CREASE

Synchronized Gait Through Folded Geometry.

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Robotics have expanded exponentially in the last decade. Within the vast examples of ambulatory robots, traditional legged robots necessitate engineering expertise and the use of specialized fabrication technologies. Micro electromechanical (MEM) robots are useful for a wide range of applications yet in most cases, difficult to fabricate and excessively intricate. Advances in pop-up laminate construction have generated a model shift in the development of robot morphologies due to their ease of fabrication and scalability from the millimeter to centimeter scale. This research continues to investigate the link between kinematics and pop-up origami structures in robotics. The objective was to design a robot that exhibited efficient and controlled locomotion minimizing number of motors. ``Crease'', an origami robot that emerges from a two-dimensional sheet into its three-dimensional configuration was developed. By amplifying a simple rotational motion through the geometry of folds in the robot, a complex gait was achieved with minimal motorized actuation. Variations in gait, control, and steering were studied through physical and computational models. Untethered Creases that sense their environment and steer accordingly were developed. This research contributes not only to the field of robotics but also to design where efficiency, adjustability and ease of fabrication are critical.

Keywords: *Digital Fabrication and Robotics, Smart Geometry, Origami Robotics, Laminate Construction.*

1 INTRODUCTION

Driven by computation, the development of mechanical components at various scales and the advancement in digital manufacturing methods, the field of robotics has grown in the last decade. Amongst ambulatory robots, conventional legged robots are valued for their ability to navigate through various terrains. However, engineering them requires robotic expertise, it is time consuming and expensive to iterate which results in limited accessibility to the design disciplines. Advances in manufacturing technologies have reduced the size of mechanical components and assemblies while improving performance (Perlmutter and Breit 2016), thus expanding the applications of ambulatory robots. However, these are for the most part difficult to manufacture or highly specialized.

These challenges have generated new fabrication and assembly methods. Research labs have investigated planar processes such as laminated fabrication as an efficient technique that requires less time (Aukes 2014). These methods are scalable from the millimeter to the meter scale. Research on origami folding principles combined with laminated construction has generated functional robotic designs (Felton et al 2014), however, many of these examples are over actuated.

Furthering investigations on action origami (Bowen et al 2013), this research proposes efficiency and gait complexity by applying principles of folded geometry and kinematics in the design, instead of increasing the number of electromechanical actuators. Using an inexpensive and easily reproducible laminated method of fabrication that incorporates flexible hinges, the team generated a robot that features a complex and controlled gait without overly complicated mechanisms.

Under the traditional approach, our design would have been very difficult to achieve because of its complexity in degrees of freedom and computation intensive kinematic analysis. Our non-traditional approach and the fabrication technique, allowed us to generate several iterations efficiently overcoming the challenges associated using traditional approaches and processes of robotic design.

2 BACKGROUND

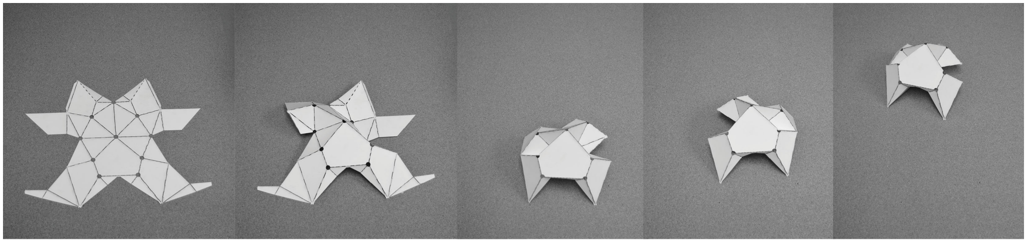
Legged locomotion has been a focus of robotics research for many decades (Raibert 1984; Waldron 1986). Legged systems are touted for their ability, unlike traditional wheeled systems, to navigate bumpy terrain and step over obstacles (Playter 2006) and to move in human environments in a more human way (Nelson 2012). A variety of topics have been studied in the context of legged locomotion, including the role stiffness plays in actuators (Robinson 1999), feet (Altendorfer 2001), spines (Khoramshahi 2013), and legs (Sprowitz 2013). Legged systems, however, are often quite expensive, limiting access to and research on these systems.

