Robotic Folding of 2D and 3D Structures from a Ribbon

Liyu Wang, Mark M. Plecnik, and Ronald S. Fearing

***Abstract*— Automatic folding has drawn increasing attention in robotics research in the past ten years. The focus has been on folding two-dimensional (2D) sheets into three-dimensional (3D) structures, but little work has been done on how structures may be formed by folding ribbons. Here we propose the concept of robotic ribbon folding including a general workflow from shape design to ribbon folding and shape retention. We also propose a method to realize robotic ribbon folding on the macroscopic scale. The method consists of minimally engineered ribbons with patterned flexures, a folding robot, and a folding scheme that relates the orientation of flexures, the type of folds and the type of structural elements. By using this method we demonstrate robotic ribbon folding into 2D static structures such as triangles and squares, 3D static structures, and planar kinematic linkages such as a simple non-crossing four-bar mechanism. Burn-in result shows a four-bar mechanism with all bars' length of 5 cm could move repeatedly for at least half an hour.**

I. INTRODUCTION

Folding has been studied in the field of robotics and automation for over twenty years. Early work used manually-folded structures to build e.g. joints in the exoskeleton for an insect-like robot [1], a gripper [2], the thorax and wing for a flying robot [3]. Folded structures have the advantage of light weight and low friction in systems on the micrometer or millimeter scale. Folding can also be good for forming abstract macroscopic structures because it is faster and it uses relatively less material than conventional subtractive or additive techniques.

Studies on automatic folding focus on folding from a 2D sheet to 3D structures where the thickness of the sheet is negligible. They have been physically demonstrated in two categories and are sometimes associated with the art of origami. The first category is robotic sheet folding, where a robot is programmed to sequentially fold a piece of cardboard or paper into a structure [4], [5]. The second category is self-folding structures and robots [6], [7], [8]. These structures or robots are sheets of highly-engineered material with patterned flexures. During folding, embedded actuators or stored energy cause the sheet to bend simultaneously at all flexures. One such sheet of material may self-fold into multiple structures depending on the activation of flexures.

In nature structure formation based on sheet folding exists in plants, but the most fundamental process of protein folding takes a different form i.e. folding from a long and thin piece. In many organisms, a protein's biological function is determined by its 3D native structure, which is physically folded from a linear string of amino acid monomers [9]. Given the biological evidence, ribbon or string folding may represent a more general method than sheet folding for forming structures [10], that is the set of possible structures may be larger. When used as a robotics and automation technology, it may be a simple and compact method to perform low-cost prototyping or on-the-fly structure generation, etc.

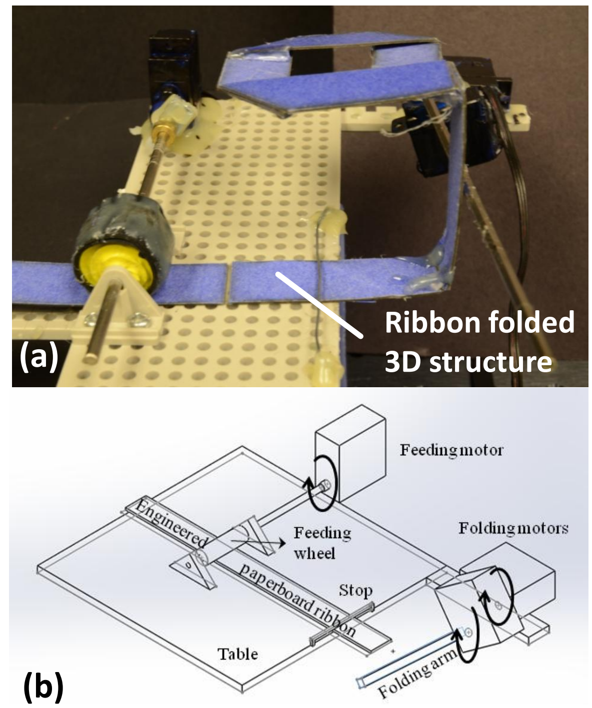


Fig. 1. Robotic ribbon folding. (a) A 3D structure with two intersected planes folded from a minimally engineered ribbon by a machine. The ribbon is minimally engineered from paperboard. (b) Sketch design of the machine that folds the minimally engineered ribbon. The machine has a feeding motor and two folding motors.

