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A Deformation Estimation Method with Experimental Demonstration for 4D Printing (3D printing and deformation) Design Applications

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Research Article

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Posted Date: May 28th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9410398/v1

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A Deformation Estimation Method with Experimental Demonstration for 4D Printing（3D printing and deformation） Design Applications

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Abstract

4D printing is the first 3D printing, followed by object deformation. 4D printing allows the user to study in a direction. As for how to change 4D printing researchers to study the problem, the shape changed. Simulation is the visualisation of the change process. For 4D printing, object deformation algorithms and simulations are used to address user needs for shape-changing. It is possible that some research is conducted through algorithmic searches and may yield estimates based on algorithms and prototypes developed through experiments. Existing 4D printing technology cannot control or predict the deformation range, nor correct it algorithmically. This article helps designers and engineers use 4D printing by experimenting with 4D printing deformation using user-friendly software through an experimental approach. Present 4D deformation results via an interface using predictive methods. This research primarily investigates the experimental validation of deformation estimation for 4D:3D printed parts following shape distortion. Primarily addressing experimental variations in 4D printing to solve the problem of software for validating the 4D printing designer-driven deformation control method.

Introduce

Additive manufacturing has been technologically perfected, and 3D printing (3D printing is also called additive manufacturing, with the dimension of height added to the length and width of a flat surface) has spawned 4D printing. 4D printing is based on 3D printing but introduces time-dependent deformation of the printed object or its constituent parts. 4D printing adds an extra dimension to 3D printing with additional stimuli. 4D printing requires considering that the material is printed and then changes shape in response to external stimuli. 4D printing can meet the needs of special modelling or rapid prototyping for certain uses, but users (designers and engineers) are not particularly skilled in the industry when it comes to printing long-term deformation conditions. because the user does not know how the object set to print will deform under external stimuli, and needs an estimation. 4D printing, some concepts can make 4D printing technology. To meet specific user needs, research on using CAD software to design for special requirements for designers and engineers is conducted. The software facilitates 4D printing in product design.

Related work'

Some research on a 4D printing experiment. Li et al.（2025） research group mainly focuses on printing the internal structure of 3D printing, which is the printing of combined lines. It focuses on how the connection of lines causes object deformation. It adopts a modular printing method. Through Xstrings, four types of cable- and module-driven interactions are supported: bending, coiling, spiralling, and compression. They do this by applying input forces to the cable to activate the interaction of the printed module. Through these tools and methods, research can achieve interaction between different parts and test. They have also researched the changes in 3D printing and wire, requiring the combination of a printer and wire. Compared with other 4D printing, 4D printing relies on printing density or material comparison. This method needs to be designed and calculated in advance.

Yan et al (2025) researched morphing scents, a thin-film structure that can be deformed and discovered the mechanism by which gases are emitted. The article combines this mechanism with deformation to better serve people. Employing basic printing modules facilitates a coherent relationship between the printed object and the resulting deformation. However, the research focuses on the printing direction that suits the user, without conducting more in-depth research. This is an actual printed application that demonstrates its effectiveness.

Ozdemir et al (2024) have researched different speeds in materials. To achieve both specific tactile properties and programmable visual appearance in single-material 3D printing, the research team proposed a manufacturing method known as “speed-controlled ironing. The research team used one nozzle for 3D printing and another to reheat the printed area at different speeds—a technique they termed “speed-controlled ironing”—to control the temperature response of the material. This printing method can print different prints on the same object, requiring two 3D printers with different interfaces, and can be used in 4D printing of different materials. However, it uses a QR code flat image instead of a 3D model.

Kortman et al (2023) have conducted some research on 4D printing—the study in the Kortman research group's discussion of 4D printing deformations. The main divisions are several variations, distinguished by magnetic versus non-magnetic characteristics, which are not found in other studies of 4D printing. Within magnetic, the authors divided the variations into ordered and disordered, and this classification of the research method is something learned from. The classification of 4D printing is different, but the process is the same. The article discusses various options for process analysis and looks at the impact of multiple directions on deformation. The research for each kind of deformation needs further depth, but the classification and process analysis is a worthy contribution. Deformation and direction parameters can be learned and adapted for further research.

Liu et al. (2023) use foam as a foaming agent in composite silicone resin ink processed by direct ink writing. The study was carried out by embedding thermally expandable microspheres as a detail to test the thermal expansion of the microspheres, the foaming of the composite silicone ink, and the performance of the expanding foam. The deformation mechanism was achieved by using the strain mismatch mechanism under thermal stimulation to release a double-layer structure for 4D printing. The article is fine as a technical application, but continued research is needed on the deformation of printed objects.

Unlike other studies, Ozdemir and Doubrovski (2020) adopt a distinct perspective, with their research centring on the application of 4D-printed mugs. The paper adopts a stepwise (partial-to-full) research methodology to investigate polylactic acid (PLA) using different material attributes. The study was conducted based on a comparison of the properties of normal PLA and low-PLA. The use of 4D printing was based on the different properties of the two PLA types. The article explores print direction and density and their implications. However, the bending test is flawed, and the experiment lacks sufficient precision. For users to use 4D printing, the density needs will need to be addressed further.

In conclusion, while 4D printing technology has progressed in recent years, visualisation of its deformation behaviour still requires experimental investigation and further data collection. To address this, the present research focused on testing 4D-printed parts in experimental rigs specifically configured for deformation analysis. The device integrates several test modules to facilitate the collection of data. This work enables designers and engineers to utilise 4D printing through estimation modelling, while also considering the development of applications and tools for multi-material 4D/3D printing. The breakthrough lies primarily in the 4D printing deformation estimation tool for predicting evaluation with experimental testing.

Method

The research has explored user demand for 4D printing, the need for accuracy to predict the actual range of accuracy, which is roughly for major estimations. This chapter is mainly experimental, the 4D printing process: 3D printing, external stimulus deformation, and deformation in the strain relationship. Another purpose of the experiment is to validate the algorithm and to understand how the deformation algorithm contributes to shape changes in 4D printing. This study explores the progression of 4D printing from experimental stages to algorithmic interactive interfaces.

The aim of the experiment：

1. To explore the relationship between materials and deformation
2. To investigate the feasibility of the algorithm for the shape changing of 4D printing material.

The test takes 2 steps

1. Stress test results for print blocks of different thicknesses
2. How the profitability of a printed object changes in response to external stimuli of the printing part for the algorithm.

Test print direction and distance variations

The experimental aspect is divided into several stages. Different print directions and different print spacing are used to study the variations.

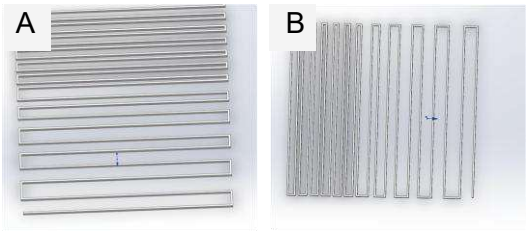


Figure 1： Different directions in 4D printing

The picture is mainly a preliminary experiment on the printing direction, and initially, the printing direction is solved by modelling in SolidWorks to force the influence of changing the printing part direction. At the same time, we also explored the relationship between print spacing and deformation. The researchers found that the larger the print spacing, the easier it is to deform, through experiments.

