

RESEARCH ARTICLE

New modeling approach for 4D printing by using kinetic components

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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 (Tibbitts, 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

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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. The shared platform will play an important role in 4D printing by making the data of various kinetic components accessible to designers and researchers worldwide. The uploaded parameters such as print settings, dimensions, and stimulus requirements can be used for many purposes. For example, it can be used for analysing the relationship between parameters and motion behavior, reverse engineering, design optimization, and predicting motion. Various simulation protocols can be utilized in modeling assemblies with the standardized kinetic components from the open kinetic library. A key advantage of the kinetic library is that the quality or reliability of the data can be improved by sharing it with other users.

The general method for 4D printing involves the design and simulation of the whole assembly of components, typically, using the finite element method (FEM) for the simulation. The understanding of how local deformations can bring unwanted collisions between parts requires a special simulation tool. However, numerical simulations of structures made of smart materials are complex and time consuming. Multiple studies have been

conducted to reduce the dimensions used in FEM simulations or arbitrarily setting simulation parameters to improve computational efficiency (Kokkinis et al., 2015; Mao et al., 2015; Kuksenok & Balazs, 2016; Mao et al., 2016). Because of the visco-elastic nature of smart materials, it is difficult to model non-linear behavior. In our approach, we have developed an empirical model to predict the motions of the kinetic components. The model is based on the motion behavior of the kinetic components and applying it to an assembly that includes the kinetic components at the joints. Empirical methods are preferable when the deformations are non-linear and existing numerical methods are computationally expensive and inefficient (Zhang & Moon, 2021). The benefit is that because no physical model is used in the simulation modeling, we can incorporate different types of kinetic components. This is a great benefit because many 4D printing examples use different physical equations and require entirely different constitutive models. The difference lies in the fact that previous studies only considered simple hinge folding, whereas we can consider more types of motions, including linear and torsion. Furthermore, when they can only simulate simple relative motions between two components, we can simulate much more complex motions involving a multitude of rigid parts along with kinetic components at the joints. When parts collide during the motion, the simulation tool can report the location of the collisions and all joint angles that incurred the collision.

Previous works were also limited to specific smart materials (Lan et al., 2009; Gladman et al., 2016; Noh et al., 2016; Choong et al., 2017; Ma et al., 2017; Akbari et al., 2018; Chen & Shea, 2018; Chen et al., 2019; Jeong et al., 2019). On the contrary, we allow the use of any smart material since the method is not explicitly tied to any smart material, as long as the motion behavior can be measured. New smart materials are being developed to improve response to stimuli for use in 4D printing (Shie et al., 2019; Zafar & Zhao, 2020). To be useful in 4D printing with FEM simulations, these materials have to be extensively characterized, and some properties such as heat transfer coefficient or photostrictive coefficient may be difficult to measure. FEM typically requires numerous parameters for the simulation. For example, 23 model parameters were used for a finite model of SMPs (Westbrook et al., 2011). On the other hand, the main advantage of the empirical method for simulation over FEM is that it does not require the physical properties of the materials but only its motion data. Another benefit of our empirical prediction model is that the simulation takes only a few seconds to run; therefore, the outcome of changes in design can be readily verified in real time. The FEM simulation method generally needs a few hours to days depending on the model and mesh size, making it difficult to adopt as a prediction tool in the design stage. With the introduction of new smart materials, the use of the empirical method for simulation can accelerate their use in 4D printing technology.