Automatic folding of a ribbon or a string has not been thoroughly investigated for the purpose of automatic structure formation. On the algorithm and design side, Cheung et al. formulated an algorithm for constructing the Hamiltonian path for an arbitrary structure as the sufficient condition for the structure being foldable from a string [10]; Risi et al. used computational optimization techniques to find the optimal ribbon-folded structure for a locomotion task in simulation [11]. On the physical implementation side, Shechter et al. introduced a self-assembly method to build 3D microstructures from a number of serially connected microfabricated panels with embedded magnets [12]. White et al. proposed

*This work was supported by Swiss National Science Foundation Early Postdoc Mobility Fellowship

All authors are with the Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, 94720 CA, USA liyu.wang@wadh.oxon.org

TABLE I
FOLDING IN ROBOTICS

	Robotic ribbon folding	Robotic sheet folding	Self-folding structures and robots
Dimension	1.5D to 3D	2D to 3D	2D to 3D
Width/length	infinitesimal	finite	finite
Process	sequential	sequential	simultaneous

a passive module and demonstrated a chain of five such modules being held by a robot arm and rotated to form a line under gravity [13]. Knaian et al. proposed a chained robot with 1-cm long segments and actuated joints, but only a chain of four segments was demonstrated, thus no 3D structure could be formed [14]. Tibbits proposed a chained structure with segments at a few centimetres and joints made of hydrophilic and rigid material, and demonstrated self-folding into 3D frames in the water [15]. There have been modular self-reconfigurable robots which adopted a chain structure [16], [17]; however modules in the middle of the chain disconnected during self-reconfiguration, thus it was no longer folding. There are also wire bending machines but they use hard metal wires to make rigid frames or springs only (for an example, see DIWire from Pensa Labs).

This paper proposes the concept of robotic ribbon folding and a method for realizing robotic ribbon folding. We establish a ribbon folding scheme which relates the orientation of flexures, the type of folds and the type of formed structural elements. We demonstrate robotic folding of ribbons to make 2D and 3D, static structures and kinematic linkages on the macroscopic scale. These structures may be used as the entire or a part of the structure of a robot, suggesting the potential application of robotic ribbon folding for robotic self-repair or shape adaptation.

The remainder of the paper is organized as follows. Section II further introduces ribbon folding and a general workflow for robotic ribbon folding. Section III describes a method for robotic ribbon folding which includes a minimally engineered ribbon, a folding robot, and a ribbon folding scheme. Section IV presents results of robotic ribbon folding of static and kinematic structures and discusses important topics on technological constraints of the proposed method and automation of shape design. Section V summarizes the paper and points out future work.

II. ROBOTIC RIBBON FOLDING

A. Ribbon Folding Versus Sheet Folding

According to the Oxford Dictionary, a ribbon is a long and narrow strip of something and a string is a series of something jointed together. A string is usually referred to as a one-dimensional (1D) structure [10], because the joints between the serial things are universal and width and thickness can be seen as negligible. However that is not the case for a ribbon, because the width is infinitesimal compared to the length even though the thickness is negligible. Therefore a

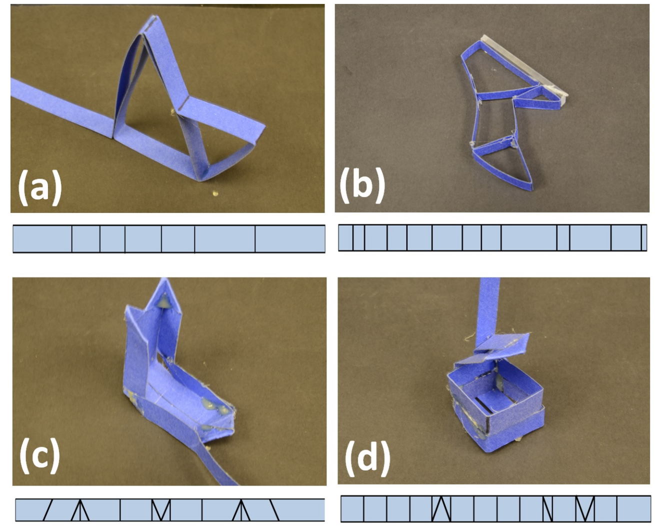


Fig. 2. A variety of structures folded manually from paperboard ribbons and their unfolded ribbons: (a) a vertical layer of a chair, (b) a planar six-bar mechanism, (c) a digger scoop, and (d) a box with a cover.

ribbon has an anisotropic cross-section and may be treated as a one-and-a-half (1.5D) structure.