According to Tao et al. (2023), the printing direction affects the shape of the printed object. Therefore, the following experiment was conducted to verify the effect of changing the printing direction. The experiment was divided into several stages. The first stage of the inquiry is the print direction inquiry. The experimental process is shown above by setting the different spacing in the empty printing direction. Pitch in the gap. The effect of print direction versus Figure 1: deformation direction was derived.

The experiment found that the direction of printing leads to a change in the direction of deformation. There is a relationship between the print direction of 3D printing and the range of deformation. Printing direction and object deformation direction can be consistent. Experimental conclusion: printing direction has a relationship with deformation. The next stage of the experiment is to test the change in deformation force in response to external stimuli.

Changing results through strain gauge area measurements

The second experimental phase will include a strain gauge region, where precise measurements will be conducted to ensure accurate results. An Arduino microcontroller will be used to read strain changes (the Arduino's function is to capture the change in value). This will facilitate the investigation of internal structural relationships through stress testing. Additional assistance:

The sensors were borrowed because the Strain Gauge was used as a reference to ensure the experiment's accuracy. Strain gauge sensor data as follows for the change:

- Base size: 6.6 x 3.4mm
- Lead specification: 3-5 cm long enameled wire; Resistance to nominal tolerance: 120 ± 3Ω.
- Sensitivity coefficient and dispersion: 2.1±1%.
- Package Content:10 x High-Precision Resistance BF120-3AA with Strain Gauge. A schematic diagram of the changes using strain gauges

Strain gauge sensors use

The computer reads off the sensor as shown above; an external 1000-ohm resistor is connected in series with the sensor to protect it during normal use. When choosing a sensor, the researcher used a strain sensor combined with an Arduino to investigate the relationship numerically. Zolfagharian et al (2020) then tested this numerically with sensors placed on 3D-printed objects for 4D printing research on shape-changing. The computer has a professional-specific determination. The novelty of this experiment lies in its l stress testing analysis of 4D printed deformation, providing a quantitative derivation of the changes. Apart from variations

in print density, all the test blocks printed during the test measured 50 mm × 70 mm. The test standard involves using electronic sensors to measure stress.; however, key details regarding the number of repetitions and uncertainty analysis are missing.

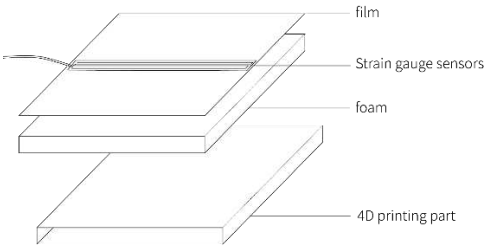


Figure 3： Strain gauge placement can be reversed according to the deformation direction.

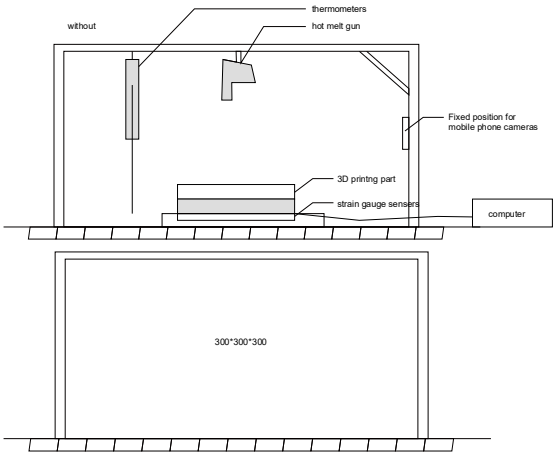


Figure 4： Rig of the experiment

The diagram above shows the experimental setup. Tested by testing 50*70*10 as well as 50*70*10 modules. The test distribution measured the change in density for strain cases of different densities: 20% 40% 60% 80% and 100%. The use of basic geometries of 10 thicknesses for the test blocks was because we chose line-based basic shapes as variations, with lines acting as thinner plasticisers. Shi [7] also does a lot to test many parts of 3D printing. Wang et al (2024) also suggested that the thickness issue was 3 layers, so the authors tested with a thickness of 5 mm, and the experiment was good for changing.

Orientation thickness affects printing, so it makes more sense to choose 5mm and 10mm. Nam and Pei [8] proposed bending the way bending in printing pattern setting. So the researcher had the main research bent. Refer also to the thickness article for 5mm and 10mm. A rig is a framework designed to categorise certain elements, better integrating testing tools.

The first stage is the testing of individual modules,

Strain gauge measurements of stabilisation deformations are explored. Sensor Arduino to computer readout for collation of data visualisations as follows.

The 3D printing part： experimental data

About printing settings

Printing temperature： 190 degree

Printing speed： 10mm/s

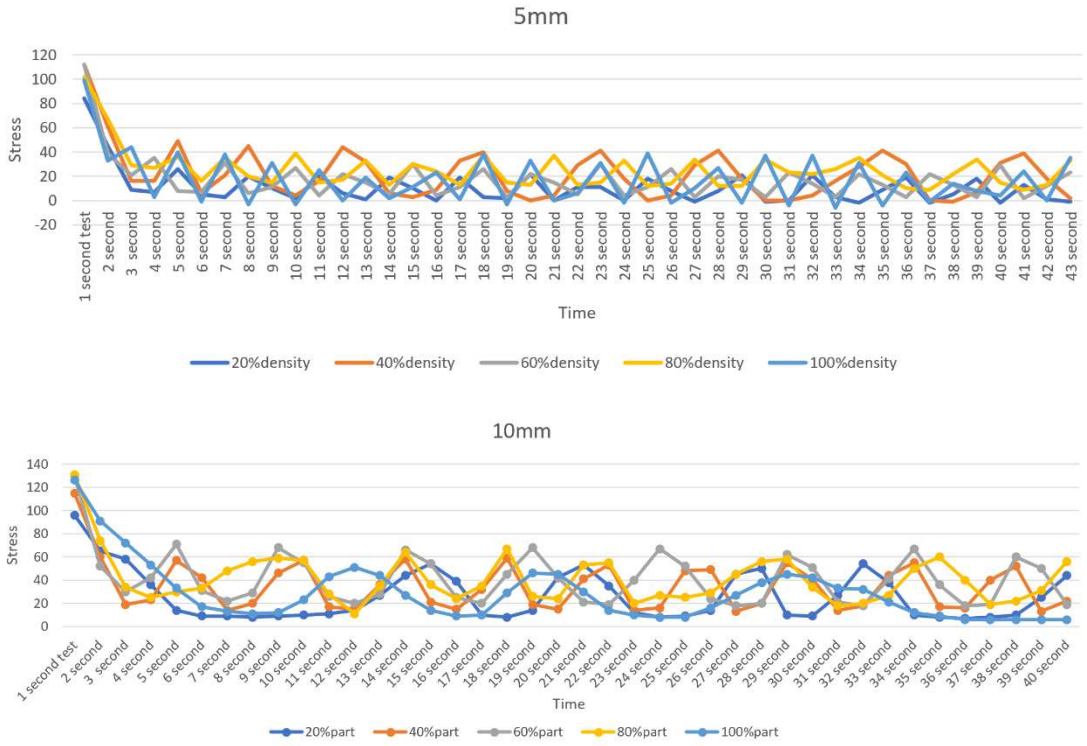
Printing bad temperature: 45 degrees

Layer height:0.2mm

This is the reference data (Wang,2017 and Lee, 2022)

The printing part is about 50mm*70mm.