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

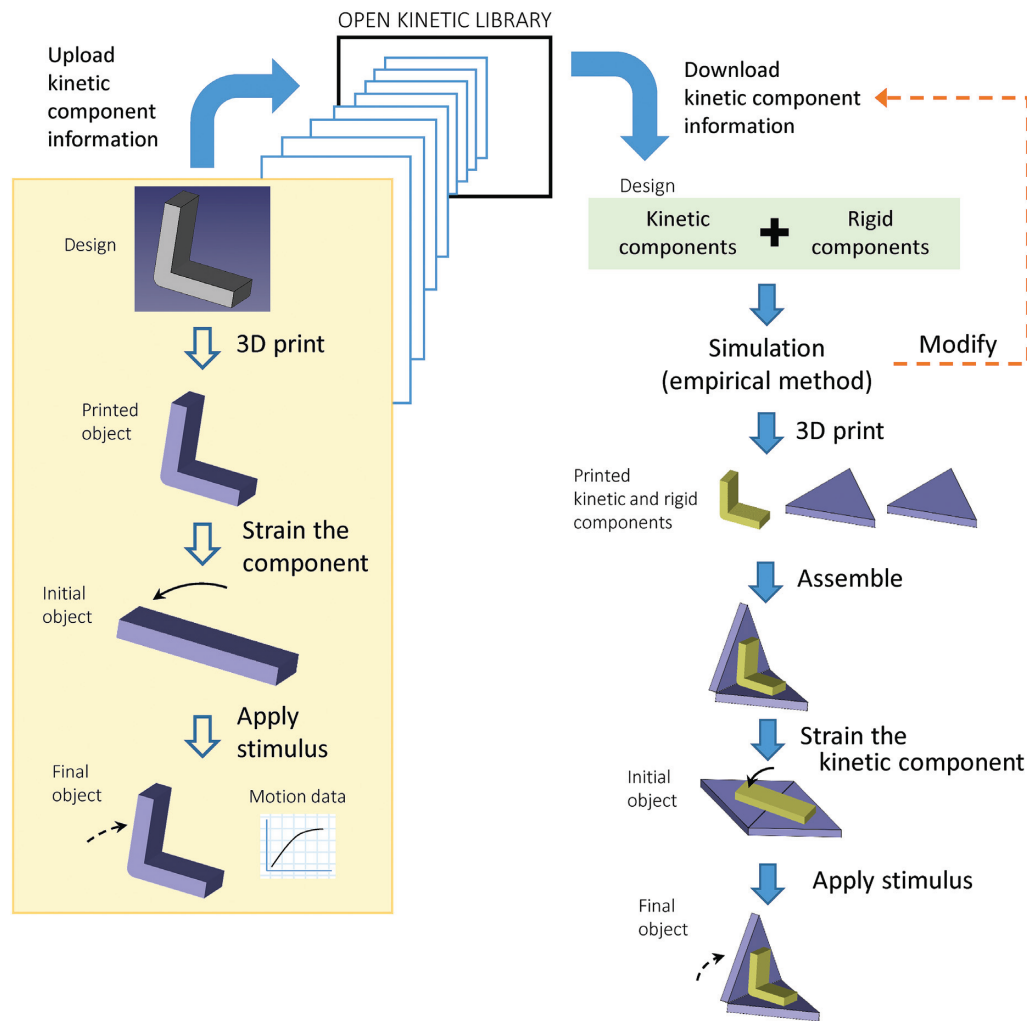


Figure 1: Proposed workflow for 4D printing using kinetic components and the empirical method. Researchers can measure the motion data for each kinetic component and store them in the open kinetic library. Users can then retrieve and incorporate available kinetic components in their design, and then simulate using the empirical method.

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 but whose motion can be predicted from the behavior of available hinge components 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

