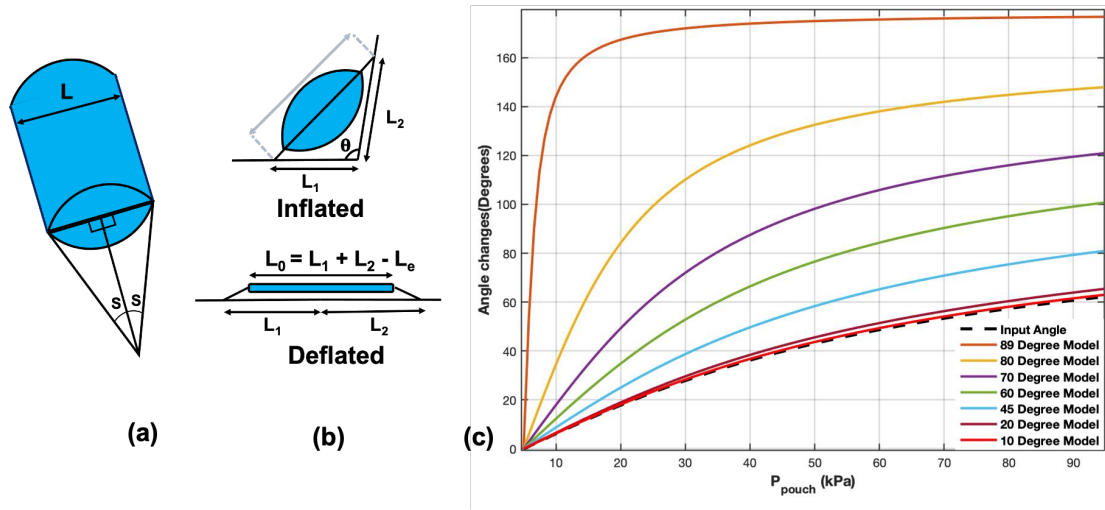


Figure 6.6: a) and b) represent the parameters required to calculate the relation of pressure and rotational angles of origami plates. c) The same pouch motor pressure was applied to the origami models. The plot shows for the origami models with plate angles closer to 90 degrees, there are increases in the rotational movements compared to other origami models and the input angle (simple fold). Therefore, this can save energy since to obtain a specific rotation, the pouch motor could apply less pressure compare to input angle or other origami models.

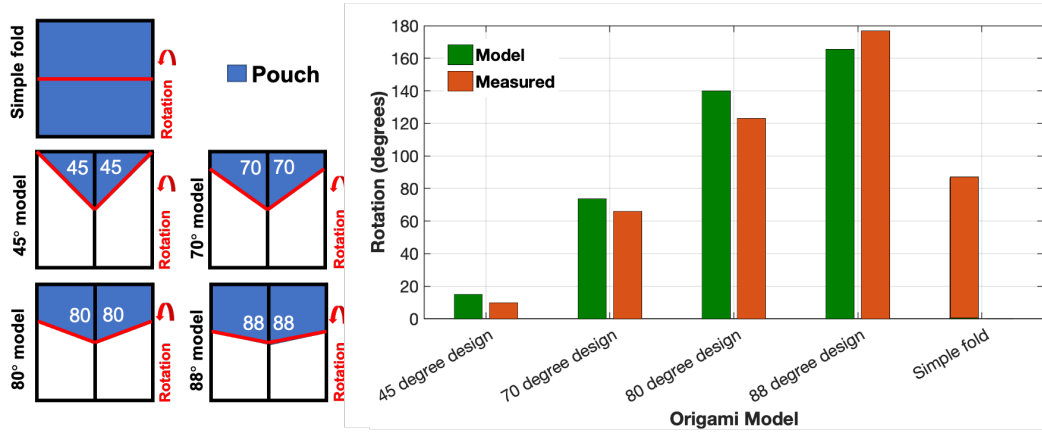


Figure 6.7: The maximum rotational output angle (red fold-line's rotation) for different origami designs from experiment and model: The maximum rotational movement on the right plot occurred on the origami models' red fold-lines on the left side. The blue color indicates the origami area, which we attached to the pouch motor to activate the origami models. Both the experimental and the model estimations indicate that the origami model with plates of 88 degrees (near 90 degrees) shows the maximum rotational movements compared to the simple fold-line or other single vertex origami models when the pouch activates them.

Marker 1 represents the “ground”. The range of movements of markers 3 and 4 is higher than marker 2, indicating the output rotational movement is larger than the input. Also, the comparison between the rotational movement of the different origami designs indicates that the origami design with $\alpha_{12} = \alpha_{23} = 88^\circ$ degrees has the highest rotational movement in the 3D space.

Figure 6.6 represents the result of the mathematical model of the pouch motor’s pressure and the rotational movement of the origami designs. The plot shows, for the same specification of pouch motors and plate measurements, the rotational angles that have been produced by the pouch motor for the output angles of origamis with near 90 degrees plates are higher than the input angle (simple fold). This is helpful to increase the performance of the pouch motors actuator to produce rotational movements and save energy.

A “simple fold” is a single-degree-of-freedom structure in which two plates are connected on only one side by a soft joint (e.g., tape in our case). This model has been assumed as the standard folding structure to compare with the proposed origami design. The experiment results in figure 6.7 indicate that the pouch motors on the proposed pneumatic origami joints cause a larger maximum rotational movement, about 8.4 times compared to the simple fold structure.

6.3 Self-lock Origami

Similar to Four-vertex, the structure of the grounded plate 1, connected to plate 2, is equivalent to a simple fold (Fig. 6.8ABa: Drawings, a hinged-like structure). Therefore, the origami’s input angle, θ_1 , and input moment are the same as the rotational angle and the

output moment of a simple fold structure with the same actuator. Different actuators could be used to increase the input angle limits. However, it is not necessary since the majority of the output angle changes ($|\theta_4|$, rotational movement) occur around the vicinity of 0° degrees input angle (Fig. 6.8ABb, around $\pm 35^\circ$ degrees). Since the actuator could be changed depending on the application, most analyses have been conducted based on the input angle, θ_1 , instead of the pouch motor's pressure. In this section, origami's angles have been studied based on the pouch motor's pressure and the generated rotational angle (input angle θ_1) for different origami models (ex. $\alpha_{12} = 89^\circ, 80^\circ, 70^\circ$). Also, input and output moments' analyses have been conducted based on input angle and for different pouch motors' constant pressures and origami models. Finally, the origami model with the best performance has been selected for modular manipulator application.

6.3.1 Motion with Different Central Angles

Figure 6.8ABa demonstrates two different configurations of the origami along with their direction of movement. Also, they include plates 1, 2, 3, and 4. Suppose the origami has actuators (pouch motors) on both sides of plates 1 and 2. To obtain the full range of motion, we need to activate both actuators. In the downward configuration, by inflating and deflating the lower pouch first and then the upper pouch on plates 1 and 2, θ_1 changes from -90° to 90° , and the output angle decreases from 0° to -180° . The upward configuration of the origami works similarly. This time we activate (inflate) the upper pouch first. Then deflate it, and inflate the lower pouch to generate the input angle range from 90° to -90° and the output angle range from 0° to 180° .

A: a) Downward configuration

Origami Plates

B: a) Upward configuration

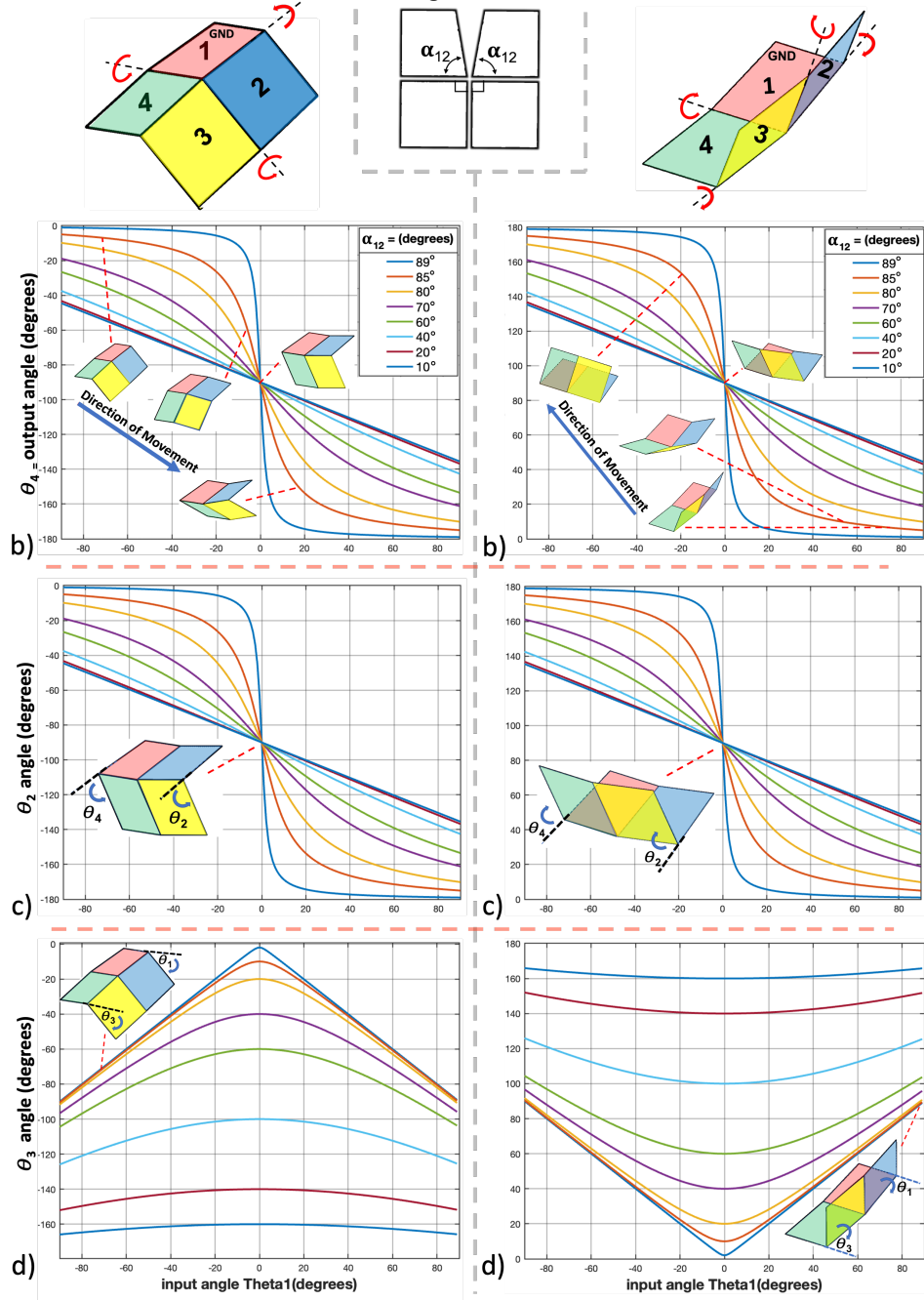


Figure 6.8: Origami plates: plates of origami with α_{12} and 90° degrees central angles. **A:** a) The origami joint with the downward configuration.

Figure 6.8: Plate 2 moves towards plate 1, while plates 3 and 4 experience downward motion. b-d) Relations of different origami angles, $\theta_1, \theta_2, \theta_3$, and θ_4 with $\alpha_{12} = 89^\circ, 85^\circ, 80^\circ$, etc. (central angles) for plates 1 and 2. The angles are marked in the plots' drawings. The θ_1 is supplementary to the angle between plates 1 and 2. The θ_4 is supplementary to the angle between plates 1 and 4. The angles θ_2 equals θ_4 . The θ_3 is supplementary to the angle between plates 3 and 4. The θ_3 and θ_1 are different due to the cuts from the central angles ($\sum_{i=1}^{41} \alpha_i \neq 360^\circ$ degrees). The arrow in b) shows the downward direction of movement from left to right. **B:** a) The origami joint with the upward configuration. Plate 2 moves away from plate 1, while plates 3 and 4 experience upward motion. b-d) Same origami angles' relations for upward configuration. The arrow in b) shows the upward movement from right to left.

The origami angles are functions of θ_1 and α_{12} (equations 5.4, 5.7, and 5.9 , Fig. 6.8).

The steep slope of the output angle, θ_4 , for the 89° degrees origami model is observed in the input angle range of $(-10^\circ, 10^\circ)$ degrees. Similar to Four-vertex, the output angle's changes speed up when the input angle, θ_1 , is near zero. Due to the symmetrical shape of origami, the angles θ_2 and θ_4 are equal. The farther the input angle gets from 0° degrees, the closer the slope of the θ_4 and θ_2 curves get to 0° degrees. Same a Four-vertex, approximately we have about 180° degrees of changes in the output angle, θ_4 . Due to the reduced central angles, the θ_3 starts from different values than θ_1 based on α_{12} and the current geometry. The downward movement starts from a similar to simple fold configuration with negative θ_3 and θ_1 angles. Then, as the input angle increases to 0° degrees, the θ_3 angle increases to 0° degrees (the flat state of input plates 1 and 2). Then, the input angle increases to a positive value, θ_3 decreases again, and the origami structure changes from a simple fold-like configuration to a downward rotational joint. In figure 6.8Ad, the convex curve is symmetrical, and its maximum value is based on the cutting angles of origami plates. Similar behavior has been observed for the upward movement in the opposite direction (Fig. 6.8Bd). Also, as the central angles of origami plates 1 and 2 change from close to 90° to 0° degrees, the slope of the curves (Fig. 6.8ABd) and their speed of motion

decrease.

6.3.2 Input and Output Moments

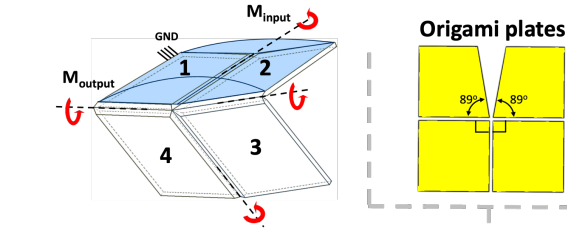
Figure 6.9 illustrates the theoretical curves of input and output moments based on θ_1 parameter (equations 5.5 and 5.10) for different pouch motor's pressure and central angles α_{12} . For the moment study, only one of the origami pouches has been considered. The top origami pouch is activated for the downward movement, and for the upward movement, the bottom pouch is. Also, the direction of input and output moments are opposite (Fig. 6.10ABa, Downward and upward movements). Since the upward and downward movements have the same moment values but in different directions (Fig. 6.9), we only analyzed the absolute value of the moments. The IP and OP represent the input and output moments for different pouch motor's constant pressures and α_{12} .

The effect of different constant pouch motor pressures on the origami's moments is studied (Fig. 6.9, downward and upward movements, and Fig. 6.10). For all the pressures, as the input angle changes from -90° to 0° degrees, the absolute value of the input moment changes from zero to its maximum value at $\theta_1 = 0^\circ$ degrees since the pouch motors work has not been converted into any motion in this state. As the origami rotates and the input angle gets farther from 0° degrees, the absolute value of the input moment decreases. Meanwhile, the absolute value of the output moment increases from 0° degrees and then decreases to 0° in a convex shape. These changes are due to observing the maximum origami's rotational motion near the 0° degrees input angle and the small input moment values near $\theta_1 = 90^\circ$ or -90° degrees. Therefore, there is a trade-off between the motion and the moment of the structure. A

symmetrical shape for the moments along the $\theta_1 = 0^\circ$ degrees axis is observed.

Figure 6.10 takes a closer look into the 89° degrees origami model's input and output moments separately. Comparing moments for different pouch motors' constant pressures (Fig. 6.9ABa, and Fig. 6.10ABbd) indicates that the higher the pressure, the bigger the input and output moments are. However, large pressure values could jeopardize the in-extensibility assumption for the pouch motor's material and result in the model's failure. We could select a material with a high young modulus while preserving flexibility properties to solve the issue. Another approach could be changing the actuator completely. Also, plots in figure 6.9ABb illustrate moments of different origami models ($\alpha_{12} = 89^\circ, 80^\circ, 70^\circ, 60^\circ$ and 45° degrees) for the 20kpa pouch motors constant pressure (the highest pressure that has been studied here). The closer the α_{12} is to 90° degrees, the bigger the moment's curves are. Also, compared to input moments of both pressure and origami models studies, the output moment's maximum values are drastically higher, although they occur in different phases of origami's configurations. The figure 6.10ABc includes the mechanical advantage curve with equation 5.10. Both downward and upward movements have the same Mechanical advantage, MA, since they are only different in their moment's directions. As the input angle increases from negative to positive the MA decreases and then increases in a concave shape. The closer plates 1 and 2 get to the flat state ($\theta_1 = 0^\circ$ degrees), the closer the MA is to zero since the output moment goes to zero. Therefore, It is best to take advantage of origami's moment in phases farther from its input plates' flat state.

A: a) Downward configuration



B: a) Upward configuration

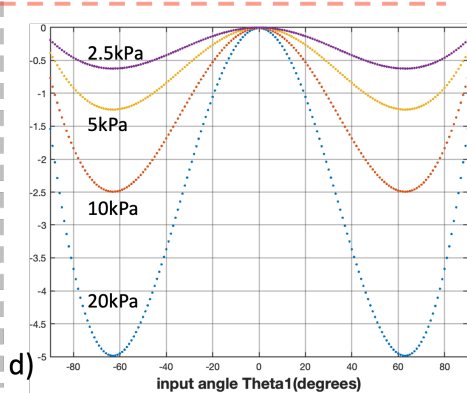
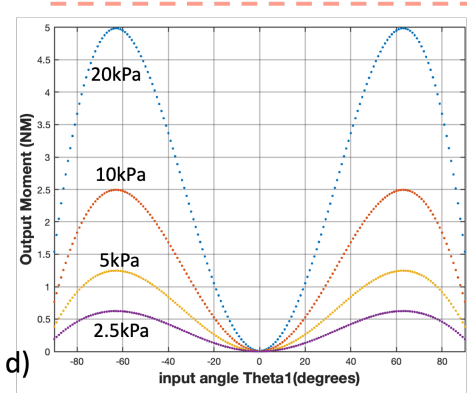
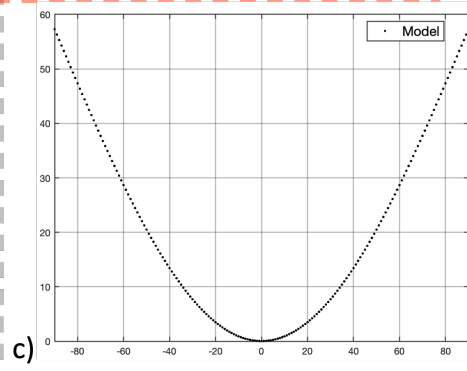
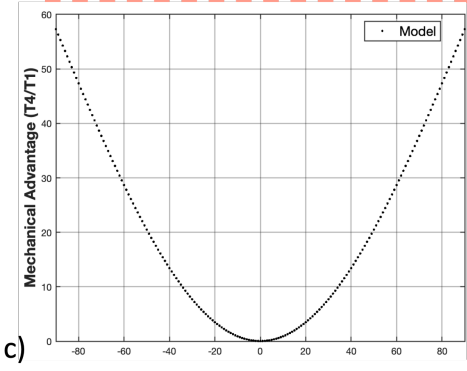
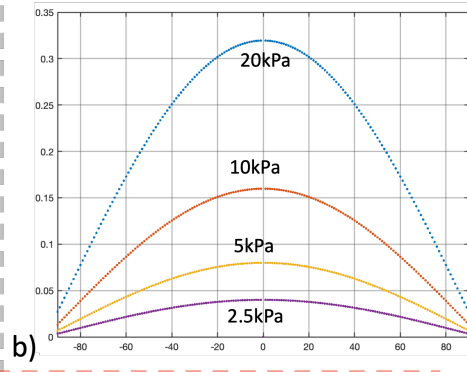
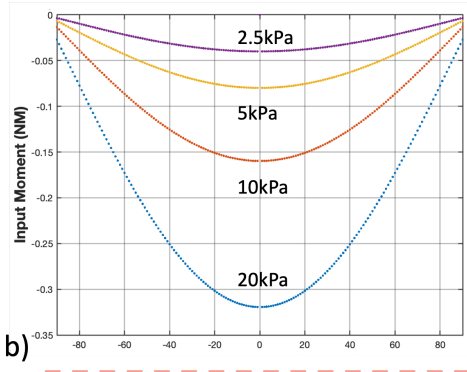
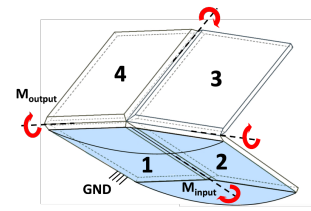


Figure 6.10: Origami plates: plates with central angles of 89° and 90° degrees.