At the start of operation, the value increases significantly because of the current, but it stabilises after a brief period. As shown in the figure of the test result. The test standard involves placing a strain sensor at the centre of the 3D-printed block for testing. The boundary conditions are determined by identifying abnormal stress variations during the test, as the strain sensor's initial readings are elevated and require time to stabilise. The test was conducted three times for accuracy. Testing uncertainty requires adjustments, including handling the strain sensor during heating. The test part—a printing module of about 50 mm × 70 mm—is easy to test



.

Figure 5: The image above shows the change in strain gauge readings for print modules of 5 mm and 10 mm thickness.
The test shown above is a printed test module placed under a strain gauge. and a further stage is the exploration of heating deformation. According to some, mechanical fluctuations[11] are normal experiments with 3D printing objects. The main reason is that it takes a certain amount of time for the strain transducer to work up at the beginning of the energisation process, resulting in a high current value. The test standard involves using electronic sensors to measure stress. The tool system's human-machine interface is expected to improve both collaborative efficiency and decision-making quality for designers and engineers, particularly in the implementation phase of product design.; however, key details regarding the number of repetitions and uncertainty analysis are missing.

The second stage is when the 3D-printed object is subjected to external stimuli to take measurements and get experimental results. Changes in external stimuli are detected by measuring the values of the sensors. The fluctuation is placed on the surface vibration that has been subjected to it. After measuring the value change, the estimation is calculated via the formula, and the result is then recorded manually. The thicker the object, the more stable it is, and the higher the printing density, the more stable it is, as demonstrated by the data. The importance of temperature led researchers to use thermometers to test and control the water temperature. To date, the system has demonstrated reasonable stability. External stimuli consist of immersion in water and external heating. Temperature is the main factor enabling both deformation prediction and variable control.

The first stage is the water temperature test, which tests the water temperature in the 3D printing products to observe whether deformation occurs and how it occurs. After several tests, there is bending deformation, minimal stretching and twisting. The next stage will be to predict whether the results after the experimental deformation are consistent with the estimations. Putting it in water is an experimental process based on Tao [5] for the 4D process, in which 3D printing is done first, and external stimulation (putting it in water) for shape changing is done based on the reference. The Arduino reads the value by adjusting the current test.

Other about 3D print temperature and speed: 30 m/s 190 degrees, more than 60 m/s 200 degrees. This setting and print speed in the test are more stable; do not rule out the impact of weather, rain and humidity, as the stability of the print material has a certain impact. Relationship between programming stress and residual strain in fused deposition modelling (FDM) for the 4D printing method. Previous experiments used existing tools, but the experimental space was limited, so the researcher proposed to use the rig solution for 4D printing deformation.

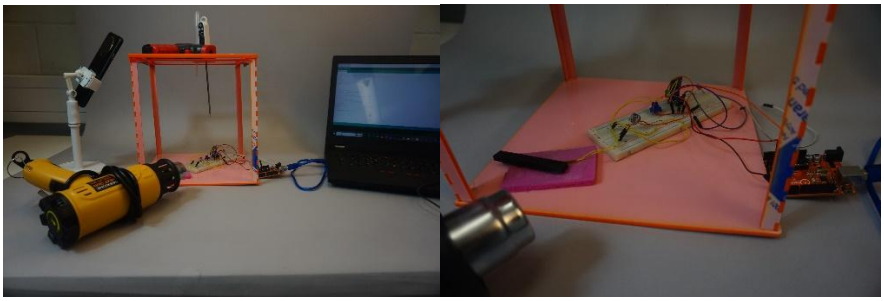


Figure 6: test part

Temperature, print thickness, and print material. Includes rapid printing of objects, hot melt guns, thermometers, and multiple combinations. For the inspection of printed objects after heating for the test

Experimental setup

Setting up the experimental rig, which was made for storage and ease of experimentation, included a transparent container shelf, a hot melt gun, a strain sensor, an Arduino motherboard, and a thermometer (infrared). The strain sensor transmits the data to the computer, linking the Arduino open-source hardware for statistical purposes in the test. The hot melt gun is used to test the heating deformation of the object/printing part, either directly or through a transparent container filled with water for the change. The rack with an empty dropper controls the water temperature; all temperatures are measured through thermometers to ensure that you can control the variable method to test the water temperature change.

Result and discussion

Experimentally derived deformation data for 4D printing. The data is to be analysed as follows.