Similar to robotic origami, robotic ribbon folding uses a robot to exert forces and fold a ribbon of material in sequence. When the material is highly engineered with embedded motors, an external robot is unnecessary and the material may be seen as a ribbon-shaped self-folding robot. In this paper we focus on robotic ribbon folding of minimally engineered passive material with an external robot.

A comparison of robotic ribbon folding with robotic sheet folding and self-folding structures and robots can be found in Table I.

B. Folding Path

The problem of how a given shape may be folded from a string has been theoretically solved by Cheung et al. with a Hamiltonian path construction algorithm [10]. The algorithm takes any 2D structure as a collection of dividable pixels and any 3D structure as a collection of dividable voxels. The collection can be viewed as a graph, where the nodes are the centers of the pixels/voxels and the edges connect adjacent pixels/voxels. Hamiltonian paths can be constructed by repeatedly adding subdivided Hamiltonian circuits until the desired shape is constructed. The Hamiltonian circuits of any two adjacent subdivided pixels/voxels may be merged to form a single circuit, which in turn may be merged with any other adjacent subdivided pixels/voxels or circuits formed in this fashion. Each Hamiltonian circuit has one of the turning motifs of straight lines or right-angle turns about X, Y or Z axis in the local coordinate system. A given shape can have multiple Hamiltonian paths but the selection of a most suitable one remains an open question.

Despite the aforementioned difference between a ribbon and a string, the same condition of having a Hamiltonian path

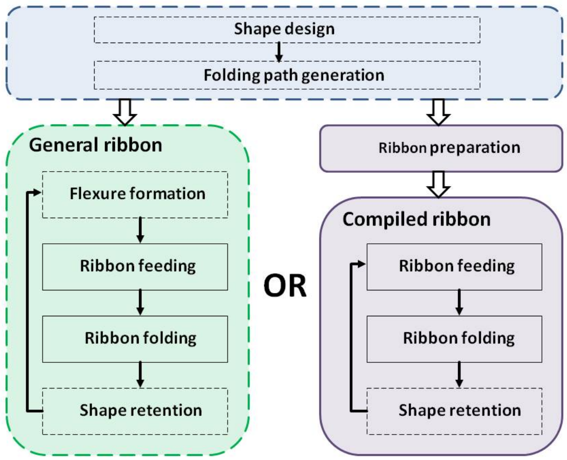


Fig. 3. A workflow of robotic ribbon folding. In the general case, a ribbon will be compiled with flexures automatically built-in with a flexure-formation module. When such a module does not exist, as in the work presented here, preparation is needed for the ribbon where flexures are pre-engineered in the ribbon. A dash-line box indicates a process which is not fully automated in the presented work.

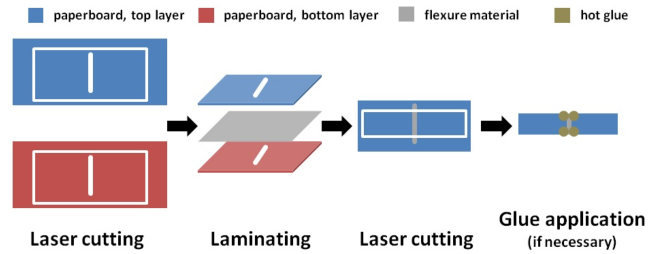


Fig. 4. Preparation process of minimally engineered ribbons based on two layers of paperboard and a layer of PET sheet in between. The process is similar to the SCM fabrication process [19] with the addition of a step of hot glue application. Here only a short ribbon containing a single flexure is shown.

may apply to ribbon folding. Due to the anisotropic cross-section of ribbons, the folding site cannot be assumed as a universal joint. However this should only have an impact on the pattern of flexures but not the path construction algorithm itself. Fig. 2 shows example structures manually folded from paperboard ribbons, including a vertical layer of a chair, a planar six-bar mechanism, a digger scoop and a container box with a cover.