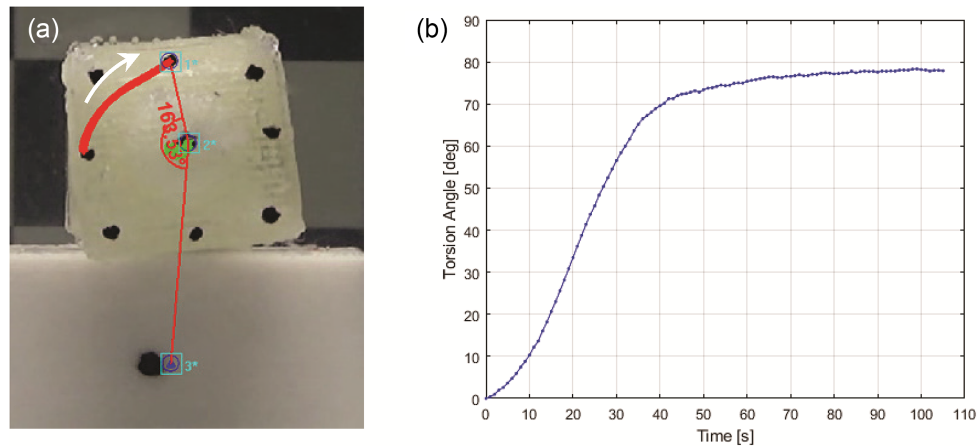


Figure 2: Collecting motion data for a kinetic component. After straining the kinetic component, a suitable stimulus is applied to recover the original shape. (a) Markers on the object are tracked and recorded to measure the change in position with time. (b) For a torsional component printed out of an SMP, the change in angle as it twists back to the original shape is recorded.

Table 1: Example data and information requirements for uploading to the kinetic library for different kinetic components.

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)

a simulation tool consisting of a modeler, an engine, and a simulator.

The modeler visualizes the design of the assembly of smart materials and rigid components. The modeler includes the simulator and the engine for visualizing the predicted outcome for the whole assembly when the kinetic components respond to an external stimulus. The engine in the simulation tool calculates the motion behaviors of smart materials with time, based on the empirical method using the motion data of the kinetic components. First, parameters and functions from the kinetic library decide the expression of deformations of smart materials when an external stimulus is applied. These data are used in the design of the assembled model in the simulator, and the engine infers the behavior of the smart material and checks collisions between parts of the model using environment values in

the simulation. When a collision is detected, the model can be modified by choosing another kinetic component until a suitable one is found.

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 (Tg) of 55°C. The printed components were first submerged in 100°C hot water for 1 minute before applying the strain. Each component was

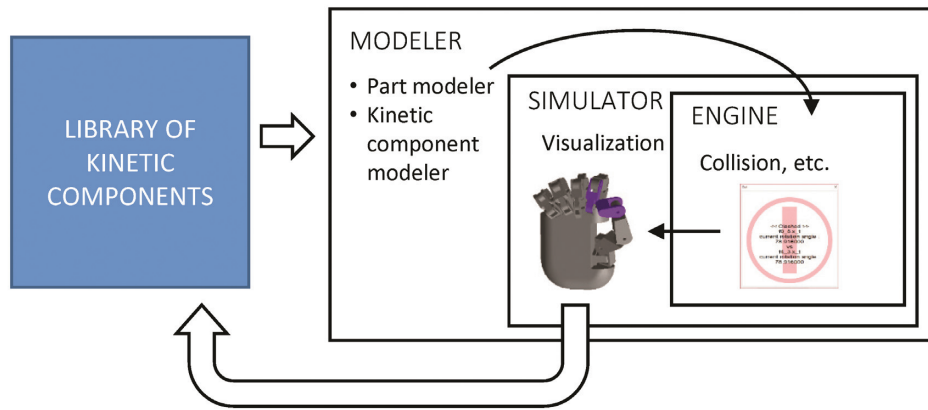


Figure 3: Schematic of the main components of the simulation using the kinetic library and empirical simulation for 4D printing. The kinetic components are taken from the kinetic library and combined with rigid parts in the modeler. The simulator visualizes the assembly and feeds it into the engine to 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.