Foldable, laminate, and origami-inspired robots have origins in early MEMS work using flat sheet laminate processes to make three-dimensional mechanisms in silicon (Pister 1992). At the core of the technologies that make these robots feasible is the concept of being able to create complex, nonlinear motion through the synthesis of common mechanical elements such as joints, springs, dampers, actuators, and sensors. Unlike common mechanical elements found in more traditional robotic systems, these components are constructed with a collection of planar fabrication techniques in which a variety of compatible materials are iteratively added and removed to create a monolithic, multi-material, electro-mechanical system. These concepts have been demonstrated at nano, micro, milli, and centimeter scales, in materials as disparate as silicon (Pister 1992), carbon fiber (Wood 2003), titanium (Sreetharan 2012), plastic, and cardboard (Birkmeyer 2009). These technologies make it possible to solve novel problems, either at size scales where traditional mechanical devices such as gears, bearings, and motors are unavailable, or at cost-scales which envision industrial-scale processes fabricating large numbers of inexpensive robots (Cybulski 2014; Shigemune 2015; Niiyama 2015).

Foldable devices have been used to address issues in bio-inspired locomotion such as walking (Hoover 2008), running (Birkmeyer 2009; Haldane 2013; Mulgaonkar, 2018), jumping (Koh 2013; Jung, 2014), and flying (Teoh 2012). A variety of strategies for actuating and powering foldable devices has also been investigated (Sitti 2003; Karpelson 2008; Niiyama 2014).

While these robots have continued to be developed and demonstrated across a variety of niche-

Figure 1
Sequence showing transformation from flat to three-dimensional configuration.



based tasks, more is now understood about how to design (Aukes 2014), plan for manufacturing (Aukes 2014a), and analyze these robots. A number of design tools have been developed for understanding the motion created from hinged, origami-inspired designs using FEA-based approaches (Shenk 2011), for enunciating functional needs and combining modular elements (Mehta 2015), or for analytically understanding the resulting dynamics of these devices (Doshi 2015; Khoramshahi 2018). This is necessary due to the dependence upon flexure-based hinges which rely on material deformation to create virtual joints, which can affect system stiffness and damping.

3 METHODS AND RESULTS

The variables studied in the design of Crease were the geometrical pattern, the material of the rigid planes, the material and construction of the flexible and rigid joints and the position of the motors in relation to the folding structure.

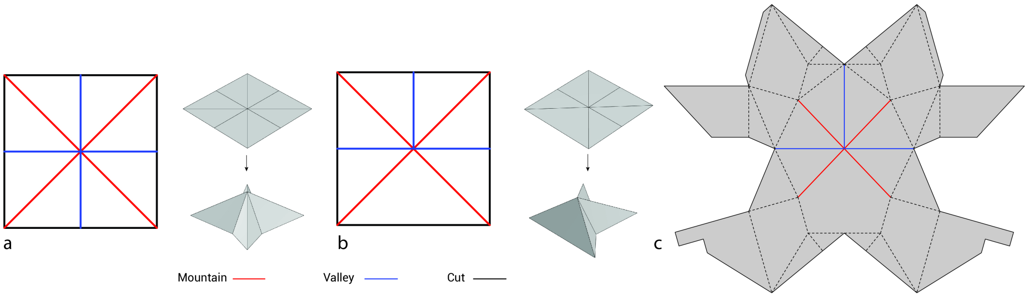
3.1 Geometric Pattern in relation to Kinematics

The range of movement in relation to the geometric pattern of folds was studied physically and digitally applying principles of parallel and spherical linkages to folded geometry. The origami waterbomb base, considered a spherical linkage, has been commonly used to generate complex origami structures (Figure 2a) (Lang 2011). In its three-dimensional configuration, Crease has four symmetrical legs joined by a modified eight-fold waterbomb base, where one fold was omitted to provide a stable ground while enabling controlled rotation of the upper body (Figure 2b, 2c).

