Master's Thesis

3D Printing of Deformable Objects

변형 가능한 물체의 3D 프린팅

August 2015

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Submitting a master's thesis of Computer Science and Engineering

April 2015

Graduate School of Seoul National University

Department of Computer Science and Engineering

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Confirming the master's thesis written by Ahmad Nasikun

June 2015

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Abstract

We present a sweep-surface modeling system for designing deformable 3D objects. Utilizing parametric cubic Bezier curve as trajectory curve, we sweep an elliptic cross-section, perpendicular to the tangent vector of the Bezier curve. While 3D Printers generally fabricate static results, we develop a mechanism to 3D Print deformable objects with several degrees of freedom. We implement spine joint, hinge joint, pivot joint, and ball-socket joint to accommodate the deformation requirement. We also provide a coupling mechanism to allow the system to divide the model into several parts, to 3D Print each of them, and finally to connect the 3D Printed results. As an example of model with one degree of freedom, we create a fish model using the sweep surface technique, to which we only employ spine joint (1-DOF). Such configuration allows the fish to bend itself to the left or to the right, simulating undulatory locomotion of the fish during swimming motion. The snake model utilizes more degrees of freedom, in which multiple joints and couplings are used to allow the model to deform in multiple ways.

Keywords: 3D Printing, 4D Printing, Sweep Surfaces, Deformable Objects, Fish Modeling, Snake Modeling

Student Number: 2013-23840

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Chapter 1

Introduction

1.1 Additive Manufacturing (3D Printing)

3D Printing brings new promise to manufacturing technology by offering higher control over physical world. Conventional manufacturing employs technology that utilizes machines–such as Computed Numerically Controlled (CNC)–to add, subtract, or manipulate materials [37]. However, 3D Printing does not mold nor cut objects in the way that conventional manufacturing technique does. Referred formally as Additive Manufacturing, 3D Printing offers a new concept of manufacturing. *Additive* term on its name describes its unique manufacturing technique that fabricates objects layer by layer, additively, either by binding or depositing raw material into layers to build a solid object. Whereas the term *manufacturing* explains the fact that 3D Printers produce those layers based on certain predictable, repeatable, and systematic processes [16].

On his book, H Libson [16] claims that 3D Printers are more accurate and versatile at fabricating complex objects, compared to any other manufacturing techniques. 3D Printing technology suits well to fabrication of complex 3D objects, even with controlled internal structure, which are impossible to handle with conventional techniques [28]. For example, the Borromean Ring, shown by Figure 1.1 b, by B. Grossman can only be fabricated by 3D Printer. 3D Printers can combine raw materials in new ways, that were impossible to do with previous manufacturing techniques. At the current stage, 3D Printers on industrial scale can manufacture object as large as a car or as small as a pin, which is barely hard to see with naked eye. For the cheaper version, average home 3D Printers are capable of printing plastic objects as big as shoebox. There are also some people who customize the 3D Printer so that it can print concrete for a small house and some that produce micro-scale objects [16].

1.1.1 Properties of 3D Printer

At its full potential, 3D Printer has 10 amazing principles, even though some of them are still not present at this moment. First, the manufacturing complexity of 3D Printer is free, meaning that fabricating object of ornaments with great complexity does not require more time, skill, and cost than printing a simple six-sided cube. The second property says that

(a)

(b)

Figure 1.1: (a) Objet24 3D Printer by Stratasys [33] and (b) Borromean Ring by Bathsheba Grossman [8]

variety is free, in which a single 3D Printer can print a wide range of models. 3D Printer should neither require assembly of parts, which makes it as its third principle, with Figure 1.2 as example. The fourth principle states that 3D Printer has zero lead time for its capability in on-the-spot manufacturing. Fifth, unlimited design space opens up by 3D Printing, in which designer can produce any model, even the very complex one that, so far, only nature can produce. The 3D Printing does not require manufacturing skill either, becoming its sixth principle. Principle seven: 3D Printing is a compact and portable manufacturing. Less by-product waste is its eight principle. The ninth principle requires it to be able to mix multiple materials, thus offering infinite shades of materials. Lastly,

Figure 1.2: Pre-assembled car 3D Printed with 3D Systems' ZPrinter 650, in which all parts are fabricated in one print job, producing a complete car from the printer without any assembly required [36]

its tenth principle, 3D Printer promises precise physical replication of a certain model [16].

1.1.2 How 3D Printer Works

Generally, 3D Printer deposits material into layers, in which the material binder will bind the material on printed area and the material on unbound area is then removed, conducted per layer [27]. 3D Printing breaks down the CAD objects with complex structures, by approximating using triangular structures, into simpler geometric structures. Therefore, the quality of the printed model depends significantly on the printing resolution or sampling of voxels [12]. The process begins with reading an STL file (Standard Tesselation Language), which is currently the standard, that describes the surface properties of unstructured triangulated surface of a 3D object. It is then followed by slicing the model into layers and orienting them as defined. The system then converts the 3D model into digital pattern that consists of many thin horizontal layers. In case the object requires support structures to maintain the steadiness of the model during printing, the machine can also print such support. In this condition, the printer will output two materials: one to print the model itself and another one to produce the supporting material. There are also some 3D Printers that use same material for both model and support. The support structure can then be disposed from the model after the printing process [44].

1.1.3 3D Printer Families

There are two families of 3D Printers, namely selective deposition printers and selective binding printers. The two families differ on how they produce the layers. Selective deposition printers deposit raw materials via a certain nozzle or syringe. This family of printers is more popular for home or office usage since it is less dangerous and/or less fragile. On the other hand, the selective binding printers family normally uses laser or addhesive to bind or to fuse raw material into layers [16]. The addhesive is deposited into certain desired pattern, thus will bond grains of material into the designed shape. This process occurs on each layer gradually, until all layers of the model are printed [44]. Industry prefers this type of family because of its ability to fabricate precised output with a high speed, resulting in smooth object [16].

- **Selective deposition printers.** After model is loaded and operations sequence is planned, 3D Printer moves the print head along some set of horizontal and vertical rails, depositing materials on places that it needs to. Normally the printer head outlines the layer shape, then it will move back and forth to fill out the contour. When the first layer is done, either the nozzle is lifted slightly or the model is lowered down, in order to lay down the material for second layer. This process is repeated until all layers are printed, resulting the desired model. This type of printer has a very good advantage for being able to use wide range of materials and to be simplified for low-end version for home-usage. Any materials that can be put into a printer head then can somehow be utilized as material of this type of printer. However, the downside is that other materials that cannot be squeezed through printer head, such as molten metal or glass, requires different/additional treatment, thus, by default, are not for this family of printers. One example is Stratasys' Objet500 that implements PolyJet technology, as depicted on Figure 1.3 a.

- **Selective binding printers.** This type of printers uses selective binding mechanism to bind or fuse materials into layers. The stereolitography (SL) uses special liquid polymer which is swept by laser beam on designated parts. Those parts will then solidify, resulting a layer of solid material. The other type, Laser Sintering (LS) printers use powder. The powder placed on a special bed is traced with a high-power laser beam, that will melt down the powder on that area. The print bed is then lowered, to allow a new set of powder to be lasered down by the beam for the next layer. Selective binding printers are better choice for industrial application for their possibility in printing metal materials and for their high level of precisions that can be configured [16]. EOSINT M 280, shown by Figure 1.3 b, is a type of 3D Printer with Laser Sintering technology.

There are wide range of materials for 3D Printers, with materials from some kind of plastic filament make the majority of them. The low-temperature thermoplastics, such as PLA (*Polylactic acid*) and ABS (*Acrylonitrile butadiene styrene*), are widely used since their spools of filament can be easily sourced. Moreover, this type of material also has low melting point that will make the printing environment safer. There are some 3D Printers that can print objects from chocolate, wood, metal, food safe silicon rubber, clay, and even dead person's ashes [44].

(a) (b)

Figure 1.3: (a) Stratasys' Objet500 [32] and (b) EOSINT M 280 [4]

1.2 4D Printing

Despite its great contribution to manufacturing, 3D Printing has a major downside, it can only produce static objects. To answer the challenge of the future, 3D Printing is further developed to be 4D Printing, in which the fourth dimension refers to time, describing the ability of printed objects to alter their shapes and function, adjusting to particular external energy, after printed from nozzle [2]. This, therefore, opens up new opportunities, for which we can use composite materials that can be programmed in certain way so that the object can transform its properties (e.g. density, volume, color, shape, etc.) when it accepts a certain stimulus from external environment. Pei [22] mentions on his paper that this new paradigm, combined with advancement of multi-material Additive Manufacturing and recent development of smart materials, will open a wide range of even more opportunities and applications to come.

A field that is very close to 4D Printing is Programmable Matter/ Material (PM), referring to the capabilty of the object to be programmed in certain mechanism, to behave in particular way under certain environment. Such material offers a new paradigm in which information can be passed through physical structuture, thus enabling structural optimization and effient assembly [43]. PM is defined as the science, engineering, and design of physical matter that has the ability to change form and/or function (e.g. shape, conductivity, density, etc.) in an intentional fashion. There are at least two possible forms of PM: (a) set of unconnected voxels with ability to automatically self-assembly and disassembly to form larger structure, and (b) 4D Printer objects whose elements are connected that can transform over time or as external energy is applied [2].