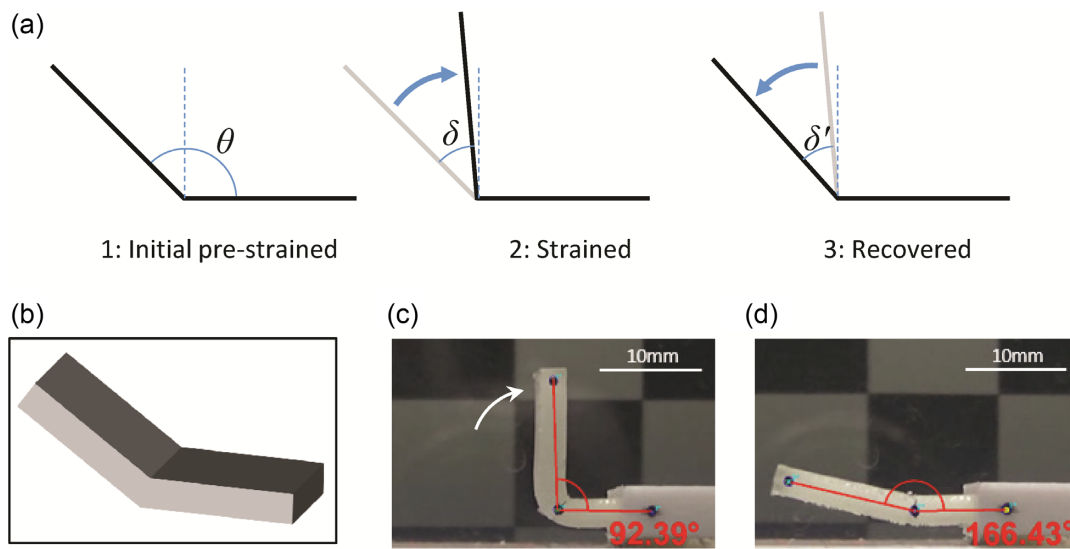


Figure 4: Motion behavior of a shape-memory polymer rotational component. (a) The component is printed out in the pre-strained position with an angle θ defining its original bending angle. Force is applied to change the component to the strained position, with an angle of strain δ . After exposure to a suitable stimulus, the SMP recovers to its initial pre-strained position with an angle of recovery δ' . (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°C hot water. The arrow in (c) indicates the direction of applied strain.

deformed 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°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°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°, 180°, and 215°) were also tested and

strained at specific angles (55°, 90°, and 125°). 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°. 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°, 180°, and 215°) 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

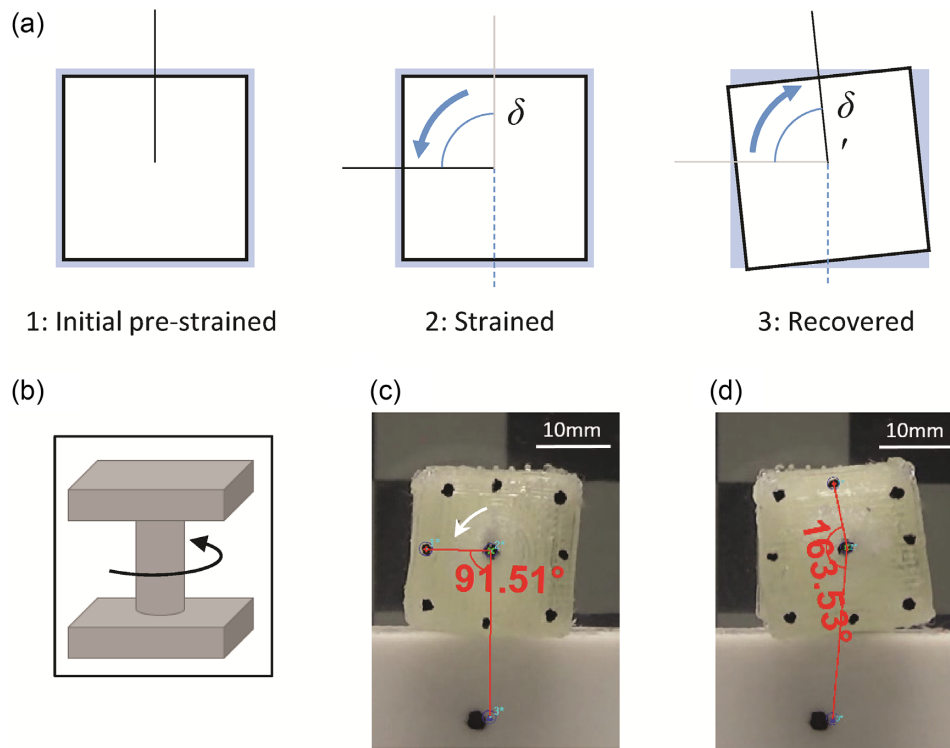


Figure 5: Motion behavior of a shape-memory polymer torsional component. (a) The component has a rigid bottom base and a top stage that rotates when the pillar is twisted to the strained position. Here, the angle of strain is defined with the vertical as reference. After exposure to a suitable stimulus, the component recovers to its initial pre-strained position. (b) The model of a torsional component. Actual SMP torsional component in its (c) strained position and (d) recovered position after immersion in 50°C hot water. The arrow in (c) indicates the direction of applied strain.