Figure 3 shows Crease in its flat and three-dimensional configurations indicating the role of each rigid plane. To achieve locomotion, a simple circular motion is translated through a pattern of flexible joints animating the rigid planes of the body (Figure 4). The modified waterbomb spherical joint enables rotation and synchronized actuation of the front and rear legs.

The rear part of the body serves as a ground con-

Figure 2
a) Original Waterbomb base design b) Modified Waterbomb used for “Crease” c) Waterbomb base in Crease folding pattern



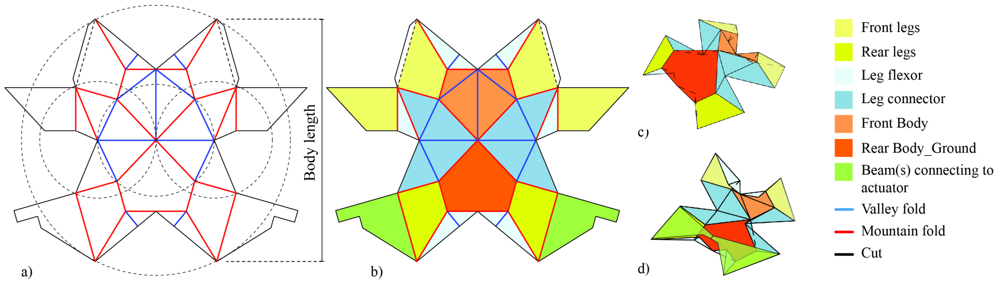


Figure 3
a) “Crease” pattern
b) Roles of planes c) 3d configuration from top view d) Underside view

nected to legs acting as parallel linkages that allow repetitive motion. Being connected through folds, the movement of the front legs is synchronized to its back legs which in turn are linked by a folding beam anchored to a motor (Figure 4 and 6). The material of the hinges and their design is critical as they allow the distribution of torque from the actuator throughout the system. While the pattern shows symmetry along axis y, the rotational motion creates asymmetrical and corresponding configurations. To take a step forward with the right leg (position B), P1 moves away from P2 while P4 and P3 touch. Conversely, to take a step forward with the left leg (position D), P4 moves away from P3 while P1 and P2 touch (Figure 4). When the right front leg moves forward it lifts higher than the other three. Once that leg touches the ground, the left hind leg lifts slightly. As the torso turns, the gait cycle repeats on the other side (Figure 4 and Figure 12).

3.2 Variations

Several prototypes that show gait variations and navigation control were generated. For these, the type, number, position and range of motorized rotation were studied in relation to the pattern of folds and connections (Figure 5). Figure 3 shows the selected pattern after proportions were studied physically and digitally in relation to motion. Sizes ranging from 6 cm to 45 cm in body length (Figure 3) were produced where prototypes ranging from 20 cm - 45 cm were

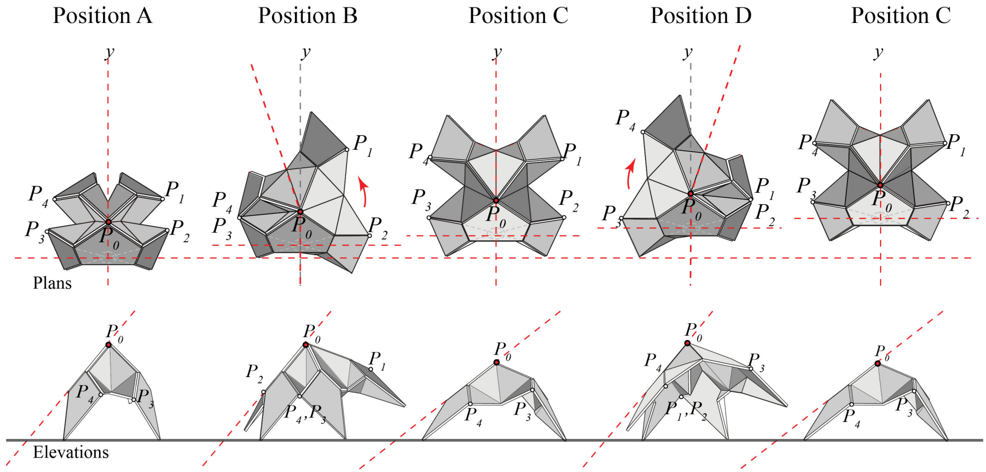
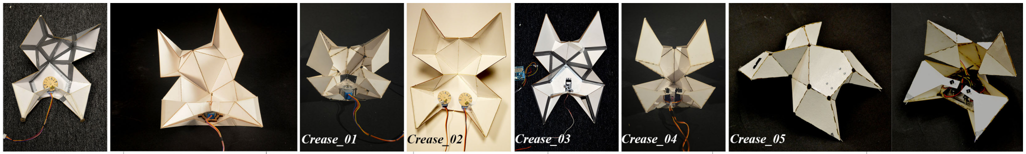