Figure 6.10: **A:** a) Origami joint with a downward configuration. A pouch with constant pressure is installed on plates 1 and 2. Input moment (M_{input}): the moment applied by the pouch motor on the input plate (plates that are covered by the pouch motor) that is not grounded. The output moment (M_{output}): the moment on the output plate (plates that are not covered by the pouch motor) connected to the grounded plate. b-d) The relations of origami's input moment, Mechanical advantage (Output moment/input moment), and output moment based on the angle changes between plates 1 and 2 for different pouch's constant pressures. **B:** a) Origami joint with an upward configuration. b-d) Same relations for upward configuration.

6.3.3 Actuators' Pressure Relation

Figure 6.11 illustrates the origami's angles as the pressure increases in the two pouches on top and bottom of the origami (equation 5.22). The plots have been divided into two parts to show the angles' behavior when different pouches are activated in the same origami configurations (downward or upward). By inflating pouch 1, the θ_1 starts increasing in both movements. The angles' movements are delayed at the beginning due to considering P_i in equation 5.23. The slope of the curve gradually becomes linear due to the actuator's geometry and limitations. When pouch 2 starts inflating instead, we experience similar behavior but in the other direction. The input plates move away from each other ($\theta_1 < 0^\circ$ degrees) instead of moving towards. In figure 6.11ACc, the $\theta_2 = \theta_4$ plot shows the origami output angle changes as the pouch motor's pressure increases from 0kpa (equations 5.22, 5.7 and 5.4). Similar to Four-vertex, most origamis' rotation occurs at the beginning of the pouch motor's inflation. As the origami models α_{12} gets closer to 90° degrees, the faster the curve reaches its maximum. When pouch 1 pressure increases in downward and upward configurations, the origami's plates 3 and 4 rotate downwards. Therefore, we observe negative changes in θ_4 and θ_2 . However, when pouch 2 pressure increases, it rotates the output plates 3 and 4 upward (positive θ_4 and θ_2).

A: a) Downward movement **B:** **C:** a) Upward movement

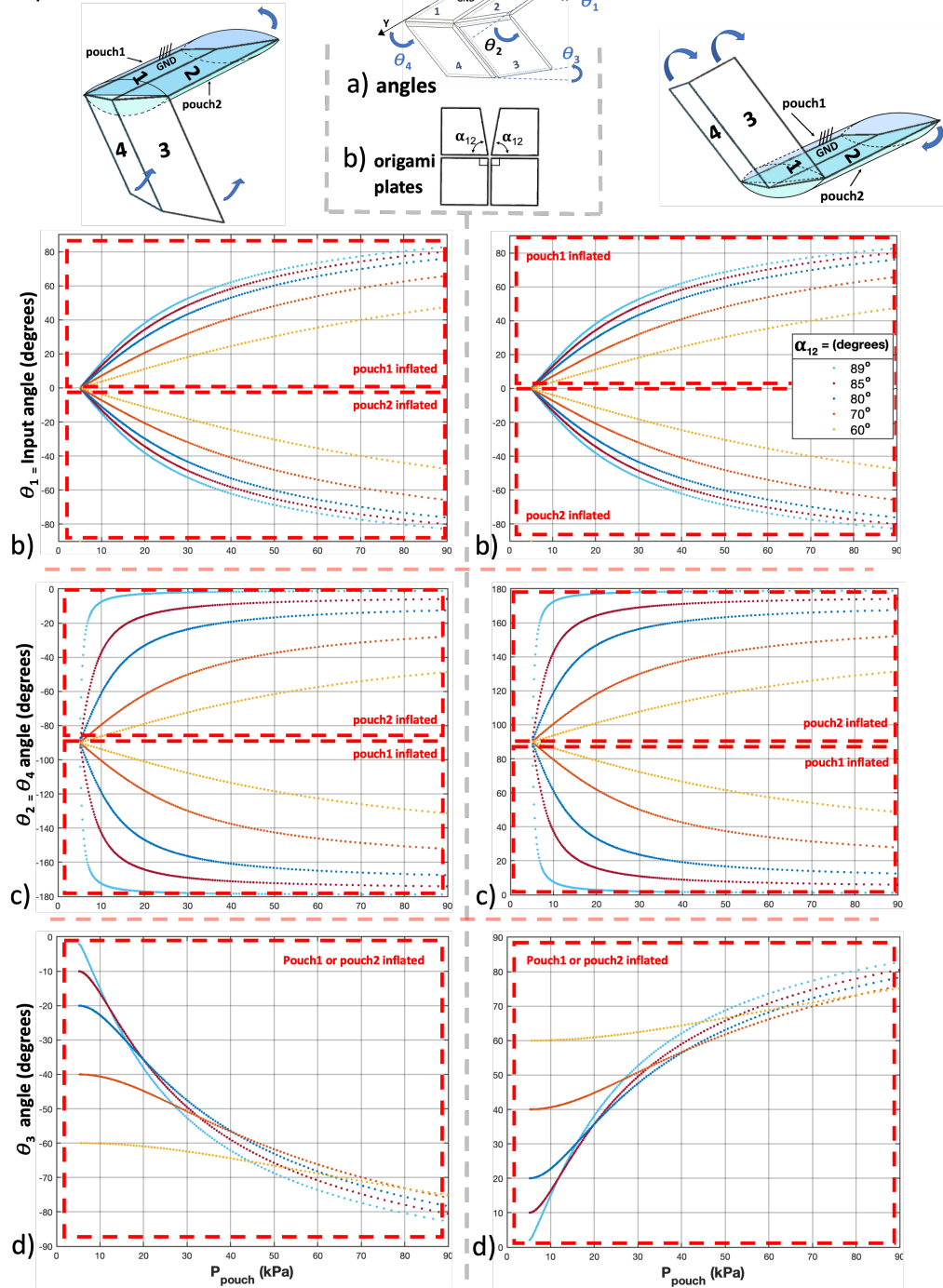


Figure 6.11: **A:** a) Origami joint configuration for downward movement.

Figure 6.11: Two pouches are installed on the top and bottom of plates 1 and 2 to activate the joint by applying different air pressures. b-d) Relations of the angles between origami plates and the pressures applied by the pouches 1 and 2 for downward configuration. **B:** a) Origami joint angles $\theta_1, \theta_2, \theta_3$, and θ_4 . b) Origami plates with central angles 90° degrees and $\alpha_{12} = 89^\circ, 85^\circ, 80^\circ$, etc. **C:** a) Origami joint configuration for upward movement. b-d) Same relations for upward configuration.

Figure 6.11ACd has parametric plots of equations 5.22 and 5.9 for downward and upward movements. Due to the origami plates' reduced central angles, the θ_3 plots have different shapes compared to θ_1 . Based on the α_{12} angles, origami models start from different values of θ_3 . However, after some steps, they become closer to each other since the origami gets farther away from its inaccessible states due to geometry constraints ($\sum_{i=12}^{i=41} \alpha_i < 360^\circ$). The smaller the missing angle is (α_{12} closer to 90° degrees), the more changes in θ_3 we experience. When pouch 1 is inflated in a downward configuration, it causes the origami to rotate downwards. Therefore, θ_1 increased and θ_3 decreased. When pouch 2 is inflated, the origami configuration becomes similar to a simple fold. Therefore, both θ_1 and θ_3 will decrease. For the upward movement, we have similar behavior for θ_1 and θ_3 , but in the opposite direction.

Some of the issues that need to be considered for the models' assumptions include: complete inflation is not possible for the 2D design of the pouch motor. Also, the initial state of the pouch might not remain completely flat. According to motion, moment, and pressure studies 89° degrees model has some advantages compared to others, such as the fastest and highest rotational changes in output angle, highest input and output moments in most origami configurations, and pouch motor's pressures. Also, since it has the minimum reduced central angle among different origami models, it is the closest model to a flat-foldable structure. Therefore, the 89° degrees model has been selected to fabricate a modular manipulator. Further studies of

this manipulator have been conducted in chapter 7.

6.4 3D-Printed Origamis' Motion

In this section, we investigated 3D-printed self-locking origami structures with varying physical properties to identify an optimal origami rotational joint. The simulation is conducted using Autodesk Inventor software. The origami plates are assumed to be solid and instead of foldlines, revolute joints are defined. To simulate the behavior of the origami joint, one of the joint's equivalent input plates is grounded. A trace, representing the joint's marker, is positioned at the outer corner of the equivalent output plate of the origami. An imposed rotational angle is applied to the rotational joint equivalent to the foldline of the 3D printed origami with ϕ angle. For a more detailed explanation of the motion simulation, please refer to chapter 4.

6.4.1 Bi-directional Origami

Figure 6.12(a) and (b) depict the trajectories of the marker of the 3D printed Bi-directional origami joint in the yz plane. Part (c) illustrates the installation of tubes, threads, knots, and pouches on the 3D printed Self-lock origami. The grounded plate and the coordinate reference frame are defined with the x-axis along the horizontal edge of the grounded plate and the y-axis along the vertical edge. The marker's motion starts from one of the folded states, either on the left ($\phi = 34^\circ$) or on the right ($\phi = 31.4^\circ$). It follows a circular path as it unfolds. This circular motion is a result of the rotation of the marker plate along the foldline

of the origami joint. When it reaches the unfolded state ($\phi = 180^\circ$), it transitions from one configuration (left/right) to the other (right/left) using the thread and tube system, accompanied by the inflation of the pouch on the opposite side. After passing the unfolded state, it continues rotating in the circular path, transitioning into the folded state in the new configuration. During this rotation, as the left pouch inflates and the right pouch deflates, the origami joint rotates towards the right side, and vice versa.

In the simulation, the equivalent marker follows a similar path with the assumption of zero thickness to transition from one configuration to another (left to right/right to left). This assumption is made because the simulation does not consider the presence of the soft fabric foldline, which provides the necessary flexibility for the origami structure. The joint experiences approximately $\phi = 300^\circ$ rotation between its grounded plate (input plate) and marker plate (output plate), with the two pouches serving as actuators. Figures 6.13 and 6.14 illustrate the relationship between time and the origami marker's positions (part c and d), including its speed (part a) and acceleration (part b). When the system holds the folded and unfolded states for a duration of 2e3 ms, the speed and acceleration decrease to zero. Part c and d depict the folded and unfolded states, respectively, along with the directions of movement.

6.4.2 Different Plate's Thicknesses and Wedge Lengths

We conducted a study on the motion of 3D printed Self-lock origami in the yz plane, focusing on the effect of different origami plate thicknesses (Fig. 6.15b) while maintaining a constant fabric width (Fig. 6.15c, space) between the plates. Our objective was to create a stronger joint capable of carrying loads. However, we observed that increasing the plate thick-

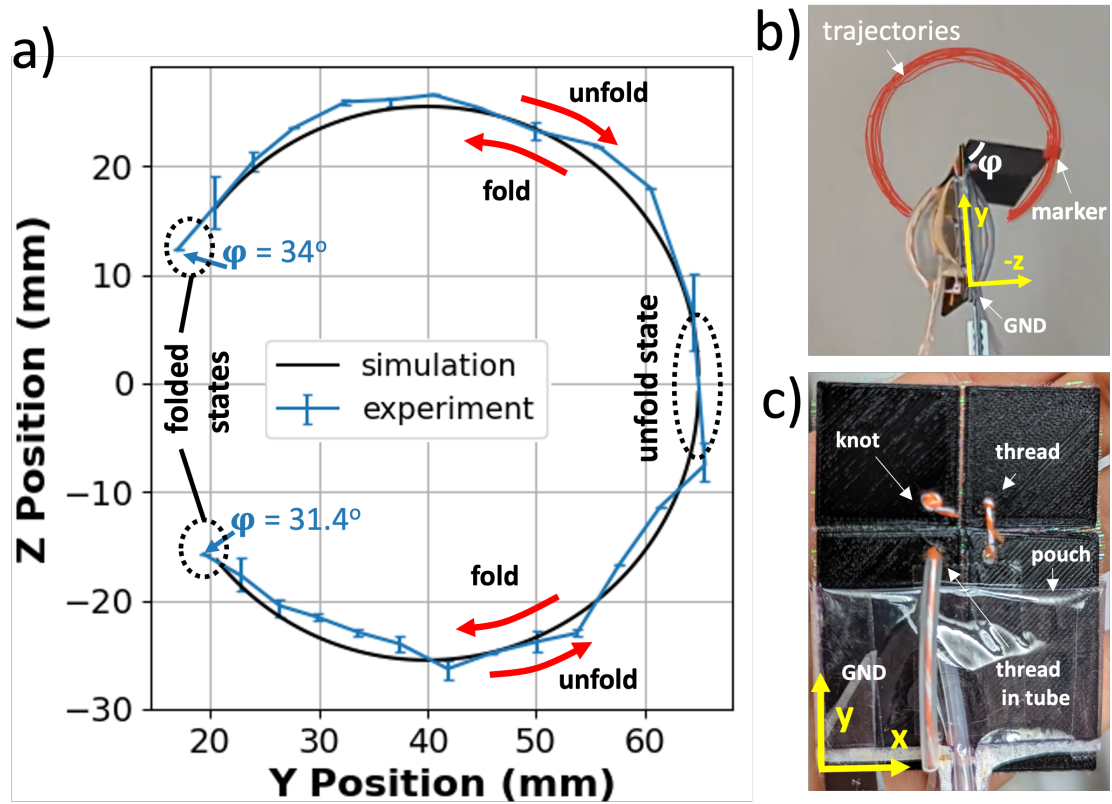


Figure 6.12: a) The yz plot for the experimental and simulated motion of the Bi-directional origami joint's marker unfolding from left to right, transitioning from the folded state to the unfolded state ($\phi = 180^\circ$, indicated in part b of the figure). Subsequently, the configuration changes from left to right (downward to upward) and the joint is folded in the right configuration creating about 300° degrees of rotational motion. b) The experiment setup for the bi-directional origami involves grounding one of the input plates, which is covered with a pouch. The origin is defined at the outer corner of the grounded plate, with the Y-axis along the plate edge and the Z-axis perpendicular to the plate. A marker is positioned at the outer corner of the output plate, which is not connected to the pouch but linked to the grounded plate. The trajectories of the marker's movement are represented in red. The variable ϕ indicates the angle between the grounded plate and the marker's plate. c) The 3D printed Bi-directional origami showcasing the inclusion of knots, threads, threads with tubes, and pouch actuators in the experiment. The grounded plate and the reference frame are shown from a top view.

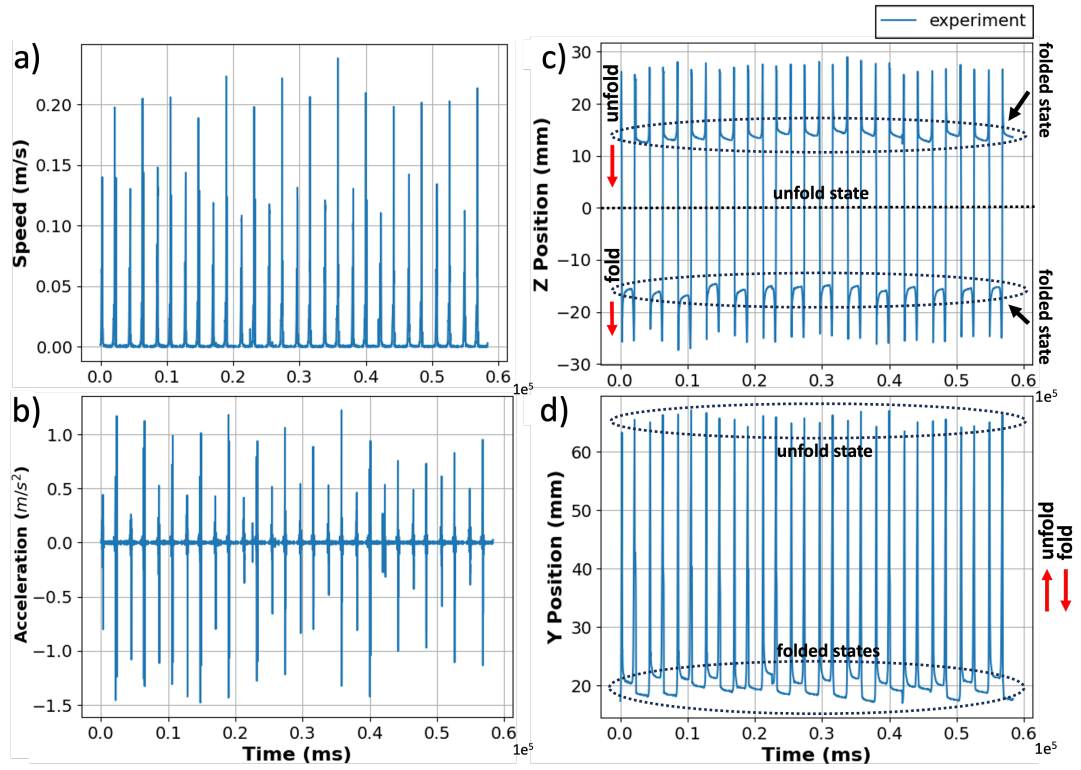


Figure 6.13: The origami marker's a) Speed plot based on time. b) Acceleration plot based on time. c) and d) Y and Z positions based on time. The folded and unfolded states, along with the directions of movement, are demonstrated in parts c and d. In both the folded and unfolded states, the system maintains the pouches inflated for approximately 2×10^3 milliseconds.

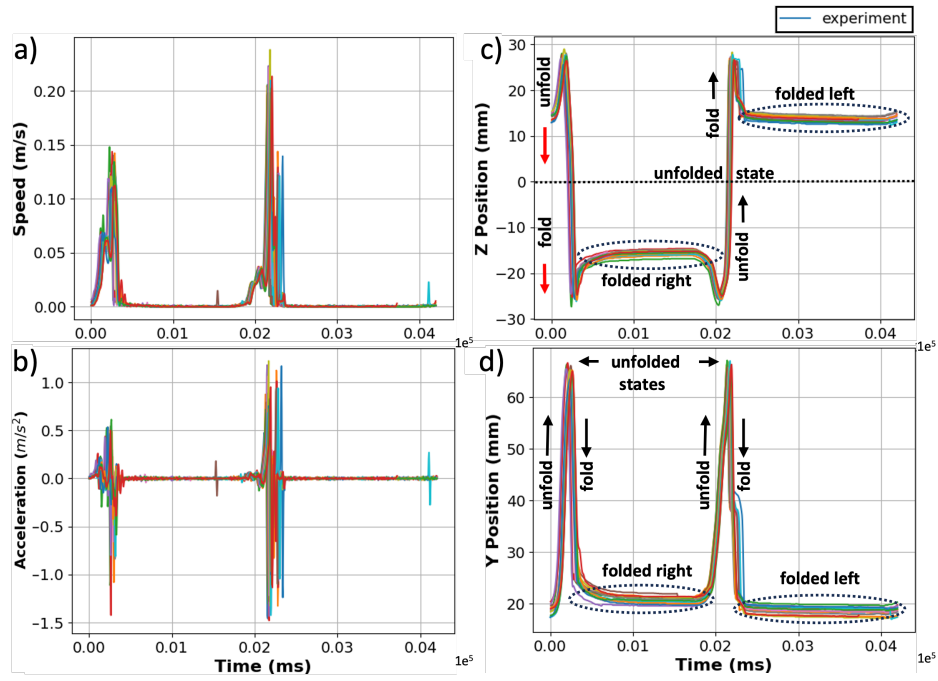


Figure 6.14: A closer look into the origami marker's a) Speed plot based on time. b) Acceleration plot based on time. c) and d) Y and Z positions based on time. The folded and unfolded states, along with the directions of movement, are demonstrated in parts c and d. In both the folded and unfolded states, the system maintains the pouches inflated for approximately 2e3 milliseconds.

ness could potentially limit the range of movement. To address this limitation, we also explored variations in the wedge length (Fig. 6.15b) of the origami plates while keeping the thickness constant. The aim was to determine if wedge length and plate thickness parameters would help maximizing the joint motion range while still accommodating load-bearing capabilities.