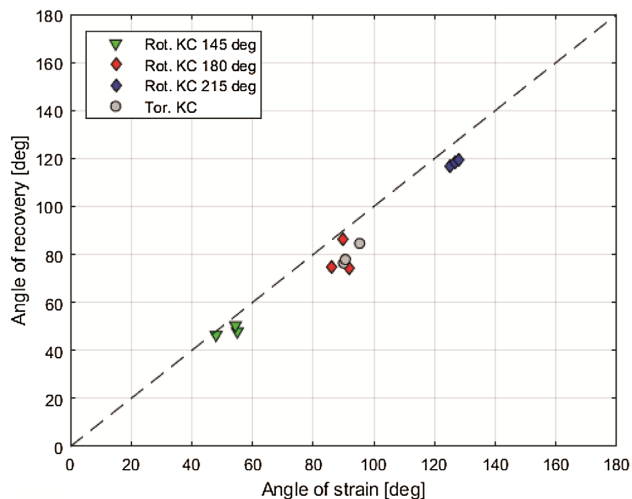


Figure 6: Angles of recovery against the angle of strain for different SMP kinetic components.

component to share via an open kinetic library makes it easier for other researchers and laypeople to use smart materials for 4D printing.

3.2. Icosahedron model

We demonstrate the use of multiple SMP-based rotational kinetic components for an assembly with rigid parts in an ico-

hedron 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

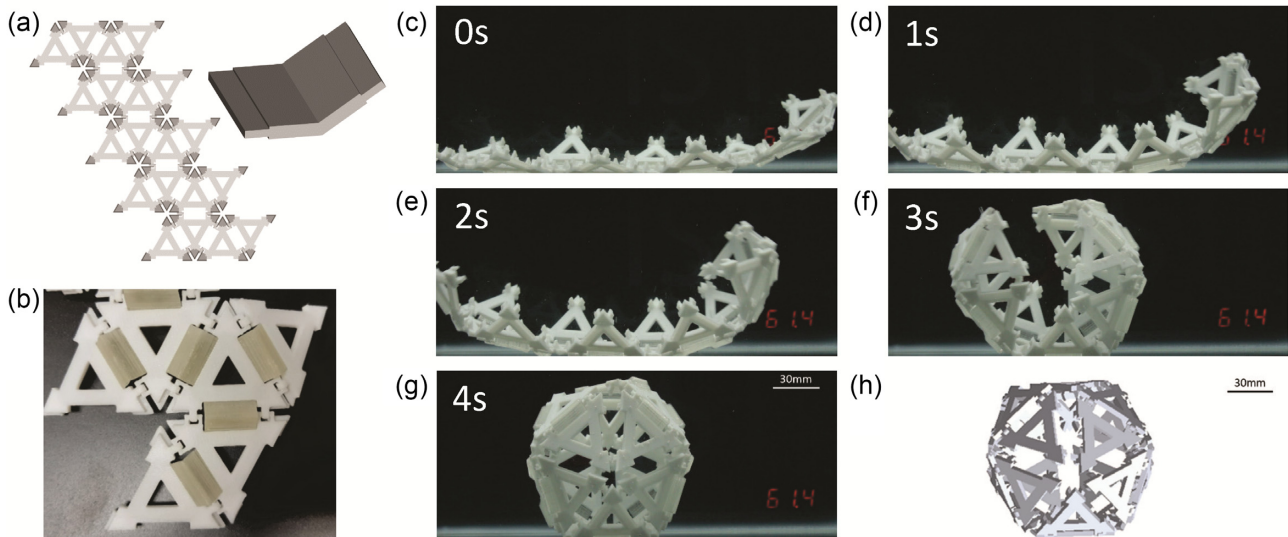


Figure 7: Self-assembly of an icosahedron model. (a) The 3D models for the icosahedron faces and a rotational hinge component (not to scale). (b) The icosahedron after printing and assembly of the pre-strained components. (c–g) Time lapse of the self-assembly of the icosahedron model in 60°C hot water. (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.