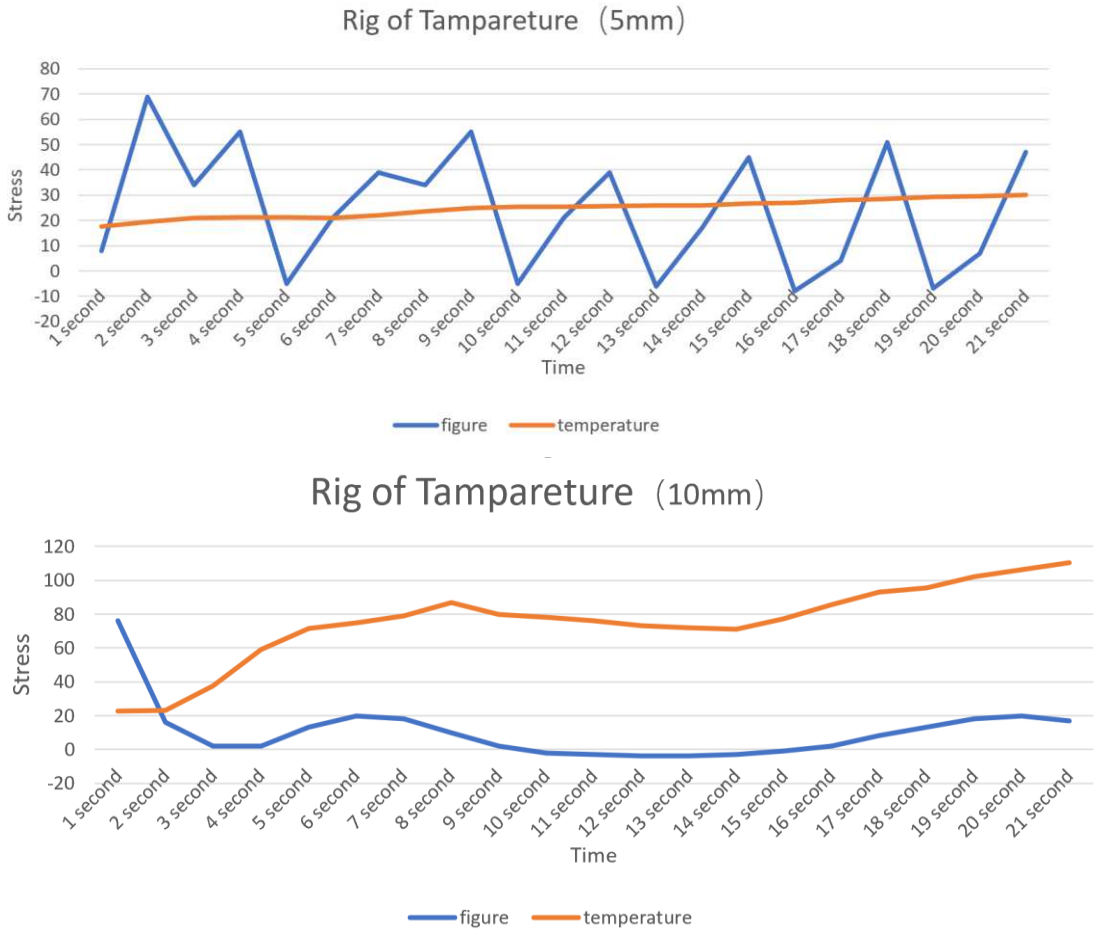


Figure 7: Test of 5mm and 10mm parts heated

For conclusions on experimental deformations, heating is relevant because it is proportional to the value. Whenever strain gauge readings are initiated and data are transferred to the Arduino, a short stabilisation period is required before data collection. Tests demonstrate a temperature-dependent correlation between the two materials' properties that is inversely proportional to their

thickness, a relationship deducible from Hooke's law and the effect of forces on different materials.

The research conducts significant experiments in 4D printing, focusing on deformation in the printing direction. The purpose of studying different printing orientations is to investigate the impact of deformation in multiple components within an actual product on the overall structure. This serves as groundwork for predicting deformation and subsequent research into the deformation of complex geometries.

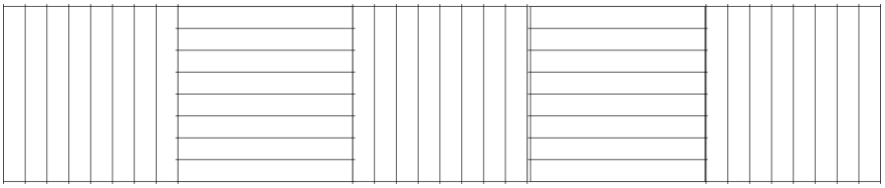


Figure 8: Print module with print direction test

In practical product design applications, complex transformations necessitate complex printing methods. The writer printed the above. As shown in Figure 8, 5 modules (each module 50mm*50mm and thickness: 2 mm) are composed of 3 horizontal and 2 vertical. The purpose of the experiment is to apply complex printing techniques in actual product design. Different combinations of print directions result in different deformations realised as combined directional deformations. Numerous researchers are exploring 4D printing using different printing density directions for experimental development and utilisation. However, printing an object in different directions at once is a bit difficult to set up the printer. Setting up different angles inside a device is not perfect. Modelling requires the use of slicing software for printing. Cura, a slicing software for 3D printing, allows different print orientations to be configured, as illustrated in the following figure:

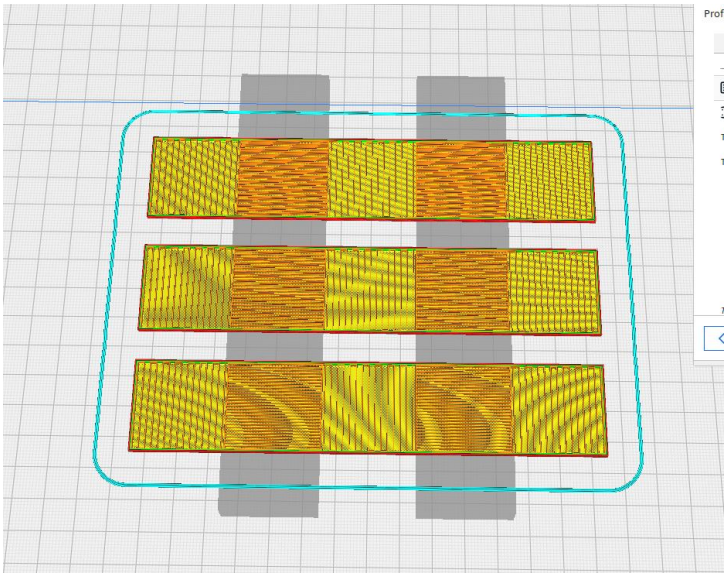


Figure 9: Setting in Cura for mix change.

It has been previously studied in the literature that the printer available at both ends to print the identity does not have such a device, as shown in Figure 9. The need to print more complex distortions with settings may be more difficult with single-head printers.

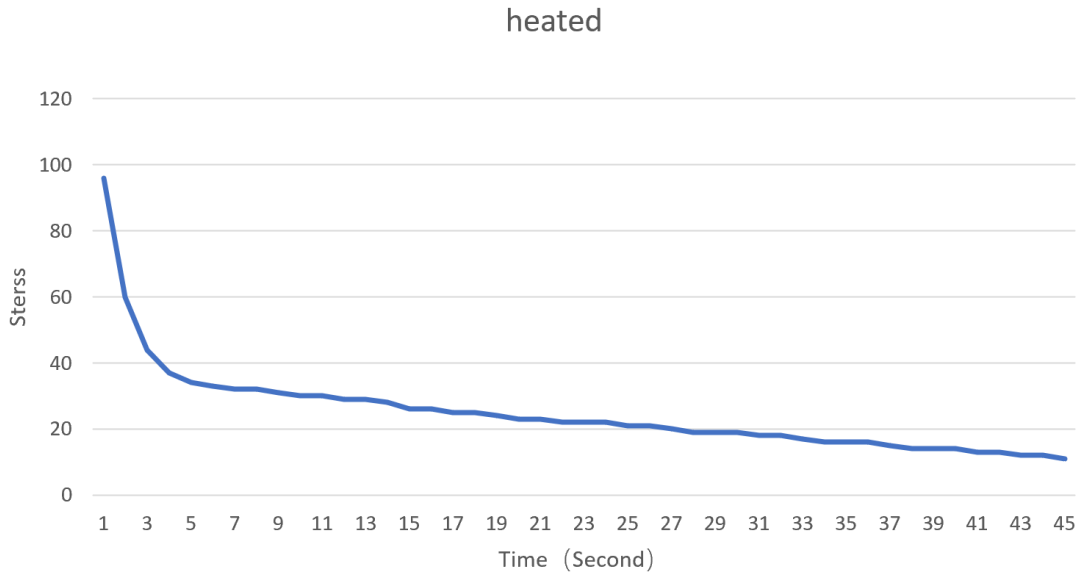
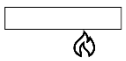
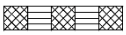


Figure 10:20%-40%density print part（The x-axis is the time, and the y-axis is the value read.）

The combination of different densities from the static is seen to present a more stable state. The stresses exhibit little variation, as illustrated in Figure 10, where the printing model settings are unchanged from before.