One field of research that implements 4D Printing is self-assembly process, a design system in which its parts build themselves, in an algorithmic construction mechanism, according to the forces and material properties designed by developers. To achieve such scheme, there are four elements required: (a) an assembly sequence that is as simple as possible for the objects to follow, for which we may use on/off or left/right/up/down building instructions as the basis; (b) programmable parts whose states (more than one) can change overtime depending on its placement or its reaction over external force; (c) force that will activate the transforma-

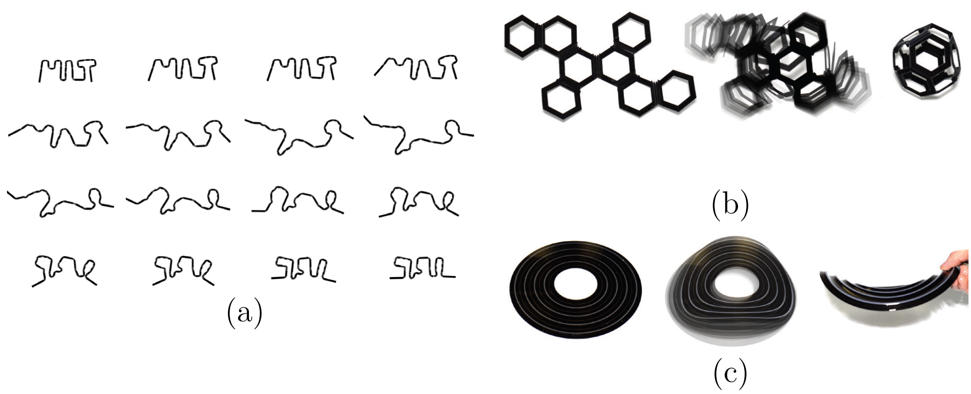
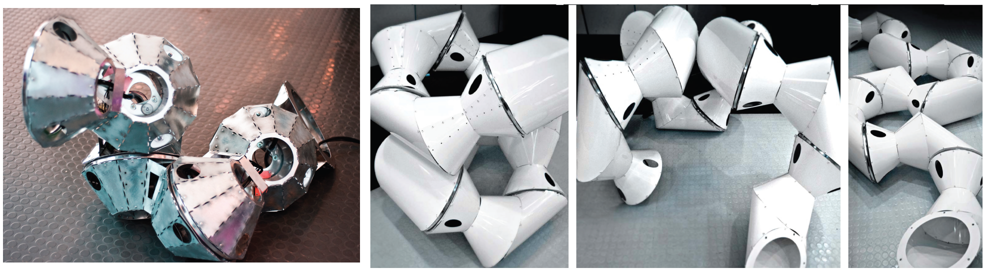


Figure 1.4: Examples of 4D Printed products by Self-Assembly Lab of MIT: (a) a strand that can transform its shape from MIT to SAL (b) flat hexadecimal faces that is able to self-fold into octahedron, and (c) a flat disc that has the capability to self-folds, becoming suddle-structure.

tion of the structure from a state to another one; and lastly (d) error correction and redundancy are required to guarantee the correctness of structure that we build [38].

1.3 Problem Statement

One very important key to 4D Printing is the usage of smart material that can fabricate multi-material object, in which over a certain stimulus the object can transform its properties, thus changing the state of the object. However, we have significant limitation for not having such 4D Printer and smart material. Therefore, our research tries to challenge how to print deformable objects, that posses 4D Printing characteristic of transformable over time, by using 3D Printer with single material only.



(a) (b)

Figure 1.5: Decibot (MIT), a reconfigurable robot chain to demonstrate self-assembly and programmable matter [38]

1.4 Contribution

We believe, after completing this research, we could contribute to the scientific community by the following:

- By using parametric cubic Bezier Curve, we create sweep surface, that represents deformable model, capable of changing its shape.
- We produce several joint models to provide various degrees of freedom (DOF) for the deformation of the 3D Printed model.
- In order to inter-connect the separated models, we design several coupling mechanisms.
- We provides Graphical User Interface (GUI) to allow user interact with the designing program in order to customize the properties of the model (number of segmentation, types of coupling, types of joint, and size of the object).

1.5 Paper Organization

The rest of this thesis is organized as follows. In chapter 2, we highlight some related works by other researchers on the 4D Printing and separation of 3D models into smaller parts. We then show our 1-DOF fish model that is constructed using sweep surface representation in Chapter 3. We explain, in Chapter 4, types of joint and coupling that we use to integrate and to allow deformation of the model. Chapter 5 features the implementation of various types of joint and coupling to produce a deformable snake model. Finally, in Chapter 6 we conclude our thesis with discussion.

Chapter 2

Related Work

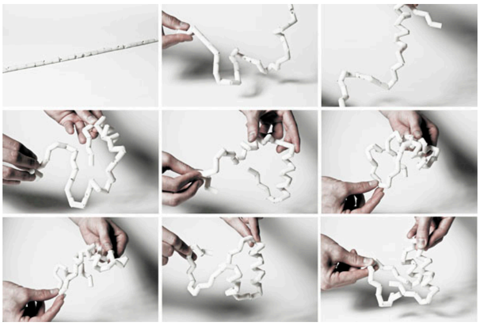
2.1 4D Printing Works

4D Printing is currently becoming hot topic in some major institutes. The Self-Assembly Lab of MIT, directed by Skylar Tibbits, has been producing great results. In 2012, they had a project named Self-Folding Proteins, in which they create a model of a single Crambin protein strand, which if thrown randomly into the air, it will randomly self-assemble into 3D structure of protein. This model gives us the full geometrical model of the protein and how it folds [41]. They extend the work into Self-Folding Surface in which flat sheets can self-fold into 3D structures [42]. Progressing even further, they create molecular self-assembly, for which, by shaking hard the structure inside a baker, it will then disassemble. If it is then being shaken again, randomly, then the parts will auto-correct and build the structure on its own [40].

Collaborating with Stratasys and Autodesk, the Self-Assembly Lab of MIT develops customizable smart materials that can transform the 4D Printed object from one state to another without human involvement. The object was designed using Autodesk's Project Cyborg and printed using Stratasys' Connex printer. By implementing this technique, using only a single multi-material print, an object can transform from 1D strand to 3D shape, from 2D surface into 3D shape, or even from one 3D to another 3D shape. The transformation can be designed to be triggered by external energy such as heat, water, light, etc [39].

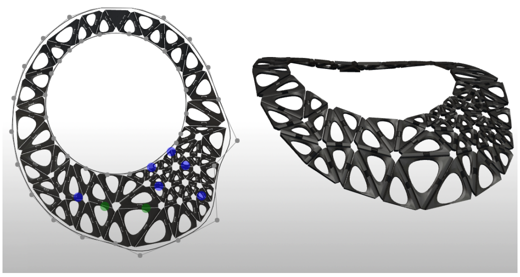
Kinematics by Nervous System uses computational model for 3D printing with joints that change their shape once being removed from build chamber. The finished object is able to self-assemble or to transform into pre-defined structure [35]. Hyperform project by Coelho uses mathematical, computational, and material folding to allow printing large structure on limited bed size of 3D Printer. Once printed, the parts unfold and stretch to extend themselves [3]. US Army funds universities to develop adaptive, biomimetic composites that have reprogrammable shapes, properties, or function when subject to external stimuli. US Navy also tests feasibility of 3D printer ammunition and builds UAV on board carrier vessels [1]

Prof. Yong Chen from University of California developed mask-image-

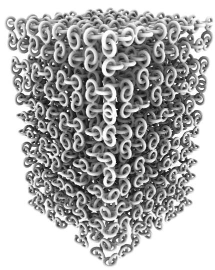


(a)

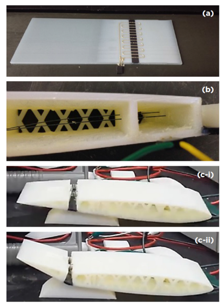
(b)



(c)



(d)



(e)

Figure 2.1: 4D Printing results: (a) 1D Protein strand by MIT, (b) BioMolecular by Self-Assembly Lab, MIT, (c) A necklace designed using Kinematics, (d) Hyperform by Coelho, and (e) wire-and-circuits compliant structure by Virginia Tech.

projection-based stereolithography (MIP-SL) process that claims to reduce the printing time. They also explore the development of faster multi-material 3D Printing process. University of Colorado and Singapore University of Technology and Design (SUTD) investigated the use of shape-memory polymer composites with grassy fibers to produce 4D parts. By controlling the amount, location, and orientation of fibers, the researchers are able to predetermine how the active composite materials will react when subjected to stimuli such as termal or mechanical forces [21]. Chirstopher B. Williams (Virginia Tech) embeds alloy wires and prints circuits into special compliant structures. The shape of the object can then be changed. Williams and Campbell merge 4D with nanomaterials, producing multifunctional nanocomposites that can change properties in response to electromagnetic waves [1].

