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DESIGN OF A RECONFIGURABLE MODULAR CHAIN FOR FOLDING 3D LATTICE STRUCTURES

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ABSTRACT

A wide range of engineering applications, ranging from civil to space structures, could benefit from the ability to construct material-efficient lattices that are easily reconfigurable. The challenge preventing modular robots from being applied at large scales is mainly the high level of complexity involved in duplicating a large number of highly integrated module units. We believe that reconfigurability can be more effectively achieved at larger scales by separating the structural design from the rest of the functional components. To this end, we propose a modular chain-like structure of links and connector nodes that can be used to fold a wide range of 2D or 3D structural lattices that can be easily disassembled and reconfigured when desired. The node geometry consists of a diamond-like shape that is one twelfth of a rhombic dodecahedron, with magnets embedded on the faces to allow a forceful and self-aligning connection with neighboring links. After describing the concept and design, we demonstrate a prototype consisting of 350 links and experimentally show that objects with different shapes can be successfully approximated by our proposed chain design.

INTRODUCTION

Self-reconfigurable modular robots contain a number of identical unit modules and are generally intended to change shapes and functions through reconfiguring their modules with respect to different applications. However, this desirable reconfiguration ability comes with a high cost since each individual module requires independent actuation, communication, power, and even sensing. We believe that the benefit of the reconfigurable ability does not have to be bonded to complicated modular robot designs that generally require a high degree of integration and miniaturization of both mechanical and electronic components. Instead, we argue that some of the intended benefits can be achieved by developing low-cost, light-weight, and reconfigurable modular materials that can be repeatedly used to construct the skeleton of different structures without requiring individual sensing/actuation, but can instead be robotically assembled/disassembled.

The general approach of our proposed method is based on a concept in which a continuous prefabricated chain of links is deposited and connected to itself at joint nodes, producing structural lattices in nearly arbitrary configurations that can be disassembled and reconfigured when desired. Our design concept can be seen as a sort of 3D printer for sparse lattices, in which a robotic manipulator arm/small construction robot lays down/carries the links of a passive (non-robotic) continuous chain to create programmed truss lattices using a hierarchy of sub-modules all formed from a single chain of links and joints. The concept will be similar to modern 3D printers that lay down a heated and extruded thread of ABS thermoplastic (i.e. Fused Deposition Modeling) onto a substrate to create arbitrary 3D structures. Instead, we will lay down a chain of rigid links

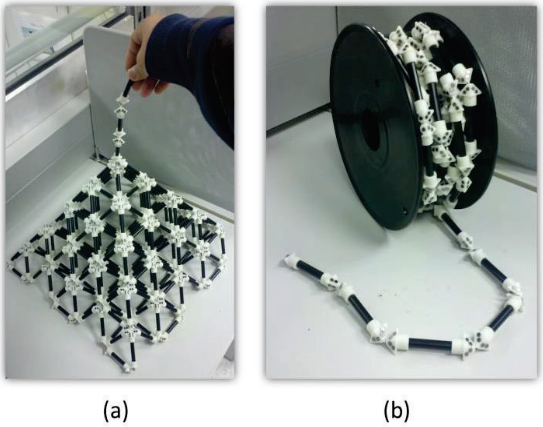

Figure. 1. PICTURES OF OUR PROOF-OF-CONCEPT DESIGN. (a) 293 LINKS ARE USED IN THE FOLDING OF THE PYRAMID SHAPE. (b) A SPOOL OF THE MODULAR CHAIN.

and joints (with appropriately designed connectors) to create lattice structures. To ensure rigidity, sub-units consisting of links folded to planar triangles will be built upon and used to form three-dimensional rigid substructures, which will be expanded to produce "large" (i.e. many-unit) target three-dimensional structures, all using a single compact general-purpose platform.

The concept provides a means of custom fabrication of structural trusses and lattices based on a simple and generic base material. By starting with a densely-packed spool of linkage chain, structures can be efficiently "deployed" in customizable configurations and geometries to meet immediate fabrication needs, and then reused/reconfigured for successive applications (see Fig. 1). The approach can be implemented in any number of size scales and materials, thereby cutting across many application domains, from millimeter-scale segment lengths for small part construction, to meter-scale segments for civil structures.