Figure 6.15a showcases the joints with different thicknesses and wedge length to thickness ratios. The space between the plates is 0.02, although it may vary due to 3D printer precision and the stretchability and deformations of the fabric. Additionally, all origamis have the reduced central angles of $\alpha = 80^\circ$ degrees. Since the joints' parameters and their range of motion are close to each other, we selected four extreme cases for the detailed analysis. The origamis highlighted in yellow, with thicknesses of 0.6mm and 1.5mm, and wedge lengths of 0.6mm, 1mm, 1.5mm, and 2.5mm, were subjected to an experiment with a 49-gram load suspended from their marker's plates (Fig. 6.16b).

Figure 6.15d illustrates the rotational motion of the joints in a yz plot. From right to left, the concave lines indicate the folding motion of the origami, while from left to right, they represent the unfolding motion. It is observed that the range of motion is reduced compared to the $\alpha = 80^\circ$ Self-lock origami without any loads (Fig. 6.19b). As the thickness of the origami plates increases, their folding range of motion also increases, allowing them to fold into smaller ϕ angles. However, if the wedge length does not increase proportionally with the thickness, it can interfere with the movement and limit the folding range compared to joints with smaller thicknesses.

Regarding the unfolding motion, a slight increase in the range of motion is observed as the origami plates' thickness increases with the same wedge length to thickness ratio (e.g.,

Thickness and Wedge Analysis

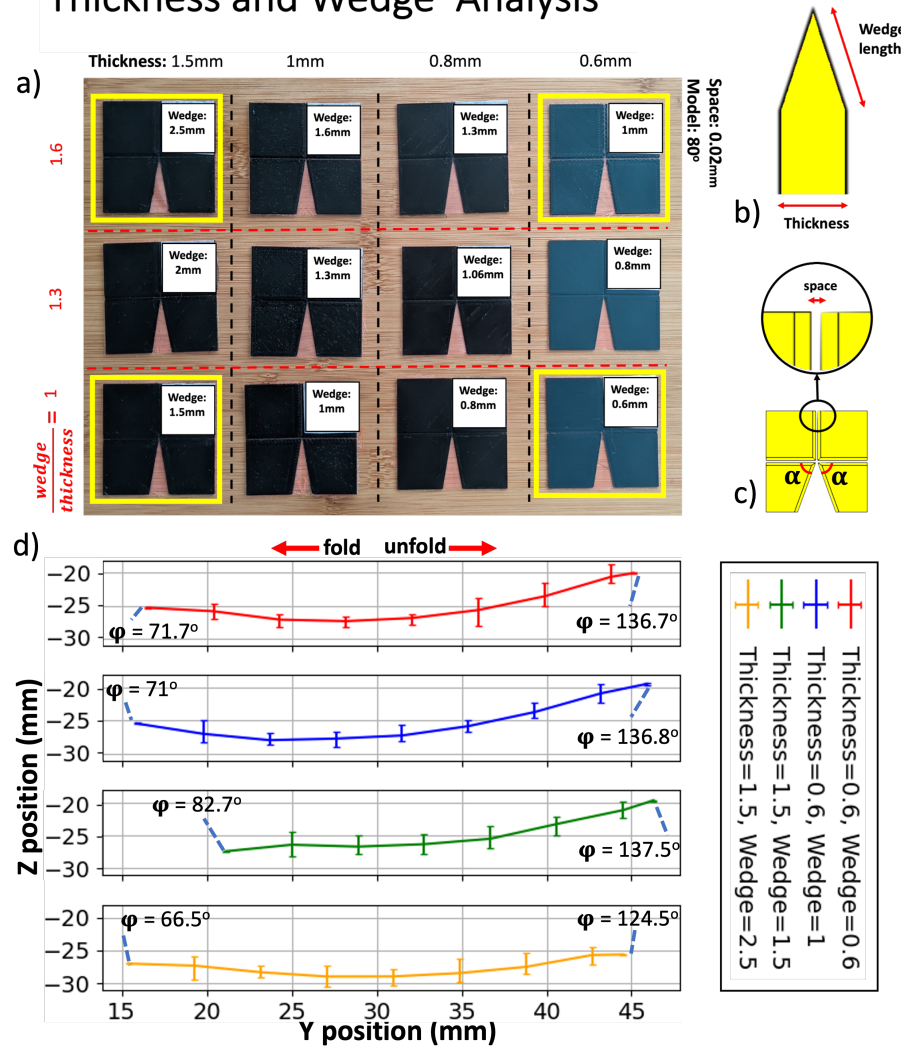


Figure 6.15: a) The 3D printed Self-lock origamis with varying plate thicknesses and wedge to thickness ratios, specifically designed to investigate their impact on the joints marker's motion while under a load of 49 grams. The space (fabric width) between the plates is maintained at a constant value of 0.02mm. Additionally, the central angles of the origamis are reduced to 80° degrees (denoted as α , part c of the figure). The highlighted origamis in yellow represent the extreme cases selected for detailed analysis and observation. b) The side view representation of the wedge length and thickness of the origami plate. c) A closer look into the space between the plates of the Self-lock origami structure. This space is filled by fabric, which plays a crucial role in the origami's motion and stability. The reduced central angles of the Self-lock origami, denoted as α , are also depicted in the figure. d) The yz motion plot of the highlighted origami markers mentioned in Part a. The origami joint folds from right to left and unfolds from left to right. The angle between the grounded plate and the marker plate of the origami is represented by the variable ϕ . The goal is to minimize the ϕ in folding and maximize it in unfolding.

Thickness = 0.6mm, Wedge = 0.6mm and Thickness = 1.5mm, Wedge = 1.5mm). However, when the wedge length is increased along with the thickness (e.g., Thickness = 1.5mm, Wedge = 2.5mm), the unfolding range of motion decreases. This is because the plates at the foldlines become too thin, creating a larger soft area between the solid plates, which hinders rotation when carrying a heavy load. In folding motions, the soft area between the joint's plates decreases as the movement progresses due to the structure's configuration. Therefore, there is a trade off between selecting a joint with a larger thickness and wedge length. For joints with initially small plate thicknesses (e.g., 0.6mm), the change in wedge length has minimal effect since they already have a large range of motion to carry a 49-gram load.

6.4.3 Different Spaces Between Plates

To investigate the effect of different space lengths (Fig. 6.15c) on the joint's motion while carrying a load, we developed 3D printed origami joints with varying fabric widths (space lengths) between their plates (Fig. 6.16c). However, it should be noted that even with the presence of wedges along the plates' edges, small space lengths may limit the joints' range of motion. To address this issue, we created additional 3D-printed origamis with varying wedge lengths but the same space lengths. For this study, we selected a thickness of 0.6mm and a reduced central angle of $\alpha = 80^\circ$. We specifically focused on the extreme cases (highlighted in yellow) to analyze the effects.

Figure 6.15b illustrates the experimental setup discussed in section 6.1.2 for the analyses. To identify the joint parameters that maximize the rotational motion along the foldline between the grounded plate and the marker's plate, we plotted the yz motion curves in Figure

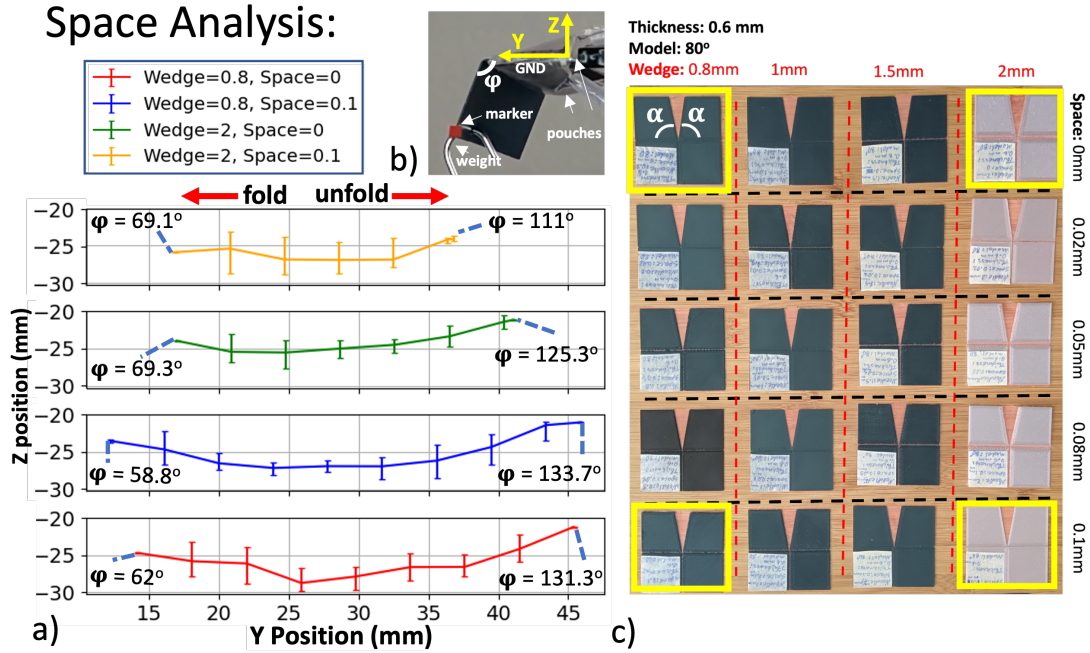


Figure 6.16: a) The yz plot for the motion of the joints' markers indicated in yellow in part c. The folding motion occurs from right to left, while the unfolding motion occurs from left to right. The variable ϕ representing the angle between is indicated in part b of the figure. b) The experimental setup for the Space, Thickness and Wedge, Fabric, and Models analysis involves grounding one of the input plates that is covered with a pouch. The origin is defined at the outer corner of the grounded plate, with the Y-axis along the plate edge and the Z-axis perpendicular to the plate. A marker is positioned at the outer corner of the output plate, which is not connected to the pouch but linked to the grounded plate. The variable ϕ indicates the angle between the grounded plate and the marker's plate. A weight of 49 grams is suspended from the marker's plate to assess the integrity and strength of the joints. c) The 3D printed origami joints with varying wedge and space lengths are created to examine the influence of these parameters on the motion of the origami. All the joints have a thickness of 0.6mm and reduced angles of $\alpha = 80^\circ$. The joints with extreme parameters, which are highlighted in yellow, are selected for further analysis and study.

6.16a for the joints with extreme parameters, including wedge lengths of 0.8mm and 2mm, and space lengths of 0mm and 0.1mm. It is important to note that even with the 0mm space length, the 3D printer would still create a small space (non-zero) between the origamis' plates due to the presence of wedges. However, these spaces are significantly smaller compared to the 0.1mm space length.

From the yz motion plots, we observed that the wedge length parameter has a more pronounced impact on the range of motion compared to the space length parameter. As the wedge to thickness ratio increases from 1.34 to 3.34 for the joints with a thickness of 0.6mm, their range of motion significantly decreases. Consequently, their maximum folding angles increase while their unfolding angles decrease. This can be attributed to the larger soft area between the plates, leading to reduced structural integrity and stiffness at the foldlines and impeding rotational movements. Even in the folded state, the geometry of the origami joints cannot fully compensate for the presence of a large soft area at the foldlines.

Among the origami joints with a wedge length of 0.8mm, the joint with a larger space length (0.1mm) exhibited slightly greater rotational motion. This suggests that creating a soft area that is not excessively large could be beneficial for the joints' movements. On the other hand, for the joints with a wedge length of 2mm, the 0.1mm space length resulted in a shorter range of rotational motion. This is because a larger space, combined with a long wedge length, creates an even larger soft and weak area at the foldlines. This exacerbates the challenges faced by the joints in terms of maintaining rigidity and supporting smooth rotational motions. To optimize the joint's performance, it is essential to carefully balance the space length and wedge length parameters. Avoiding excessively large spaces and overly long wedge lengths can

help mitigate the formation of a substantial soft area, thereby improving the overall structural integrity and enabling more efficient rotational movements in the origami joints while carrying loads.

6.4.4 Different Netted Fabric Materials

To study the impact of different netted materials on the motion of origami joints along the foldline, we utilized Organza, Stainless steel, Cotton, and Fiberglass materials (Fig. 6.17b) in their fabric forms. Figure 6.17a showcases 3D printed origami joints utilizing various fabric materials with a mesh texture to bind with the PLA material from the 3D printer. For the experiment, we selected a thickness of 1mm, the wedge length of 1.6mm, the reduced central angle of $\alpha = 89^\circ$, and a space of 0.02mm between the origami plates.

Figure 6.17c demonstrates the rotational motion of these joints in the yz plane to identify the optimal material that provides the best rotational motion along the foldline between the grounded plate and the marker plate. The top plots represent the motion of the joints without any additional weight, while the bottom plots depict the same experiments with an additional weight of 49 grams. From right to left, the convex lines represent the folding motion of the joints, and from left to right, they depict the unfolding motion. As anticipated, the joints without any added weight exhibit a greater range of motion. However, it is worth noting that the Stainless steel (metal) material displays the smallest range of motion in both the weighted and unweighted scenarios due to its inherent stiffness. Even in the absence of any additional weight, the actuator encounters challenges in folding the netted Stainless steel sheet. Despite its stiffness, the material does not enhance the movement of the marker when weight is applied.

Fabric Analysis

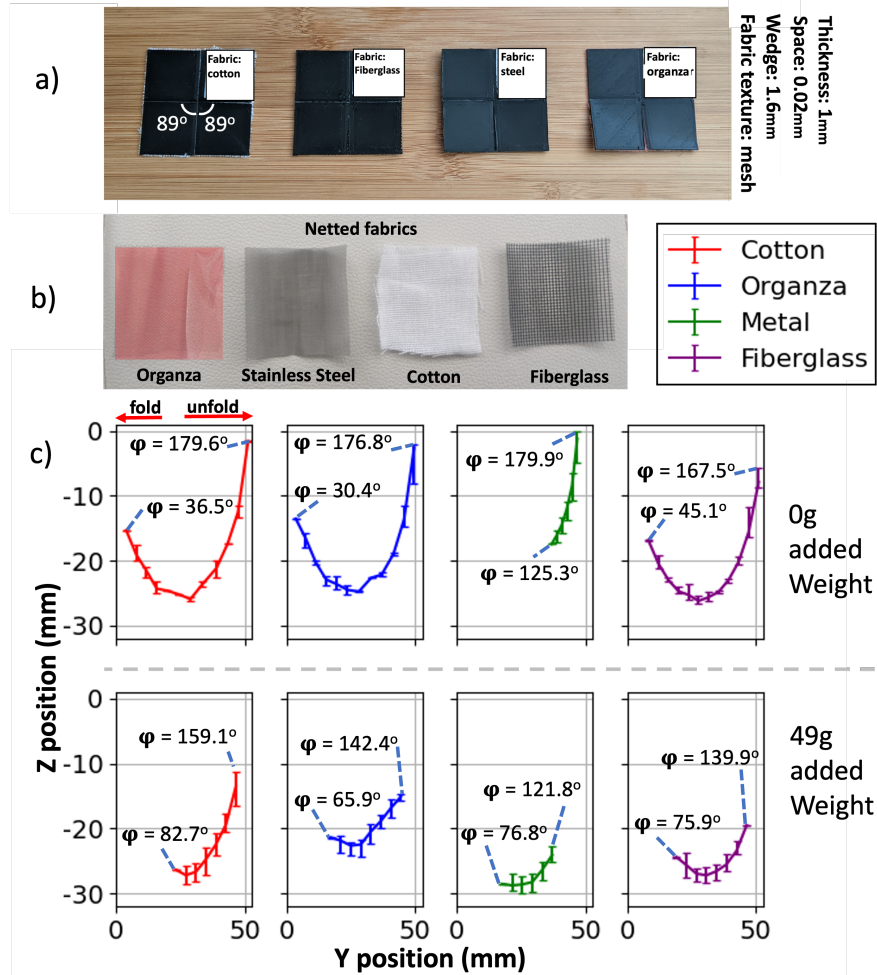


Figure 6.17: a) The 3D printed Self-lock origami joints are constructed using different netted fabrics as their middle layer, including Cotton, Fiberglass, Stainless Steel, and Organza. These joints have a reduced central angle of 89° , a thickness of 1mm, a wedge length of 1.6mm, and a space of 0.02mm between their plates. To ensure binding with the 3D printing material, PLA, all the fabrics have a mesh texture. b) The different fabrics that have been used to 3D print the origami joints on. c) The yz motion plots for the the origami joints' markers with different fabric materials as their middle layer. The top plots represent the motion of the markers without any additional weight, while the bottom plots depict the motion of the markers with a 49-gram weight attached to their plates. The variable ϕ represents the angle between the joint's grounded plate and its marker's plate. In the plots, the folding motion occurs from right to left, and the unfolding occurs from left to right.

Among the other three fabrics, Organza and Cotton exhibit the largest rotational motion. The joint utilizing Fiberglass fabric demonstrates a shorter range of motion compared to Cotton and Organza when weight is added, primarily due to its lower thread count, resulting in a weaker foldline. The joint utilizing Organza fabric showcases a greater folding range compared to Cotton (e.g., $\phi = 30.4^\circ$ vs. 36.5°) in both weighted and unweighted scenarios, attributed to its small stretchability properties. Conversely, Cotton performs better in unfolding with $\phi = 179.6^\circ$ vs. 176.8° , although it experiences wear and tear over time. As Organza fabric possesses the highest thread count, it exhibits the longest durability. Consequently, we have selected Organza fabric as the optimal material for the origami joint.

6.4.5 Different Central Angles

To study the effect of varying central angles on the motion of Self-lock origami joints in the YZ plane, we have developed 3D printed joints with different reduced central angles, denoted as α (see Fig. 6.18). These joints have a thickness of 1mm, a wedge length of 1.6mm, and a space of 0.02mm between their plates. These Self-lock origami structures consist of two plates with central angles of 90° and two with central angles of $\alpha = 60^\circ - 89^\circ$ (see Fig. 6.18b). One of the plates with a central angle of α is grounded. The reference frame is defined on its outer corner, with the X-axis along its horizontal edge and the Y-axis along its vertical edge (see Fig. 6.19a). A marker is defined on the outer corner of the plate adjacent to the grounded one, with a central angle of 90° . The variable ϕ represents the angle between the grounded plate and the marker's plate.

The YZ plots in Figure 6.18b illustrate the rotational motion of the markers to deter-

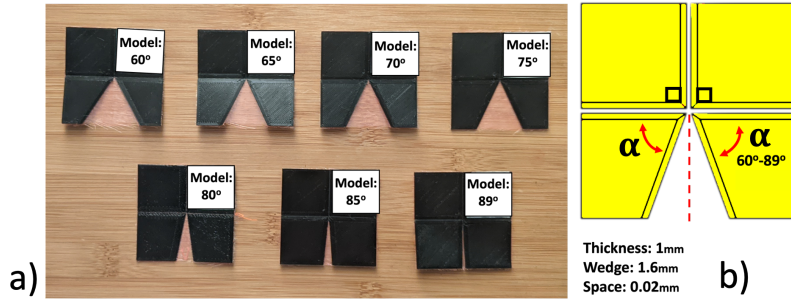


Figure 6.18: a) 3D printed Self-lock origamis with reduced central angles ranging from $\alpha = 60^\circ$ to $\alpha = 89^\circ$ are fabricated. These origamis have a uniform thickness of 1mm, a wedge length of 1.6mm, and a space of 0.02mm between their plates. b) The origami joints' plates are composed of two plates with a fixed central angle of 90° and two other plates with central angles varying from $\alpha = 60^\circ$ to $\alpha = 89^\circ$.

mine which central angle can produce the maximum range of motion in the downward direction. From right to left, the convex line represents the folding motion, while from left to right, it represents the unfolding. Both simulation and experimental data show a drastic decrease in the range of motion in the Z-axis as the central angle α decreases from 89° to 60° . Consequently, the maximum folding angle increases from $\phi = 28.7^\circ$ to 69° , while the maximum unfolding angle decreases from $\phi = 172.9^\circ$ to 117.8° . Therefore, selecting the origami joint with a higher central angle α enhances the motion performance of the joint. However, it is important to consider a trade-off when designing the joint. Increasing the α angle, along with the limited extensibility of Organza fabric at the foldline, can potentially cause the joint to change its configuration and direction of movement when subjected to large forces or when required to carry a heavy load. This trade-off should be taken into account during the design process to ensure the joint's stability and reliable performance in various operating conditions.

