RESEARCH ARTICLE

New modeling approach for 4D printing by using kinetic components

Woorim Choi1, Dahong Kim1, Sungjae Lee1 and Yong-Gu Lee1,2,*

1School of Mechanical Engineering, Gwangju Institute of Science and Technology, 123 Cheomdangwagi-ro, Bukgu, Gwangju 61005, Republic of Korea and 2Artificial Intelligence Graduate School, Gwangju Institute of Science and Technology, 123 Cheomdangwagi-ro, Bukgu, Gwangju 61005, Republic of Korea

*Corresponding author. E-mail: lygu@gist.ac.kr

Abstract

The use of smart materials in three-dimensional (3D) printing incorporates a temporal dimension to the printed object in a technique that is aptly named four-dimensional (4D) printing. In most 4D designs, the smart material is used for the whole body of the object and the final configurations can be predicted with the aid of simulations. The motions of smart materials are non-linear and computationally expensive to predict even through advanced numerical solvers. To enable the ease of integration of smart materials to 3D printing, we introduce (i) standardized kinetic components made of smart materials that exhibit basic mechanical motions, such as bending and twisting, to be used as active components for mechanical assemblies with rigid parts; (ii) an open kinetic library concept where anyone can download data on kinetic components to use in their designs, as well as upload and share their own; and (iii) simulations based on the empirical method using the kinetic components in the assembly. We provide two design implementations that utilize the standardized kinetic components: an icosahedron and a mounting platform.

Keywords: 4D printing; smart materials; kinetic library; neural networks; empirical simulation

1. Introduction

Additive manufacturing or three-dimensional (3D) printing allows the fabrication of complex 3D shapes (Zanchetta et al., 2016; Takeda et al., 2020) without the use of molds, and is finding widespread applications in various industries, including construction (El-Sayegh et al., 2020), art (Yang et al., 2021), education (Buehler et al., 2016), thermodynamics (Kim & Yoo, 2020), medicine (Prendergast & Burdick, 2020), and aeronautics (Ceruti et al., 2019; Stolt & Elgh, 2020). One of the advantages of 3D printing is the ability to incorporate multiple materials and smart materials including shape memory polymers (SMPs), shape memory alloys, and hydrogels in prescribed locations in space. The material composition can vary within the object, allowing new mechanical characteristics and behaviors (Sharma & Gurumoorthy, 2020). Four-dimensional (4D) printing, a new branch of 3D printing, aims to print parts and assemblies that exhibit shape changes in a controlled manner through designed stimulations. The added dimension denotes time where the shapes of the 3D printed parts change as programmed by the designer. The possible stimuli that trigger the shape change can encompass many environmental factors such as temperature, humidity, pH, and electric current (Tibbits, 2013, 2014).

Common 4D printed designs use smart materials for the whole body with deformations occurring only in local areas. These deformations can affect a large portion of the body even though the motion is concentrated in a small area. We sought to factor out some commonly used traits in these local deformations and reuse them within other host designs. By observing the most common deformations in 4D printed objects, we...
concluded that there are regions where shape changes were not prominent and other regions that showed large deformations leading to large movements of satellite regions. In other words, there were active and also passive regions. If the part is physically isolated based on the activity, we can denote each element to be active or passive (Ge et al., 2014; Peraza-Hernandez et al., 2014; Raviv et al., 2014; Deng & Chen, 2015; Yu et al., 2015; Wu et al., 2016). We used the term kinetic components to denote the active elements as they are the driving components that move the passive elements. This view closely resembles the practice in a mechanical design where passive links are connected by joints to exhibit kinetic movements. The only difference is that the joints become active and play the role of actuating the linked passive elements. Kinetic components made from smart materials can be assembled with passive elements and form an assembly that can be self-driven to move.

Many studies have described the use of smart materials as kinetic components to synthesize the motions of linkages (Ge et al., 2014; Noh et al., 2016; Akbari et al., 2018; Chen & Shea, 2018). In these studies, however, the authors have not explicitly mentioned the benefit of standardizing and reusing kinetic components, although many applications shared common kinetic components. In this respect, we propose to standardize the most basic kinetic components: linear, rotational, and torsional components; we also propose the concept of an open kinetic library that will contain data about these kinetic components for anyone to access and use.

Standardized kinetic components are components that can be used to introduce movement to an assembly in the same way that standard screws and nails are used to keep structures together. Components for each mechanical motion (linear, rotational, and torsional) can be made available in the open kinetic library with varying dimensions that can be chosen depending on the magnitude of motion required. The standardization of kinetic components is advantageous in various ways. It can accelerate the use and development of 4D printing technology by improving compatibility: Models of 4D kinetic components can be shared with anyone for use in any type of assembly. It can also reduce the cost and time spent from trial and error: Users can conveniently select and use the kinetic component that fits their model. Kinetic components created by researchers can be uploaded to the kinetic library. The critical information required is the motion behavior of each component. The collection of kinetic component data can be uploaded to an online server and shared freely through an open kinetic library that will contain data about these kinetic components for anyone to access and use.