In the following sections, we first review related work, and then detail the important aspects of our design. After this, the two different prototyping processes are described in section IV. We finish by validating the efficacy of our proof-of-concept design by demonstrating the folding process of five basic geometries in section V.

RELATED WORK

In order to position our proposed design concept, in this section we briefly review the previous works that are most relevant to our project. The existing limitations of these works are not meant to be critical, but rather serve as the driving forces during the formation of our design concept.

Reconfigurable/Modular Robots

A variety of modular robots have been successfully designed and prototyped in the past two decades. As thoroughly summarized in a recent review [1], although each of them possesses distinctive shapes and features, none of them were produced in large quantities, preventing researchers from fully exploring the possible applications of modular robots at a large scale.

Even if a number of modular robots can transform into a large robot/structure, a significant portion of these modular units will be required to serve as the internal structure maintaining the integrity of the entire shape. For those modules that are only used as support materials inside a larger robot/structure, it is a waste to equip them with the same number of sensors and actuators compared to the ones serving more functional purposes. In fact, the mechanical strength of those modular robots may have already been compromised when complicated electronics and actuators are densely packed inside them. This may prevent them from forming any large shape in the first place.

Swarm Robots

Recently, over a thousand swarm robots have been deployed to demonstrate impressive assembly behaviors on a 2D surface [2]. The large number of these robots makes the entire system a good resource to investigate how biological assembly occurs in nature. But for the purpose of building 3D structures, these swarm robots cannot use themselves as the building blocks, but have to carry and manipulate separate construction materials from somewhere else. Highly distributed tasks among many collaborative robots might be an optimum solution to collect materials and build different types of habitats in nature, but may not be suitable for constructing large structures when modular building blocks are pre-fabricated.

Origami-inspired Folding

Deployable origami-inspired panel folding can realize the reversible transformation between 2D and 3D shapes [3], but sandwiching techniques are often required in order to make the folded 3D structure strong enough to withstand external loads [4]. In addition, once the mountain/valley creases are determined, the bi-state feature of the origami folding only allows the 2D panel to form a designated 3D structure.

Compared to origami folding, our proposed method allows reversible transformations between 1D chain, 2D plane, and 3D lattice structures which further improves the compactness of the folding technique.

Programmable Matter & Cellular Materials

The concept of the programmable matter is that the same amount of the material can be used to form different shapes without being consumed by the formation of any permanent fixed structure. However most of the design concepts are still at the simulation stage and can only be demonstrated with magnetic fluid.

On the other hand, cellular materials – the closest counterparts of programmable matter that currently exist – have demonstrated appealing mechanical properties by assembling a number of strong but lightweight carbon fiber struts into a lattice structure [5]. The resulting structure exhibits very large Young's modulus at low density, but also requires high assembly/disassembly precision.

Additive Manufacturing

Additive manufacturing such as 3D-printing allows the formation of arbitrary spatial geometries from a simple base material (typically acrylonitrile butadiene styrene (ABS)). Although different sparse in-fill patterns have been designed in order to save materials and prototyping time [6], 3D printers generally print parts that are greater than 50% density and require hours of operation for prototyping centimeter scale parts.

Although the convenience of making personalized parts can be achieved, the prototyping process of additive manufacturing is irreversible making it nearly impossible to recycle the materials or change the design on the fly.

NOMENCLATURE

a	Edge length of the rhombic dodecahedron
b	Edge length of the shaded triangle
c	Edge length of the shaded triangle
h	Height of the rhombic pyramid
s	Semi-perimeter of the shaded triangle
α	Opening angle at the base of the rhombic pyramid
β	Opening angle at the base of the rhombic pyramid
$A_{triangle}$	Area of the shaded triangle
A	Area of the rhombic pyramid
V	Volume of the rhombic pyramid

DESIGN OF THE RECONFIGURABLE CHAIN

In this section, we systematically unfold the important design considerations of our reconfigurable modular material from three different aspects, namely, the basic chain structure, the shape of the node, and the coupling methods between neighboring links.