During experiments on 4D printing deformation, it was observed that heating applied in the 3D printing stage induced deformation. Through certain combinations of static heating and deformation printing methods, useful experimental results can be obtained. The heating temperature and the strain are proportional. Heating is thermal expansion and contraction, with more causing bending and material density related to the temperature, and strain is proportional. The formula validation is basically consistent with preliminary qualitative conclusions through experimentation. The primary purpose is to explore the use of 4D printing by designers and engineers for experimental purposes.

Stage	1. static	2. heated objects	3. line assembly	4. line-grid assembly
Diagram				
experimental purpose	Understanding normal deformation0%,20%,40%,60%,80%,100 % (Thickness 2mm,5mm,10mm)	Understanding heating deformation	A combination of deformations in different directions	Whether deformation is related to the print pattern
Experimental method	Understanding the stresses inside the print block	Experiment with heating the printed object with a hot melt gun.	Tests using modules printed in different directions to form a 1*5 print strip.20%-40%-20%-40%-20%	1*5line-grid print

Conclusion of the experiment	Print density is related to deformation, as is thickness.	Temperature affects the deformation of prints.	Wavy deformation occurs in relation to the print direction, and obviously, the experiment works.	Less deformation in the mesh section.

Table 1: Summary of several experiments on stress

Table 1 above illustrates the progression of several experiments. Static to dynamic to combinatorial evolution. Temperature and material print density are two ways to change the bending, and temperature correlates with it. For experimental refinement, a step-by-step laboratory approach can be implemented to test, in particular, the interplay between printing direction and printing density variations. 4D printing accuracy is not very high, depending on the user's use. In industrial products for artwork, 4D printing achieves only a limited precision. The printed objects contain PLA and a modified PLA (referred to here as LOW PLA) that differ in their deformation characteristics. Specifically, the density variations between these materials result in different Young's moduli, thereby influencing the extent and nature of deformation. Due to limitations on the materials available for the laboratory printer, only PLA and LOW-PLA can be used.

Basic algorithms

Based on previous research. Fundamental algorithms refer to the basic principles of tensile and compressive deformation, which can essentially be derived from Hooke's law. Expansion and contraction are primarily due to thermal expansion and contraction. Algorithms play a big role in estimation, and they help to predict the shape. Human-computer interaction primarily concerns computer input and output, and the communication between computers and users (IxDF,2025). This is about understanding the internal logical interaction. The inputs and outputs required by the algorithm are as follows:

Input: 3D printing shape, temperature.

Output: predict shape (Main dimensions length, width, and height. Auxiliary software generates new geometric models.)

The main thing is to get a data forecast for the user. Algorithms are available to help prototype software later. Algorithms are devised to transform original geometric forms into deformed geometric forms. Deformation stimuli, such as temperature, need to be considered. The algorithm mainly introduces new values through existing geometric values. The fundamental geometric elements are points, lines, planes, and solids. Multiple points connect to form lines; multiple lines constitute a plane; multiple planes form a solid. Therefore, to achieve changes on another surface, the algorithm must start from the fundamental points and lines. It must transform the original points into the pointing part after deformation. Therefore, to achieve changes on another surface, the algorithm must proceed from fundamental points and lines. It transforms points from their original state into deformed points. In mechanical analysis within physics, derivations are fundamentally achieved through simplified geometric methods (De León and Rodrigues, 2011). Computational algorithms for 4D-printed deformation require the application of this approach.

The algorithm advances by modifying wire lengths to establish new configurations.

The primary transformations considered are tension, compression, folding, and bending. Hooke's law, a fundamental principle in elasticity theory, is particularly relevant here. It describes the linear relationship between stress and strain (unit deformation) in a solid material under external force. Materials that satisfy this law are called linearly elastic or Hooke's type materials.

The printed objects are then used to perform stress tests and heating deformation experiments. Multi-directional printing combined with testing can yield variable results. Unlike the uniform direction, there is no change in deformation in multiple directions.

Many practical materials, such as a colourful bar of length L and cross-sectional area A, can be mechanically modelled by Hooke's law – it is unit elongation ε (or contraction) E(strain) is proportional to the tensile (or compressive) stress at a constant factor σ (called the modulus of elasticity), i.e:

$\sigma = E\varepsilon$

or

After this, the formula can be deduced after the compression force and E elastic modulus, and A cross-sectional area can be derived. However, 4D printing is subject to external stimuli and not direct force. The force is pressure from the water, which is not counted (Including the buoyancy of the water, which does not count as a 4D print deformation). The test standard involves using electronic sensors to measure stress. Boundary conditions are defined by changes in electrical current. However, the number of repetitions and a detailed uncertainty analysis are not provided. To improve reproducibility, we recommend specifying the repetition count (e.g., n≥3) and conducting a sensitivity or error propagation study. However, critical information is missing: the number of repetitions used in the experiments, and any form of uncertainty analysis (e.g., error bars, sensitivity study).

Basic algorithm of the shape

Input: some shape data

Output: shape data.

Int E;

Int L;

Int O;

Int LN;

LN=L+1/E*L*0;

Lifting and retraction

Algorithm

Normal tensile shrinkage deformation is easy to get the conclusion, the experiment is also complete as proof, and the test force is not a good test. Stretching and compression involve just a one-dimensional change. Bending is due to a different partial expansion. In algorithm development, the main focus is on force and stress. It is mainly derived from the mechanics of geometry from previous physics. The algorithm has also been derived and verified, with its form primarily tested. There is some derivation in the mechanics itself, in addition to reviewing other literature. Wang et al. (2025) and Sun et al. (2024) employed a similar method. The researcher performed numerous data tests to confirm consistency. This fundamental algorithm is deduced through reasoning.

Complex algorithm

The print density is set at 100% of the print thickness on both sides when printing slices. The basic algorithm uses Hooke's law to complete simple stretching and contraction. However, for complex bending and folding algorithms, derivation is required. But it still cannot be separated from Hooke's law and its derivation. This process is a mechanical analysis.

Image caption: Printing is divided into several layers. When printing is different

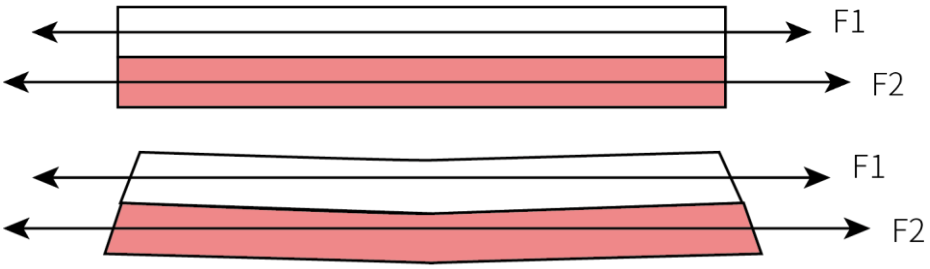


Figure 10: Force and deformation

The diagram illustrates the deformation principle.