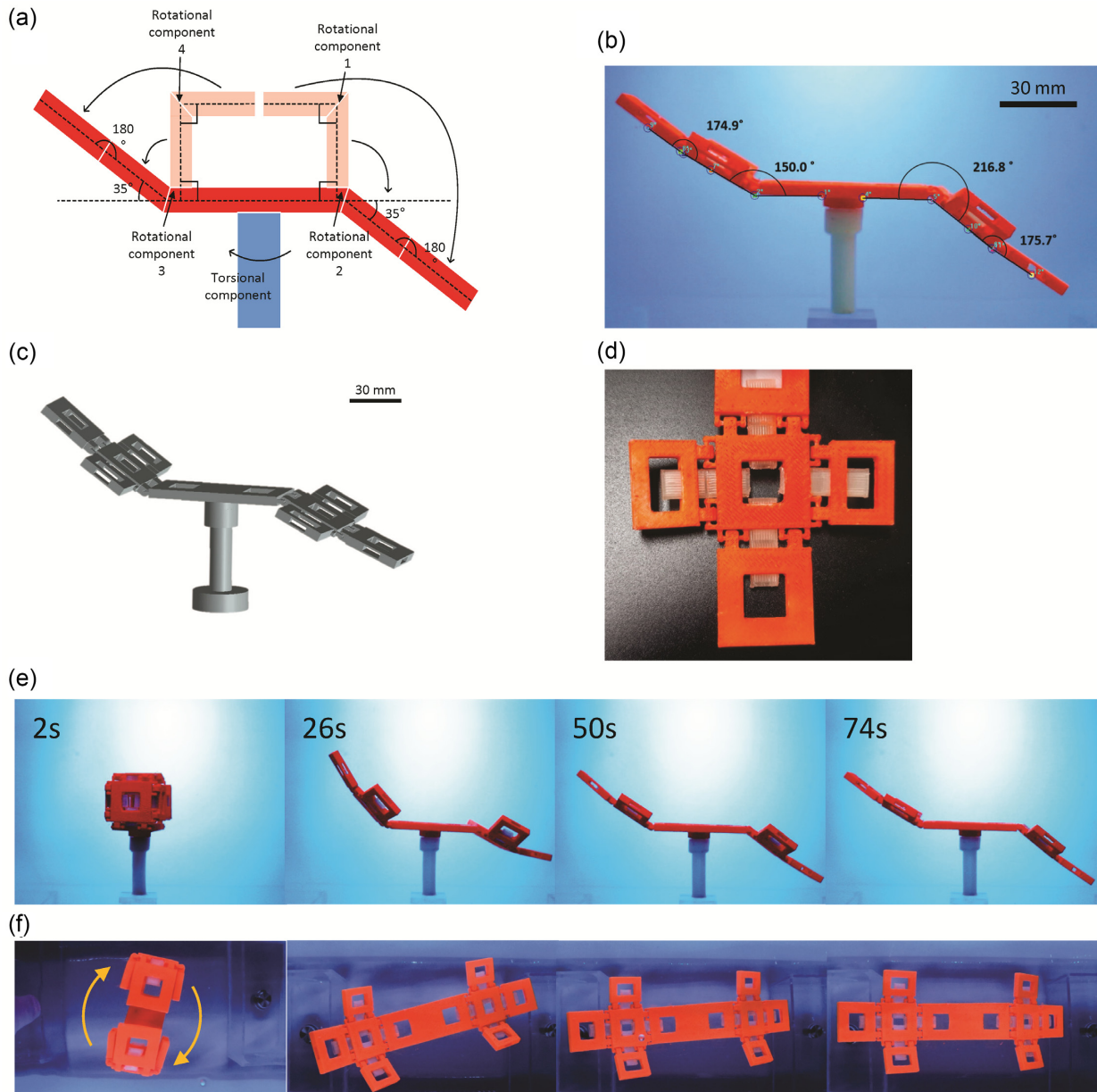


Figure 8: Mounting platform. (a) The design for the mounting platform incorporates multiple rotational components for unpacking and a torsional component that twists the whole body. (b) The final unpacked platform, with four of the rotational component angles, is shown. (c) The final simulation result. (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 rep-

resentation, 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.