3D Structure Formed by an Eulerian Path

In our design, we propose to fold the target structure with light-weight, but inherently strong truss structure. Our previous work has proved that any arbitrary 2D shapes can be approximated by folding strings along a semi-Eulerian path [7]. Previous work on sequential folding or modular assembly[8] were mainly inspired by DNA origami at the nanometer scale [9]. Most of these existing macro-scale folding/reconfiguring methods have been focused on filling out all the empty space without considering using the building materials efficiently to achieve better weight/load ratio.

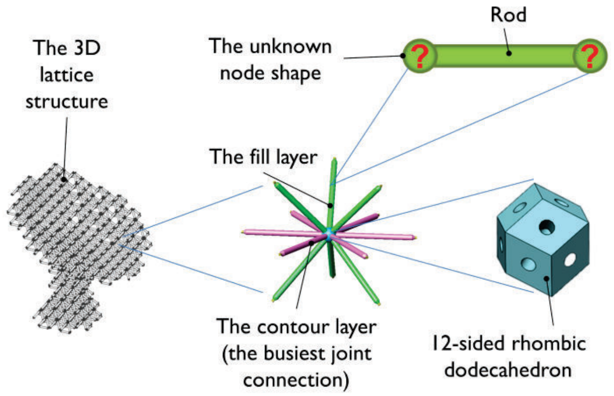

Figure. 2. SCHEMATIC DRAWING SHOWING THE DIFFERENT COMPONENTS AT THE BUSIEST CONNECTION JOINT INSIDE A LARGE THREE-DIMENSIONAL LATTICE STRUCTURE (AN ANTENNA FRAME).

We intentionally introduce mechanical constraints into the system by chaining up a series of identical links. The advantage is twofold: First, each individual link can easily locate its global position based on its piecewise information relative to its neighboring links saving the need of local sensing. Second, from a practical point of view, during the assembly and disassembly process, a piece of continuous 1D chain provides friendly infrastructure to organize deployment/storage of the used/unused units (links).

Geometry of the Node

As shown in Fig. 1, regardless the final size of the target truss structures, they all share the same types of joint connections where the chain of links meets itself at joint nodes. To meet this requirement, each link of the chain should contain two identical nodes at the ends of one common rod (see Fig.2 *top right*). Depending on the planning algorithm, different arrangements of the nodes can form different types of joints inside a large three-dimensional lattice structure (as shown in Fig. 2 *left*). Theoretically, the busiest joint may need to connect as many as 12 links through 12 identical nodes. Based on their different functions in the lattice structure, the rods at the joint can be further categorized into contour and fill layers (see Fig. 2 *middle*).

If we remove all the rods from the busiest joint and only leave the nodes with all the connecting sites exposed, the resulting joint can be geometrically represented as a 12-sided rhombic dodecahedron (see Fig. 2 *right*). Similarly, any other joint configuration can be seen as a partially formed set of 12 (the busiest joint) with some number of nodes missing. In this way, in order to design the basic shape of each individual node, we need to find a solution to cut the 12-sided rhombic dodecahedron into 12 identical shapes so that each of them can be used as the generic shape for the connector node.

The cutting process can be divided into two steps. As shown in the top row of Fig. 3, the edge length of the original rhombic dodecahedron is a. Firstly, a small rhombic

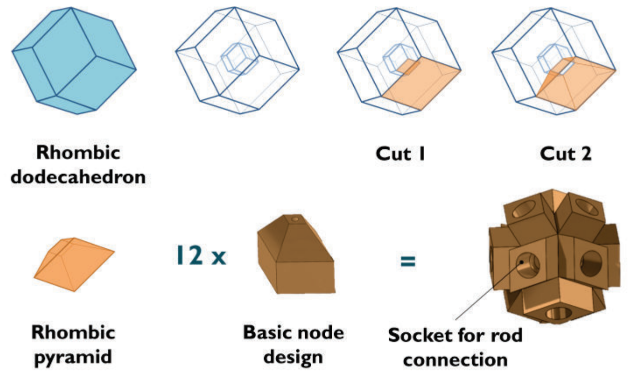

Figure. 3. THE FORMATION OF THE BASIC NODE GEOMETRY. *TOP ROW*: A SMALLER RHOMBIC DODECOHEDRON IS FIRST FIT INTO THE CENTER OF THE BUSIES CONNECTION JOINT. *BOTTOM ROW*: AFTER A SERIES OF CUTTING PROCESS, THE RHOMBIC PYRAMID SHAPE IS SELECTED TO FORM BASIC GEOMETRY OF NODE DESIGN.