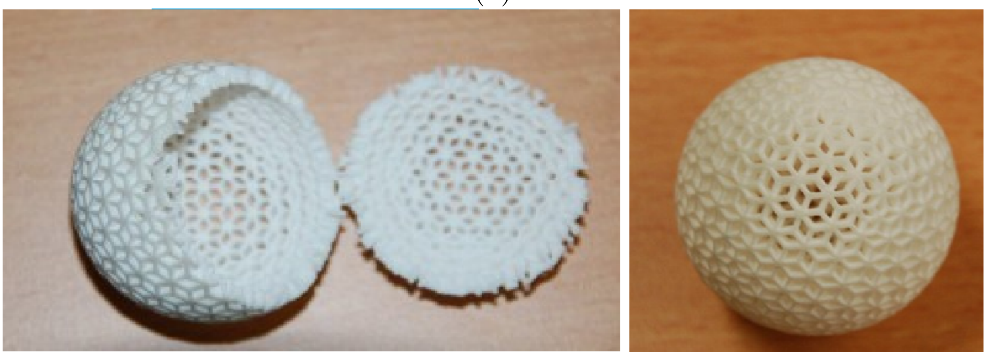
2.2 Bridging 3D Printing to 4D Printing

One main challenge in 3D Printing is its inability to fabricate object larger than build volume of the printer [18]. For example, 3Dison Plus by Rokit, allows users to print up to 225mm x 145mm x 150mm objects [26], and if one is willing to print larger models, the 3D Printer cannot accommodate. Therefore, we need to be able to partition our 3D model into smaller parts whose size is in the range of 3D Printer build volume.

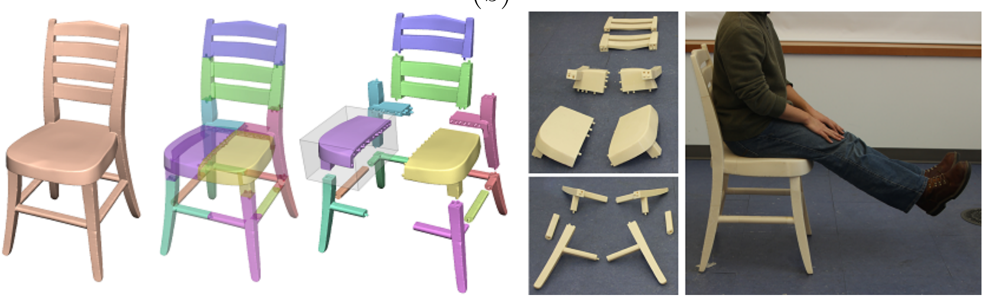
There are generally three approaches to inter-connect 3D Printed parts: (a) by employing 3D interlocks [45, 30] (b) by gluing the printed parts [29], and (c) by using male and female connectors [17, 18]. For the case of 3D interlocks, we don't have to create tiny connectors since we can use each part's geometry. It also has smooth and clean surface on the connection without any drilling. Gluing provides a strong connection between parts, however the connection is permanent, and thus once the parts are connected the glue disallows the disassembling and reassembling. Even though female and male connectors are very common for inter-connecting separated parts, the strength of connections highly depends on the design [31, 18].

For our work, we use coupling as connectors of separated parts. Because the connections are not permanent, it supports disassembling and reassembling the parts. Moreover, considering the fact that we segmented the model on its tube-like connections, we could generate the couplings in certain way that are strong enough to sustain the parts connection. Even though it requires creating extention of the part, the geometry is also quite simple to produce. Moreover, significant difference in our work from aforementioned researches is that our model is deformable after printing, thus we need to minimize its effect on distracting the deformation of the model.

(a)



(b)



(c)

Figure 2.2: Various types of parts connections: (a) 3D interlocks, (b) glue, and (c) male and female connectors

Chapter 3

Sweep-Based Fish Modeling

We model a sweep-based representation of a fish as the first object of our work. We choose to model a fish because it can be modeled with only one degree of freedom (DOF), allowing the body parts to bend left and right. The sweep-surface represention can simplify the fish modeling while maintaining the general structure of a common fish: the height increases from the head to the body, then decreases again before reaching the tail part, and raises again to form the tail. In order to make the fish body deformable, we segment the fish body into thin, tube-like structures, that are joined by connector to hold those segments together.

3.1 Fish Model and Locomotion

A big field of research in the field of propulsion mechanism of a fish is the study on how fish uses its muscles to resolve the water resistance during its motion [7]. Many researches are done to study theoretically the undulatory motions of fish. In order to analyze the propelling mechanism of fish in the water, Lighthill proposes 'reactive' theory, that investigates the reactive forces of small volume of water and body parts of fish that is in contact with the water. [14]

Although fish has a great number of variations, studies report that 2D body undulation patterns among fishes are very similar. Fish that are on steady swimming have a very similar undulatory locomotions when viewed from above [13]. The majority of fish generally produce thrust by bending their bodies, generating propulsive wave. Figure 3.1 shows the side view of 4 fish with various shapes.

3.2 Sweep Surface Representation

We can generate a sweep surface by moving a cross-sectional curve $C(u)$ along a trajectory curve $T(t)$. For example, given a cross-sectional $C(u)$ and a trajectory curve $T(t)$ as well as a time-varying linear transformation $L(t)$, we can define a bivariate sweep surface $S(u,t)$, for $0 \leq$

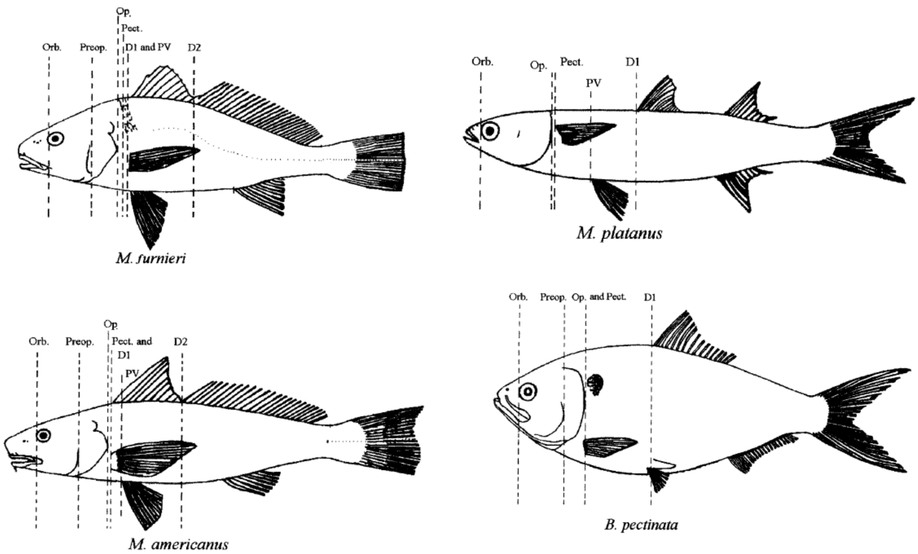
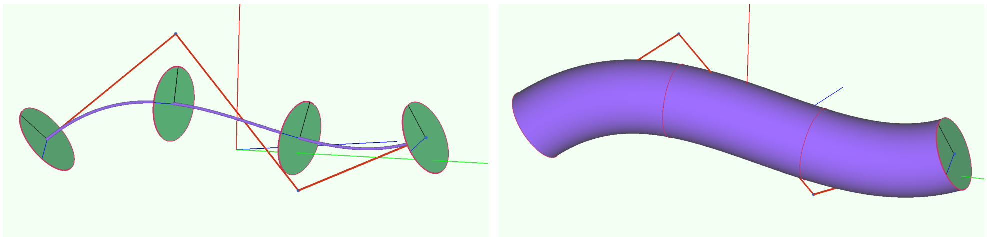


Figure 3.1: Side view of body shape of several types of fish, taken from [25]

$u, t \leq 1$, as follows:

$$S(u,t) = L(t) \cdot C(u) + T(t), \tag{3.1}$$

where the linear transformation $L(t)$ usually represents the rotation and scaling of a cross-sectional curve. Tangent vector can serve as the orientation guide, calculated on each sampling position of the curve as the derivative of the trajectory curve $T(t)$, which is generally a Bezier Curve or NURBS. Figure 3.2 shows the construction of a sweep surface with homogeneous radii, in which (a) depicts the cross-sections on control points and (b) exhibits the full sweep surface over the curve, with the circle serving as cross-sectional curve.



(a) (b)

Figure 3.2: Sweep-based representation. Figure (a) shows the cross-section discs on control points, while figure (b) is the image of a sweep-surface.