References

- Akbari, S., Sakhaei, A. H., Kowsari, K., Yang, B., Serjouei, A., Yuanfang, Z., & Ge, Q. (2018). Enhanced multimaterial 4D printing with active hinges. *Smart Materials and Structures*, 27(6), 065027.
- Buehler, E., Comrie, N., Hofmann, M., McDonald, S., & Hurst, A. (2016). Investigating the implications of 3D printing in special education. *ACM Transactions on Accessible Computing (TACCESS)*, 8(3), 1–28.
- Ceruti, A., Marzocca, P., Liverani, A., & Bil, C. (2019). Maintenance in aeronautics in an Industry 4.0 context: The role of augmented reality and additive manufacturing. *Journal of Computational Design and Engineering*, 6(4), 516–526.
- Chen, T., Bilal, O. R., Lang, R., Daraio, C., & Shea, K. (2019). Autonomous deployment of a solar panel using elastic origami and distributed shape-memory-polymer actuators. *Physical Review Applied*, 11(6), 064069.
- Chen, T., & Shea, K. (2018). An autonomous programmable actuator and shape reconfigurable structures using bistability and shape memory polymers. *3D Printing and Additive Manufacturing*, 5(2), 91–101.
- Choong, Y. Y. C., Maleksaeedi, S., Eng, H., Wei, J., & Su, P.-C. (2017). 4D printing of high performance shape memory polymer using stereolithography. *Materials & Design*, 126, 219–225.
- Deng, D., & Chen, Y. (2015). Origami-based self-folding structure design and fabrication using projection based stereolithography. *Journal of Mechanical Design*, 137(2), 021701.
- El-Sayegh, S., Romdhane, L., & Manjikian, S. (2020). A critical review of 3D printing in construction: benefits, challenges, and risks. *Archives of Civil and Mechanical Engineering*, 20(2), 1–25.
- Ge, Q., Dunn, C. K., Qi, H. J., & Dunn, M. L. (2014). Active origami by 4D printing. *Smart Materials and Structures*, 23(9), 094007.
- Gladman, A. S., Matsumoto, E. A., Nuzzo, R. G., Mahadevan, L., & Lewis, J. A. (2016). Biomimetic 4D printing. *Nature materials*, 15(4), 413–418.
- Jeong, H. Y., An, S.-C., Seo, I. C., Lee, E., Ha, S., Kim, N., & Jun, Y. C. (2019). 3D printing of twisting and rotational bistable structures with tuning elements. *Scientific Reports*, 9(1), 1–9.
- Kim, J., & Yoo, D.-J. (2020). 3D printed compact heat exchangers with mathematically defined core structures. *Journal of Computational Design and Engineering*, 7(4), 527–550.
- Kokkinis, D., Schaffner, M., & Studart, A. R. (2015). Multimaterial magnetically assisted 3D printing of composite materials. *Nature Communications*, 6(1), 1–10.
- Kuksenok, O., & Balazs, A. C. (2016). Stimuli-responsive behavior of composites integrating thermo-responsive gels with photo-responsive fibers. *Materials Horizons*, 3(1), 53–62.
- Lan, X., Liu, Y., Lv, H., Wang, X., Leng, J., & Du, S. (2009). Fiber reinforced shape-memory polymer composite and its application in a deployable hinge. *Smart Materials and Structures*, 18(2), 024002.
- Ma, J., Franco, B., Tapia, G., Karayagiz, K., Johnson, L., Liu, J., Arroyave, R., Karaman, I., & Elwany, A. (2017). Spatial control of functional response in 4D-printed active metallic structures. *Scientific Reports*, 7, 46707.
- Mao, Y., Ding, Z., Yuan, C., Ai, S., Isakov, M., Wu, J., Wang, T., Dunn, M. L., & Qi, H. J. (2016). 3D printed reversible shape changing components with stimuli responsive materials. *Scientific Reports*, 6(1), 1–13.
- Mao, Y., Yu, K., Isakov, M. S., Wu, J., Dunn, M. L., & Qi, H. J. (2015). Sequential self-folding structures by 3D printed digital shape memory polymers. *Scientific Reports*, 5, 13616.