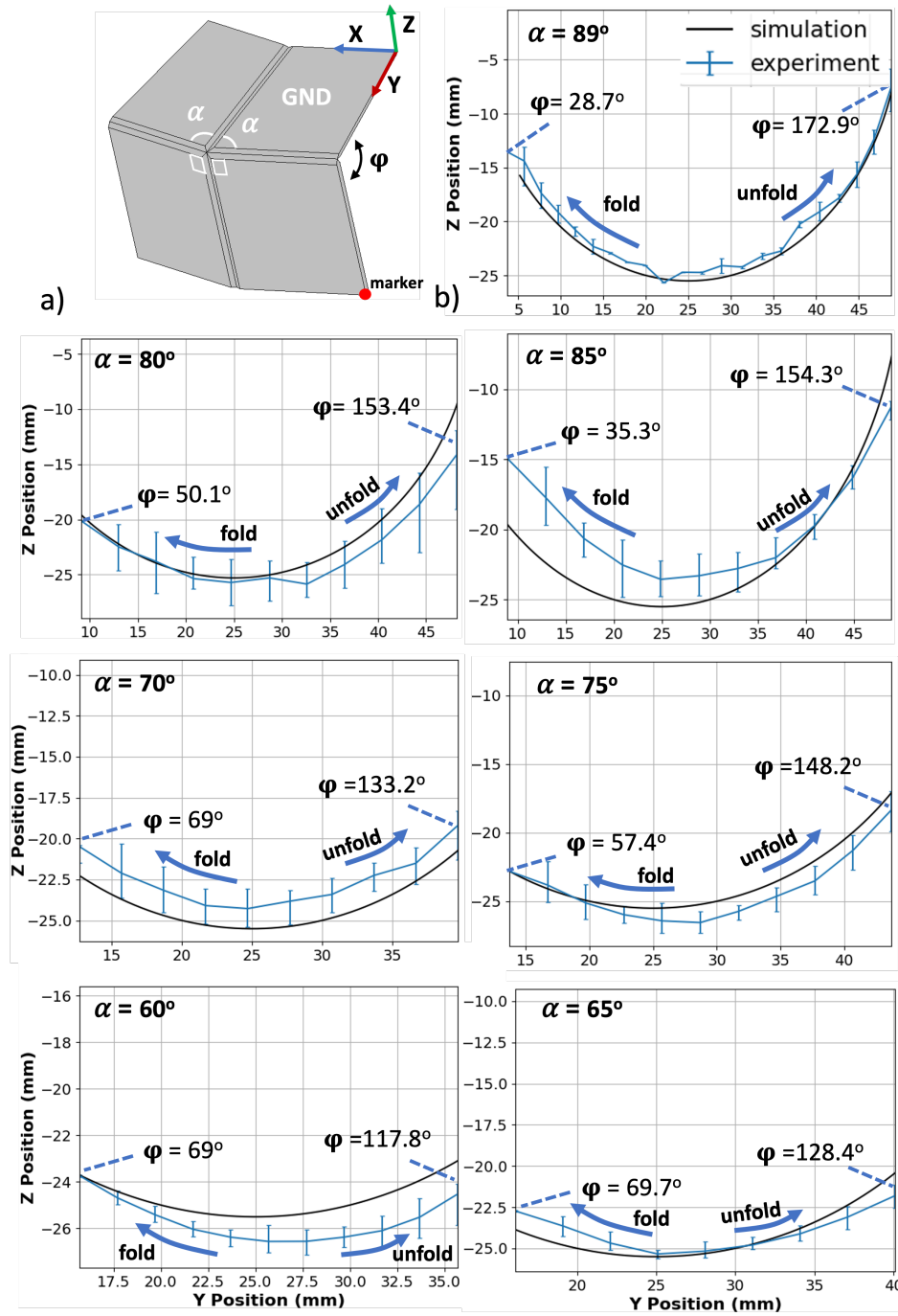


Figure 6.19: a) The setup for both the experiment and simulation. One of the plates with a reduced central angle α is fixed in place as the grounded plate. The plate adjacent to it, with a fixed central angle of 90° degrees, contains a marker on its outer corner to monitor the rotational motion of the joint. A reference frame is defined at the outer corner of the grounded plate.

Figure 6.19: The angle between the grounded plate and the marker plate is denoted as φ , which is used to estimate the joint's maximum folding and unfolding capabilities. b) The YZ plots of the motion of both simulated and 3D printed origami joints with varying α angles ranging from 89° to 60° . In the plots, the folding motion is shown from right to left in a convex shape, while the unfolding motion occurs from left to right. It can be observed that as the α angle increases, the maximum folding angle φ decreases, while the maximum unfolding angle φ increases.

Chapter 7

Application: Manipulators

We developed origami manipulators as proof of concept. They could cover a wide range of motions while benefiting from the origami structure's properties, such as compactability, lightweight, conserving energy, high-speed rotational motion, and large moment. The manipulators we designed, simulated and studied in this section could be divided into three categories: Rotational, Translation, and Modular manipulators. All the manipulators have different combinations of origami joints connected to each other. The Translational and Modular manipulators are simulated only with Self-lock origami structures and the Rotational manipulators have been fabricated.

7.1 Rotational Manipulators

The rotational manipulators with different origami models, α_{12} , have been designed and simulated in Autodesk Inventor Software (Fig. 7.5 and 7.2). They consist of two origamis connected on only one of their plates. Connecting them on more than one plate could jeopardize

their mobilities. This connection is a welded joint (Fig. 7.5Aa) and treats the plates between it as one long plate linking the two origamis. The connection is between one of the output plates of the first origami and one of the input plates of the second origami to obtain optimal rotational movement. There is a possibility of an overlap between the first origami's output plates and the second origami's input plates while the manipulators move. To avoid the situation, we could cut the plates at a slight angle in those problematic areas (Fig. 7.5Ab). Cutting them would not affect the manipulator's movements since the areas do not include the origami plates' central angles.

7.1.1 Four-vertex Origami with Cutting and Binding Method

The Four-vertex origami with cutting and binding method is faster, cheaper, and easier to produce. Due to its flat-foldability, it can fit in small places that traditional robots cannot reach (Fig. 7.1.a). Therefore, it can be used for inspection applications. Due to the waterproof properties of its materials, it is working on water and underwater as well (Fig. 7.1.b). It is compliant and can survive accidents such as dropping, sliding, and crushing by heavy objects (Fig. 7.1.c). It can be produced in different sizes (Fig. 7.1.d) and shapes (Fig. 3.4.c) for various applications. One of its advantages compared to other origami robots is the fact that it is flat-foldable and it can be made at a very small scale. Also, both the actuator and the origami could be made from biocompatible materials, which makes it a great candidate to be sent inside the body as well.

Figure 7.2 shows the preliminary design of a manipulator that uses two of the pneumatic modules (pouch motors) connected in series, to obtain a complex range of motion. Figure

7.3a) shows the physical prototype and figure 7.3 b) and c) demonstrates the robot's ability to grasp objects of different sizes. We used a vise as the mounting part in our experiment. To simplify the motion simulation in figure 7.2, we defined rotational motion directly between the plates instead of modeling the pouch motors forces due to the complexity of the soft material's behavior. In each origami, the plates with defined motion in between them are called "active plates," and the other pair of plates are called "passive plates." In the model, our focus is on the bending movement. We put five markers (Base, Joint1, Marker1, Joint2, Marker2) at the top corner of the plates to track their movement. Figure 7.2 part (b) shows the large rotations at Marker2. Joint1 and Marker1 have smaller rotations compared to Marker2. The Joint1 movement is not significant enough to be seen in the plot. Since Marker1 is on one of the "passive plates," it has more rotational displacement than Joint1 on the "active plate". The same thing applies to Marker 2. The combination of the movements on both origamis creates a circular motion.

Figure 7.4 shows the rotational movement of two combined origami joints in different steps. Step 1 is the initial state. From step 1(the straight position) up to step 4 (the bending position), the manipulator moves until it bends to the desired position by inflating and deflating the pouches. In the experiment, the manipulator has two sides (the front and back). We have one separate pump and vacuum for pouches on each side of the manipulator to obtain the straight position and the bending position. Pouches on the backside inflate simultaneously and produce a rotation at each joint. This results in the manipulator bending and holding an object. Then, the manipulator can be straightened and release the object by deflating the backside pouches and inflating the front side pouches.

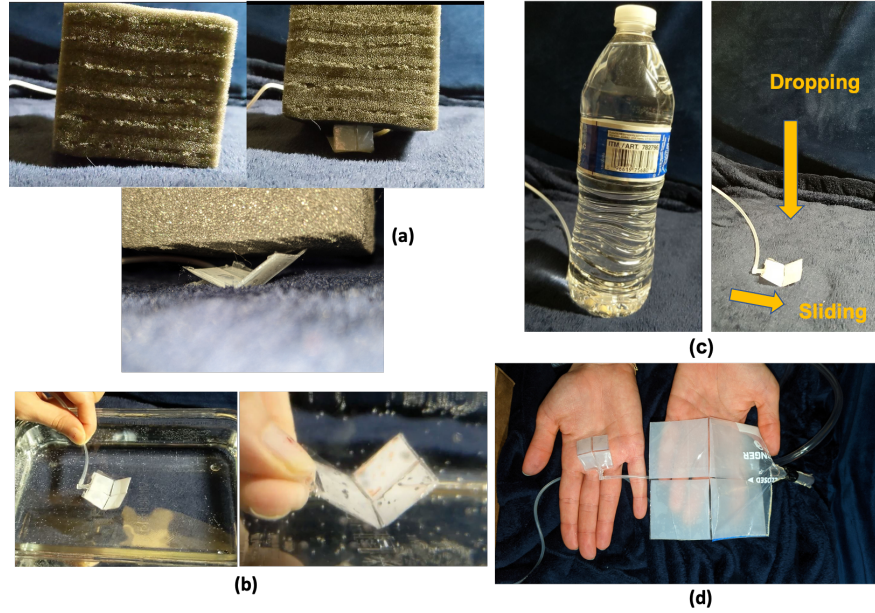


Figure 7.1: a) It can fit into small places due to its size and flat-foldability properties. b) It can perform on the water as well as underwater too. c) It can be dropped, slide and crushed by heavy objects and continue to work afterward without any damages. d) The origami can be produced in different sizes for different applications.

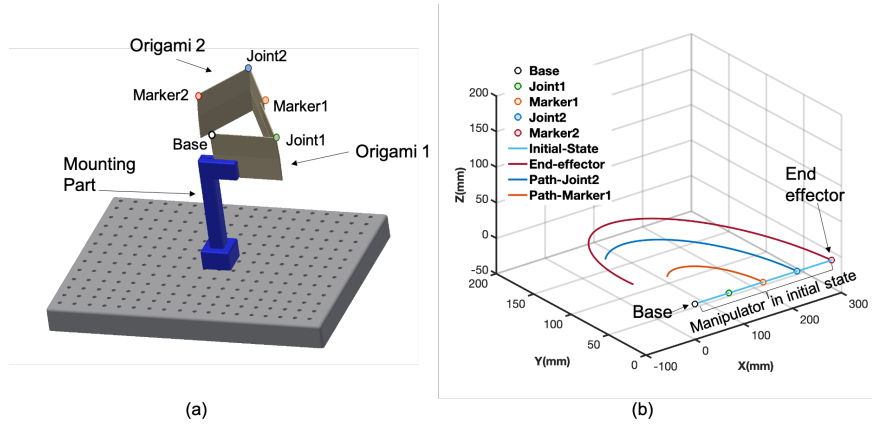


Figure 7.2: a) The design of the manipulator: The origami manipulator consists of two origamis. It is grounded on an aluminum plate using a mounting part to analyze the origami manipulator's movement. b) The simulation of manipulator's movement from the straight state to the bending. Markers (points at the upper corner of the plates) are added to the structure to track each plate (from the Base to the end effector). The path of the end effector's marker and the markers near that show a curved motion starting from the initial state (straight blue line).

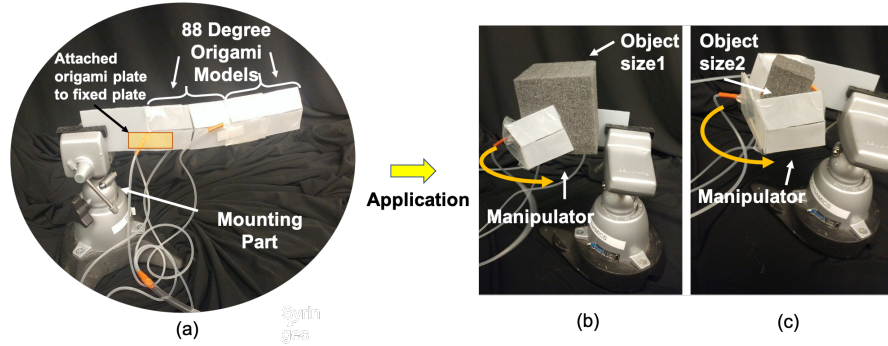


Figure 7.3: a) The manipulator made of two origami model with plate's angles of (a) = (c) = 88° degrees. It has been stabled on the ground using a mounting tool. b) and c) The manipulator is capable of taking objects of different sizes.

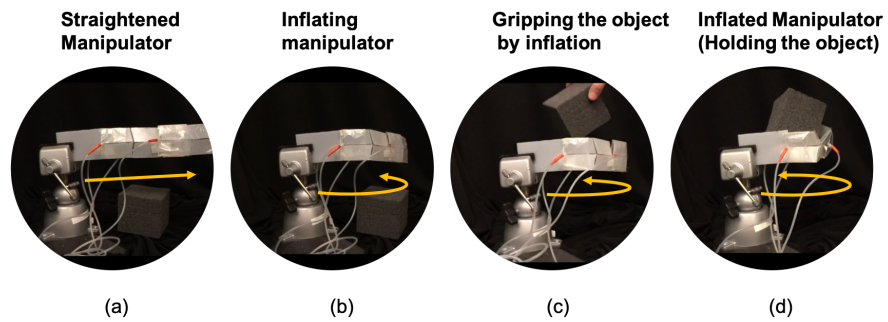


Figure 7.4: The figures from (a) to (d) shows the proposed manipulator during different stages of gripping

The manipulator weighs 27 grams. The maximum weight the manipulator with two origami could hold is about 10 grams while maintaining its structure. Due to the origami structure, it can adapt to hold various sizes of objects (Fig. 16.b and c). Also, it can straighten up and become as flat as a sheet of paper. However, connecting the plates with tape as their soft joints results in a poorly structured manipulator. This current configuration is not suitable for lifting heavy objects, but changing the soft joint between the plates and using other materials for attachment can solve the problem. We will investigate that in our research.

7.1.2 Self-lock Origami

In all the simulations with Self-lock origami structure, we refer to the closest possible configuration to the origami's flat state as a semi-flat state. In this state, the summation of all the angles between origami plates (absolute value) is at its maximum. Using this condition and origami equations 5.4, 5.7, and 5.9, we could obtain the semi-flat state origami angles. All the origami plates have a 25mm width before reducing the central angles to create different origami models. Except in the translational manipulator, the length of origami plates is 25mm as well. To track the manipulator's motion in Self-lock origami, a marker has been defined on the corner of the second origami's output plate (Fig. 7.5Aa-d).

In the manipulator, both of the origamis have the same configuration (ex. both are downwards) and a defined maximum possible rotational motion (from a semi-flat state to the MPF) for the simulation. Figure 7.5 illustrates the coordinate system of manipulators (part a) and the 2D motion plots for their different origami models. In the xz plot (Fig. 7.5Bb), no movement is observed along the x-axis. The less movement we experience along this axis, the

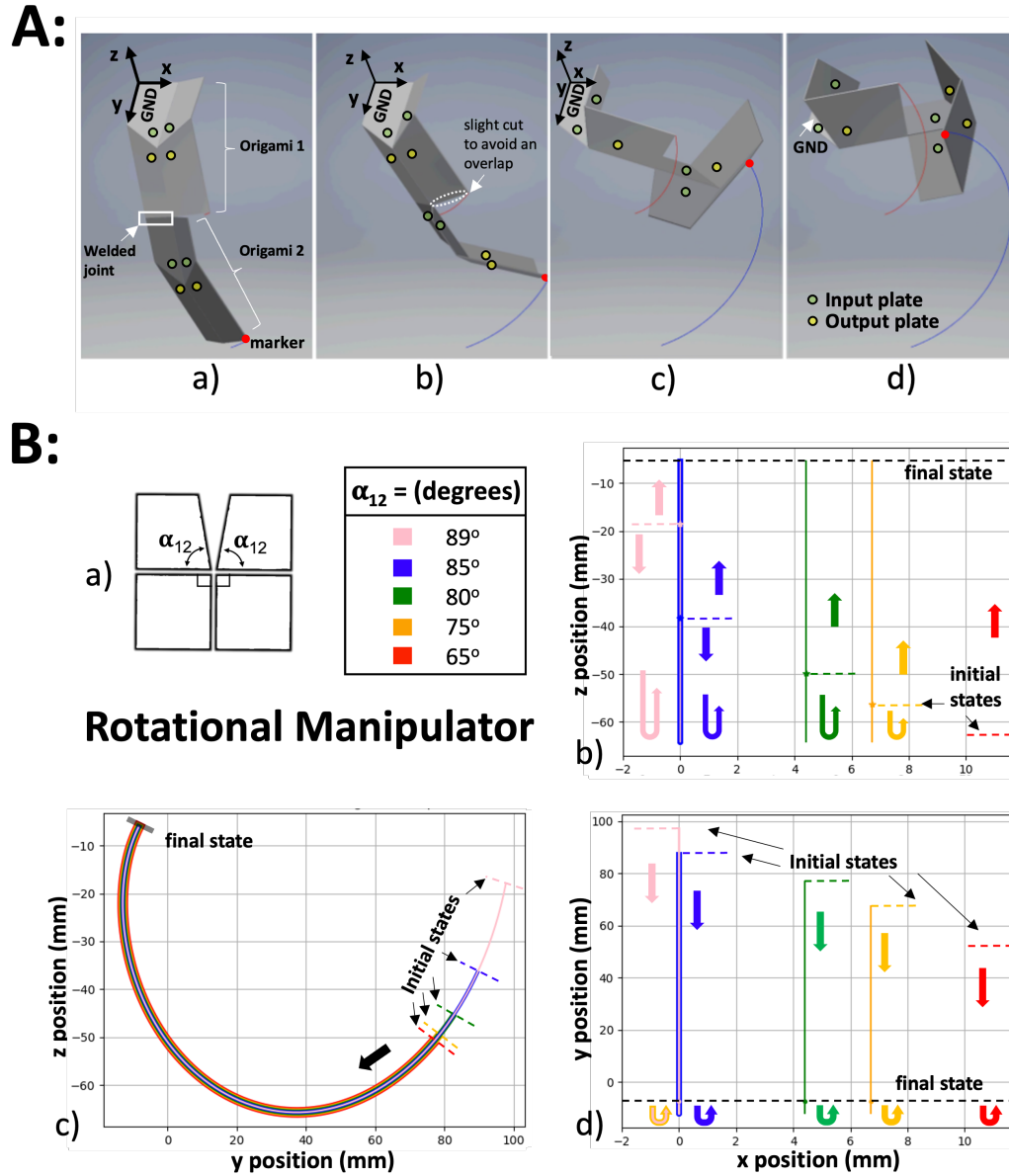


Figure 7.5: **A** a-d) Folding simulation of a manipulator with two 80degrees origamis connected. The input plates (central angle = α_{12}) and output plates (central angle = 90degrees) are shown with green and yellow circles, respectively. The reference frame and the marker are used to trace the manipulator's end-effector. a) The Welded joint is defined to connect the origamis. b) The cut is implemented to avoid the origami plates' overlappings.