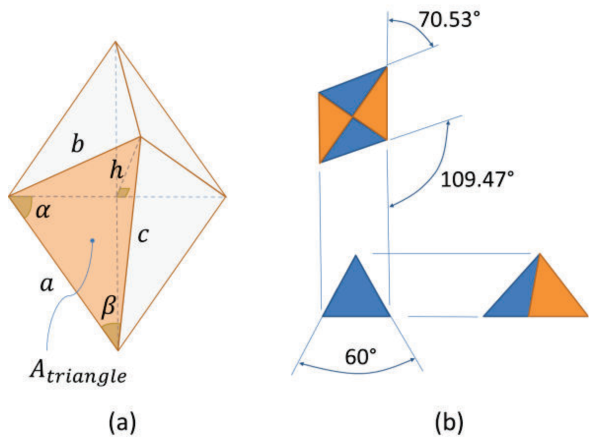

Figure. 4. THE IMPORTANT DIMENSIONS OF OUR NODE DESIGN. (a) THE RHOMBIC PYRAMID WITH FOUR SYMMETRICALLY IDENTICAL FACES. (b) SCHEMATIC DRAWING OF THE NODE DESIGN SHOWING THE CRITICAL ASSEMBLY ANGLES.

dodecahedron (with edge length equals $a/n, n > 1$) is concentrically placed inside the original one. And then, the four vertices from one face of the small rhombic dodecahedron are connected with the corresponding vertices from the outside rhombic dodecahedron. The shape bounded by the two faces and four edges is a rhombic pyramid. It has four symmetrically identical faces and is hereinafter used as the basic shape for our node design.

After adding a simple base with a socket for the rod connection, 12 of these rhombic pyramid nodes can seamlessly form the busiest connection joint without any assembly issues (see Fig. 3 *bottom row*). Although we found other basic shapes that can also be used to construct the node and form the same joint, the rhombic pyramid shape allows us to maximize the contact area between the neighboring nodes.

As the uniformly extruded rod is inherently stronger and stiffer than the connection joints inside a reconfigurable lattice structure, the contact area between the two nodes is critical to

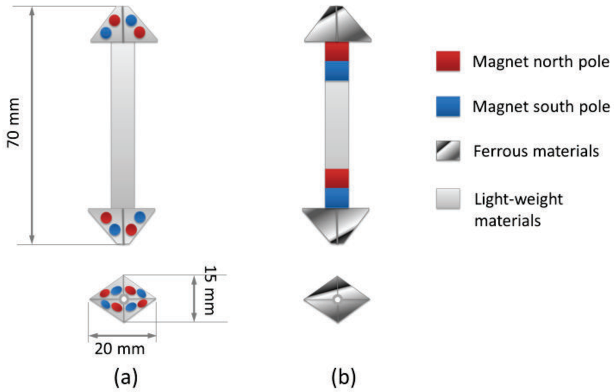

Figure. 5. TWO DIFFERENT TYPES OF MAGNETIC COUPLING USED IN OUR PROTOTYPE (a) TYPE-I – EMBEDDING PAIRED MAGNETS DIRECTLY AT THE CONTACTING SITES. (b) TYPE-II – TRANSMITTING MAGNETIC FORCES THROUGH THE NODE MADE OF FERROUS MATERIALS. *NOTE*: THE CENTRAL HOLE IS FOR ANCHORING CONNECTING STRINGS.

the stability of the entire structure. Since our proposed design is aiming for implementing the reconfiguration ability into the structures that are at either small or large scale, we are interested in knowing how the size of the node design can affect the contact area between nodes.