3.3 Creating Fish Model

In order to create a sweep-surface representation of a fish, we need to provide a linear transformation of its radii (two dimensions) and points location. The inputs for radii and locations are defined on the control points, and then linearly interpolated on each sampling points of the curve $T(t)$. For this fish representation, cubic Bezier Curve is utilized, implemented with formula of Farin [5], as follows:

$$
\begin{aligned}
T(t) &= B_0^3 b_0 + B_1^3 b_1 + B_2^3 b_2 + B_3^3 b_3, where \\
B_0^3 &= (1-t)^3 \\
B_1^3 &= 3(1-t)^2 t \\
B_2^3 &= 3(1-t)t^2 \\
B_3^3 &= t^3
\end{aligned}
\tag{3.2}
$$

where the B_i^3 represents the *Bernstein polynomials*. As described in [5, 23], the general form of Bernstein formula is as following:

$$B_i^n(t) = \binom{n}{i} t^i (1-t)^{n-1} \tag{3.3}$$

For the sake of rendering and Mesh model creation, we sample the Bezier Curve into 1024 sampling points. On each of the sampling point, we calculate the value of point location, its respected radii, and its tangent vector. The tangent vector is simply the derivative of cross-sectional curve $T(t)$ that can be computed using the following formula by Farin [6].

$$\frac{dT(t)}{dt} = 3(b_1 - b_0)(1-t)^2 + 6(b_2 - b_1)(1-t)t + 3(b_3 - b_2)t^2 \tag{3.4}$$

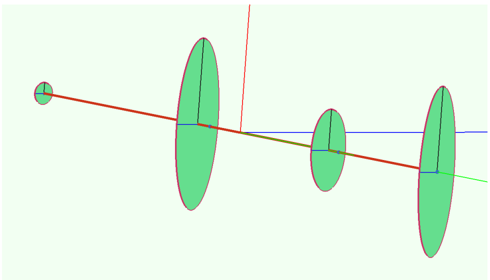
Provided that we have following forward difference formula

$$\Delta b_i = b_{1+1} - b_i \tag{3.5}$$

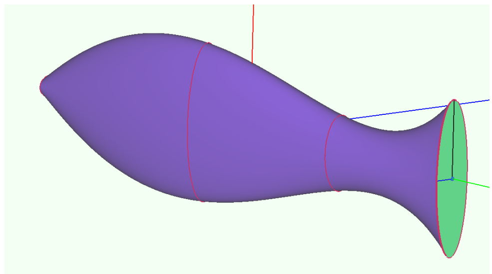
we can write the derivative formula as follows:

$$\frac{dT(t)}{dt} = 3(\Delta b_0 B_0^2 + \Delta b_1 B_1^2 + \Delta b_2 B_2^2) \tag{3.6}$$

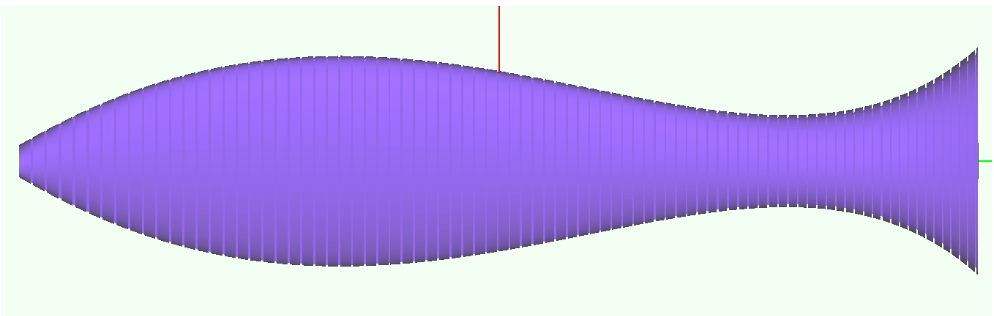
Using this point as the center, we compute a cross-section ellipse that is perpendicular to the tangent vector. The radii of of the ellipses are linearly interpolated from vertical and horizontal radii, computed at the sampling point. The ellipse–that is perpendicular to tangent vector–is then swept accross the Bezier Curve $T(t)$, with its radii changing in every sampling time. Figure 3.3 a and b show the development of such surface.



(a)



(b)



(c)

Figure 3.3: Sweep-based development. Figure (a) shows the Bezier Curve with cross-section ellipses of fish model, while (b) is the respected sweep-surface. Figure (c) displays the side view of the fish.

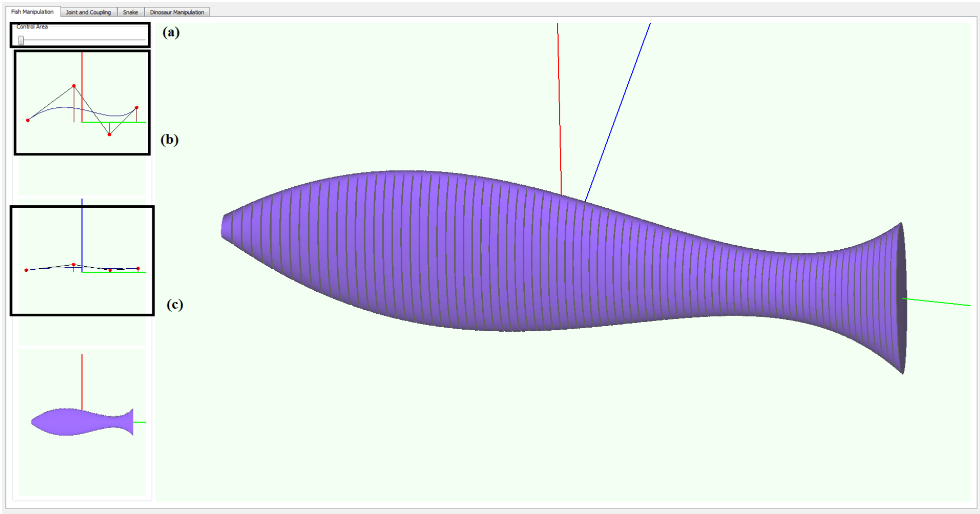


Figure 3.4: GUI for fish modeling.

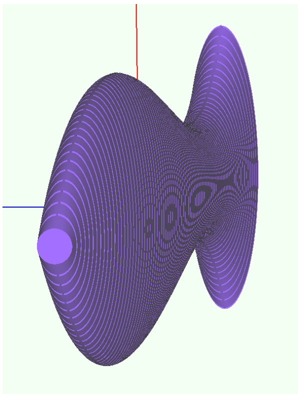
We create a fish for the first model because we can simplify the fish model so that it has one degree of freedom without violating the general structure of regular fish. With one degree of freedom, the model can be bent left and right, representing the swimming motion of a fish in the water. This bending motion, together with streamlined-body of the fish, plays significant role in allowing the fish to swim.

For more user interaction, we develop a GUI (Graphical User Interface) that allows the user to control the fish, shown at Figure 3.4. For example, user can make the tail part to be a little bit thicker, or to increase the height of its head. The slide bar is designed to enable user control the thickness of each segment of the fish.

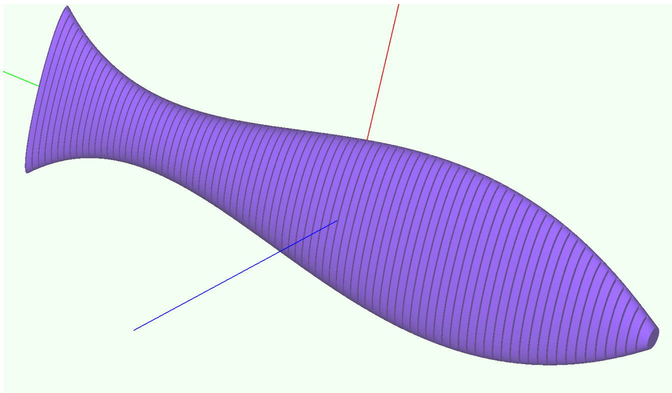
3.4 Printing Fish Model

The implementation of the one degree of freedom is conducted by segmenting the fish body into thin slices of tube-like structures, which are connected by a central axis. The axis represents the vertebrae (spinal columns) of the fish that plays important roles: (a) to connect the partitioned tube-like segments and (b) to serve as the guideline for the movement of the fish. We define the spacing between segments in accordance to the flexibility and strength that the structure needs to support. Larger distance between segments will give higher flexibility but the strength might decrease, and vice versa. In the case of 3D Printing, such characteristics are highly dependent on the properties of the material. Demanding high level of flexibility that is not supported by the material might cause the model to easily break. On the other hand, the object might not be able to move, due to its stiffness, if either the segment is too thick or the distance between segments is too close.

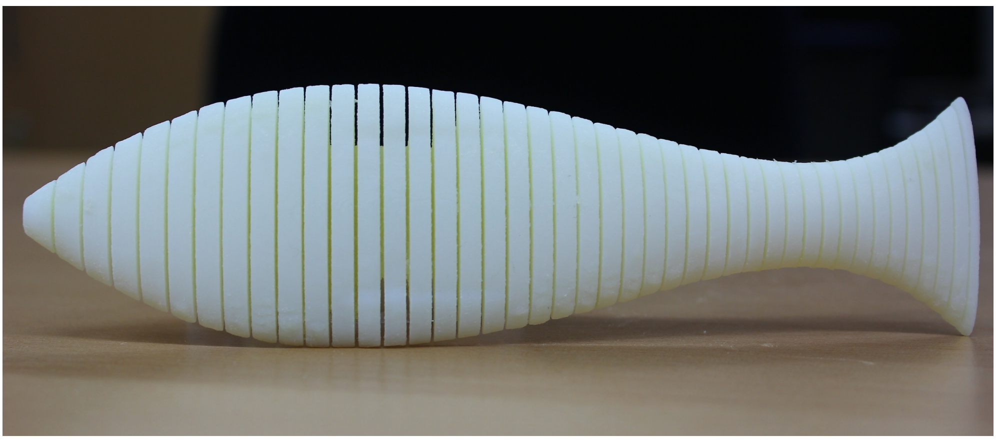
After we obtain a triangle mesh representation from the sweep-surface representation, we use basic edition of netFabb to convert the model into 3D printable STL format and to check the validity of the model. We then print our model, to get the result as shown by Figure 3.5.



(a)



(b)



(c)

Figure 3.5: (a) and (b) are the corresponding fish design, while (c) is the 3D Printed result.