Figure 7.5: **B:** a) The origami plates that are used in the manipulator with $\alpha_{12} = 89, 85, 80, 75, 65$ degrees etc. as the central angle. Both of the manipulators' origamis have the same α_{12} . b-d) Motion comparison of manipulator's end-effector (marker) with different origami's central angles. The initial state is the origami's closest possible configuration to the flat state (all the angles between the plates are 180 degrees). The final state is the maximum possible folding angle, 36.51 degrees, between the input and output plates (defined manually).

less deviation we have from the desired rotational movement (a simple rotation around a point in the x-axis). All the manipulator models have the same range of motion on the z-axis. The manipulators with the central angles $\alpha_{12} = 89, 85, 80, 75, 65$ degrees follow the z-axis linearly. The farther the central angles of origamis get from 90 degrees, the farther the origami's linear movements are from axis $x = 0\text{mm}$. Also, their semi-flat states are farther from $z = 0\text{mm}$. These positionings occur due to geometrical configurations and closeness of origami with α_{12} near 90 degrees to a revolute joint. In the xy plot (Fig. 7.5Bd), 75 and 80 degrees models have about 30 and 20 degrees cut from their central angles. Theirs are higher than the 89 degrees model (2 degrees central angles' cut). The bigger the cutting angle, the shorter the range of motion is on the y-axis. The 89 and 85 degrees manipulators have similar and very close rotation around $x = 0\text{mm}$ due to their very small central angle cuts. Due to defining the common $MPF = 36.51^\circ$ degrees state for all the manipulator models, their final states and positions in all plots are the same.

Furthermore, the figure 7.5Bc yz plot presents the rotational motion experienced throughout a cycle. All the manipulators' models demonstrate a rotational motion in the same direction but in a different range. The larger their central angle cuts are, the bigger the inaccessible configuration area near their flat state. Therefore, their semi-flat configuration (initial state) starts farther away in the range of motion. This is the reason the 65 and 89 degrees manipulators have the smallest and largest range of rotational motions among the simulated manipulators in

yz plot, respectively. Also, the marker cannot start from exactly zero position along the z-axis since the cut has been made, and the origami models cannot be completely flat. The movements of different rotational manipulators' models in the 3D space are demonstrated in the Appendix. As the manipulators' central angles α_{12} decreases, the directions of the deviations the manipulators experience from the downward rotational movements on both origamis move away from the reference frame in the 3D space. See the Appendix for more details about the figure and the 3D plots.

7.1.3 3D printed Origami

The manipulators are developed using the 3D printed origami joints. In this subsection, we examine the motions of two types of 3D printed rotational manipulators: the Bi-directional manipulator and the Self-lock manipulator. For the experiments, one of the two origami plates covered by pouch motor actuator is fixed as the grounded plate at the base. The reference frame is established at the outer corner of the grounded plate (Fig. 7.6a and 7.9a). The Y-axis is defined along the vertical edge of the grounded plate, and the Z-axis is perpendicular to that plate. A marker is placed by attaching a red squared tape at the outer corner of the farthest origami plate from the base on the grounded plate side. This marker helps track the movements of the end-effectors. In the simulation, a Trace is defined at the same position as the marker. The measurements used for the joints and pouch actuators are the same as those of the Bi-directional origami joint and its pouch actuators.

Figures 7.6cd and 7.9bc depict the binding and cutting connections between the origami joints in both the simulation and the 3D printed versions. For the binding connection, constraints

were defined in the CAD model to restrict the movement of the origami plates in all directions. These constraints were applied between the plates with the binding marks shown in the figure. The same effect is achieved in the 3D printed version by printing their CAD models. However, to prevent overconstraint of the manipulators, cutting connections are necessary. One of the plates next to the binding plates may need to be cut after printing, or it can be designed with a shorter length before 3D printing. This ensures proper flexibility and freedom of movement in the manipulators. The figures provide specific instructions for the cutting locations. Additionally, variables ϕ_1 and ϕ_2 are defined between the plates of each joint (Fig. 7.6a and 7.9a) to estimate the maximum folding and unfolding angles for origami 1 and origami 2, respectively.

7.1.3.1 Bi-directional Manipulator

The Bi-directional manipulator is composed of two Bi-directional origami joints with similar tube, thread, knot, and pouch architectures (Fig. 7.6cd). Two types of pouches, Type A for origami 1 and Type B for origami 2, are used in this manipulator (Fig. 7.6a and 6.1.2e). To prevent interference between the connections and tubes of the pouch in origami 2 with the rotations of origami 1, pouch Type B is designed with a sideways connector. Figure 7.6a illustrates the direction of movement for the manipulator. Both pouch actuators on the same side of the origami joints are connected to the same solenoid using a 3-way connector. Depending on the position of the pouches in the manipulator, their inflation and deflation stages may vary slightly. Starting from the intermediate figure where the origamis are in the unfolded state with ϕ_1 and ϕ_2 close to 180° , the manipulator has the capability to fold either to the left or right (as shown in the left or right figures), as well as unfold in the opposite direction.

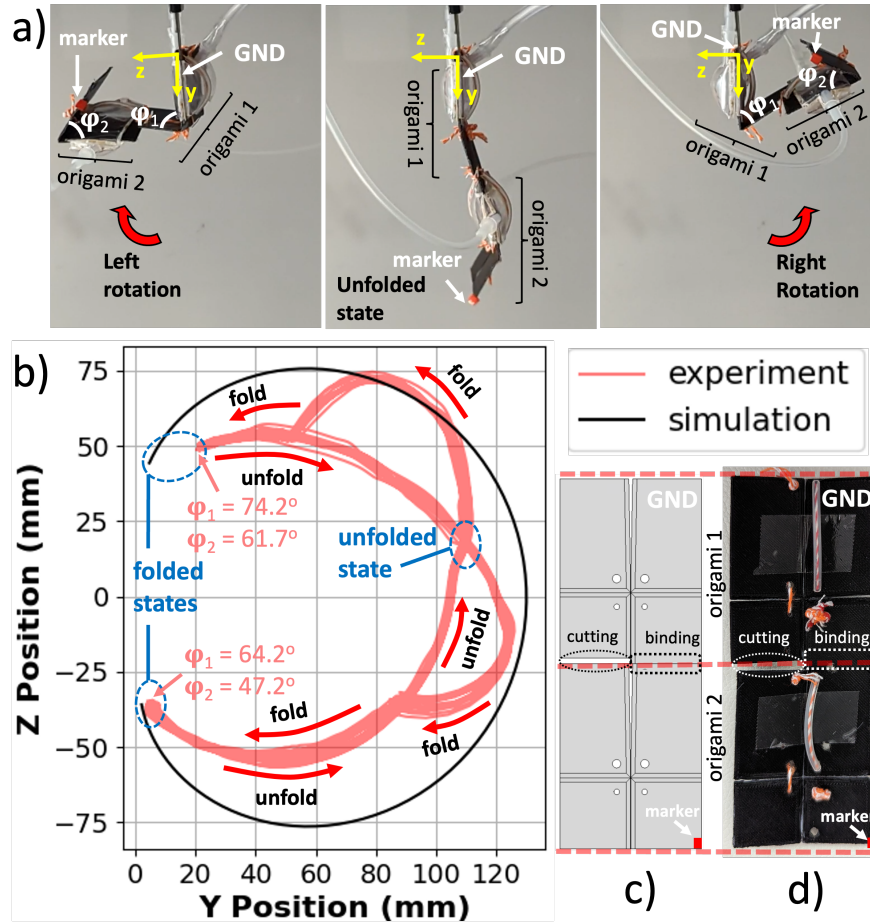


Figure 7.6: a) The manipulator consists of Bi-directional origami joints 1 and 2. In the left figure, the manipulator is folded towards the left side. In the middle figure, the manipulator is in the unfolded state, with both origamis nearly flat or close to a flat state. In the right figure, the manipulator is folded towards the right side. For origami 1, pouch Type A is used with a connector at the bottom. For origami 2, pouch Type B is used with the connector and tube positioned sideways to avoid interfering with the movements of origami 1. In this setup, one of the two plates covered with a pouch at the base is grounded. The reference frame is defined at the outer corner of the grounded plate. To track the manipulator's motion, a red squared marker is installed at the manipulator's end-effector. The variables ϕ_1 and ϕ_2 represent the maximum folding angles of origami 1 and origami 2, respectively. b) The YZ plot shows the motion of the manipulator marker in both simulation and experiment. The plot includes the two folded states of the manipulator, one to the right and one to the left, as well as the unfolded state in the middle. These states demonstrate the range of motion of the manipulator, showcasing its ability to fold in both directions and unfold back to the initial state.

Figure 7.6: The origami 1 and origami 2 in the manipulator have different maximum possible folding angles, denoted as ϕ_1 and ϕ_2 , respectively. This difference in maximum folding angles is influenced by various factors, such as the weight each origami carries and their positions at different stages. The direction of the folding and unfolding motions is indicated by arrows. The folding motions exhibit two convex lines, one after the other, due to the differences in ϕ_1 and ϕ_2 values. c) and d) The CAD design and the 3D printed version of the Bi-directional Manipulator. The red dashed lines indicate the locations of the two Bi-directional origami joints in the manipulator. Both the CAD model and the 3D printed version feature the equivalent grounded plate and marker to record the data. The binding part showcases the connection point where the two origami joints are joined together as a single long solid plate. The cutting part highlights the specific locations where cuts have been made in both the model plate and the 3D printed version. These cuts are made to avoid over-constraining the manipulator's movement and ensure its proper functionality.

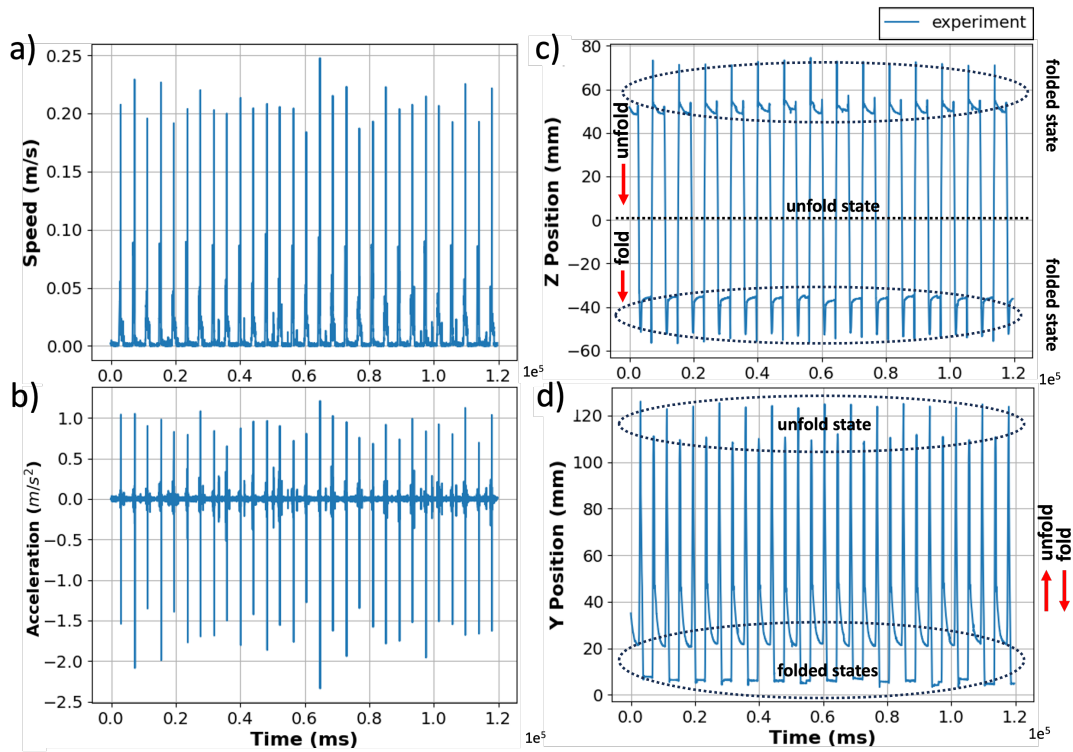


Figure 7.7: For bi-directional Manipulator's end-effector: The origami marker's a) Speed plot based on time. b) Acceleration plot based on time. c) and d) Y and Z positions based on time. The folded and unfolded states, along with the directions of movement, are demonstrated in parts c and d. In both the folded and unfolded states, the system maintains the pouches inflated for approximately 4e3 milliseconds.

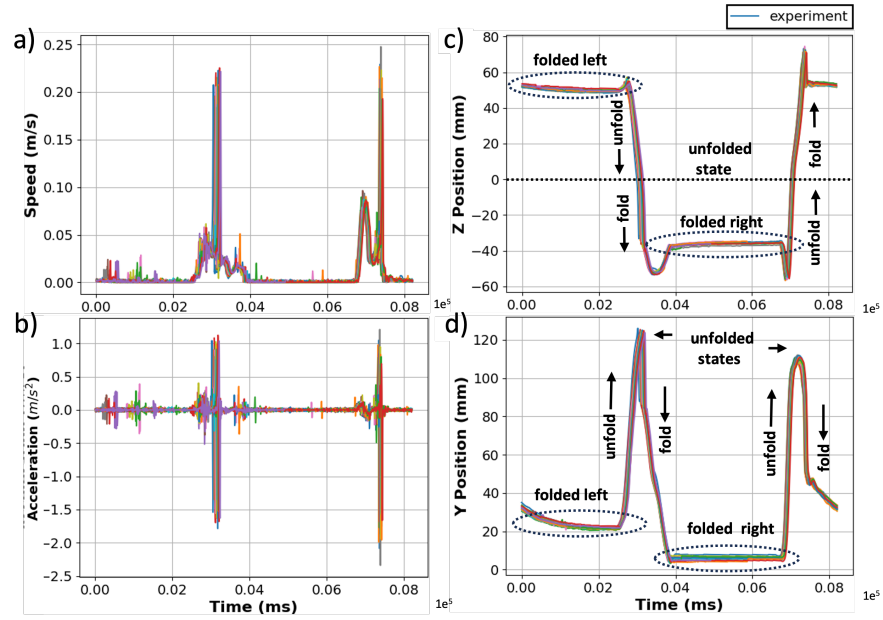


Figure 7.8: For bi-directional Manipulator's end-effector: A closer look into the origami marker's a) Speed plot based on time. b) Acceleration plot based on time. c) and d) Y and Z positions based on time. The folded and unfolded states, along with the directions of movement, are demonstrated in parts c and d. In both the folded and unfolded states, the system maintains the pouches inflated for approximately 4×10^3 milliseconds.

Figure 7.6b displays the motion of the manipulator's marker in the YZ plane. Similar to part a, the manipulator has two folded states, one to the left and one to the right, as well as the unfolded state described above. The origami 1 demonstrates a larger maximum folding angle, such as $\varphi_1 = 74.2^\circ$, compared to origami 2, where $\varphi_2 = 61.7^\circ$, in both folding directions. This discrepancy in folding angles highlights the lower motion performance of origami 1 due to the additional weight of origami 2, which is connected to origami 1 and requires it to bear the extra load. In contrast, origami 2 does not carry the weight of any other joint, allowing it to achieve a slightly higher folding angle. The simulation shape may differ from the experimental results, but the overall range of motion is expected to be within the same range. The reason for the variation is that the joints have different maximum possible folding angles for each origami due to factors such as the load they need to carry or their position in space. If the movement of the origamis in different stages is crucial for a specific application, it is possible to utilize additional control valves. By employing separate control valves for each pouch, it becomes feasible to independently control the inflation and deflation stages of the pouches, allowing for more precise and customized manipulator movements.

In Figure 7.6b, the unfolding motion of the manipulator starts from the bottom of the plot. Initially, the manipulator is in a folded state on the right side (as shown in Figure 7.6a, right). From this folded state, the manipulator begins the unfolding process, gradually extending and changing configurations (left to right/upward to downward) towards the top of the plot. After reaching the unfolded state, origami 1 completes its folding rotation to the left earlier than origami 2, resulting in two different convex folding lines one after the other. Both the simulation and experimental manipulators end up in similar folding positions. Rotating

from left to right occurs similarly. Depending on the knots and tubes used in the experiment, the manipulator may not achieve its maximum folding capacity. Although each of the origamis has a larger maximum folding angle compared to a single Bi-directional joint, the 3D printed manipulator can fold into itself almost completely in both directions.

Figures 7.7 and 7.8 illustrate the relationship between time and the origami marker's positions (part c and d), including its speed (part a) and acceleration (part b). When the system holds the folded and unfolded states for a duration of 4×10^3 ms, the speed and acceleration decrease to zero. Part c and d depict the folded and unfolded states, respectively, along with the directions of movement.

7.1.3.2 Self-lock Manipulator

The main difference in the Self-lock manipulator compared to the Bi-directional manipulator is its ability to rotate only in one configuration, about 180° degrees. Unlike the Bi-directional manipulator, which can fold and unfold in both directions, the Self-lock manipulator remains locked in a single folding direction. The Bi-directional origami joints in this manipulator are without any holes, threads, or tubes (Fig. 7.9bc). Figure 7.9a illustrates the manipulator's folded state at the top and the unfolded state at the bottom. The actuator mechanism used in this manipulator is similar to that of a bi-directional manipulator. The pouches cover the upper plates of the origamis, with two Type A pouches used on the bottom and top parts of origami 1, and two Type B pouches used on the top and bottom parts of origami 2.

Figure 7.9d demonstrates the YZ plot for the manipulator's marker motion. Similar to the Bi-directional manipulator, the folding motion from right to left occurs with two convex

lines in sequence, as origami 1's folding motion ends sooner than origami 2 due to the weight it carries. The unfolding motion occurs from left to right. The marker's motion during the first half of unfolding is a bit scattered due to the position of the pouch and the space restrictions for inflation. After the first half, the inflation and deflation of the origami pouches attempt to synchronize in the middle of the unfolding convex line motion and the motion becomes more consistent as the pouches' spaces are no longer confined. This synchronization allows for a smooth and controlled unfolding of the manipulator until it reaches the unfolded state. The origami 2 unfolds completely with $\phi_2 = 180^\circ$, while origami 1 unfolds to an angle of $\phi_1 = 157.8^\circ$ due to the weight of origami 2 that it carries. By coordinating the timing of the pouches' inflation and deflation, the manipulator can achieve a more consistent and predictable motion during the unfolding process. The simulation approximately follows the same path with the assumption that both origamis have the same maximum folding and unfolding angles.

Figures 7.10 and 7.11 illustrate the relationship between time and the origami marker's positions (part c and d), including its speed (part a) and acceleration (part b). When the system holds the folded and unfolded states for a duration of 3e3 ms, the speed and acceleration decrease to zero. Part c and d depict the folded and unfolded states, respectively, along with the directions of movement. By combining a reduced central angle in the Self-lock manipulator and considering the extensibility of the Organza fabric, it is possible to create a strong and stable structure. The smaller central angle helps overcome the extensibility of the fabric, ensuring that the manipulator maintains its desired configuration even when subjected to heavy loads or external forces. This feature is particularly advantageous in applications where stability and resistance to configuration changes are crucial, allowing the manipulator to perform reliably and

effectively under challenging conditions.

7.2 Translational Manipulators

To achieve the translational motion, four origamis with a zig-zag configuration have been used. This means the origamis are alternatively in downward and upward configurations (Fig. 7.12Bb and 3.5C). Similar to the rotational manipulator, the origamis are connected on only one of their plates, and some perimeter cuts are made to avoid overlapping between the origamis' movements. Figure 7.12Ba top view shows the location of these connections (Welded joints) and cuts. To obtain the closest possible motion to a linear translational movement, the manipulator's geometry is required to be symmetrical. Therefore, the origamis parameters have been developed (Fig. 7.12Bb-Right). The user defines the MPF angle, $\gamma = 36.51^\circ$, and $d = 25mm$ (MPF's height) based on the joint's materials and structure. The parameters f and q could be calculated using the Trigonometric ratios. The length of first and last origami's input plates are 25mm. The manipulator's simulations with different origami's central angles, α_{12} , have been implemented. Figure 7.12B shows the initial and final states of the 89degrees manipulator's translational movement in different views. All the joints started from a semi-flat state. They will be activated simultaneously. The first and the last joint will be folded to the 90degrees output angle. The second and third joints' final configurations are MPF. Therefore, the final positions for all the translational manipulators with different central angles are same.