C. General Workflow

Robotic ribbon folding involves a number of processes to translate a design to a folded structure. In the general case as illustrated in the left side of Fig. 3, the workflow starts with designing a structure for a target function. A path is then constructed to identify how the structure may be folded from a single ribbon. A robot with a given configuration of motors can then plan how to form flexures and how to fold a ribbon. This will enable the machine to physically form flexures on a general-purpose ribbon, feed and fold it, and add bonds to keep the shape of a folded structure. The workflow extends previous work [10], [11] by integrating processes from design to folding. It also considers the physical constraints of a passive ribbon and includes processes such as flexure formation and shape retention.

The presented work here focuses on the automation of two of the processes i.e. ribbon feeding and ribbon folding. For design automation, an example for planar kinematic linkages such as the one in Fig. 2b is described in [18], where the dimensions of six-bar linkages are directly computed from a desired input task specified by a user. Automated construction of a Hamiltonian path is in principle a solved problem as aforementioned. For automated flexure formation, technical solutions such as knife cutting, laser cutting, and mechanical clamping etc. exist. When the flexure-forming process is not part of the machine's function, as shown in the right side of Fig. 3, a compiled ribbon needs to be prepared and engineered with patterned flexures.

III. A METHOD FOR ROBOTIC RIBBON FOLDING

The method for robotic ribbon folding here consists of three technical components i.e. a minimally engineered ribbon, a folding robot, and a ribbon folding scheme.

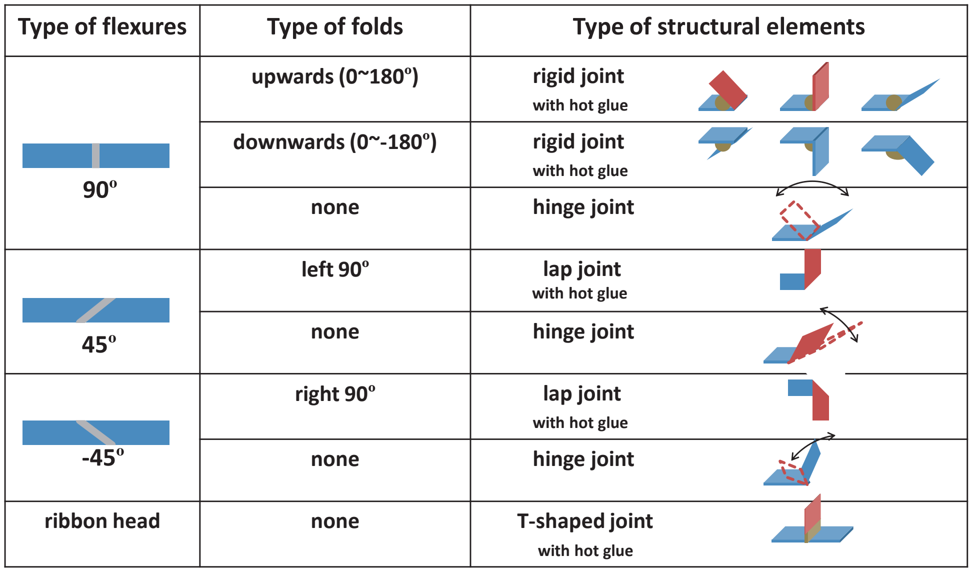
A. Minimally Engineered Ribbon

The ribbon is minimally engineered with patterned flexures in the form of flexures in a sandwich structure. The sandwich structure has one layer of paperboard on each side and a layer of polyethylene terephthalate (PET) sheet in between. The paperboard and the PET sheet has a thickness of 0.35 and 0.05 mm respectively. They were prepared into the sandwich structure through the smart composite microstructures (SCM) fabrication process [19]. As shown in Fig. 4, a design layout including the location and orientation of the flexures is firstly sent to a laser cutting machine to cut the two layers of paperboard; the two layers of paperboard are then joined by the PET layer and the three layers are bonded with thermal adhesives (not illustrated) through a laminator; the sandwich structure is further cut by laser to form the engineered ribbon while creating the flexures. The material cost for a 1cm-wide ribbon is $ 0.09 per metre in the USA. To enable automation of shape retention of a folded structure (Fig. 3), hot glue may be pre-applied adjacent to the flexures and the glue could be activated by an external heat source.