In this work, two types of components are required for 4D printing by assembly: rigid and kinetic components, in analogy to bones and joints (Fig. 1). In the design stage, the user can choose standard kinetic components from the open kinetic library suitable for their model. The assembly including the rigid and kinetic components can be tested in simulation for any collisions or discrepancies in its motion. If there is any interference, the user can modify the components and run the simulation again. Once verified, the rigid and kinetic components can be printed and then assembled. The rigid and kinetic components are typically printed separately since the material used is different. For the material used in this study, the assembled model needs to be set to the initial object configuration. The
introduction of the required external stimulus then changes the initial object to its final object configuration.

2. Library of Standardized Kinetic Components for Empirical Simulation

In this study, we describe two examples of kinetic components (rotational and torsional) and how they may be compiled for an open kinetic library. We also applied the kinetic components in two different 4D assemblies with rigid parts.

The motion behavior of the kinetic components, when an external stimulus is applied, can be determined by tracking markers in the kinetic component (Fig. 2). The change in motion should be recorded with time as well as other parameters depending on the type of motion (Table 1). These data can be uploaded to the kinetic library for anyone to use. The kinetic library can host a multitude of kinetic components with varying magnitudes of motion. Because there can be so many of them available, the kinetic library can be categorized to narrow down the possible selection of kinetic components that can be used, e.g. in terms of the material type or the motion (linear, bending, torsion, etc.). The data from the kinetic library can be used in simulations for assembly with 4D printed objects.

A user might need a kinetic component that is not on the library but whose motion can be predicted from the behavior of similar components (e.g. the motion behavior of a rotational hinge component with a bending angle of 40° may be predicted from the behavior of available hinge components with initial bending angles of 20°, 35°, 45°, 75°, etc.) using a deep neural network (DNN). The uploaded information of kinetic components with similar design parameters, stimulus environment (i.e. temperature for heat-activated SMP), and motion behavior data will serve as the training dataset for the DNN to predict the behavior of requested non-existent kinetic components. On the other hand, the design parameters of a kinetic component can also be reverse engineered from the desired motion behavior using DNN.

After selecting the appropriate kinetic component from the kinetic library, the motion data, together with the designed assembly with rigid components, can be fed to a simulation to predict how the whole object will move with respect to the directed motions. Figure 3 shows the structure of the proposed method that has two main components, the kinetic library, and
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Figure 2: Collecting motion data for a kinetic component. After straining the kinetic component, a suitable stimulus is applied to recover the original shape. (a) Markers on the object are tracked and recorded to measure the change in position with time. (b) For a torsional component printed out of an SMP, the change in angle as it twists back to the original shape is recorded.

| Kinetic component | Parameter/data | Description |
|-------------------|----------------|-------------|
| All types         | Kinetic component ID | Tag that would identify the component from other components (e.g. SMP Rotational 145°, SMP Rotational 90°, etc.) |
|                   | Material type    | Indicates the type of smart material needed to print out the component |
|                   | Dimensions       | Dimensional footprint of the component (L × W × H) |
|                   | Print parameters | Includes all printer settings that will enable other users to print kinetic components directly |
|                   | Object file      | Mesh file for printing the component |
|                   | External stimulus requirement | Describes the external stimulus in which the smart material can be deformed, e.g. temperature |
| Rotational component | Initial pre-strained angle | The angle that the hinge is bent for a hinge-like component similar to the one described in this paper |
|                   | Angle of strain  | How much the hinge is bent more |
|                   | Thickness        | Thickness of the arms of the hinge |
|                   | Motion behavior data | Change in bending angle vs. time (in sec) as the component recovers from strain |
| Torsional component | Diameter | The dimensions of the rod (for the torsional component similar to the one described in this paper) |
|                   | Angle of strain  | How much the rod is twisted |
|                   | Motion behavior data | Change in the torsion angle vs. time (in sec) as the component untwists after strain |
| Linear component  | Maximum displacement | The maximum displacement measured for the component |
|                   | Motion behavior data | Displacement vs. time (in sec) |

3. Examples

3.1. Kinetic components

In this study, we utilized two kinetic components in the form of a hinge (rotational component) and a twisting rod (torsional component). Both components were 3D printed (Moment1, Moment Co., Ltd, Korea) from an SMP (SMP 3D filament, SMP Technologies, Inc., Japan) with a glass transition temperature (T_g) of 55°C. The printed components were first submerged in 100°C hot water for 1 minute before applying the strain. Each component was...
Figure 3: Schematic of the main components of the simulation using the kinetic library and empirical simulation for 4D printing. The kinetic components are taken from the kinetic library and combined with rigid parts in the modeler. The simulator visualizes the assembly and feeds it into the engine to simulate the motion of all components. When a collision or other error occurs, the user will be asked to retrieve another kinetic component from the library.