As shown in Fig. 4, the two opening angles at the base of the rhombic pyramid are:

$$\alpha = sin^{-1}\,(\sqrt{6}/3) \qquad (1)$$

$$\beta = \,sin^{-1}(\sqrt{3}/3) \qquad (2)$$

with the height

$$h = \sqrt{6}a/3 \qquad (3)$$

we can calculate the edge lengths as follows

$$b = \sqrt{(a * sin\beta)^2 + h^2} = \sqrt{15}a/3 \qquad (4)$$

$$c = \sqrt{(a * sin\alpha)^2 + h^2} = \sqrt{12}a/3 \qquad (5)$$

Based on Heron's formula, the area of the shaded triangle can be calculated based on the lengths of its sides by using the following equation:

$$A_{triangle} = \sqrt{s(s-a)(s-b)(s-c)} = \sqrt{11}a^2/6 \qquad (6)$$

where $s = \frac{a+b+c}{2}$ is the defined as the semi-perimeter of the shaded triangle.

Therefore, the area A and volume V of the rhombic pyramid are:

$$A = \,4 \cdot A_{triangle} = 2\sqrt{11}a^2/3 \qquad (7)$$

$$V = 4\sqrt{3}a^3/27 \qquad (8)$$

Besides distributing and guiding the contact forces, the plain contact surfaces themselves cannot directly provide any coupling forces between neighboring nodes. However its size determines the type of the latching mechanism that can be implemented in order to provide required the coupling forces. Therefore these two parameters (A and V) are important design factors.

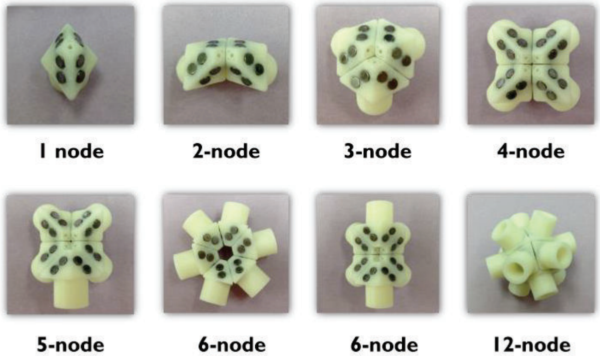

Figure. 6. POSSIBLE CONNECTION JOINTS SUPPORTED BY TYPE-I COUPLING METHOD. *NOTE*: EXCEPT FOR THE START AND THE END, ALL THE OTHER CONNECTION JOINTS HAVE EVEN NUMBER OF NODES INSIDE ANY FOLDED LATTICE STRUCTURE. RODS WERE REMOVED FOR BETTER VISIBILITY OF THE NODES.

Connection between the Nodes

The coupling between adjacent nodes is the key to maintaining the rigidity of the reconfigurable lattice structure. Depending on the size of the resulting link design, they are two major locations that can be potentially used to incorporate different coupling methods as shown in Fig. 5.

When the size of the target structure is larger than the centimeter scale, the type-I method is a good option since contact sites are abundant for implementing different types of surface features for latching mechanisms [1]. Currently we chose small neodymium magnet (3.2mm in diameter, 1.6mm in thickness, N52 grade) to validate our design concept due to its easy implementation, good strength (2.5N magnet-magnet pulling forces), and self-alignment features.

As shown in Fig. 6, the four faces of the rhombic pyramid provide an ideal platform for the alternating male-female coupling pattern. Different types of connection joints can be easily formed upon contact.

As the size of the target structure getting smaller than the centimeter scale, the size of the node and rod will also need to be reduced accordingly. Therefore fewer contact surfaces will be available for implementing type-I coupling and locations of the coupling sites need to be further pushed back towards the middle of the rod. In this case, adopting type-II coupling methods can be a good way for latching the two adjacent nodes. To this end, magnets with alternating poles can be directly attached to the ends of a rod leaving the contact sites between nodes plain. As long as the nodes are made of ferrous materials that possess good magnetic permeability. Simulation of the magnetic field confirmed that the resulting magnetic forces can help the formation of different joints inside a folded 3D structure (see Fig. 7).