The two-dimensional plots of the manipulators' movements using a marker and defined reference frame (Fig. 7.12A) are presented in figure 7.12C. In the translational movement,

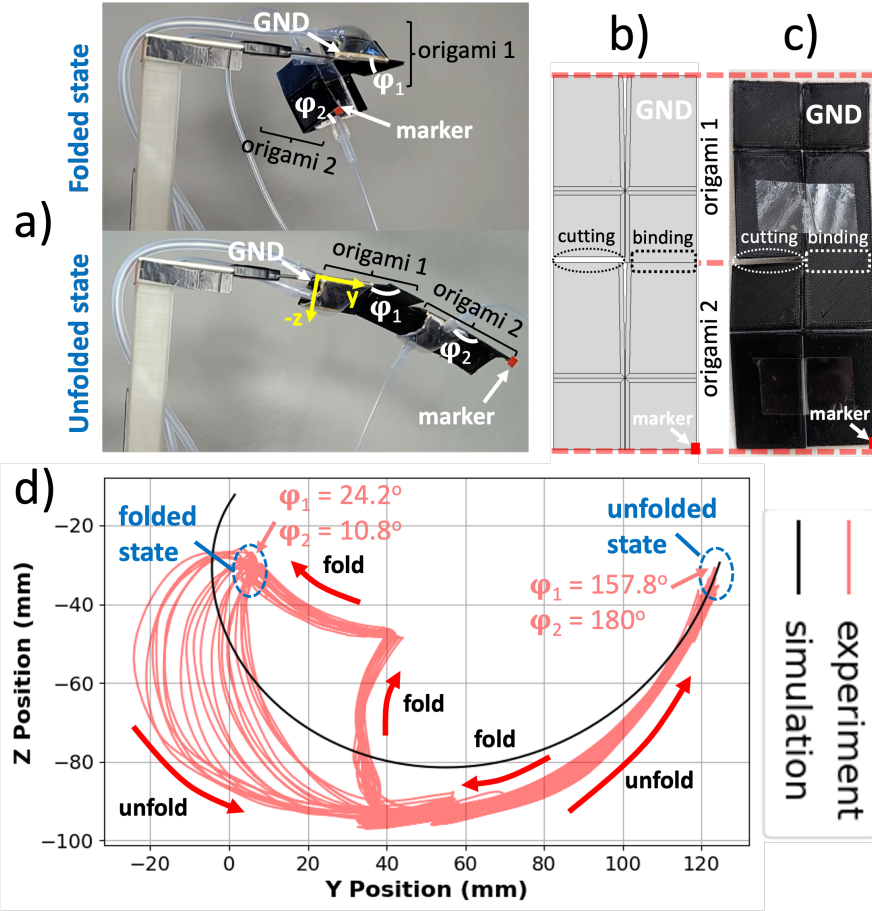


Figure 7.9: a) The manipulator's folded and unfolded states. The manipulator consists of two origami joints, where origami 1 utilizes pouch Type A with a connector at the bottom, and origami 2 employs pouch Type B with a sideways connector and tube to avoid interfering with the movements of origami 1. In this configuration, one of the plates covered with a pouch at the base is grounded, and a reference frame is established at the outer corner of the grounded plate. A red squared marker is installed at the manipulator's end-effector to track its motion. The variables ϕ_1 and ϕ_2 represent the maximum folding angles of origami 1 and origami 2, respectively. In the top figure, the manipulator is folded downward, while in the bottom figure, the manipulator is in the unfolded state, with both origamis nearly flat or close to a flat state, indicated by ϕ_1 and ϕ_2 being close to 180° . b) and c) The CAD design and the 3D printed version of the Self-lock Manipulator. The red dashed lines indicate the positions of the two origami joints, which have been designed based on the measurements of the Bi-directional joint but without incorporating any holes, tubes, or threads. Both the CAD model and the 3D printed version include the equivalent grounded plate and a marker to facilitate data recording. The binding section illustrates the connection point where the two origami joints are securely joined together to form a single elongated solid plate.

Figure 7.9: The cutting section highlights specific locations where carefully placed cuts have been made in both the model plate and the 3D printed version. These strategic cuts have been implemented to prevent excessive constraint on the manipulator's movement, ensuring its optimal functionality. d) The YZ plot illustrates the motion of the manipulator marker in both simulation and experiment. The plot showcases two states: a folded state on the left and an unfolded state on the right. These states highlight the manipulator's range of motion, demonstrating its capability to fold in a downward configuration and subsequently unfold back to its initial state. It is important to note that origami 1 and origami 2 in the manipulator have distinct maximum possible folding and unfolding angles. These folding angles are influenced by various factors, including the weight carried by each origami and their positions at different stages. The arrows in the plot indicate the direction of the folding and unfolding motions.

we expect a motion along the y-axis. For all the manipulators, a linear behavior is observed along the y-axis and z-axis in the xy and xz plots (Fig. 7.12Ca and Cc). Also, the less movement the manipulators experience in the x and z axis, the less deviation they have from the desired motion. In yz plot (Fig. 7.12Cb), the 89degrees manipulator has a closer motion to the $z = 0mm$ axis. The farther the origami models get from $\alpha_{12} = 90^\circ$ degrees, the range of motion in the z-axis increase and the y-axis decreases, and their movements changes from a translational to a rotational motion. Similar to rotational manipulators, the reason is related to the amount of the central angles' cuttings. Among all the translational manipulators, the 89° degrees model produces the most optimal translational movement for different applications. A combination of translational and rotational joints' motions could be used for complex tasks. This is helpful in explorations where various motions are required in a limited space.

7.3 Modular Manipulators

Using the origami design in a modular structure could provide the opportunity to create and mimic traditional robots' complex movements. We can achieve this by replacing

Directed Manipulator

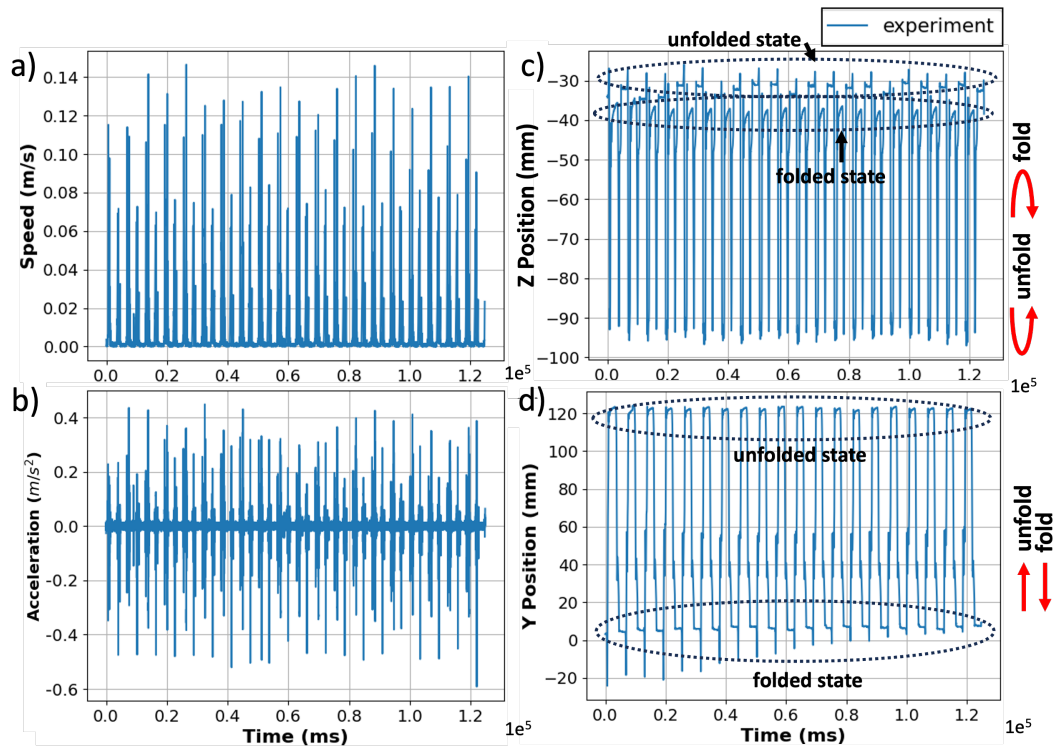


Figure 7.10: For one-directional Manipulator's end-effector: The origami marker's a) Speed plot based on time. b) Acceleration plot based on time. c) and d) Y and Z positions based on time. The folded and unfolded states, along with the directions of movement, are demonstrated in parts c and d. In both the folded and unfolded states, the system maintains the pouches inflated for approximately 3×10^3 milliseconds.

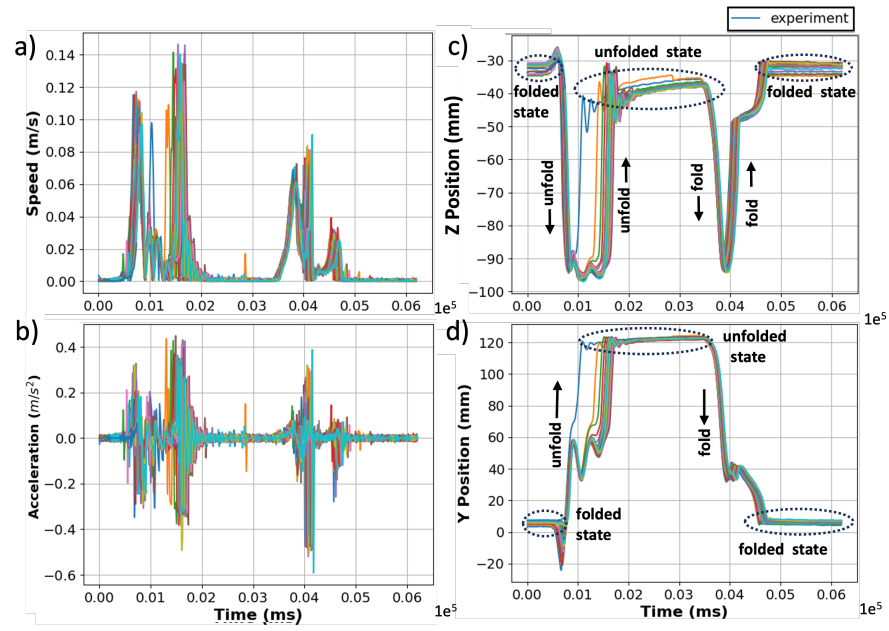


Figure 7.11: For one-directional Manipulator's end-effector: A closer look into the origami marker's a) Speed plot based on time. b) Acceleration plot based on time. c) and d) Y and Z positions based on time. The folded and unfolded states, along with the directions of movement, are demonstrated in parts c and d. In both the folded and unfolded states, the system maintains the pouches inflated for approximately 3e3 milliseconds.

Translational Manipulator

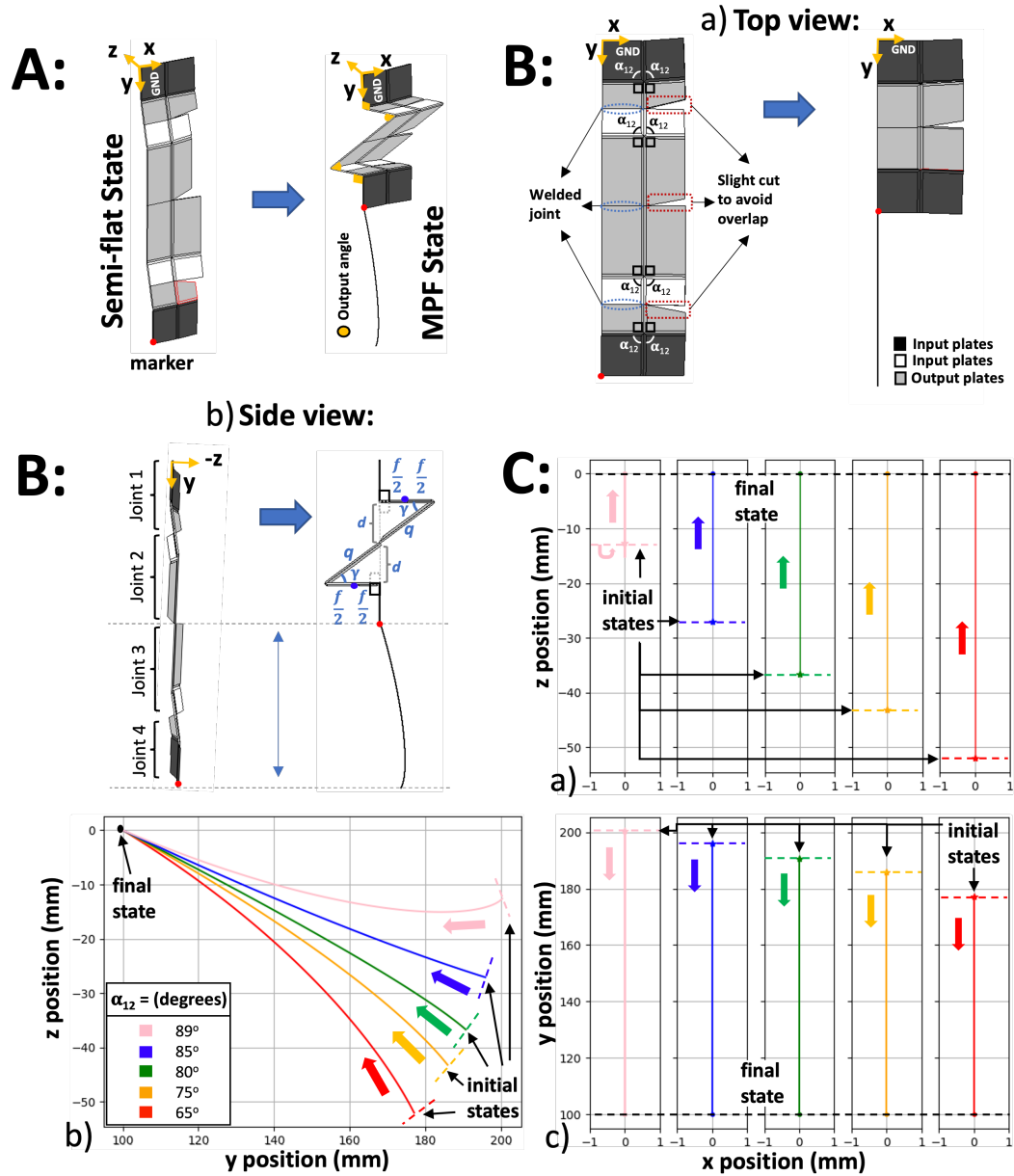


Figure 7.12: Simulations of translational manipulators. **A:** The 89degrees translational manipulator. Left: initial (semi-flat) state. Right: final (MPF) state. A marker and a reference frame are defined. The origamis' output angles (between input and output plates) are colored in gold on the right figure.

Figure 7.12: **B:** a) Top view from the same manipulator's states. Left: The welded joints are defined between the origamis to connect them together. Cuts are made to avoid the overlapping between origamis' plates while they are moving. The α_{12} is the central angle that has been changed (89 85 etc.) for different manipulator models. The output plates have 90degrees central angles. The input and output plates with different dimensions are color coded with black, white, and grey. Right: The finale state. b) Side view of 89degrees manipulator's initial and final state. Left: The manipulator has four origami joints. Right: The required parameters to create a symmetrical zig-zag pattern for translational motion are f , q , d , and γ . **C:** a-c) Two-dimensional workspaces of translational manipulators with different central angle plates. Their initial and final states, and their direction of motions are marked. They have separate initial states and common final state positions.

their linkages with origami plates. The modular manipulator (Fig. 7.13A: Manipulator) with 89degrees origami joints (Fig. 7.13Bc) presented here could provide rotational motions in different directions. Therefore, it has a larger workspace compared to the simple rotational and translational manipulators (Plots in Fig. 7.5B, 7.12C, and 7.13C). The modular manipulator consists of two structures. One includes origamis connected to each other similar to the manipulators we discussed before (Fig. 7.13A: Configure 1). The second one (Fig. 7.13A: Configure 2) has origamis connected to the bounding plate at one of their input plates (the plates covered with pouch). The bounding plate was designed to connect the origami plates at different angles to change or increase the manipulator's workspace. The bounding plate could be designed in different shapes to help the origami robots to explore different locations.

In the binding phase (Fig. 7.13A: Binding), we defined constraints of movements in 3 directions or welded joints to create configurations 1 and 2. Then, we connected the last origami joint to the base (an aluminum plate that had been grounded) to install the manipulator for the simulation. Also, similar to other manipulators, cuts are made to avoid origami joints overlapping each other's movements. By defining different rotational motions on the origami

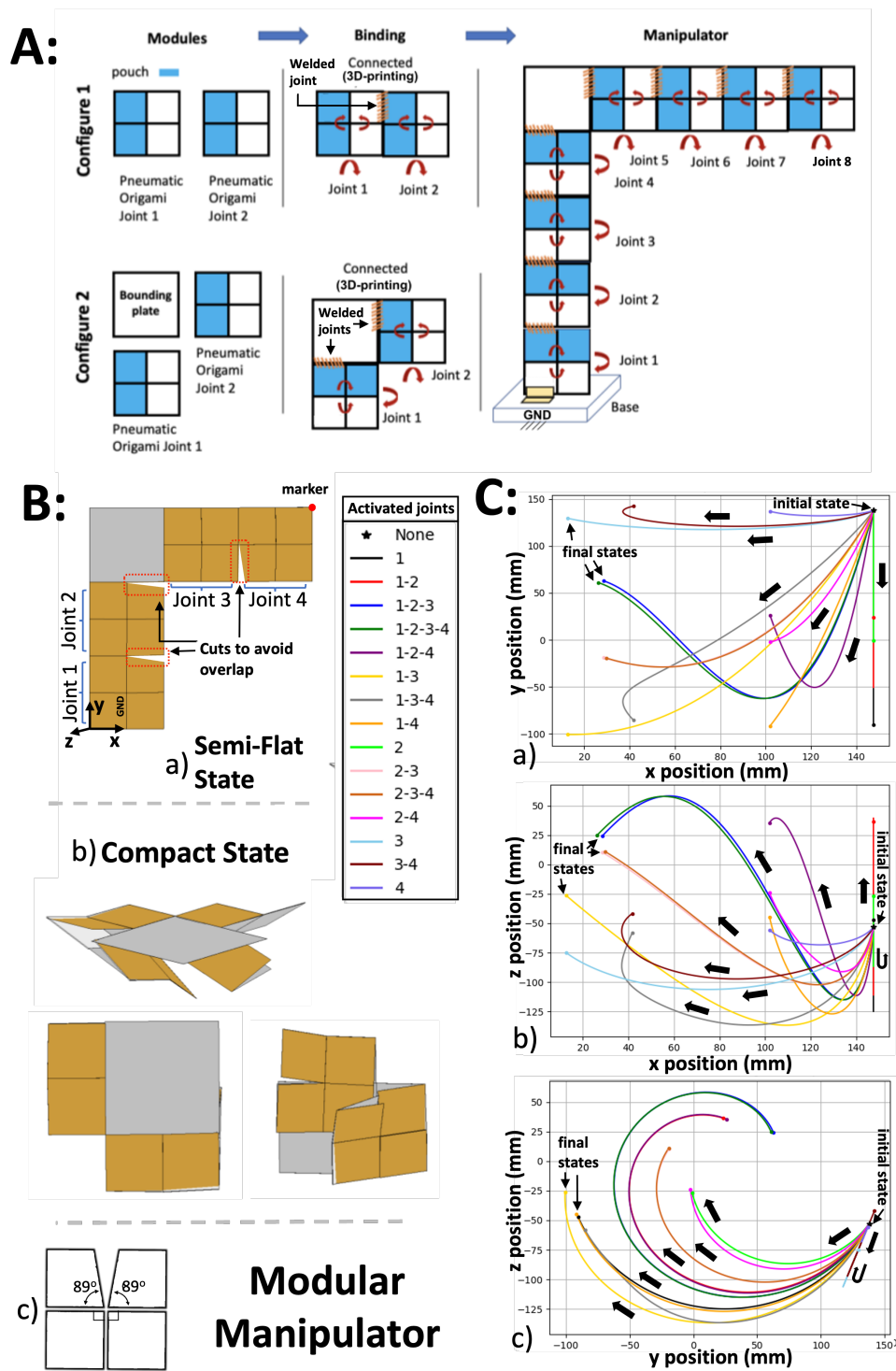


Figure 7.13: **A:** Modular manipulator's production process. Designing modules phase: creating origamis and the bounding plate (Configurations 1 and 2).