Figure 4: Motion behavior of a shape-memory polymer rotational component. (a) The component is printed out in the pre-strained position with an angle \( \theta \) defining its original bending angle. Force is applied to change the component to the strained position, with an angle of strain \( \delta \). After exposure to a suitable stimulus, the SMP recovers to its initial pre-strained position with an angle of recovery \( \delta' \). (b) The model of a rotational component (hinge). Actual SMP rotational component in its (c) strained position and (d) recovered position after immersion in 50\(^\circ\)C hot water. The arrow in (c) indicates the direction of applied strain.

dehomed using tools and fixtures based on the motion behavior of the component. For the rotational component, the hinge was bent at the center (Fig. 4), while the torsional component was twisted at the pillar (Fig. 5). In this strained position, the components were cooled down by immersing in 18\(^\circ\)C water. The recovery process can be done by exposing the component to a suitable stimulus. In this case, the SMP used can be recovered by exposing to heat at temperatures around the glass transition temperature, otherwise known as the glass transition region. For the kinetic components used in this part of the study, the recovery process was done by immersing in 50\(^\circ\)C water. The motion behavior during recovery was video recorded and tracked using point markers on the components. Analysis of the motion was done using an image analysis software (ProAnalyst, Xcitex Inc., USA).

For the rotational hinge component, three different kinds of bending angles (145\(^\circ\), 180\(^\circ\), and 215\(^\circ\)) were also tested and strained at specific angles (55\(^\circ\), 90\(^\circ\), and 125\(^\circ\)). Figure 6 shows the angle of recovery for the specific angle of strain applied to each component. Only one type of torsional component was used and tested in this respect, with a torsion angle of 90\(^\circ\). The kinetic components do not recover fully, but clusters could be observed for each component, indicating good repeatability. We defined the recovery ratio as the angle of recovery divided by the angle of strain. The average recovery ratios for the three rotational components (145\(^\circ\), 180\(^\circ\), and 215\(^\circ\)) and torsional component were 92\%, 88\%, 93\%, and 87\%, respectively. The recovery ratio can be affected by inconsistencies in the 3D printing process, including internal stresses and the temperature of the printing bed. Non-linear properties of the printing material can also affect the recovery ratio. However, using an empirical method eliminates the compound problem of determining the material properties and factors that need to be fed into the simulation. Gathering motion behavior data for a particular kinetic
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3.2. Icosahedron model

We demonstrate the use of multiple SMP-based rotational kinetic components for an assembly with rigid parts in an icosahedron model. The icosahedron is composed of 20 rigid triangular faces printed using polycarbonate (Fortus 450mc, Stratasys Ltd, Israel) and connected with 20 hinges made of SMP. In nature, many viruses can be described with this shape. The dihedral angle is 138.19°, and the polyhedron is tightly closed when all dihedral angles form this particular angle.

As we have noted in the previous section, our simulation is based on empirical observations of the movement of the kinetic components at marked locations. Before the model is printed, simulations were performed using a library of kinetic components to assess if the used kinetic components result in the correct motions and the final displacements. First, the rigid parts of the application were designed in a commercial computer-aided design (CAD) software (NX10, Siemens PLM, USA). The skeleton of the icosahedron was modeled as in Fig. 7a. Hinges were designed between the mating faces of the icosahedron to insert rotation. The parts are then imported to the simulation tool, where it is assembled. After the joining rules are instructed, the motion of the combined parts at the hinges needs to be determined. We keep a library that hosts various types of kinetic components with varying magnitudes of motion. For the icosahedron, we designed the model to self-assemble from a flat structure, thus needing a rotational component that can bend to 138.19° from 180°. The assignment of the rotational components at the hinges was made, and the simulation determined how the whole assembly of rigid parts will move with respect to the directed rotational motions at the hinges by the rotational component. In many cases, collisions may happen, or in particular, for this icosahedron model, the bending angle of hinges may not be enough to lock the faces together. In this case, the...
Figure 7: Self-assembly of an icosahedron model. (a) The 3D models for the icosahedron faces and a rotational hinge component (not to scale). (b) The icosahedron after printing and assembly of the pre-strained components. (c–g) Time lapse of the self-assembly of the icosahedron model in 60 °C hot water. (h) The final simulation result.