Figure 4
Gait cycle

Figure 5
Taxonomy of
Creases.



Crease Type	Folded Beam	Stepper Motor	Servo Motor	Bluetooth Control	IR Sensor	Size
Crease_01	(1)	(1)	-	-	-	25 cm
Crease_02	(2)	(2)	-	-	-	25 cm
Crease_03		-	(1)	-	-	25 cm
Crease_04		-	(2)	-	-	25 cm
Crease_05		-	(2)	(2)	(2)	30 cm

Figure 6
Crease_01
Underside view. a)
Position B b)
Position C c)
Position D

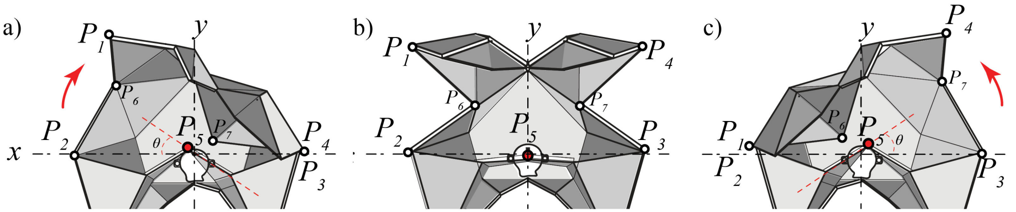
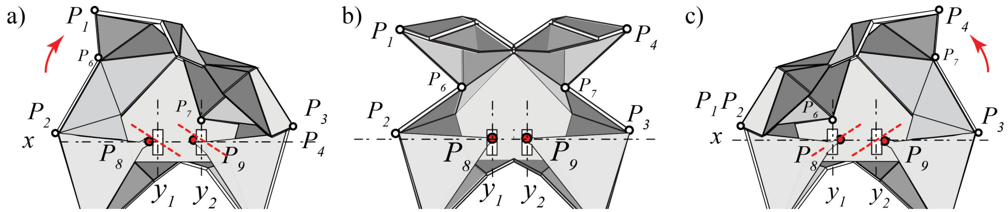


Figure 7
Crease_04
Underside view. a)
Position B b)
Position C c)
Position D



actuated using either stepper or servo motors. Tethered and untethered variations were produced showcasing different levels of control. For our discussion, Crease_01, Crease_04 and Crease_05 were selected as origami robots that displayed key differences.

3.3 Control

In all of the 20 cm - 45 cm Crease prototypes, the micro controller and actuation components were housed onto the rigid ground plane. An Arduino Uno with an Adafruit motor shield v2.3 was used to program the stepper motor in the tethered Creases whereas a lightweight Arduino Nano was used to program the two servos in the untethered configurations.