- Noh, K. S., Seo, H. W., & Lee, Y. G. (2016). 3D printing structures that exhibit torsions. In *Proceedings of the 2nd International Conference on Progress in Additive Manufacturing*, Singapore.
- Peraza-Hernandez, E. A., Hartl, D. J., Malak, R. J., Jr, & Lagoudas, D. C. (2014). Origami-inspired active structures: A synthesis and review. *Smart Materials and Structures*, 23(9), 094001.
- Prendergast, M. E., & Burdick, J. A. (2020). Recent advances in enabling technologies in 3D printing for precision medicine. *Advanced Materials*, 32(13), 1902516.
- Raviv, D., Zhao, W., McKnelly, C., Papadopoulou, A., Kadambi, A., Shi, B., Hirsch, S., Dikovsky, D., Zyracki, M., & Olguin, C. (2014). Active printed materials for complex self-evolving deformations. *Scientific Reports*, 4, 7422.
- Sharma, G., & Gurumoorthy, B. (2020). Iso-material contour representation for process planning of heterogeneous object model. *Journal of Computational Design and Engineering*, 7(4), 498–513.
- Shie, M.-Y., Shen, Y.-F., Astuti, S. D., Lee, A. K.-X., Lin, S.-H., Dwijaksara, N. L. B., & Chen, Y.-W. (2019). Review of polymeric materials in 4D printing biomedical applications. *Polymers*, 11(11), 1864.
- Stolt, R., & Elgh, F. (2020). Introducing design for selective laser melting in aerospace industry. *Journal of Computational Design and Engineering*, 7(4), 489–497.
- Takeda, H., Ohtake, Y., & Suzuki, H. (2020). 3D printing CFD simulation results using structural mechanics. *Journal of Computational Design and Engineering*, 7(3), 287–293.
- Teoh, J. E. M., Zhao, Y., An, J., Chua, C. K., & Liu, Y. (2017). Multi-stage responsive 4D printed smart structure through varying geometric thickness of shape memory polymer. *Smart Materials and Structures*, 26(12), 125001.
- Tibbitts, S. (2013). *The emergence of 4D printing*. TED Talks.
- Tibbitts, S. (2014). 4D printing: Multi-material shape change. *Architectural Design*, 84(1), 116–121.
- Westbrook, K. K., Kao, P. H., Castro, F., Ding, Y., & Qi, H. J. (2011). A 3D finite deformation constitutive model for amorphous shape memory polymers: A multi-branch modeling approach for nonequilibrium relaxation processes. *Mechanics of Materials*, 43(12), 853–869.
- Wu, J., Yuan, C., Ding, Z., Isakov, M., Mao, Y., Wang, T., Dunn, M. L., & Qi, H. J. (2016). Multi-shape active composites by 3D printing of digital shape memory polymers. *Scientific Reports*, 6, 24224.
- Yang, Y., Ohtake, Y., & Suzuki, H. (2021). Mesh processing for improved perceptual quality of 3D printed relief. *Journal of Computational Design and Engineering*, 8(1), 115–124.

- Yu, K., Ritchie, A., Mao, Y., Dunn, M. L., & Qi, H. J. (2015). Controlled sequential shape changing components by 3D printing of shape memory polymer multimaterials. *Procedia Iutam*, 12(1), 193–203.
- Zafar, M. Q., & Zhao, H. (2020). 4D printing: Future insight in additive manufacturing. *Metals and Materials International*, 26(5), 564–585.
- Zanchetta, E., Cattaldo, M., Franchin, G., Schwentenwein, M., Homa, J., Brusatin, G., & Colombo, P. (2016). Stereolithography of SiOC ceramic microcomponents. *Advanced Materials*, 28(2), 370–376.
- Zhang, Y., & Moon, S. K. (2021). Data-driven design strategy in fused filament fabrication: Status and opportunities. *Journal of Computational Design and Engineering*, 8(2), 489–509.