It is important to recall that our proposed folding path follows a semi-Eulerian path, and therefore except for the start and end, all the connection joints have even number of nodes to allow pairing between alternating poles.

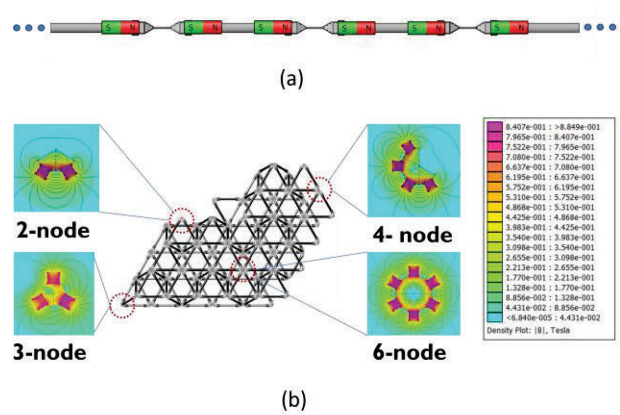

Figure. 7. 2D SIMULATION OF THE MAGETIC FIELDS BY USING TYPE-II COUPLING METHOD. (a) ALTERNATING THE POLES AT THE TWO ENDS OF EACH ROD. (b) 2D SIMULATION OF THE MAGNETIC FIELDS AT DIFFERENT CONNECTION JOINTS IN A 3D RECONFIGURABLE LATTICE STRUCTURE.

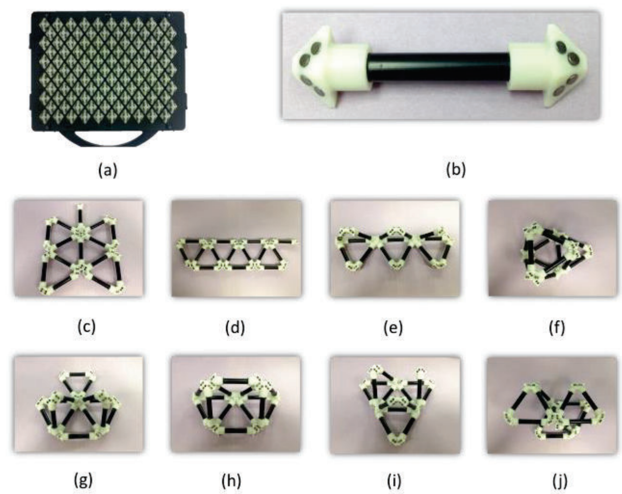

Figure. 8. The PROTOTYPING PROCESS OF NODES VIA 3D PRINTING. (a) A TRAY OF 110 3D-PRINTED NODES. (b) EXAMPLE OF A SEPARATE LINK. (c)–(j) VARIATIONS OF 2D AND 3D STRUCTURES FOLDED BY A 14-LINK CHAIN.

Although we used permanent magnets for both of the two coupling methods, the same idea can be upgraded to incorporate a variety of controllable interlocking/latching mechanisms, e.g. the electropermanent magnetic connector [10], the mechanical latching mechanism [11], [12], and even the reversible soldering connector [1].

FABRICATION PROCESS

As will be demonstrated in the Experimental section, our proposed modular material requires hundreds of links during the folding process. Based on the two different types of the coupling methods, we also experimentally explored two rapid