Simulation must be repeated using a different kinetic component at the hinges until a suitable one is found. For the empirical method applied here, simulations using 20 similar hinge components take less than 1 second, making repeated calculations easy. Hinges that allow bending at angles slightly lower than the required dihedral angle of 138.19° may also be used for this model. The printed and assembled icosahedron model (Fig. 7b) was finally immersed in 60 °C hot water. Subsequent deformation of the structure is shown in Fig. 7c–g. The final object is in good agreement with the simulation (Fig. 7h).

3.3. Mounting platform

In this part of the study, we combine multiple kinetic components, three rotational components with different bending angles, and a torsional component for the design of a mounting platform that unpacks and twists without any external power supply. The design can find use in solar panels, temporary advertisement displays, etc.

Figure 8 shows the designed mounting platform and the location of hinges where the rotational kinetic components were installed. The design used a total of eight rotational components (six hinges with a final bending angle of 180°, a hinge bent at 145°, and a hinge bent at 215°), and a torsional component that twists the whole body by 90°. Initially, the mounting platform is packed like a box by straining the rotational components. This configuration consumes a small space and is more suitable for storage and transportation.

Like the icosahedron model, the rigid components in the mounting platform were 3D printed in polycarbonate (Fortus 450mc, Stratasys Ltd, Israel), and subsequently spray-painted to an orange color. The kinetic components were then inserted at the edges (Fig. 8d). When packed, the rotational components should be bent at 90° angles (Fig. 8a), while the unpacked configuration utilizes three different angles. This was achieved by straining three unique types of rotational kinetic components to an angle of 90°. As the platform unpacks in 60 °C hot water, it also twists with the torsional component attached to the base (Fig. 8e and f). Unpacking was rapid, while the twisting of the torsional component took more than 1 minute. In concept, the speed of motion of the torsional component can be adjusted by using a different SMP material or different dimensions of the component. Figure 8b shows the final angles of four of the rotational components as seen in the side view. The two rotational components farthest from the center of the body achieved recovery angles (174.9° and 175.7°) less than the angle of strain (approx. 180°). In contrast, the rotational components near the center of the body achieved recovery angles (150.0° and 216.8°) greater than the nominal angle of strain (approx. 145° and 215°, respectively) due to the greater additional mass from the rigid components. To reduce the gap between simulation and actual values, the effect of additional mass can be accounted for if the amount of force is considered for the motion behavior of the kinetic component and should thus be included in the uploaded data. In addition, precision printers that support smart materials should also be developed to improve repeatability.

The panels of the platform are hollow, making it convenient to monitor the motion of the rotational component. In actual use, this may not be necessary. The rate of the deformation, the total amount of time for the deformation, and the order in which the individual deformation at the hinges occurs can all be customized by selecting the right SMP material used for the kinetic component. Adjusting design parameters (thickness, diameter, and height), print settings (infill percentage, print direction, feed rate, etc.), and controlling the heat transfer rate by using additives for the SMP will also affect the motion behavior of the kinetic component (Mao et al., 2015; Yu et al., 2015; Teoh et al., 2017). Furthermore, the glass transition temperature can be fine-tuned to make the structure respond differently from the environmental stimulus (Mao et al., 2015; Yu et al., 2015). For designers and researchers working on applications, optimizing the kinetic components individually may not be possible. As such, they may benefit more from using an open kinetic library as we have proposed in this work.
Figure 8: Mounting platform. (a) The design for the mounting platform incorporates multiple rotational components for unpacking and a torsional component that twists the whole body. (b) The final unpacked platform, with four of the rotational component angles, is shown. (c) The final simulation result. (d) Part of the actual printed mounting platform before applying strain to the kinetic components (white). (e) The mounting platform unpacking as seen from the side and (f) twisting as seen from above. The images were taken at the same time points for the side and top views, with the side view camera tracking only one side of the unpacking platform.

4. Conclusions

We proposed the use of standardized kinetic components that can be made accessible to everyone through an open kinetic library for use in simulations. The simulation used in this study is based on an empirical method to predict the motion of 4D printed components. Because we use an empirical method, there is no limitation in supporting new uncharacterized materials for 4D printing as long as the motion behavior is well defined. Examples of standardized components that can be reused in various applications were introduced. These kinetic components are supported in the simulation tool by allowing the representation, storage, and replay of the motion data. We have proposed a way to standardize kinetic components through the concept of a kinetic library where anyone can define unique kinetic components and upload their motion behavior and parameters for everyone to access and use. We have provided two assemblies that use standardized kinetic components: an icosahedron model transformed from a flat structure and a mounting platform that can unpack and align itself to a specific direction without a power source. The first example shows the possibility to print flat structures and make the assembly fold itself to a target shape. The second example presents a mechanism that
is self-powered and initially compact, suitable for storage and transportation.

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Conflict of interest statement

None declared.

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