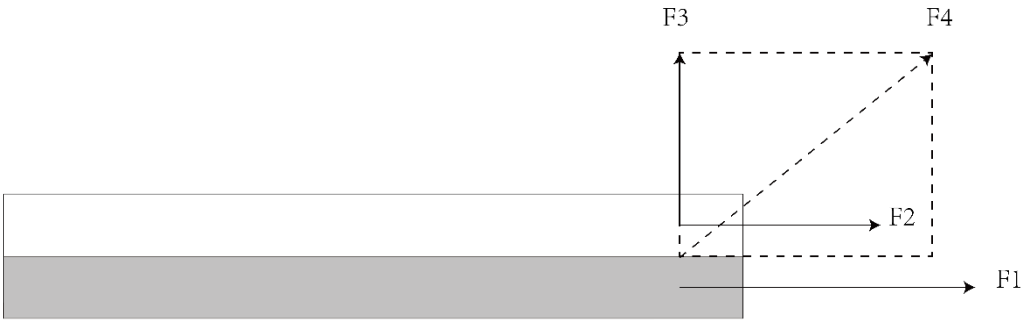


Figure 11: Photo caption 4D print of all forces, F4 is the combined force of F1, F2, and F3, F1 and F2 are the expansion forces, and F3 is the tension between the two objects. The combined force F4 determines the direction of deformation and the part curve around.

Complex algorithms are complex model deformation, bending and twisting, and linking about force. The figure assumes that grey areas possess a higher Young's modulus printing density than white areas, and vice versa by default. Variation is inversely proportional to Young's modulus thickness, which means different 2-layer print densities of the same print material or 2 layers of different materials.

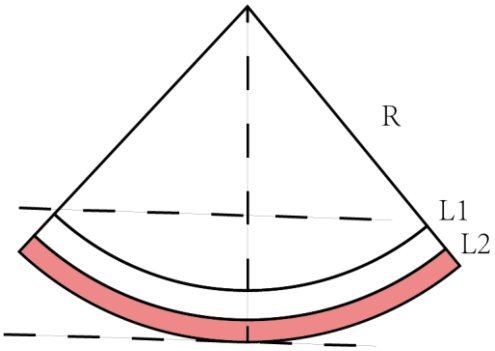


Figure 12：deformation of part

$$l=\frac{(l_1+l_2)[3(1+m)^2+\left(1+\frac{mE_2}{E_1}\right)(m^2+\frac{E_1}{mE_2})]}{6(1+m_2)(l_1-l_2)\Delta t}$$

This is primarily derived based on the temperature differential and the material's print thickness and is derived from the mechanical analysis in Figure 12 above. This constitutes research into deformation at the user needs level. Primarily involving force analysis, the resultant force and component forces thus constitute the cause of bending. Due to the mechanical interaction between the two components, m denotes the Young's modulus affecting the material. This primarily concerns elastic tensile forces and the decomposition of component forces into resultant forces. For the precision of this algorithm, Wang et al. (2025) also similarly illustrated the algorithm as somewhat usable in natural 4D printing applications and useful in them. The formula mainly uses mathematical inference to provide parameter support for the following. Validated by data in practice. The calculated value here is the geometric radius. After deformation, the bend has a circumference. Here, it is calculated geometrically based on these parameters. So, the researcher knows some data of the length, width and height after deformation. These data can be used to construct a three-dimensional model. Young's modulus represents material properties and is typically employed in the context of material deformation.

Input: shape data, temperature, Young's modulus, and density of material

Output: shape data. of shape after 4D Printing deformation.

Comparison of data models brings about model healing. Folding requires consideration of the degree of bending of the layers. The result is a three-dimensional model. The deformation of 4D printing is achieved through stretching, shrinking, bending, and folding (Pei and Nam,2018). The deformation of 4D printing may also form other forms, which are basically derived from the previous ones. However, 4D printing deformation needs to consider some data inputs of external stimuli, including material temperature. This is the input parameter required in the algorithm. Mainly requires the user to input corresponding data. Since Young's modulus is a range, the predicted result is also roughly a range.

The derivation of this formula requires consideration of internal forces. The group must solve the adhesive force of the material and the expansion and contraction of the printing object. Also, in some literature, in 4D printing deformation tests, the angle of deformation is a predicted value of change. Also, in some literature on 4D printing deformation tests, the angle of deformation is a predicted value of change. As well as calculating the radius of the bends for 4D printing changed. The shape changed. The detail is here. The following changes can be made with Rhino. This needs to be considered in the interface. This is a method for reducing error.

Since mechanical derivations are all based on idealised conditions, software definitely includes some things that are not taken

into consideration. There is a range of possible deformations during the process, which is a problem that needs to be considered. However, for 4D printing applications, the error in model and product design is considered jointly by designers and engineers, and such error is required to remain within a specified range. In the calculation, only the bending radius is obtained, which involves development, and the Young's modulus is generally also a range, so the final calculation result is a changing interval, which is a tolerance range. In engineering, consideration of the error range is essential, with user experience determining the acceptable margin of error. Accordingly, the algorithm is designed to work in concert with user experience; the page can be rendered as long as the error remains within the range tolerable to users. In contrast to the previous section, the algorithm presented here originates from mechanics. Consequently, it requires wider deployment and comprehensive testing across a greater number of software application scenarios.

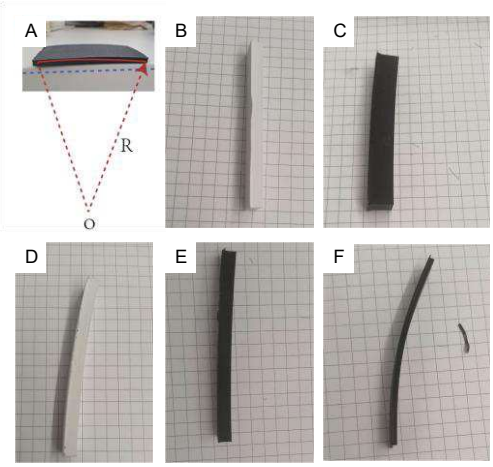


Figure 13: A: Explain the relationship between the bending center and radius. B-F: Describe the deformation of different thicknesses in warm water (temperature control is the same length and the same thickness is not the same) inside the warm water

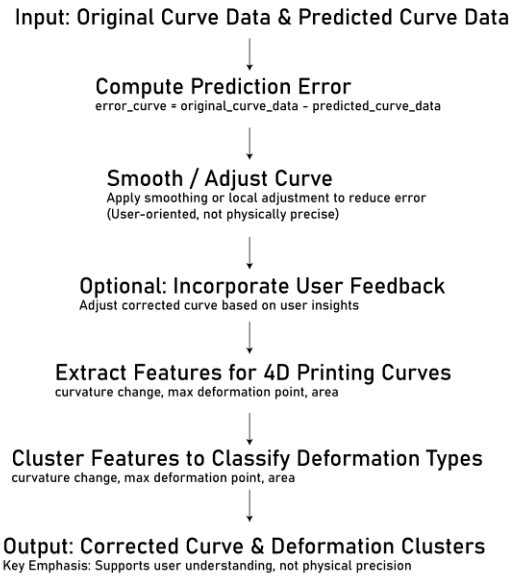
The deformation was observed by 3D printing some steps of external stimuli, and the grids illustrate the obviousness of the deformation. The experimental method is from the study of TAHOUNI [7]. The experiment employed a controlled variable approach, keeping the material, warm water temperature, length, and width constant while varying only the thickness. The water was heated to 50 °C based on the ten reference data points from Wei et al. (2010).Then go through the calculations to work out the difference from the expected problem, and refine the algorithm again. The difference between the estimation and the actual is not significant. The ruler provides only a rough estimate and requires improvement in terms of precision. It can only indicate basic deformation for the test of deformation.