B. Folding Robot

A folding robot was designed and prototyped to fold the minimally engineered ribbon. The machine has two modules i.e. a feeding module and a folding module.

As shown in a sketch in Fig. 1b, the feeding module has a pinch wheel driven by a continuous rotating servo motor (labelled as feeding motor, Feetech, China) situated on a horizontal table with a dimension of 16 cm x 6 cm. The friction between the wheel and the ribbon moves the ribbon towards the folding module. The folding module has a rigid arm with a length of 14 cm which is actuated



Type of flexures	Type of folds	Type of structural elements
90°	upwards (0~180°)	rigid joint with hot glue
	downwards (0~-180°)	rigid joint with hot glue
	none	hinge joint
45°	left 90°	lap joint with hot glue
	none	hinge joint
-45°	right 90°	lap joint with hot glue
	none	hinge joint
ribbon head	none	T-shaped joint with hot glue

Fig. 5. A ribbon folding scheme showing the relations between flexures, folds and joints. Three orientations of flexures (90°, 45°, and -45°) can be folded into rigid joints and lap joints with the help of hot glue for shape retention. They can also form hinge joints without being folded nor with hot glue.

by two motors (labelled as folding motor, Feetech, China). One of the motors moves the folding arm in its horizontal orientation up and down to fold. The other motor rotates the arm between the horizontal and the vertical orientation, so that it can be placed above or below the ribbon if necessary. The folding motors are situated on an extended structure 3.5 cm away from the edge of the horizontal table. All motors are controlled with an Arduino Leonardo microcontroller board connected to a laptop computer. The robot including the two modules and the microcontroller costs ca. $ 70 in the USA.

C. Ribbon Folding Scheme

Previously a couple of theoretical folding schemes were proposed for simulated ribbon folding. For example, Cheung et al. defined seven tiles for string folding i.e. left and right turning tiles about X, Y, or Z axis, and going straight without turning [10]; Risi et al. defined five types of folds i.e. four 45° bends in the upward, downward, leftward, and rightward directions, and no bend [11]. However the anisotropic cross-section of the real ribbon requires these theoretical folding schemes to be modified. Given the limitation in the number of degrees-of-freedom (DOF) of the robot, a folding scheme is therefore established which relates the orientation of flexures, the type of folds and the resulting type of structural elements.

As illustrated in Fig. 5, we encode three basic orientations of flexures on the minimally engineered ribbon: 90°, 45°, and -45° with respect to the longer edge of the ribbon. Since the folding arm can only move up and down, the 90° flexures will be either folded upwards between 0°-180° or downwards -180°-0°. With the addition or activation of hot glue, the folds would become angled rigid joints. For the 45° flexure, we define only one type of fold which is a left 90° fold when looking towards the direction of ribbon feeding, and this fold would form a lap rigid joint with hot glue. For the -45° flexure, we define a right 90° fold in the similar way hence also a lap rigid joint. It is important to note that to achieve these two folds the folding arm must rotate 180° (or -180°). For all the flexures, there is also the possibility of having neither fold nor hot glue, and that would result in a kinematic hinge joint. In the case of the 90° flexure it would form a hinge joint where the axis of rotation is perpendicular to the plane of joint movement. In the case of 45° or -45° flexure it would form a hinge joint where the axis of rotation is at an angle with the plane of joint movement. In addition to the three orientations of flexures, there is also the ribbon head, which can form a T-shape joint with the addition or activation of hot glue.

IV. RESULTS AND DISCUSSION

To demonstrate the efficacy of the proposed method, 2D static structures, 3D static structures and planar kinematic linkages were folded by the robot. In all the demonstrations here, ribbons had a length of 40 cm and a width between 0.5 cm and 1.5 cm. The motors of the robot were controlled with predefined speed and duration in an open loop manner to reach target angular positions.