Figure 7.13: Binding phase: connecting the origamis to each other and the bounding plate by using Welded joints on only one of their plates (to avoid over-constraining them). Manipulator: assembled manipulator with eight origami joints installed on a grounded aluminum base. **B:** a) Semi-flat State: Top view of the modular manipulator's closest possible configuration to the flat state with a square bounding plate and two origamis connected to two sides of it. b) Compact state: Top, bottom, and side views of the maximum possible folding configuration, MPF, of the modular manipulator. c) The 89degrees origami plates are used in the manipulator. **C:** a-c) Two-dimensional plots of Modular manipulator's movements with combinations of different activated (folding simulation) origami joints. Motion's directions, initial and final states are presented with arrows and labels. The dot shape shows the final state of each activated origami's combinations with their colors.

joints, the manipulator could take various shapes in the simulation. Figure 7.13**Ba** and **Bb** shows a modular manipulator's compact and semi-flat states with two 89degrees origamis (Fig. 7.13**Bc**) on two sides of its square bounding plate. In the semi-flat state, none of the origamis have been activated, and the manipulator is in the closest possible configuration to the flat state. In the compact state, all joints have been activated and folded to the MPF configuration. Therefore, the size of the manipulator decreases.

The plots in figure 7.13**C** present the modular manipulators' movements in the two-dimensional workspaces. In these simulations, different joint combinations have been activated by their joint number orders (folding from semi-flat to MPF state). For instance, activated joints 1-2 describe the folding of joint 1 and then the folding of joint 2 without overlapping joint 1. The manipulator has defined a marker and reference frame (Fig. 7.13**Ba**) to obtain the workspace. The marker shows large ranges and different directions of motion in all the xy, yz, and xz planes. It is observed that if only the joints on one side of the bounding plate are activated, the manipulator behavior is linear on at least one of the workspaces. The joints 1, 2, and their combination (1-2) generated linear movement in xy, and xz plots (Fig. 7.13**Ca** and

Cb). Also, joints 3, 4, and their combination (3-4) produced a linear behavior in yz plot (Fig. 7.13Cc). The activated origami joints 1-2-3 and 1-2-3-4, have similar motion since after joints 1, 2, and 3 are activated, joint 4 does not have much space for folding, and the manipulator's configuration stays close to 1-2-3. Also, they have the maximum rotational motions due to experiencing less overlapping when origamis are folding based on their joints' numbers.

One of the advantages of using origami in modular manipulators is the ability to convert them into structures with small volumes due to the joints' geometries. Manipulators can achieve this by moving their origamis into MPF or semi-flat states (Fig. 7.13Ba and Bb) in different directions. Also, depending on the application, we could exclude some of the manipulator's joints, like joints 3 and 6 (Fig. 7.13A: Manipulator), to produce different manipulators. We could accomplish this by folding the joints using their actuators and holding them in that state. This will be investigated furthermore in the future.

Chapter 8

Conclusion and Future Work

This chapter presents the conclusions drawn from the research and identifies areas that require further investigation for future work.

8.1 Future Work

In this section, we addressed the challenges associated with the joint and explored its potential for future applications.

8.1.1 The Joint Functionality

One of the issues involves the assumption that we currently have two actuators positioned on the top and bottom of the origami's input plates in order to facilitate folding and unfolding of the structure. One area that we will look into is the role of spring in reducing the number of actuators that could be used for the joint. For instance, a rubber band could act as a spring torsion and provide spring back force to contribute to the unfolding or folding process.

With this method, we only need one pouch motor to unfold the origami by overcoming the rubber band force or vice versa. It could also help deflate the pouch motor air using the back force of the spring. The stiffer the spring is, the higher pressure is required for the pouch motor to overcome the spring force, and the higher the possibility of the pouch motor's failure due to the deformation of its material. Also, the larger the spring's stiffness, the more bending moment it could generate for different applications. Therefore, there is an exchange that worth to be investigating.

A study is required to investigate the joint's moments using various fabrication methods in order to optimize its performance. Additionally, different origami models can be employed to achieve diverse motions for various applications. Thus, the development of a program that can take user-defined positions for robot exploration and suggest suitable origami models capable of achieving the desired motion is essential. Furthermore, a control scheme needs to be established for the joint to manipulate its configuration based on the desired end-effector position of the manipulator, enabling it to perform specific tasks effectively.

8.1.2 Potential Applications

The origami structure holds great potential in the field of robotics, Health, Rehabilitation, transportation, and explorations, offering several advantages in their design and functionality. One key advantage is the compactness and space-saving nature of origami-inspired structures. By utilizing folding and unfolding mechanisms, origami allows for the creation of complex structures that can be collapsed and expanded as needed. This compactness is particularly advantageous in humanoid robots, as it enables them to navigate tight spaces, maneuver

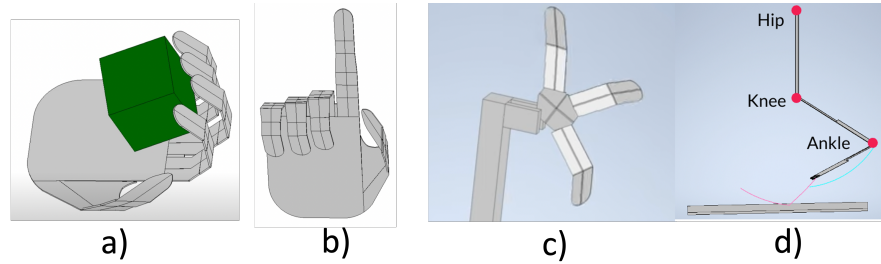


Figure 8.1: CAD models: a) humanoid origami hand grabbing an object. b) humanoid origami pointing. c) 3-finger origami hand. d) origami leg

through obstacles, and perform tasks in constrained environments. The ability to fold and unfold also facilitates easy transportation and storage of humanoid robots, making them more practical for real-world applications.

Another advantage of integrating origami structures in humanoid robots is their inherent flexibility and adaptability. Origami-inspired joints and mechanisms offer a high degree of flexibility, allowing for smooth and precise movements. This flexibility enables humanoid robots to mimic the natural range of motion and articulation of human limbs, enhancing their ability to interact with the environment and perform complex tasks. Origami structures exhibit excellent structural integrity when unfolding, providing stability and support during locomotion and manipulation. This flexibility, combined with the lightweight nature of origami materials, contributes to humanoid robots' overall agility and efficiency, making them more capable of performing a wide range of tasks and adapting to different scenarios. Figure ?? illustrates different hand, leg, and humanoid CAD models that we have developed using Self-Lock origami joints.

In conclusion, the integration of origami structures in humanoid robots offers advantages such as compactness, space-saving design, flexibility, and adaptability, and mass produc-

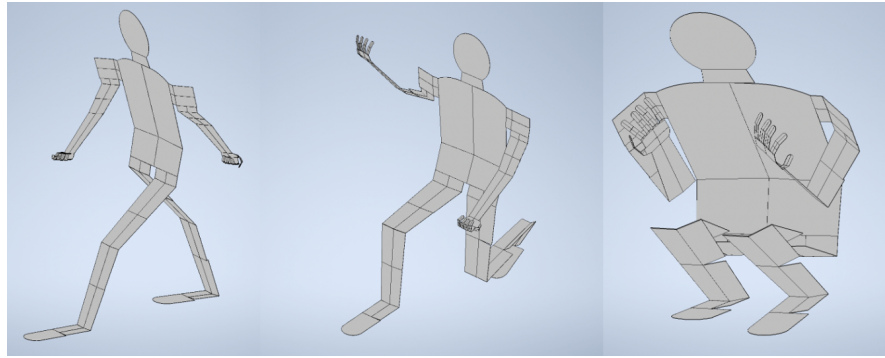


Figure 8.2: CAD model of Humanoid origami in different configurations

tion at low cost. By leveraging the principles of origami, researchers and engineers can create advanced humanoid robots with improved mobility, dexterity, and versatility, opening up possibilities for applications in healthcare, service robotics, and human-robot collaboration.

8.2 Conclusion

The purpose of this research was to explore the potential of using origami structures as a replacement for traditional rotational joints in robots, with the aim of improving overall performance. Our analysis included motion simulations, as well as theoretical and experimental measurements. Our findings indicated that the Self-lock origami joint had a number of advantages over traditional rotational joints.

Firstly, It was found to be pressure-efficient, which is crucial in robotics applications where power consumption is a key consideration. Additionally, this joint provided high-speed rotational movement close to the flat state phases, which can be important in situations where fast and precise movements are required.

Furthermore, the joint offered high output moment in folded phases, which can be

beneficial for applications where the robot needs to exert force or torque. The flat-foldability and bi-directional movement of the origami structure make it an attractive option for modular joint development, enabling different types of movements, such as translational and rotational, in various directions.

The size, weight, and material adaptability of origami structures make them particularly promising for use in a range of robotic applications. For example, in exploration scenarios where space and energy availability are limited, or in medical instruments where precision and dexterity are essential. Overall, our research suggests that the Self-lock origami joint has significant potential to improve the performance of robotic systems in a variety of contexts.

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Appendix A

Appendix

A.1 Description of A.4-A.7 figures

The movements of the origami with different reduced central angle positions in the three-dimensional plots are presented in figures A.4-A.7. The origami type represents the origami plates before connecting the plates to show the cuts' location in the origami. The plate which has marker1 is grounded. After connecting the plates, the simulation was implemented. They start from -35° degrees as the imposed actuator's rotational angle on origami's input plates and create downward movements (the upward movement is similar but in the other direction). The corresponding pouch motor actuator could only provide a limited range of rotational angles. Marker1, marker2, marker3, and marker4 (Traces) are the origami corners showing the simulated motion of the structures. The initials 1-4 illustrate the origami corners' positions at the initial state ($\pi - 35^\circ$ degrees input angle, θ_1). The majority of the origami types have a similar rotational motion in slightly different directions. The markers of output plates illustrate

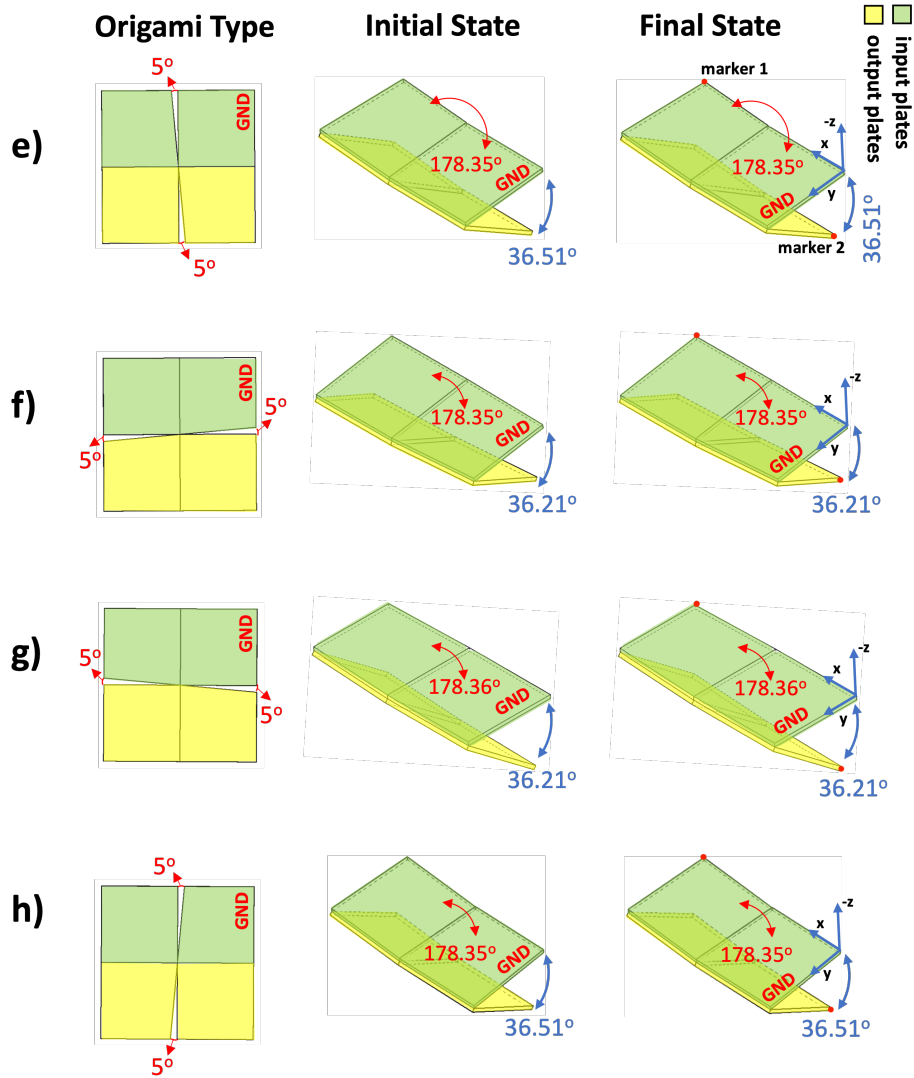


Figure A.1: e-h) Initial and final states of Self-lock origami with a decreased central angle in different positions. The central angle cuts are divided between the input and output plates. Initial state: Closest possible configuration to the flat state of the input plates (180° degrees angle in between). Final state: A defined Maximum Possible Folding configuration (MPF) between the grounded and the output plate (36.51° degrees). After defining the MPF angle due to the position of the cutting angles in parts f) and g), origami's MPF angle between the grounded and output plates becomes 36.21° degrees. Origami type: Position of the origami's decreased central angle before the plates' assembly (defining revolute joints between plates). The input and output plates are highlighted with green and yellow colors, respectively. Markers 1, 2, and the reference frame is defined to trace the input and output plates' motions. The angles between the input plates and between the grounded and the output plate are measured at the initial and final states to study the origami's states. The origami types e-h have no rotational movement from the initial to the final state.

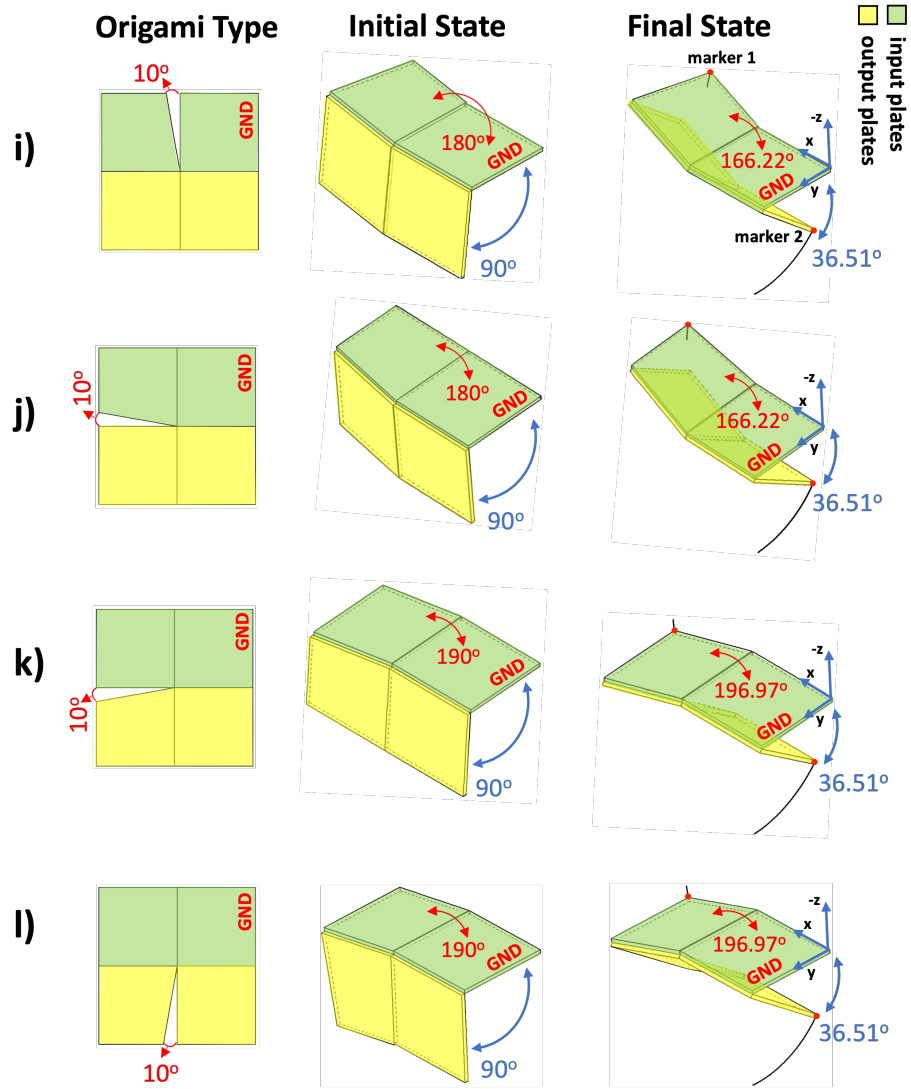


Figure A.2: i-l) Initial and final states of Self-lock origami with a decreased central angle in different positions. The central angle cuts are present in only one plate. Initial state: Closest possible configuration to the flat state of the input plates (180° degrees angle in between). Final state: A defined Maximum Possible Folding configuration (MPF) between the grounded and the output plate (36.51° degrees). Origami type: Position of the origami's decreased central angle before the plates' assembly (defining revolute joints between plates). The input and output plates are highlighted with green and yellow colors, respectively. Markers 1, 2, and the reference frame is defined to trace the input and output plates' motions. The angles between the input plates and between the grounded and the output plate are measured at the initial and final states to study the origami's states. The origami types i and j could form the input plates' flat state (180° degrees between them) since the cut is in one of the input plates. For all origami types i-l), there is a rotation of 90° to 36.51° degrees between the grounded and the output plates.

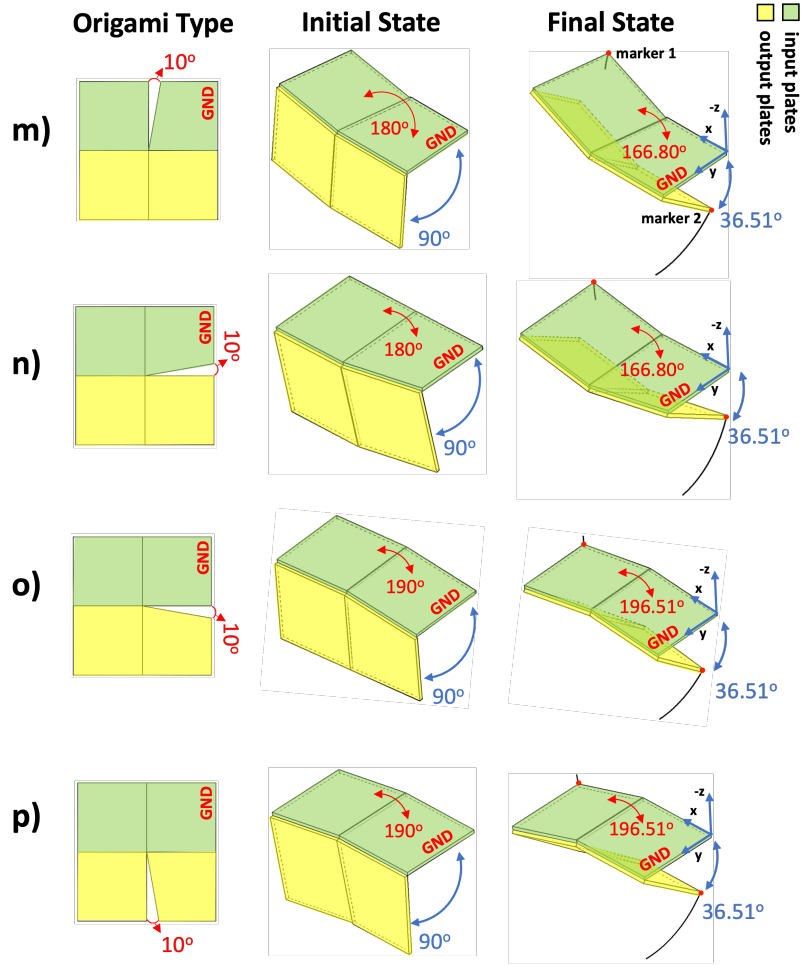


Figure A.3: m-p) Initial and final states of Self-lock origami with a decreased central angle in different positions. The central angle cuts are present in only one plate. Initial state: Closest possible configuration to the flat state of the input plates (180° degrees angle in between). Final state: A defined Maximum Possible Folding configuration (MPF) between the grounded and the output plate (36.51° degrees). After defining the MPF angle due to the position of the cutting angles in parts n) and o), origami's MPF angle between the grounded and output plates' outer edges becomes 37.67° degrees. Origami type: Position of the origami's decreased central angle before the plates' assembly (defining revolute joints between plates). The input and output plates are highlighted with green and yellow colors, respectively. Markers 1, 2, and the reference frame is defined to trace the input and output plates' motions. The angles between the input plates and between the grounded and the output plate are measured at the initial and final states to study the origami's states. The origami types m and n could form the input plates' flat state (180° degrees between them) since the cut is in one of the input plates. For all origami types m-p), there is a rotation of 90° to 36.51° degrees between the grounded and the output plates.

drastically more rotational movement than the input plates' markers. If the cuts are not located in the input plates, the origami experience a limited range of motion in markers 2 and 4.