3.5 3D Printed Deformable Fish

We print our model using Objet24, a 3D Printer produced by Stratasys. It uses VeroWhitePlus (Rigid Opaque White) as the model material and FullCore 705 non-toxic gel-like photopolymer support as the support material. The VeroWhitePlus has elongation at break of 10-25% and modulus of elasticity of 2000-3000MPa [34]. We tested the model with various thickness for the connector between each fish segment. Taking the elongation at break and modulus of elasticity into consideration, we print 3 various thickness of the connector: 1^0, 2^0, and 4^0 of the thickness of the fish, meaning the thickness of the connector is the $sin(1^0)$, $sin(2^0)$, and $sin(4^0)$ times the thickness of the fish body, consecutively. The fish with thickness of the connector of 1^0 becomes very flexible but is lack of strength, consequently it breaks easily. On the other hand, the fish whose connector thickness is 4^0 has a very stiff property, unable to bend. The 2^0 thickness has the best among the three, balancing the trade-off between strength and flexibility.

(a) (b)

Figure 3.6: Output of 3D Printed fish: (a) the bendable model and (b) the stiff, not-bendable one.

Chapter 4

More Degree of Freedom with Joints

In order to provide more degree of freedom to the printed objects, we employ joints in our modeling. There are several joints in animal body that allow some parts of the body to move with certain degree of freedom. For this research, we utilize *synovial joint*, which is a type of joint that allows the body to move significantly. There are 6 types of synovial joints in the animal body, namely: (a) hinge joint, (b) pivot joint, (c) ball-socket joint, (d) ellipsoid joint, (e) saddle joint, and (f) plane joint. In addition to that, as what we add to the fish (for 1 DOF), we also implement *cartilaginous joint* that is required on the spinal movement, enabling the model to bend to the right or left.

4.1 Body Motion

The joints allow the body parts to move. At the same time, they also limit the motions to certain degree. Here is the list of motions that certain joints can allow [24, 20]:

1. **Flexion**. Flexion is used to describe a movement that *decreases* the angle between two body parts. Bending the elbow is one example of a flexion.

2. **Extension**. Extension is the opposite of flexion. It is the type of straightening movement that *increases* the angle of two parts of body. For example, straightening the elbow from a bended position.

3. **Abduction**. Abduction describes the motion that pulls a structure or body part *away* from the midline of the body. One example of abduction is splaying the legs when doing a split.

4. **Adduction**. Adduction refers to a motion that pulls a structure or body part *toward* the midline of the body or towards the midline of a limb. Bringing the knees together to stand up straight is one example of an adduction.

5. **Medial Rotation**. It describes the rotation of a limb segment about its longitudinal axis, such that the anterior surface *faces* the

midline of the body. For example, rotates he toes so that it points the midline.

6. **Lateral Rotation**. It refers to rotation of a limb segment about the longitudinal axis, in a way that the anterior surface *faces away* the midline plane. One example is turning the lower limb to that it points away the midline.

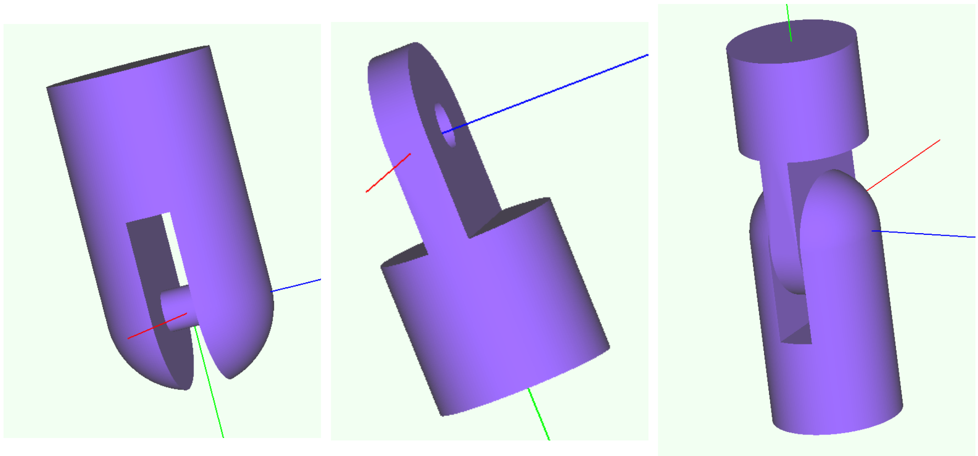
7. **Pronation**. Pronation refers to *inward* rotation around vertical axis. Rotating the forearm so that the palm faces down (while the forearm is flexed) represents an example of pronation.

8. **Supination**. Supination is the opposite of pronation, meaning *outward* rotation about vertical axis. For example, with the forearm flexed, rotating it in such way so that the palm faces upward.

9. **Circumduction**. Circumduction is the circular movement of a limb. It is the combination of flexion, extension, adduction and abduction. The spinning of the arm when performing a serve in a tennis game is one example of a circumduction.

4.2 Joint Modeling

For this project, we limit ourself to work only with three types of joint: hinge, pivot, and ball-socket joints.



(a) (b) (c)

Figure 4.1: Hinge joint: (a) top part, (b) bottom part, and (c) combined.

1. **Hinge** joint. Hinge joint, as depicted on Figure 4.1, allows the body parts to have flexion and extension. The joint that connects leg and foot is hinge joint. Another example is the joint on arm and forearm.

2. **Pivot** joint. Shown by Figure 4.2, pivot joint limits the motion of body parts to be pronation and supination only. One example is radio-ulnar joint, just below the elbow, that allows us to twist our arm.

3. **Ball-socket** joint. Ball joint is the most-complete joint since it allows the limbs to move in all axis, as can be seen on Figure 4.3. The legs are connected to the body with ball-socket joint, so are the arms to the body.

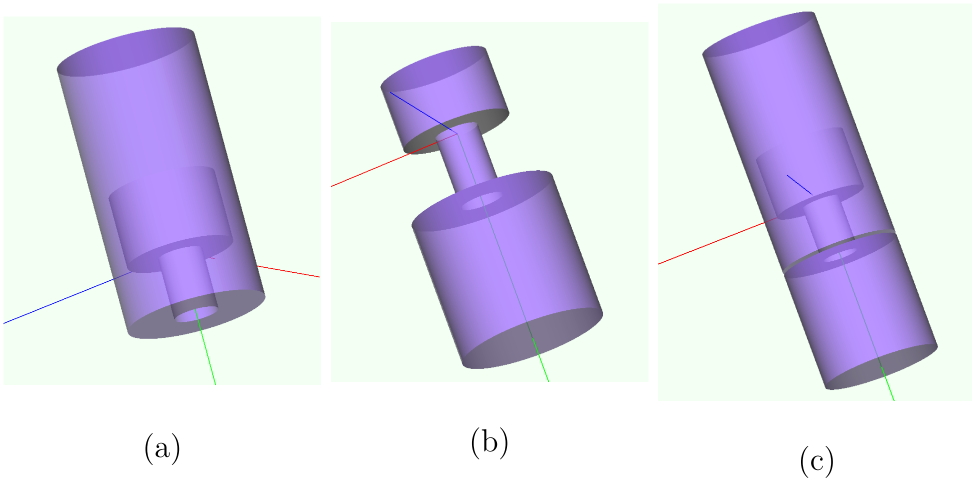


Figure 4.2: Pivot joint: (a) top part, (b) bottom part, and (c) combined.

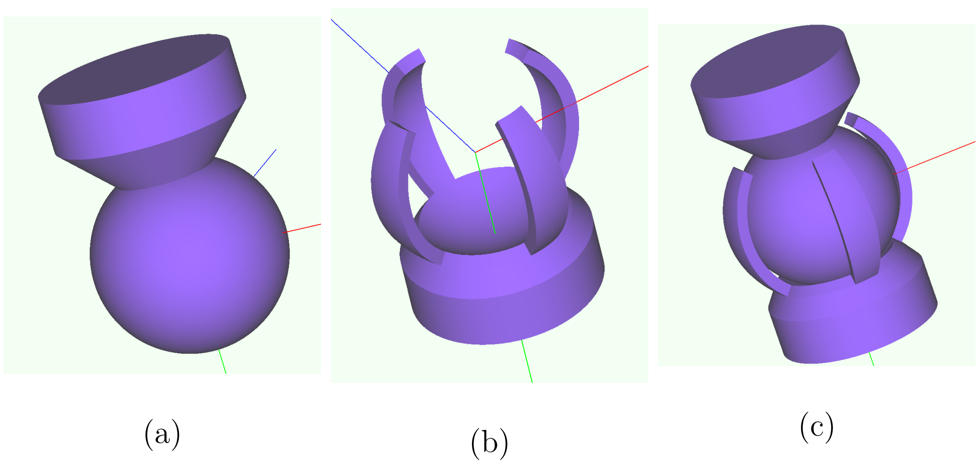


Figure 4.3: Ball-Socket joint: (a) top part, (b) bottom part, and (c) combined.