A. Robotic Folding of 2D and 3D Static Structures

For 2D static structures, the robot folded a planar triangle with two folds, a planar square with three folds, and a 2D square with three folds. For 3D static structures, the robot folded a structure with two intersected planes out of six folds. Since automation of hot glue dispensing within a robotic system is not the focus of the paper and has been previously addressed [20], [21], [22], hot glue was manually applied to

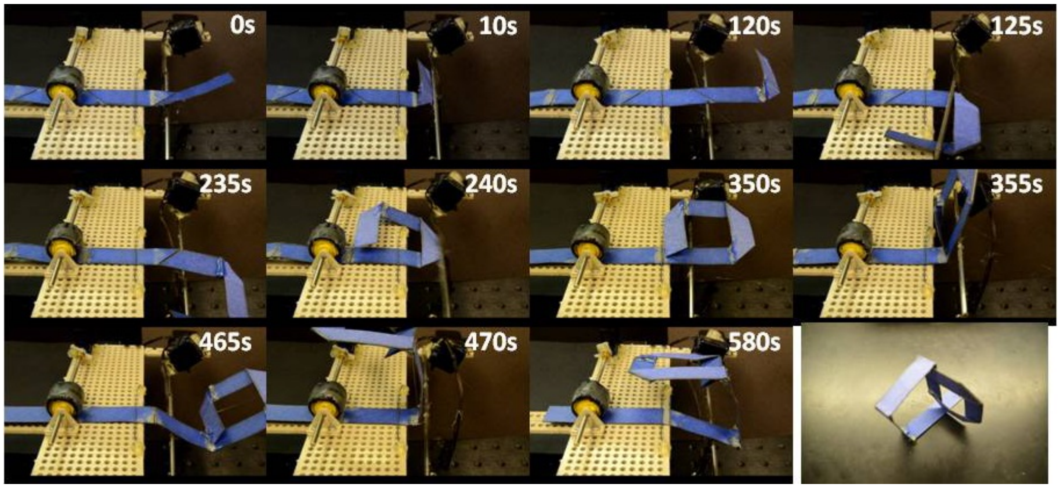


Fig. 6. Snapshots of robotic ribbon folding of a 3D static structure with two intersecting planes. From the start to t=350 seconds, the robot folded the first plane of the structure from three 45° flexures into three lap rigid joints. From t=350 seconds, the robot folded the second plane of the structure from three 90° flexures into three 90° angled rigid joints.

the joint after each fold. A duration of 110 seconds was set to allow the hot glue to be applied and cooled between any two folds. It was also possible to manually apply the hot glue to the ribbon surface as part of the preparation process, and in that case the shape retention process could be semi-automated with a hot air gun (see a complementary video).

Fig. 6 shows snapshots of robotic folding of the 3D static structure. From the start to t=350 seconds, the robot folded the first plane of the structure from three 45° flexures into three lap rigid joints. From t=350 seconds, the robot folded the second plane of the structure from three 90° flexures into three 90° angled rigid joints.

The success rate for robotic folding of the three 2D structures was 100% with three trials for each structure. The success rate for robotic folding of the 3D structure was four out of seven trials. Reasons that led to failure include the folded structure not being able to pass the stop and being too heavy to be supported.

The challenge of folding a heavier structure may be solved by (1) having a vertically moving table under the folding arm, or (2) having a uniformly distributed upward air flow around the folding arm, or (3) feeding the ribbon such that the creases are within the vertical plane. The challenge of a complex structure poses limitation on the proposed method for robotic ribbon folding. This is related to the problem of collision avoidance: the folding sequence should not only make sure that the folded structure does not self-intersect, but also guarantee that it does not collide with the robot especially the folding arm. Folding a 3D structure from inside out may be one of the principles to find a foldable path with the current robot.

B. Robotic Folding of Planar Kinematic Linkages

For kinematic linkages, the robot folded a planar simple non-crossing four-bar mechanism with all bars' length of 5 cm. Since the joints in such a mechanism are not rigid, hot glue was only needed to connect the ribbon head back onto the ribbon to form a T-shape joint. Hot glue was pre-applied on the ribbon head and in the target area of connection. It was automatically activated by a hot air gun hanging over the machine during folding.