A.2 Description of A.8 figure

Figure A.8 represents the rotational manipulators' movements in the 3D space. The Ground, M1, M2, M3, M4, and M5 markers have been defined on the origamis' corners to trace all the motions. The Initial state column illustrates the configurations of different manipulators' models when they are in the closest possible configuration to the flat state. The drawings on the right-hand side of the 3D plots show the origami plates used in each manipulator. The simulation starts from the initial state to the maximum possible folding configuration of the manipulator's origamis. Depending on the origami's central angle, the initial state for each manipulator is different. The position of the M4 marker is depicted on the manipulators' reference frame x-axis. At the initial state, as the origami's central angles decrease ($89^\circ \rightarrow 85^\circ \rightarrow 80^\circ \rightarrow 75^\circ \rightarrow 65^\circ$), the M4 markers' positions move further away from $x = 0$ mm. Also, the manipulator's rotational movement in the 3D space changes from the desired downward rotational movement to rotational movements in different directions.

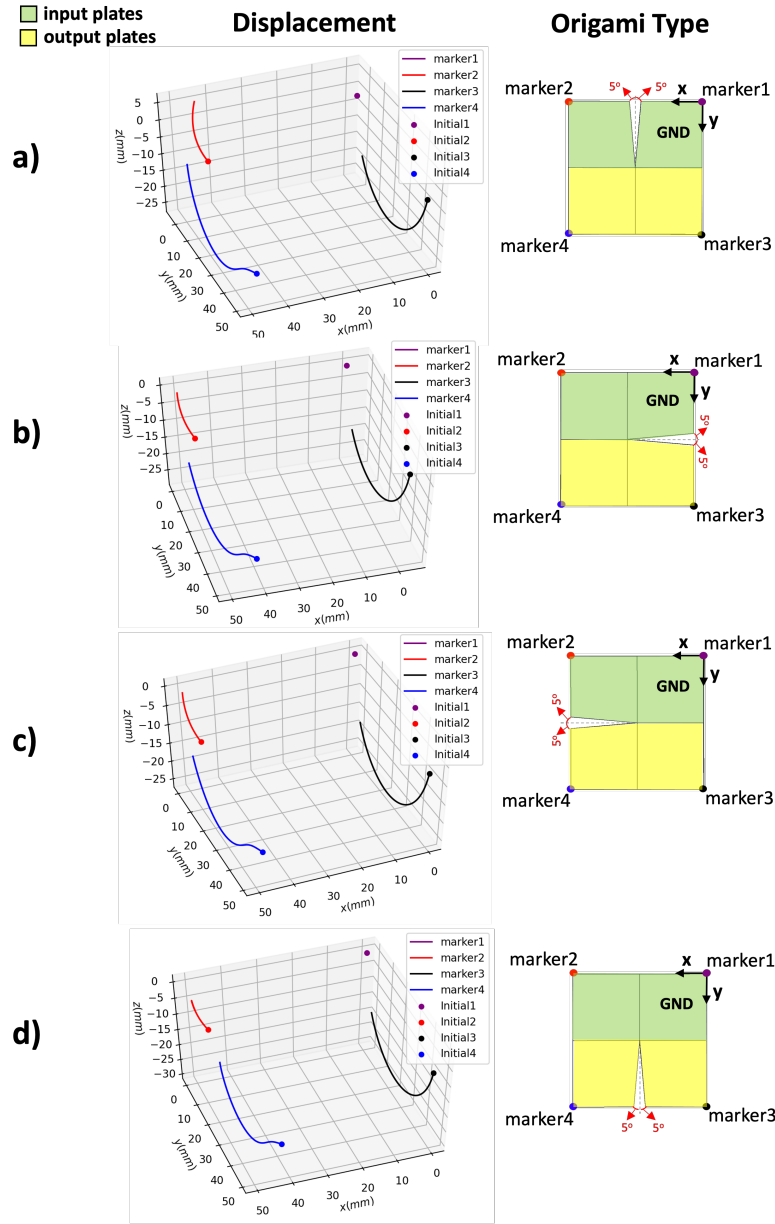


Figure A.4: a-d) 3D Displacements of origami's corners with different reduced central angle positions. Markers 1-4 trace the corners. The input angle starts from -35° degrees and will have a downward motion until it reaches the maximum possible bending configuration. The "Origami Type" column shows the positions of cuts from the central angles. A reference frame is established on the grounded plate to track the markers' movements. The input and output plates are green and yellow colors, respectively. The markers at their initial state are indicated by dots in their corresponding colors. Origami type d) demonstrates the smallest rotation among all the origamis (a-d) for markers 2 and 4 as there are no cuts in the central angles of the input plates, resulting in a limited range of motion for the input plates.

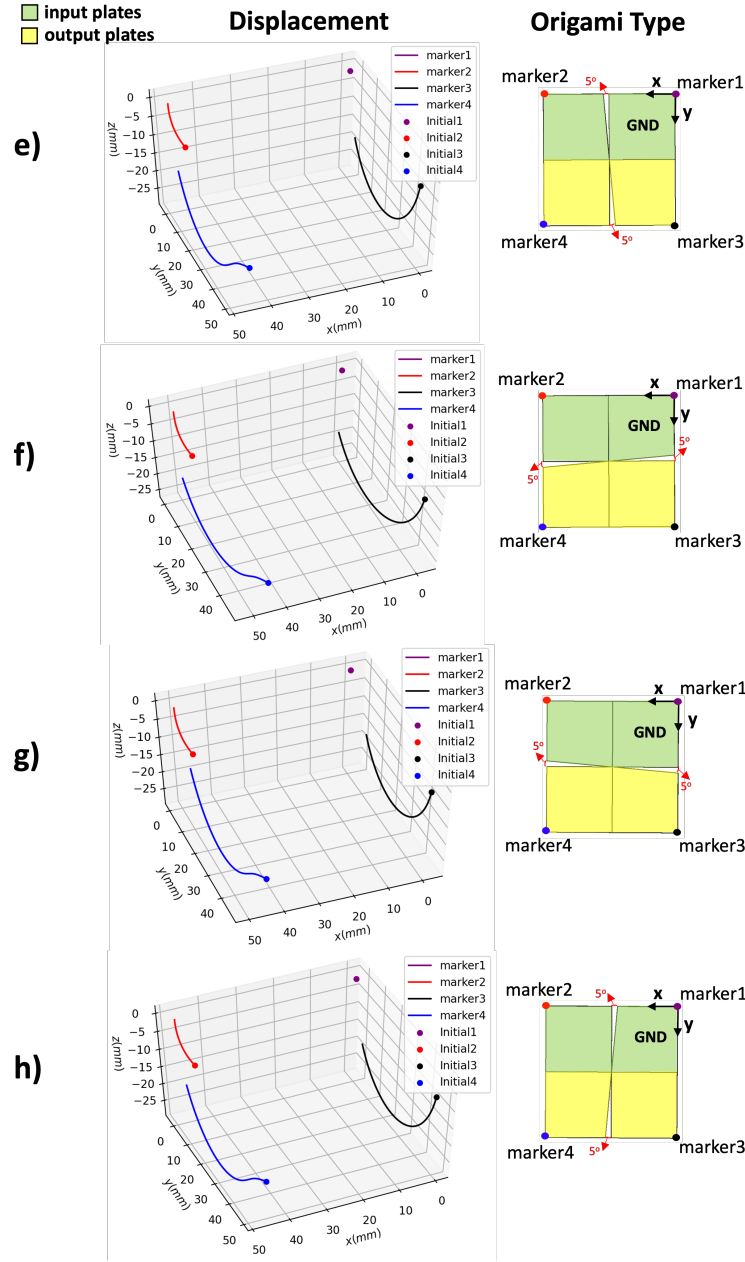


Figure A.5: e-h) 3D Displacements of origami's corners with different reduced central angle positions. Markers 1-4 trace the corners. The input angle starts from -35° degrees and will have a downward motion until it reaches the maximum possible bending configuration. The "Origami Type" column shows the positions of cuts from the central angles. A reference frame is established on the grounded plate to track the markers' movements. The input and output plates are green and yellow colors, respectively. The markers at their initial state are indicated by dots in their corresponding colors. Depending on the position of the cuts, the origami's movements are in slightly different directions.

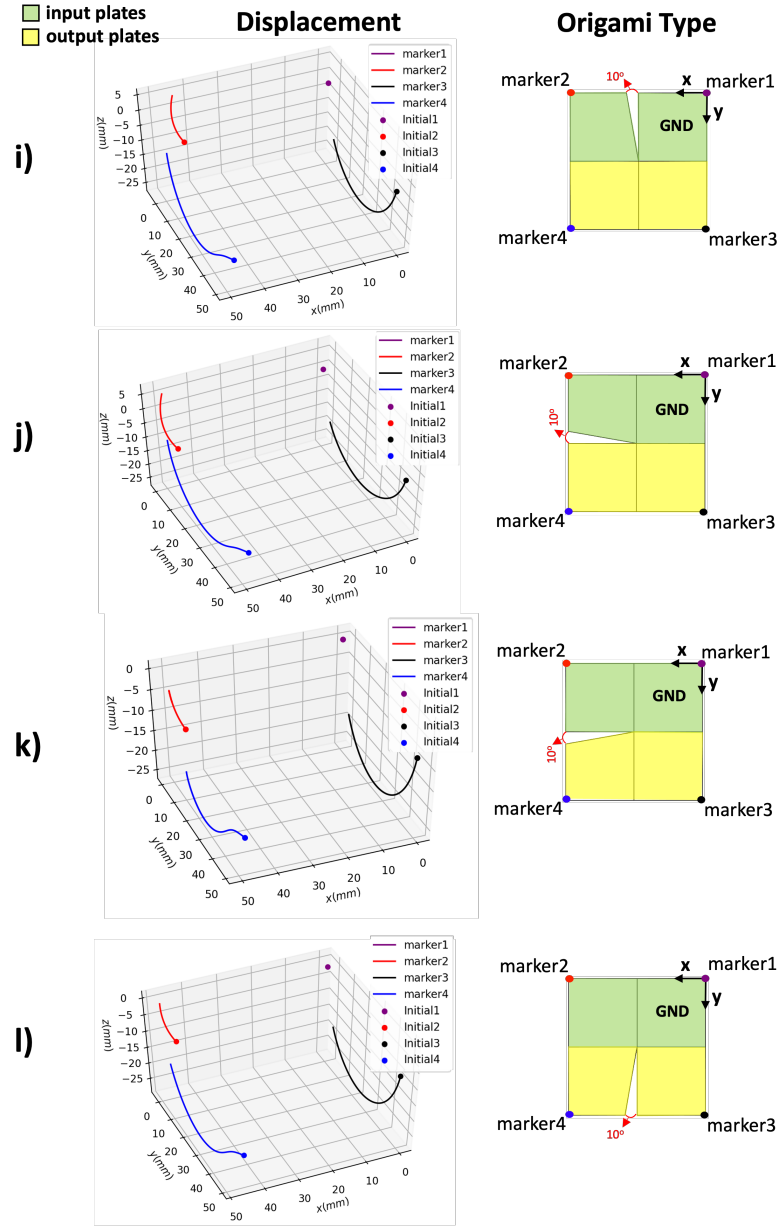


Figure A.6: i-l) 3D Displacements of origami's corners with different reduced central angle positions. Markers 1-4 trace the corners. The input angle starts from -35° degrees and will have a downward motion until it reaches the maximum possible bending configuration. The "Origami Type" column shows the positions of cuts from the central angles. A reference frame is established on the grounded plate to track the markers' movements. The input and output plates are green and yellow colors, respectively. The markers at their initial state are indicated by dots in their corresponding colors. Origami types k) and l) demonstrate the smallest rotations among all the origamis (i-l) for markers 2 and 4, as there are no cuts in the central angles of the input plates, resulting in a limited range of motion for the input plates.

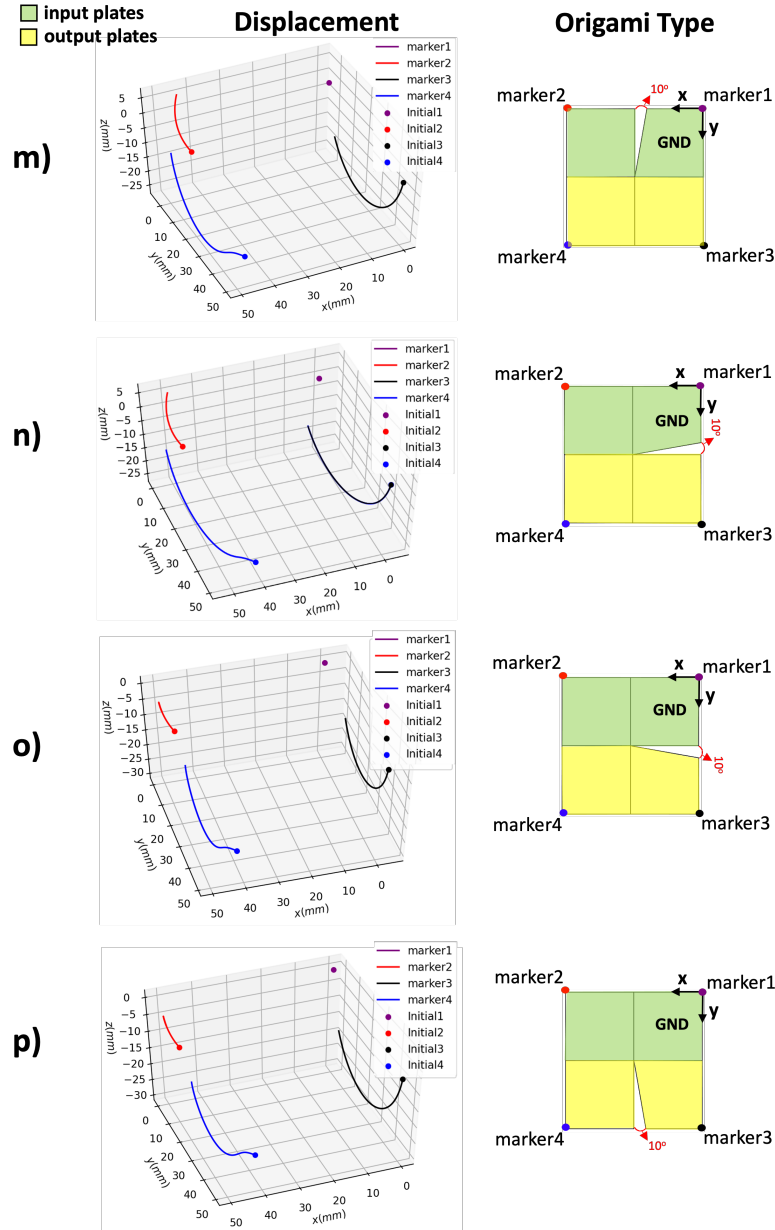


Figure A.7: m-p) 3D Displacements of origami's corners with different reduced central angle positions. Markers 1-4 trace the corners. The input angle starts from -35° degrees and will have a downward motion until it reaches the maximum possible bending configuration. The "Origami Type" column shows the positions of cuts from the central angles. A reference frame is established on the grounded plate to track the markers' movements. The input and output plates are green and yellow colors, respectively. The markers at their initial state are indicated by dots in their corresponding colors. Origami types o) and p) demonstrate the smallest rotation among all the origamis (m-p) for markers 2 and 4, as there are no cuts in the central angles of the input plates, resulting in a limited range of motion for the input plates.

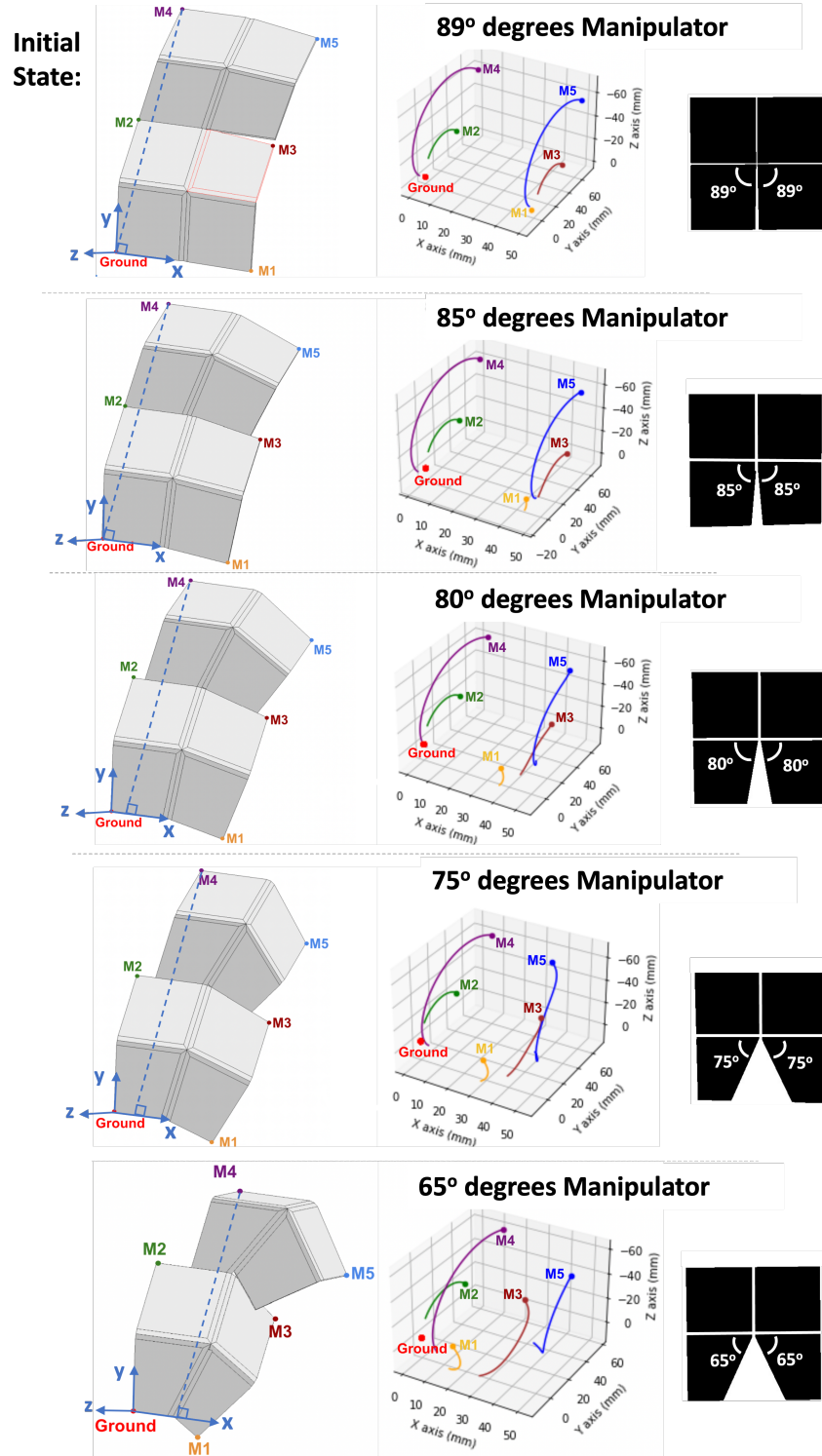


Figure A.8: Movements of rotational manipulators with two origamis in the 3D space. The manipulators have identical central angles for both origamis.

Figure A.8: The Ground, M1, M2, M3, and M4 corners are used to track the movement. The initial state represents the closest configuration to the origami's flat state. The initial position of each origami's corners is indicated in the 3D plots with dots. The input plates are in dark grey, and the output plates are in light grey. A reference frame is defined at the Ground corner of the manipulators. The M4 corner's position is specified on the x-axis. On the right-hand side of the 3D plots, the origami plates with their corresponding central angles used in the manipulators are depicted. As the central angles of the origamis deviate from 90° degrees, the position of M4 moves away from $x=0\text{mm}$. Also, the manipulators' plates rotate more toward each other instead of generating a downward rotational movement.