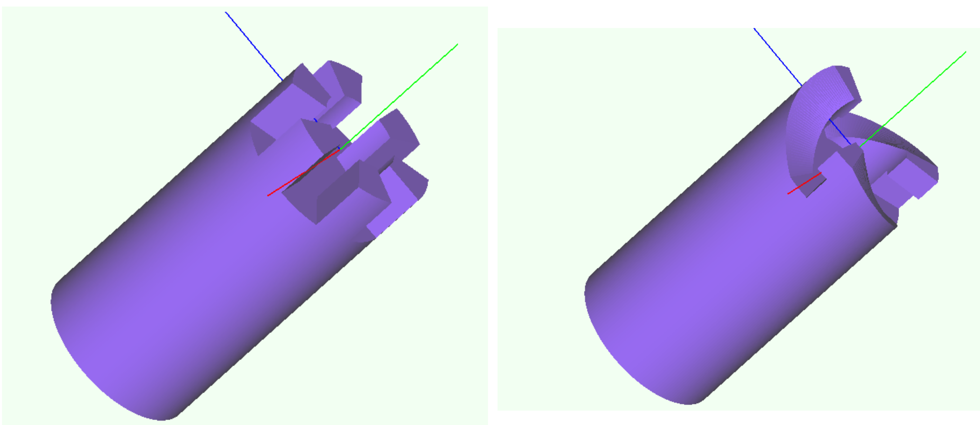
4.3 Coupling Modeling

One very important advantage that 3D Printing provides is the ability to print a fully functioning object without requirement for assembly. Therefore, we could print a single working system of an animal body with joints embedded to the body, so it can move with certain degree of freedom. However, sometimes the printer size limits the dimension of object that we can print. If we need to print a sufficiently large object, we could do so by dividing the objects into smaller parts, printing each part, and then assembling them after the 3D Printing is done. One way to make the assembling process easier is by adding *coupling* at the end of each body part.

We choose some couplings that are not complicated in design, but at the same time, are strong enough to stick parts together. Figure 4.4 shows two coupling designs that we implement in this work.

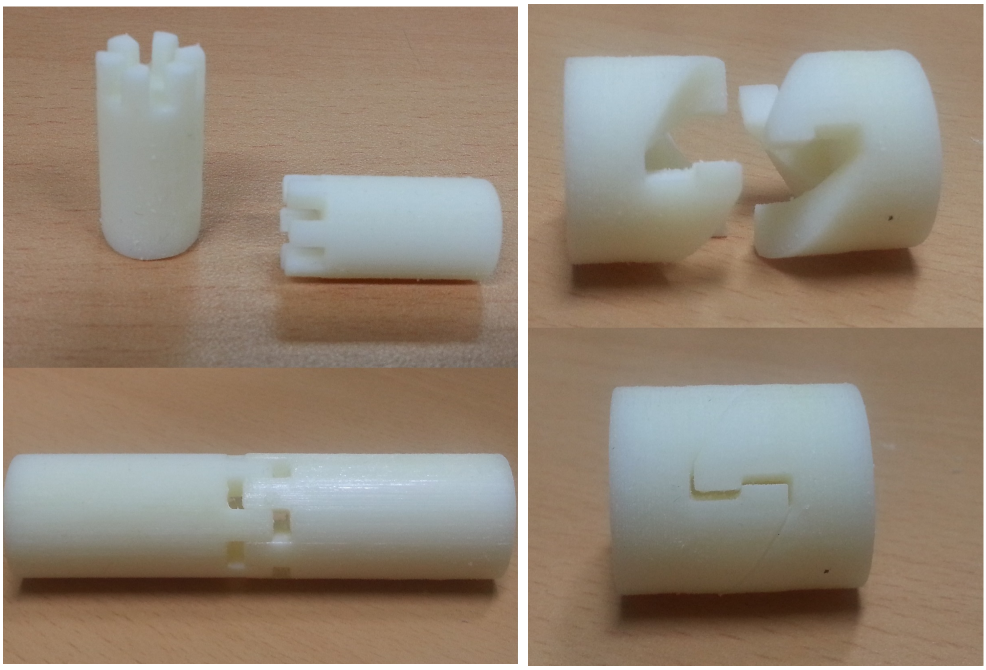
4.4 Printing Result

Using Stratasys' Objet24, we print the sweep-surface based joint and coupling models. The result of 3D Printing of couplings is shown by Figure 4.5, while that of joints can be seen at Figure 4.6.



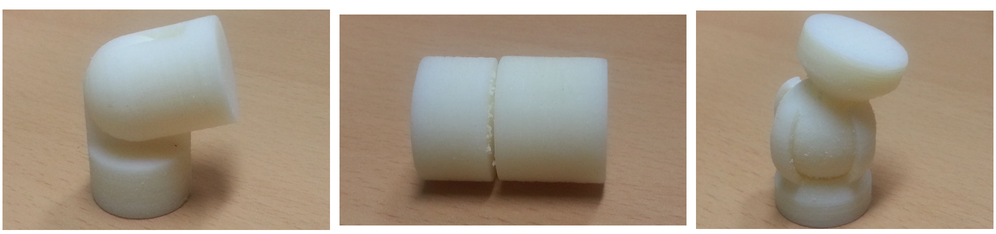
(a) (b)

Figure 4.4: Couplings: (a) symmetric regular and (b) gear-like coupling.



(a) (b)

Figure 4.5: 3D Printed couplings: (a) symmetric regular and (b) gear-like coupling.



(a) (b) (b)

Figure 4.6: 3D Printed joints: (a) hinge joint, (b) pivot joint, and (c) ball-socket joint.

Chapter 5

Snake Modeling

5.1 Snake Modeling

The general body of a snake skeletal structure consists of vertebrae and ribs, as depicted by Figure 5.1; and the body is then connected to a skull for the head. The linked vertebrae generally represent the snake structure, in which around 130-150 of them interconnect one to another, forming the general structure and also controlling the movement of the snake. On each vertebra, there is a rib attached to it, which functions to protect internal organs of the snake. Two consecutive vertebrae are connected in certain way, using ball-socket joint, so that there will be a rotation between those two vertebrae, allowing the snake to bend for lateral undulation, hence moving forward. The rotation along vertical axis is ranging from 10 to 20 degrees, a slight amount of rotation. However,

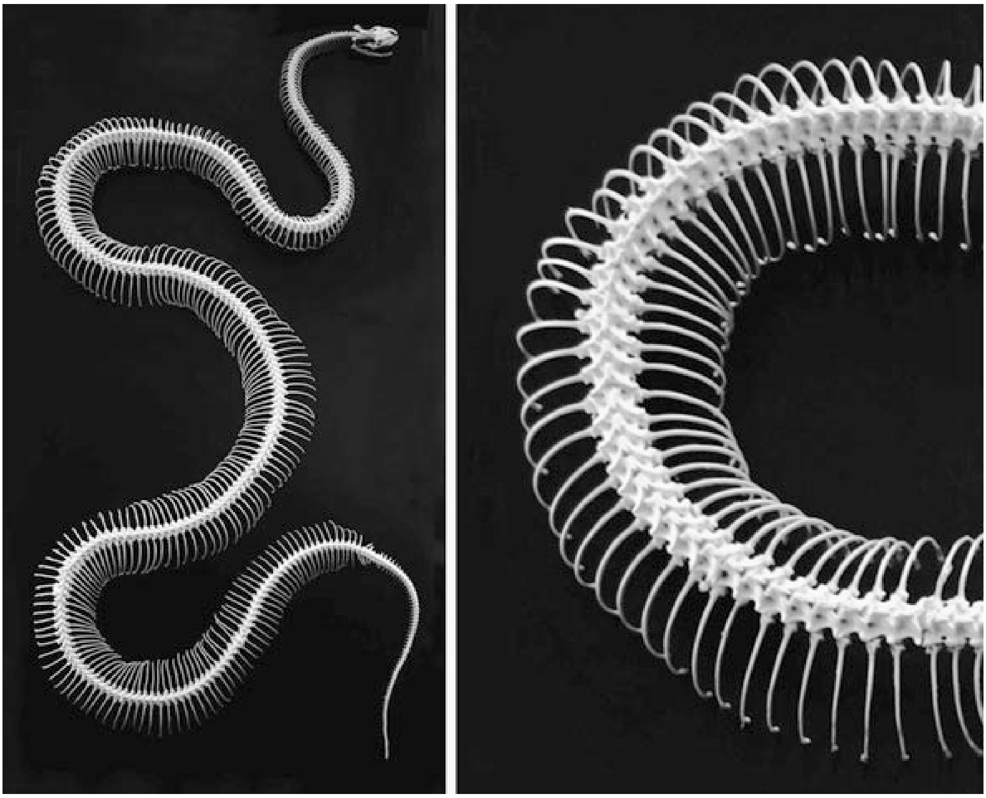


Figure 5.1: Skeletal structure of a snake

since there are many of connected vertebrae, they are all summed up into large number, and thus giving significant flexibility to the snake. Another reason for only slight amount of rotation allowed is to provide more strength for the interconnection between vertebrae, which in fact, provides more protection to the spinal due to excessive twisting [15].