3.3.1 Actuation. Fundamentally featuring the same pattern, in Crease_01 the rear legs are connected with a single folded beam to a stepper motor (Figure 6) while in Crease_04 the rear legs are connected with individual folding beams to corresponding servo motors (Figure 7). In Crease_01, P5 is in the middle of the connecting beam. In neutral positions of the robot

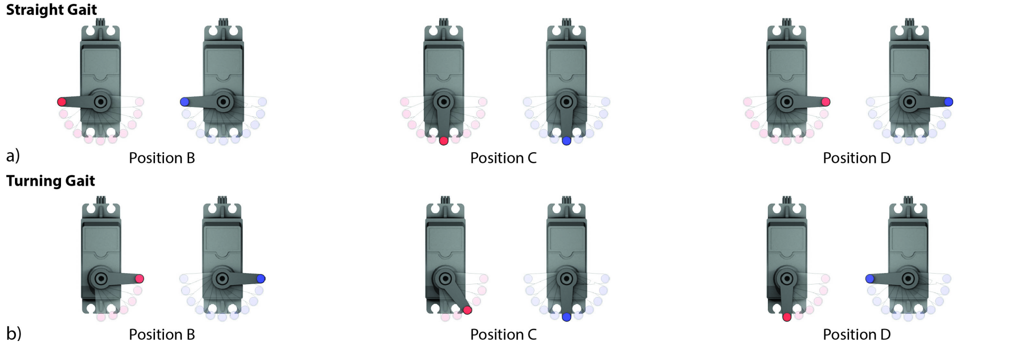


Figure 8
Servo positions as seen from the underside of Crease_04. a) Straight gait b) Turning to the right

(position A and C), P5 is where axis y and x cross (0, 0). As this point rotates controlled via a stepper motor, the position of the legs vary accordingly. If P5 is in the (-x, y) quadrant, points P3, P4 approach each other while P1, P2 separate (Figure 6a) and vice versa when P5 is located in the (+x, +y) quadrant (Figure 6c). For every 360° cycle of the motor, Crease_01 goes from position B to position D.

In Crease_04, P8 and P9 are associated with their respective folded beams and servo motors. When P8 and P9 are in the (-x, y) quadrant, points P3, P4 approach each other while P1, P2 separate (Figure 7a) and vice versa when P8 and P9 are located in the (+x, +y) quadrant (Figure 7c). For every 180° cycle of each servo motor, Crease_04 goes from position B to position D.

This difference, enables variation in gait and steering. In Crease_01 the gait is slower and smoother than in Crease_04. Conversely in Crease_04, the use of servos produces faster gait and the pairing of one servo motor to one rear leg gives it the ability to be steered. Crease_05 is similar to Crease_04, but is untethered and controlled remotely.

3.3.2 Steering. The Arduino code controlled the rotational angle domains for the motors. Both open and closed loop systems were studied. The first one, allowed to steer Crease by modifying inputs through potentiometers. The closed system will be discussed in 3.3.3 Sensing.

The prototypes that exhibited the best control in steering were Crease_04 and Crease_05. To achieve this, each actuating beam was connected to their respective servo motor. The repetition of movement of one hind leg in relation to the other caused the body of the origami robot to turn either right or left. Full rotation clockwise and anticlockwise allowed the robot to back track its path.

These two prototypes achieved sharp and accurate turns, unachievable in the prototypes using a single motor. For instance, right turns were accomplished by increasing the frequency of the right servo motor in relation to left. For sharper turns, the frequency of one motor was increased even more with respect to the other. The accelerated movement of the right leg, resulted in steering the robot left and vice versa (Figure 8 which shows the position on the underside of Crease_04).

3.3.3 Sensing. A sensing capability was attained by implementing a Bluetooth control and a pair of distance infrared sensors enabling the control of movements remotely and untethered (Crease_05). An Arduino was used to program rotational actuators incorporating a real-time feedback loop that permits Crease_05 to avoid obstacles while walking. The infrared sensors, connected to the front legs, measured the distance to any approaching obstacles. A closed feedback loop was created between the IR sensors and the servos where if an obstacle was far away, the