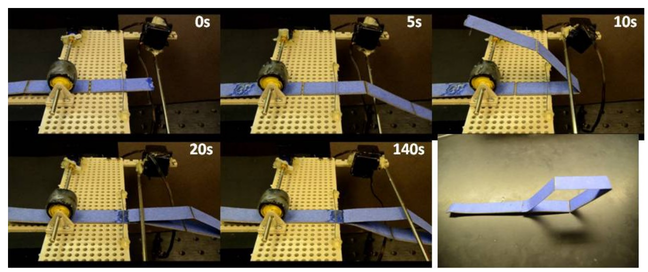


Fig. 7. Snapshots of robotic ribbon folding of a planar four-bar kinematic mechanism. From t=20 seconds to t=50 seconds, a hot air gun on top of the machine was switched on to melt the pre-applied hot glue. At t=50 seconds, the hot air gun was switched off and the hot glue was let cool passively.

Fig. 7 shows snapshots of robotic folding of the four-bar mechanism from three 90° flexures. The arm first rotated 150° near the middle of the three flexures, bringing two bars closely above the other two (t=10 seconds). The feeding wheel then fed the lower two bars forward to pass the stop, while the arm rotated another 30° to let the ribbon head lie back onto the ribbon (t=20 seconds). From t=20 seconds to t=50 seconds, the pre-applied glue was heated by the overhanging hot air gun and subsequently cooled naturally to form the T-shape joint. Refer to the complementary video for further detail.

The success rate for robotic folding of the four-bar mechanism was four out of five trials, where one trial failed due to weak hot glue connection for the T-shape joint. Burn-in was done by attaching the four pieces at the end of a 13-cm lever arm actuated by a 0.13 Nm servo motor (HS-55, Hitec, South Korea) and pressing them against a rigid horizontal surface at a range of frequencies from 0.37 Hz to 1.42 Hz. All four pieces survived the half-hour long test.

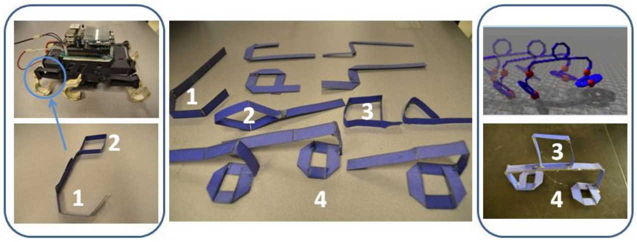


Fig. 8. Structures folded automatically by the machine, including 1 - angled ribbon, 2 - four-bar linkage, 3 - square, and 4 - intersected planes. These structures could be assembled into the leg and hip of the OpenRoach robot [23] (left) or the simulated creature (right) (figure modified from [11]).

Fig. 8 shows some of the structures folded by the robot based on the proposed method. These structures may be used as the entire or a part of a robot. For example, on the left of Fig. 8, a planar four-bar mechanism and a multi-linkage ribbon with angled rigid joints may be assembled into a replacement hip and leg for the OpenRoach robot [23]; a 2D static square structure and two of the aforementioned 3D static structure may be assembled into the body frame of a biped robot which has similar configuration as the one in simulation [11]. This suggests that one of the potential applications of the proposed method for robotic ribbon folding could be self-generation of structures for robotic self-repair or shape adaptation [22].

V. CONCLUSIONS AND FUTURE WORK

The paper proposed the concept of robotic ribbon folding as a biologically plausible approach to structure formation. A general workflow was formulated, which consists of processes of shape design, folding path construction, flexure formation, ribbon feeding, ribbon folding and shape retention. A method for physical realization of robotic ribbon folding was proposed, which includes minimally engineered ribbons with patterned flexures based on paperboard and PET sheet, a 3-DOF folding robot with a feeding module and a folding module, as well as a folding scheme which relates the orientation of flexures, the type of folds and the type of structural elements. We demonstrate for the first time robotic ribbon folding into 2D and 3D static structures and planar kinematic linkages on the macroscopic scale. Burn-in shows a simple non-crossing four-bar mechanism could move repeatedly for at least half an hour.

While the presented work preliminarily proves the concept of robotic ribbon folding, many aspects of the technology shall be improved. As discussed in Section IV, a folding path planning algorithm will be developed and implemented. A flexure formation module will be added to the machine so that a general-purpose ribbon can be used. This module may use knife cutting from one side of the ribbon to form unilateral flexures or mechanical clamping from both sides of the ribbon to form bilateral flexures. It would also be interesting to investigate simultaneous folding of a ribbon with embedded actuators and/or sensors.

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