Material Description	Actual test (mm)
PLA 10*50 *70	12
PLA 5*10*70	10
PLA 2*10*70	9

Table 2:Preliminary test results are shown in the table.

Since the researcher had problems with the ruler's scale in his hand (The criteria outlined above are valid), as shown in Figure 13, the accuracy of the measurements was limited to millimetres. The data also verified the reasonableness and accuracy of the algorithmic formulas. Primarily obtained through research using a ruler for measurement. The preliminary verification was achieved primarily through geometric methods applied to the grid paper (best for the test and to show the deformation), The background of the diagram above shows the centre of the circle, determined by measurements taken using a ruler. The average value was confirmed through three tests. The precision was not entirely as expected, with some discrepancies present. This may also be attributable to the material used during printing. Employing a standard ruler with a minimum scale of 1mm challenge to achieving greater accuracy. As shown in Figure 6.6, the diagram illustrates the existing constraints. Preliminary basic confirmation indicates it is accurate, effective, and valid. Perhaps more effective measurements are required. This assessment demonstrates that while applying the algorithm to the practical process involves some errors, it nevertheless illustrates its accuracy and demonstrates specific effectiveness.

By identifying certain discrepancies in the data, corrections can be made using the approach illustrated in Figure 13. This involves analysing extensive data alongside user-expected data. Refine through design and implementation. Under this methodology, a degree of accuracy enhancement is achieved. This is demonstrated by experimental feedback. The manuscript mistakenly treats the visual mapping nodes in Grasshopper as a quantitative modelling algorithm. This approach does not offer numerical precision, nor has it been subjected to regression or error analysis for validation. Its purpose is purely to support user understanding of deformation and to facilitate designer–engineer collaboration, rather than to deliver physically accurate estimations or to account for changes. Compared to existing research, this study focuses on investigating various material factors in 4D printing and conducting experiments to validate findings, thereby laying the groundwork for subsequent interface systems.



Fiure 14: User-Oriented Curve Correction & 4D Printing Classification

Deformation adjustments depend mainly on data errors, leading to changes in data variance.

The variance formula is as follows:

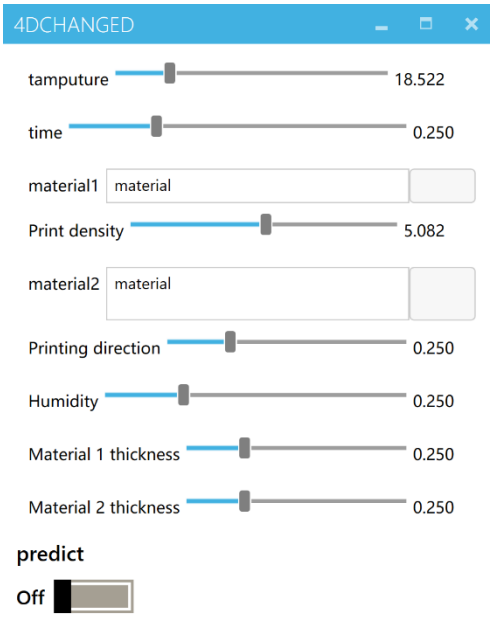
$$Var(X) = E[(X - \mu)^2]$$

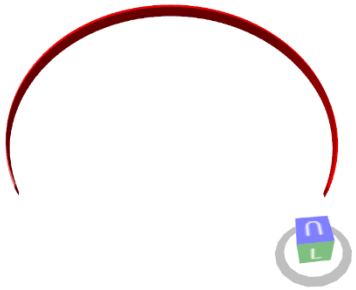
where E(X) denotes the expected value of X (i.e., the mean $\mu = E(X)$). X is for the test times. Basic variance is calculated for stability assessment. Clustering algorithms and iterative refinement can enhance algorithm stability. The research dataset includes Y1 to Yn. The regression calculation principles are as follows:

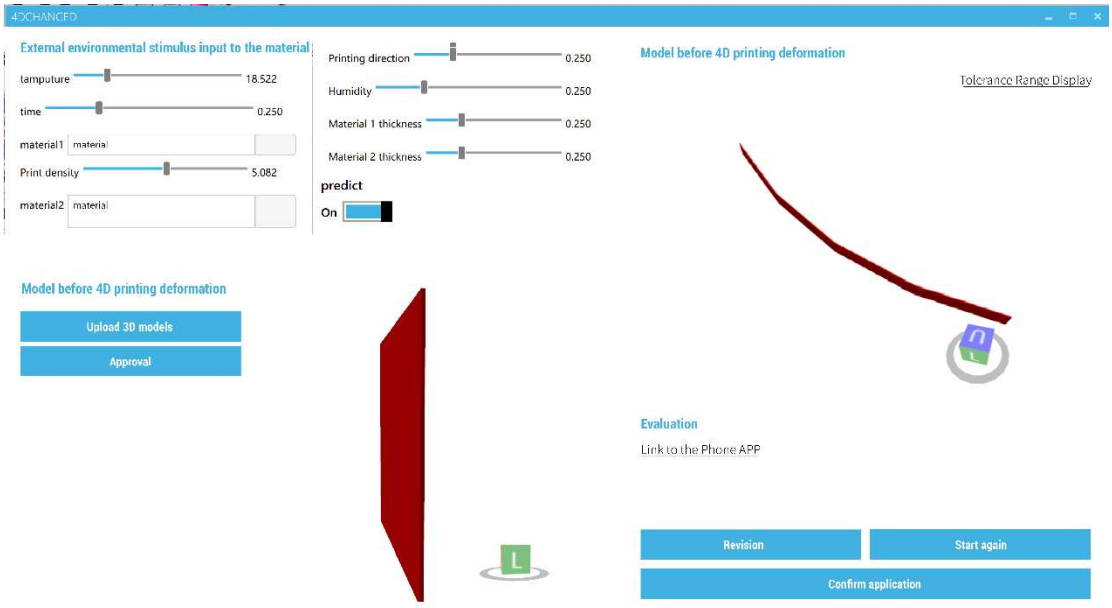
{\displaystyle \sum _{i}(Y_{i}-{\bar {Y}})^{2}=\sum _{i}(Y_{i}-{\hat {Y}}_{i})^{2}+\sum _{i}({\hat {Y}}_{i}-{\bar {Y}})^{2},}

The principle of regression analysis demonstrates a certain degree of rationality. Acceding the Pearson correlation coefficient to anazyle.

UI design.