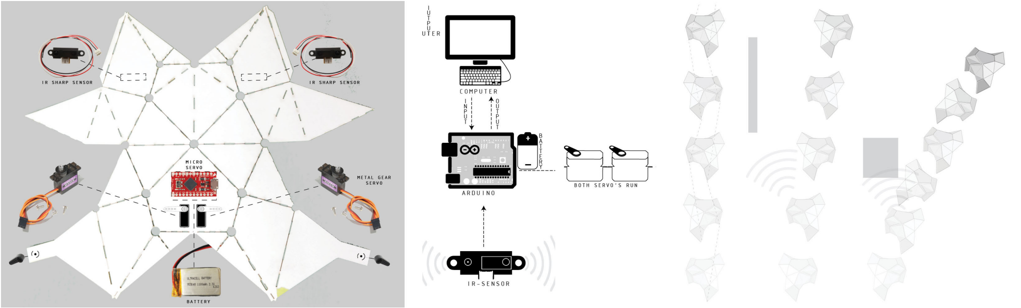


Figure 9
Crease_05 showing actuation and sensing components in relation to folding pattern and its impact on obstacle avoidance

robot made a soft turn and if the obstacle was near, it made a hard turn (Figure 9).

3.4 Simulation

Crease's gait is challenging to simulate using traditional means due to its multiple degrees of freedom and under actuated mechanism. Therefore the implemented workflow merely validates and verifies one possibility of the kinematics of its motion.

The transformation from flat to three-dimensional configuration was analyzed and simulated using Origamizer and Origami Simulator. Origamizer (Tachi 2010) and Origami Simulator (Ghassaei, Demaine, and Gershenfeld 2018) were used to test pattern iterations and to simulate the resultant folded configurations. By using a normal mapping technique, Origami Simulator aided in identifying planar relationships between faces which was considered in designing the proportions for the folded pattern (Figure 10a). The kinematics of the folded planes and specifically the relation between the actuating angles of the rear legs and resultant motion of the front legs were studied using a Dassault Solidworks, McNeel Rhino, Grasshopper and Kangaroo (Piker 2013) workflow (Figure 10b).

3.5 Fabrication

As a fabrication method, a fast and inexpensive pop-up laminate construction was used where the body was digitally produced using simply a Universal 150W laser cutter and an Apache AL18P thermal laminator. Depending on the size of the prototype, different

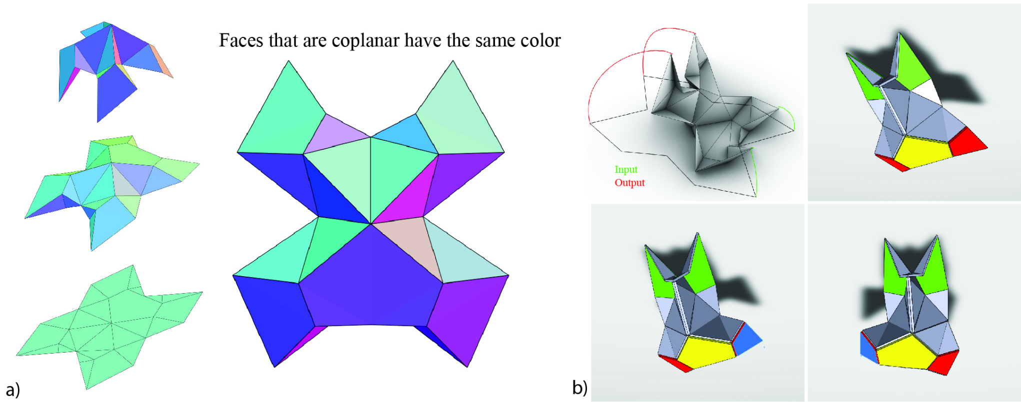


Figure 10
a) Computer graphics normal mapping where faces with same color are coplanar
b) Study of input (green) and output angles (red) and Solidworks Simulations

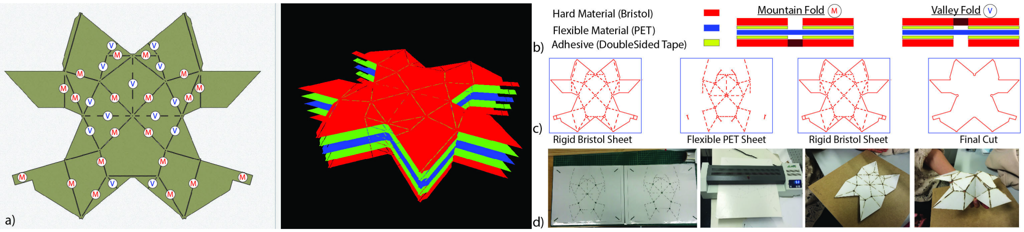


Figure 11
CAD to CAM workflow a) PopupCAD layup b) Valley and mountain folds c) Cut pattern d) Fabrication steps