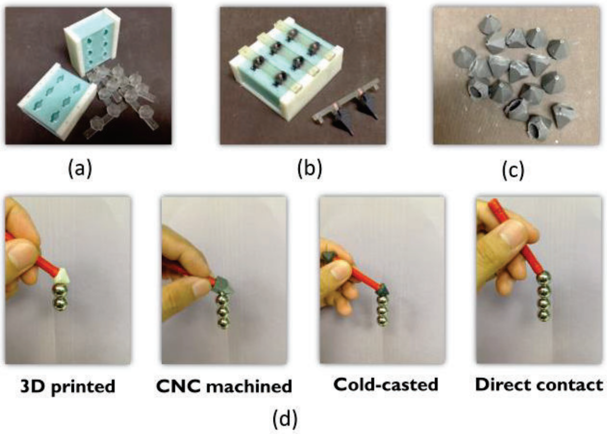

Figure. 9. PROTOTYPING PROCESS OF NODES BY USING COLD-CASTING METHOD. (a) 3D-PRINTED POSITIVES AND THE SILICONE RUBBER MOLD. (b) & (c) COLD-CASTED PARTS MADE FROM THE MIXTURE OF FINE IRON POWDER AND RESINS. (d) COMPARISON OF MAGNETIC FORCES WITH NODES MADE OF DIFFERENT MATERIALS. *NOTE*: EACH STEEL BALL WEIGHTS 8.4 GRAMS. THE RED ROD IS THE OFF-THE-SHELF GEOMAG PART.

prototyping methods in order to maximize their performance in different application scenarios. We believe a good all-around design should also consider the manufacturing methods.

The type-I coupling method has the magnetic latching mechanism directly embedded at the contact sites. Therefore it does not require special materials for the nodes. As shown in Fig. 8. An array of 110 nodes can be printed in 36 hours by using Stratasys's *u*Print. Each individual link weights 5.7 grams, and is composed of two 3D printed nodes and 53 mm long ABS tube. As shown in Fig. 8 (c) and (d), one chain can be folded into a variety of objects ranging from 2D to 3D shapes with only 14 links.

As we mentioned in the previous section, type-II coupling requires ferrous materials with good magnetic permeability to allow the transmission of the magnetic fields between neighboring nodes. Instead of using CNC machined metal nodes, we found that cold-casting method can enable us to cost-efficiently fabricate a large number of ferrous parts with good precision in a short period of time (see Fig. 9 (a)-(c)). Cold-casting is a well-established molding technique involving mixing the epoxy resins with a small amount of metal powder, and is mainly used by artists to fabricate metallic looking statues at low cost. In our case, we used high metal-resin volume ratio (99.9% iron powder/epoxy resin >7:1) and therefore each cold-casted node weights around 1.2 grams -- only 18.2% percent of the CNC machined one -- but can still effectively direct magnetic flux as well as the CNC machined one as shown in Fig. 9 (d).

However, compared to the 3D printing method used by our type-I node design, the cold-casting method needs two separate molding processes for the silicone mold and final parts, respectively. At our current design stage, the latter requires more manual work and prototyping time. Therefore in order to efficiently demonstrate our proof-of-concept design, we chose type-I nodes for the rest of the experiments.

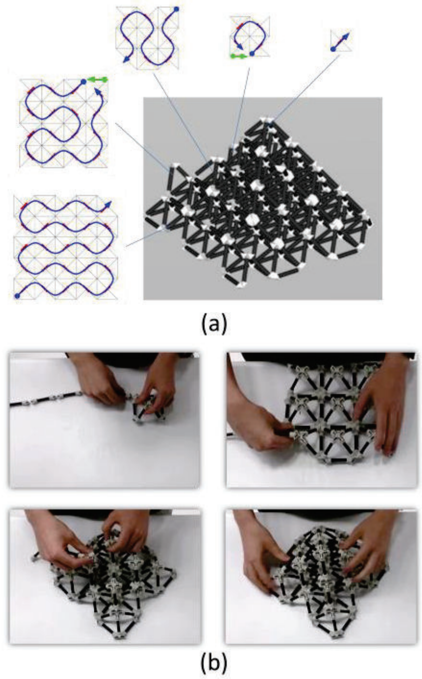

Figure.10. EXAMPLE OF THE FOLDING PROCESS. (a) THE SEPARATE FOLDING PATHS FOR CONSTRUCTUING DIFFERENT LAYERS OF A PYRAMID. (b) SNAPSHOTS SHOWING THE DESMONSTATION OF PLANNED FOLDING PROCESS.

EXPERIMENTAL EVALUATION

In order to demonstrate the reconfigurability of our proposed design, we prototyped 350 links (700 nodes) based on the type-I coupling method due to its relatively efficient prototyping process. The resulting modular chain can be compactly organized and stored by using a spool (see Fig. 1(b)) and folded into a variety of shapes by following different folding paths as demonstrated in Fig. 10 and 11.