With the help of muscles positioned on the each side of the snake, which are attached to the ribs, the snake can move around. Locomotion of the snake is determined by relaxation and contraction pattern of these

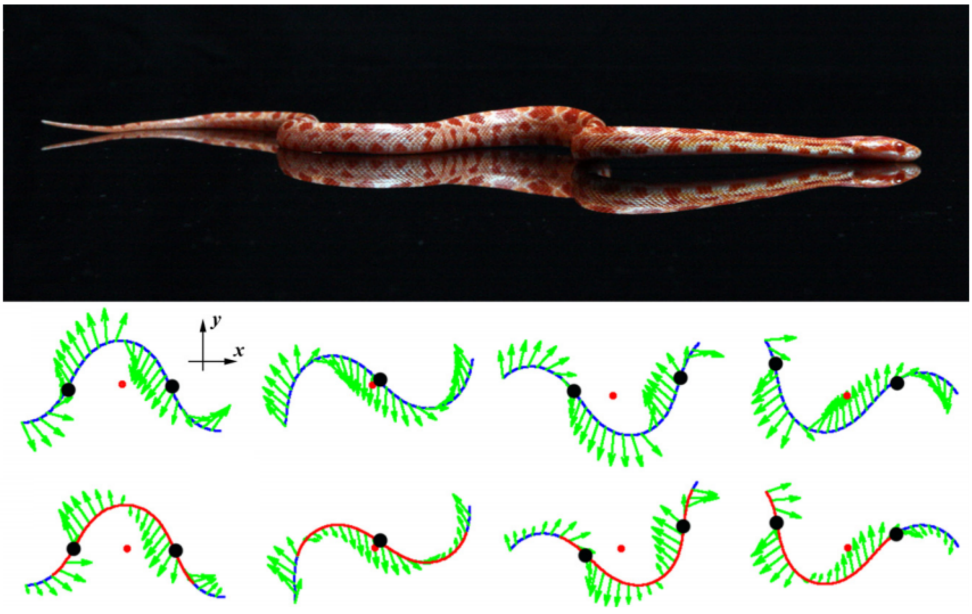


Figure 5.2: Lateral undulation by weight distribution

muscles. When the muscles on one side are contracted while the other muscles on the other half are relaxed, the body of the snake will be bent [15]. Hu et.al,. on his paper [11], mentions that such limbless locomotion can be as efficient as legged locomotion on other animals, and would be versatile on movement under uneven environment and/or narrow spaces.

Most snakes move around under a mechanism called *lateral undulation*, or sometime addressed by *serpentine crawling*, in which the snake bends itself to form a continuous wave [10][15]. While staying on that motion, the snake pushes its body against the surface, thus pushing the snake forward. In order to move forward, just like other terrestrial animals, snake manages its weight distribution in lateral undulation, by periodically loading and unloading its belly, concentrated on particular points of contacts [11], as illustrated by Figure 5.2. Such locomotion then allows the snake (a) to propel itself over a rough, uneven ground, (b) to be able to move around on a non-firm surfaces, such as sand dunes and marshland, and (c) to maintain stability over an irregular terrain [10].

For our research, we simplify the snake model so that we only work with general characteristics of it. We believe that the vertebrae are the most important properties, thus we model them using segmented tube-like cross sections. Since Objet24 has build volume limit that disallows us printing large-sized snake, we divide the snake into four parts.

5.2 Segmenting the Snake

For model with more degrees of freedom, we embed the joints and couplings, presented in previous chapter, into the model. The idea is to make the snake deformable by employing some joints. To allow users to have more role in the configuration of 3D Printed model, they can choose what type of joint to connect snake body parts. We then segment the snake model into several parts, which are connected using coupling.

Using similar technique to create fish model in previous chapter, we develop a sweep surface representation of a snake model. With several in-

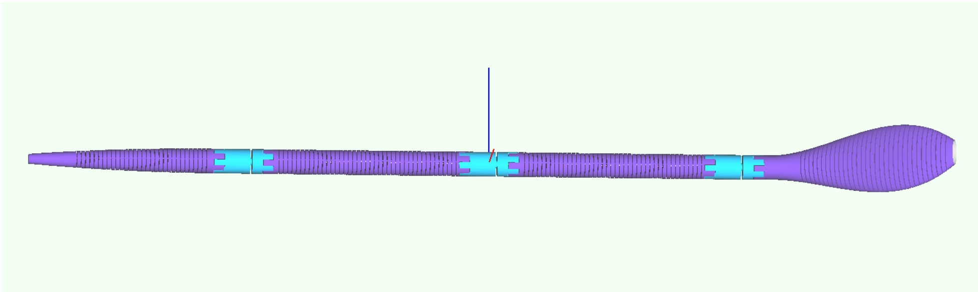


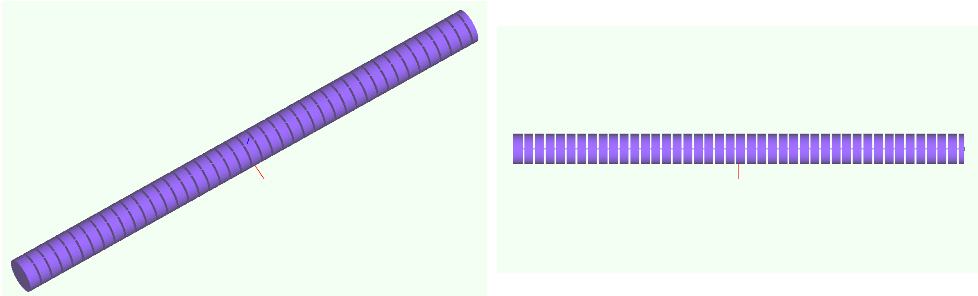
Figure 5.3: A snake model, divided into 4 segments with 3 joints connecting them.

puts from the users, namely coordinates, radii, joint length, and coupling length, the system will construct a sweep-surface representation. In order to print larger model and to allow more degree of freedom, we divide the snake into four parts, which are head, upper body, lower body, and tail. Between each consecutive parts, a joint is provided to allow movement on the model. There are three types of joints that we employ to our system, as described in previous chapter, which are pivot joint, hinge joint, and ball-socket joint. Since we also need to provide some mechanism to stick one body part to another or to a certain joint, each of the body parts and joints is installed with a coupling. As depicted in Figure 5.3, such configuration will allow the users to reconfigure the 3D Printed model, either changing the type of connecting joint, changing the coupling, or extending/shrinking the snake model.

In addition to three *synovial joints* (hinge, pivot, and ball-socket) that are mentioned earlier, we also provide the model with *cartilaginous* *joint*. We add a spine joint to our model, trying to resemble the spine joint in vertebrae, thus allowing the snake model to have more degree of freedom. It is implemented by partitioning the sweep surface into smaller thin segments, each of them is connected by a connector which is strong enough to hold them together, yet it is sufficiently thin to allow flexible movement of the body part. The spine joint, shown in Figure 5.4, allows the body of the snake to bend like original snake, enabling to form a curve shape. All of the body parts of the snake are installed with this type of joint. Some exceptions are added on tail and head, to restrict some permitted motion. Since the head need to have a curvy part, we do not add spine joint on initial, curvy part of it, making it have static, non-deformable curve at the initial. On the case of tail, since the end part is relatively smaller compared to initial part, the spine joint is omitted to avoid breakage. Each of body parts is displayed on Figure 5.5, in which image (a) shows the head, image (b) displays the tail, while image (c) and (d) provide the screen capture of upper and lower body part model of the snake.

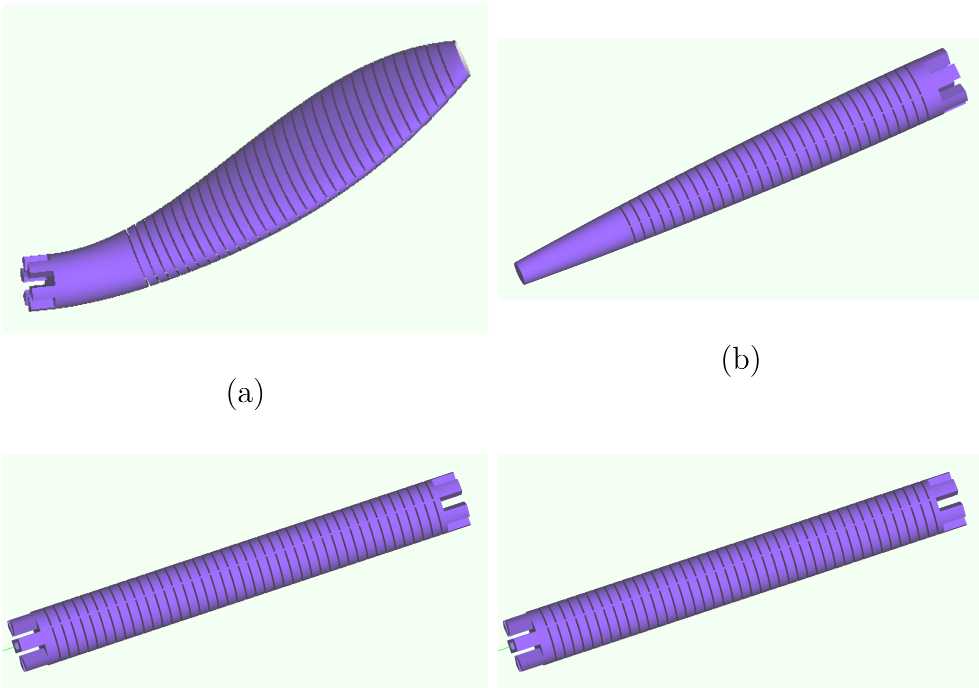
5.3 Joints for More Degrees of Freedom

In order to make the model reconfigurable, even after the printing, we provide plug-and-play joint mechanism. Both ends of the joint are



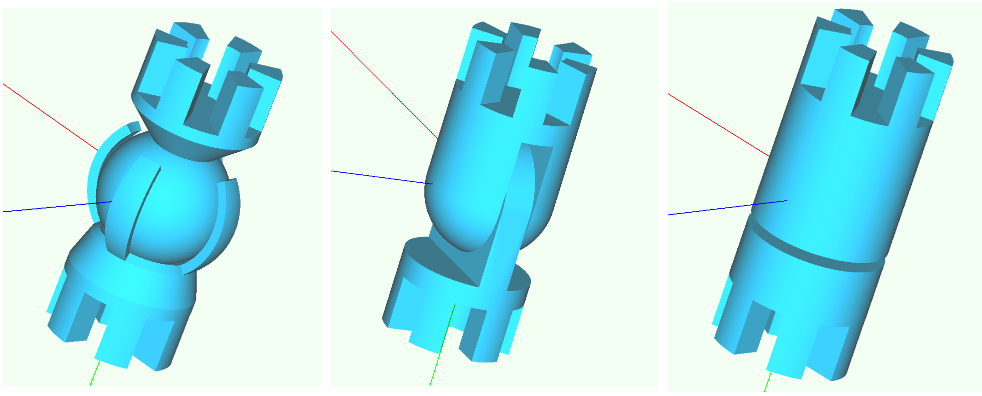
(a) (b)

Figure 5.4: Spine joints.