flat stock materials were employed. For prototypes ranging from 20-45 cm, a flexible 0.7 mm PET membrane was laminated between two rigid planes of 3 mm Bristol card stock (Figure 11). Several iterations of laminated flexible joints were studied and optimized using popupCAD (Aukes 2014), an open source software platform designed specifically for laminate constructions. The hinges used were castellated and laminated (Figure 11b). The flexible PET membrane was weakened through castellation offering the necessary strength and flexibility for the desired movement. Variations in length and frequency of cuts in the castellated joints were tested to achieve robust yet flexible connections. Figure 11 shows the pattern and sectional assemblies for mountain and a valley folds. Circular notches were cut out to relieve stress at vertex intersections.

4 CONCLUSIONS AND FUTURE RESEARCH

By establishing a relationship between the configuration of the folds and the resulting range of motion, this research efficiently achieves complex gait of an origami robot while minimizing the use of electromechanical actuation. Pop-up laminate construction combined with the principles of kinematics in origami folding offer a paradigm shift in methods of design at various scales ranging from the millimeter to the meter scale. Crease is a contribution not only to the field of robotics, but also in other fields especially in design and architecture where material, manufacturing, assembly and kinematics are of utmost importance.

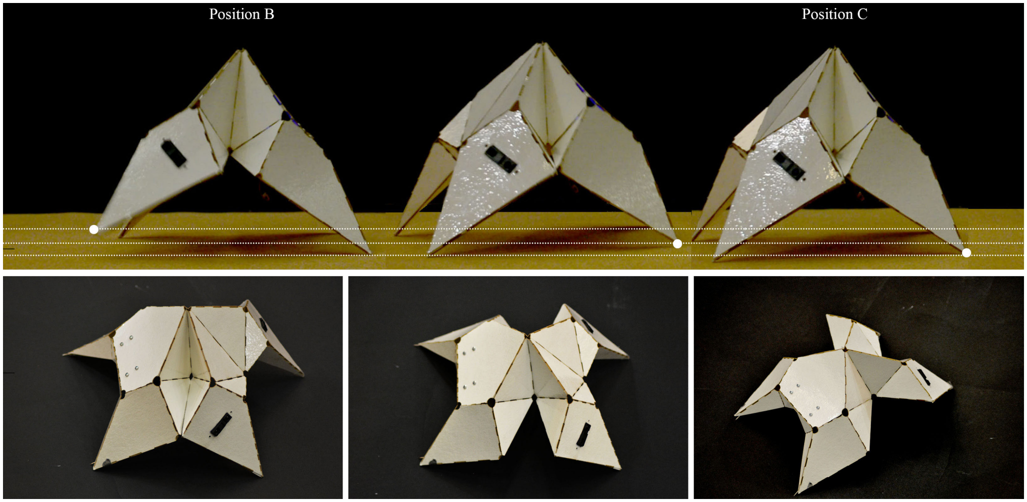


Figure 12
Crease_05 Gait cycle

4.1 Future Research

Inherent in its deployment method, a future development will be the transformation from its two-dimensional to its three-dimensional configuration in real time (Miyashita et al 2015) to adapt to different environments. 4d printing and embedding smart materials can be used for self-actuation of folds. As for the rigid planes, the integration of high strength, low weight materials, such as carbon fiber and fiberglass composites, could be used to achieve robust prototypes capable to withstand harsh conditions (Tiliakos 2013). Integrating smart sheet materials within the laminates can provide added functions (Ozevin 2014). Advances in functionally graded and multi-material 3d printing offer the possibility of material gradients targeting the desired levels of rigidity or flexibility in the folds. Examples of thick-origami promise the translation of this pattern to the meter scale opening its applications to the field of architecture.

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