In contrast to hours of fabrication time required by the 3D-printing process, once the folding path of a target structure is planned, all of our demonstrated structures can be quickly folded in a few minutes. In addition, the disassembly process takes even less time since the chain structure can automatically guide the unfolding process by moving from one unlatched link to the other sequentially.

As shown in Fig. 12, our design concept can also be scaled up to form much larger structures. The reconfigurability of the chain structure allows the same number of links (1554 of 0.3m strut) to be constructed into either two solar panels or one antenna frame. Since the links are all connected by compliant strings in a piecewise manner, the extra/excessive links can be easily attached/removed. In this case, the shell of a space habitat can be built by extending the chain to 7560 links.

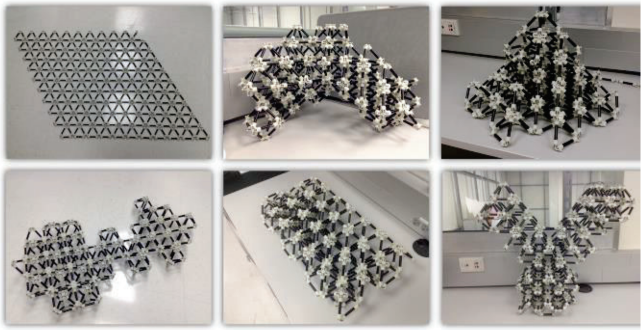

Figure.11. VARIATIONS OF FOLDED SHAPES BOTH IN 2D AND 3D (329-LINK).

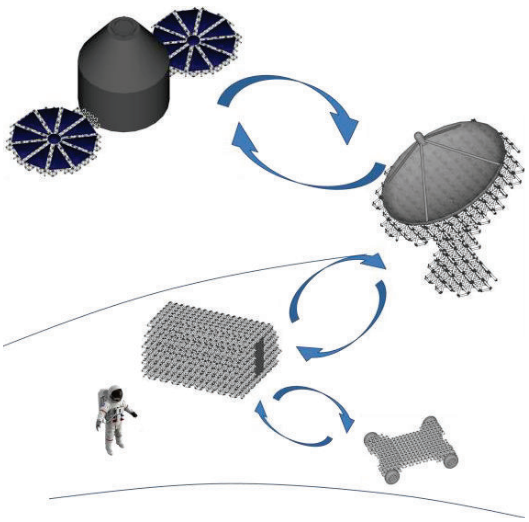

Figure.12. POTENTIAL APPLICATIONS OF OUR PROPOSED CHAIN DESIGN IN SPACE EXPLORATION. *NOTE*: THE FRAMES OF THE ANTENNA AND SOLAR PANEL ARE ALL FOLDED BY THE SAME CHAIN WITH 1554 LINKS.

With an active cell mechanism [13], the chain can also morph into shorter one, so that smaller structures can also be formed without the need of changing the chain. If we reduce the length of each link to half its original length, and remove 3534 links, the same chain can be used to form a chassis of a planetary rover.

CONCLUSION AND FUTURE WORK

We have designed and prototyped a new type of reconfigurable modular material that can be easily deployed/recycled to fold/unfold 3D lattice structures. Important design criteria were detailed about the shape of the nodes, the coupling between nodes, and the prototyping methods for two different types of magnetic latching mechanisms. We experimentally demonstrated that our design can facilitate the formation of different connection joints needed for building 3D structures, and the reconfigurability of our design can be clearly observed in both small (14-link) and large (350-link) structures. Due to its light-weight and high pre/post deployed volume ratio, we believe that our proposed design will be beneficial to a number of applications, including space exploration, construction in remote environments, and others where material weight and therefore reconfigurability is at a premium.

In future work, we will further improve the strength of coupling forces between connector nodes via mechanical latching mechanisms, as well as designing algorithms for structures of varying lattice density and strength. We will also be working towards a robotic "printer" using the chain to autonomously lay down lattice components to construct structures of arbitrary desired shapes.

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