(a) (b) (c) (d)

Figure 5.5: Body parts: (a) head, (b) tail, (c) upper body, and (d) lower body.



(a) (b) (c)

Figure 5.6: Examples of joint: (a) ball-socket joint, (b) hinge joint, and (c) pivot joint

installed with a coupling that is compatible with the end of a certain body part, thus allowing user to reconnect two body parts with various joints. Images on Figure 5.6 display three different synovial joints that we implement in our program.

5.4 Feature-Preserving Deformation

During deformation of a model, there are cases when we want to preserve some constraints within a model, meaning that we do not want to deform every part of model in similar way. For example, in car modeling, we might want to preserve the shape of a gear, even though we bend the pipe. Yoshioka [46], Masuda [19], and Habbecke [9] implement various constraints-preserving mechanisms in their works of model deformation.

In our work, we allow the shape alteration of the snake model, but we restrict the full modification of the joints by maintaining the straigtness and local structure of the model. Given the value of radius, length of joints, and coordinates of the control points, the system will produce a straight joint, even if the general structure of the snake is bended. We only want straight joints because bent ones will not work well to serve their defined purposes. For example, in case of ball-socket joint, if the control points are not collinear then the main curve will not be a straight line producing a not-perfectly round sphere. The deterioration will also occur on the pivot joint and hinge joint.

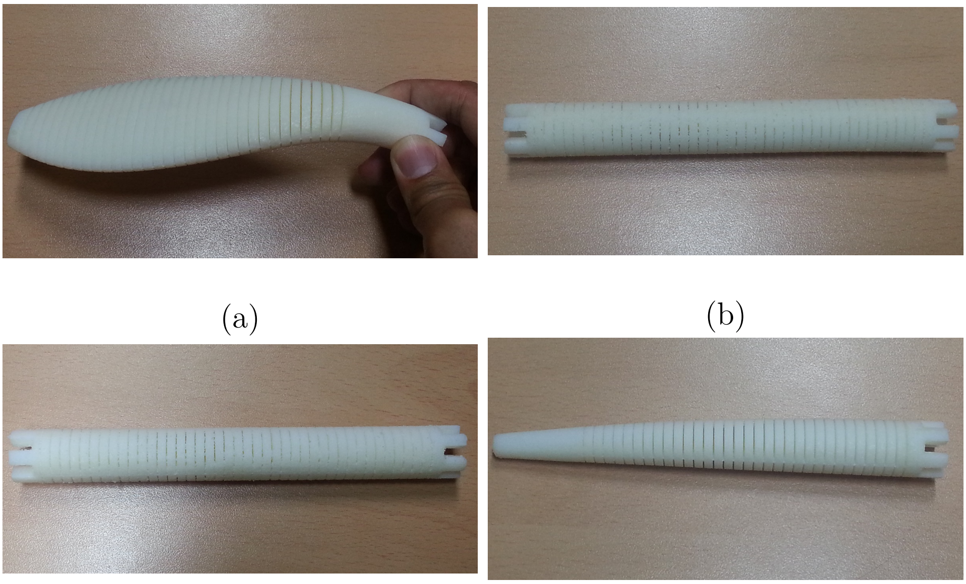
5.5 Printing Result

From the model that we construct, we print each body parts and joints using Objet24. The result of 3D Printed model, after the support material removed is shown by Figure 5.7.

5.6 Constraints of the Physical World

5.6.1 Flexibility vs strength

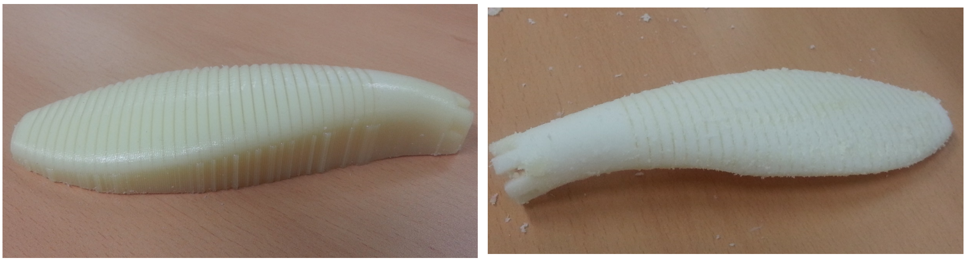
One of our main goals is to allow several degree of freedom on the model, via implementing different types of joint. Among those joint, we



(a) (b)

(c) (d)

Figure 5.7: 3D Printed body parts of the snake (a) head, (b) upper body, (c) lower body, and (d) tail.



(a) (b)

Figure 5.8: 3D Printed head (a) before and (b) after the support is removed.

use spine joint quite extensively for the body parts, in order to allow the body to be flexible, allowing the body to bend into certain degree. The spine joint is represented in segments of cross section which are linked by a connector. We need to make the connector to be strong enough to hold the segments, but also to be flexible enough to allow the body to bend in certain degree, imitating the motion of a snake. With the model material that we use (VeroWhitePlus), we need to make further adjustment to allow better flexibility to the snake, without sacrificing the strength.

5.6.2 Taking out support material

After the model is printed, there is another process required, that is, to manually take out the support material from the printed model. While it is useful in maintaining the object's shape during printing, we need to remove the support material after the printing to fully have flexible body parts of the snake. We have to be careful in taking it out since reckless action might break the connector between cross-section segments. Since the space between two consecutive segments is narrow and it has quite amount of depth, it is very difficult to perfectly take out all support material from the model. The consequence is the increased stiffness of the model, disallowing it to bend as intended. Figure 5.8 shows condition of snake's head, before and after the removal of the support.

Chapter 6

Conclusions

We have presented a modeling system to construct deformable 3D models, based on sweep-surface modeling technique. Using a parametric cubic Bezier Curve as the central curve, we swept an ellipse cross-section perpendicular to the tangent vector of the central curve. The radii and coordinates of each cross-section are interpolated linearly based on the input radii and coordinates at the four designated control points. Unlike general 3D Printing that normally outputs static model, we have developed a mechanism to allow printed model to have various degrees of freedom, thus making the 3D Printed object to be deformable. To provide such mechanism, we have employed several joints, namely spine joint, hinge joint, pivot joint, and ball-socket joint. We also have implemented coupling mechanism that allows the system to divide the model into several smaller parts, then to 3D Print each part separately, and finally re-connect all parts to construct the full body of deformable model.

For one degree of freedom, we have developed a fish model, equipped with spine joint. The joint allows the fish model to simulate swimming movement of the fish, by bending its body alternativtely to the left and to the right, representing its undulatory locomotions. For higher degree of freedom, we have designed a snake model with multiple joints and couplings, allowing the 3D Printed snake model to deform in various ways.

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초 록

본 논문에서는 스웝 곡면 모델링 방식을 이용하여 변형 가능한 3차원 물체들을 디자인하는 방법을 제안한다. 3차 베지에 매개 곡선을 궤적 곡선으로 삼아 타원형의 단면을 궤적 곡선에 수직이 되도록 스웝한다. 3D 프린터는 일반적으로 정적인 결과물을 생성하는 데에 반하여 본 시스템은 여러 자유도를 갖는, 변형 가능한 물체를 3차원으로 출력하는 기법을 제공한다. 여러 가지 변형 조건을 만족하기 위해 척추관절, 경첩관절, 추축관절과 구상관절이 구현되었다. 또한 모델을 여러 부분으로 분할하여 각각을 출력하고 그 결과물을 연결하기 위한 결합부의 추가를 제공한다. 1의 자유도를 갖는 모델의 한 예로 척추관절만을 이용하여 생성한 물고기 모델은 좌우로 굽어 헤엄치는 움직임을 묘사할 수 있다. 뱀 모델은 다수의 관절과 결합부를 이용하여 높은 자유도로 여러 가지 방식으로 변형할 수 있다.

주요어: 3D 프린팅, 4D 프린팅, 스웝 곡면, 변형 가능한 물체, 물고기 모델링, 뱀 모델링

학번: 2013-23840