4DCHANGED
tamputure
18.522
time
0.250
material1
material
Print density
5.082
material2
material
Printing direction
0.250
Humidity
0.250
Material 1 thickness
0.250
Material 2 thickness
0.250
predict
Off




4DCHANGED
External environmental stimulus input to the material
tamputure
18.522
time
0.250
material1
material
Print density
5.082
material2
material
Printing direction
0.250
Humidity
0.250
Material 1 thickness
0.250
Material 2 thickness
0.250
predict
On
Model before 4D printing deformation
Upload 3D models
Approval
Model before 4D printing deformation
Tolerance Range Display
Evaluation
Link to the Phone APP
Revision
Start again
Confirm application

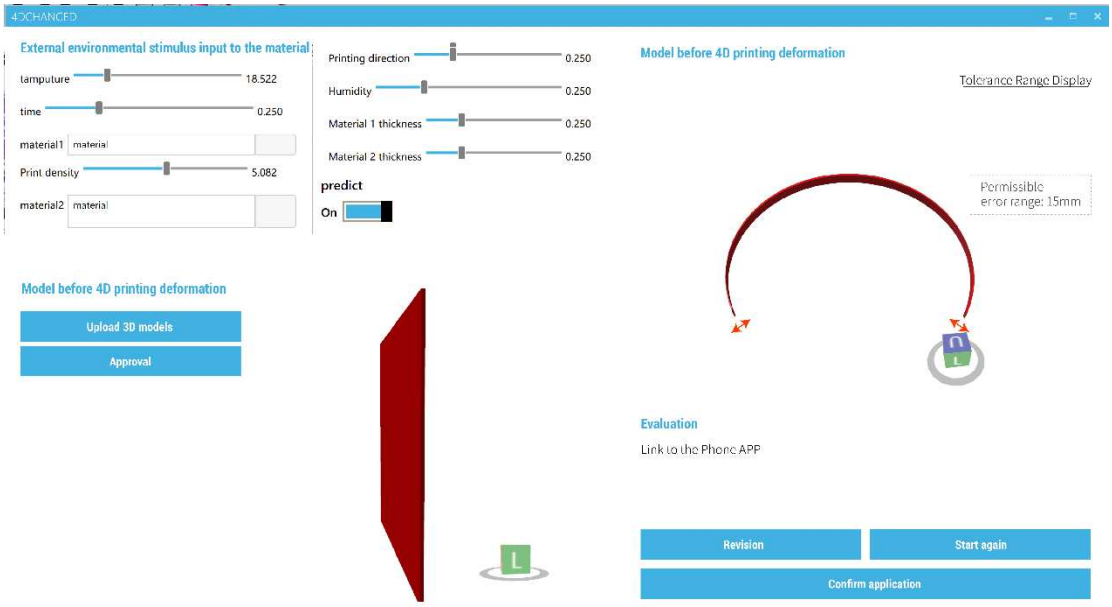


Figure 15: The interface for shape changing

The tool interface illustrates the range of 4D printing deformation estimation and the use of Rhino Grasshopper for design. Tailored to meet user requirements for print deformation based on prompts within the prototype interface of the sketch. As engineering inevitably involves errors (Lopez et al,2010), these discrepancies must be addressed. This is a visual representation of the 4D printing experiment. The previously calculated material properties were within a range, so the final deformation estimate should also be a range, as shown in Figure 14. These findings reveal the extent to which external factors influence 4D printing temperature and print density, as observed during the experimental process. This is primarily achieved through computational estimation, Rhino GH, utilising algorithms via modules (Bai et al,2025). Through the implementation described above, one can understand the input of changes in 4D printing and the output of the deformed 4D print. The interface is better for setting parameters. The user research of the usability test involving 12 participants demonstrated the system's usefulness, primarily concerning whether its usability was satisfactory. The usability score of 4.2 out of 5 indicates that it fundamentally meets requirements, confirming its utility in the paper (Bai et al., 2025).

Usability testing is a necessary testing method (Benyon, 2019) for measuring human. The main was found during the prototype and technical prototype for Grashopper, and the implementation of the Grashopper plugin for the Human UI plug-in for the 4D printing deformation visualisation. The purpose of the study is to conduct usability testing on the designed and implemented interface to see whether it meets user needs and improve. Usability testing is mainly for software prototypes, such as Rhino's Grasshopper plug-ins and human UI plug-ins.

Measurements

Qualitative interviews

The questions ask for the interview to use for measurement, respectively, and how you made it available or not. What suggestions do you have for the software? Tell the tester the scope and task. The tester tests it and then gives feedback and analyses the changes. The key questions focused on whether participants used the tool and what improvements they suggested. These questions addressed the prototype sketch, Grasshopper implementation, and UI, respectively. Both primary and follow-up questions were asked based on each interviewee's background.

Experimental settings

There are four improvements. Others can be classified according to the user's occupation. The user usability test was conducted with 12 scholars in a combination of online and offline methods. The interview test was conducted online through Teams for feedback.

Findings- Qualitative analysis Theme A: Usability

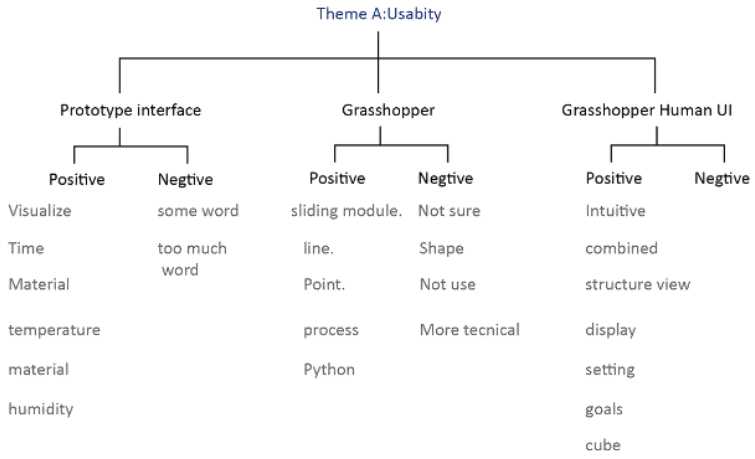


Figure 15: Theme A: Usability analysis

Usability testing of the Prototype interface (12 participants) revealed that 75% (9/12) found the software useful, with only 25% (3/12) rating it as useless. Most of them have too many settings, and it is unclear what the setting data is for. For the Grasshopper interface implementation, most people think it is useful (7), fewer people (5) think it is useless. The main reason is that the evaluation is more technical, and the researcher chose to interview designers and engineers first. Grasshopper is only a part of the technical implementation and is not very meaningful for usability testing. User usability testing is more user-oriented than software quality testing, which is oriented towards software algorithms and stability (Benyon,2019). As for the Grasshopper human UI implementation, all participants think it is useful and clearer.

For qualitative analysis, these usability words are classified into positive and negative categories. Regarding the sketch, most data focus on usability and simulation fidelity to 4D printing. But 4D printing is novel; the challenge is managing data. But more data for the user could confuse the usability; they said," More words are difficult to use; I cannot choose where to start". This means that the simpler it is, the more user-friendly it will be if the deformation factors of 4D printing are met. Many people think that the usability test of Grasshopper is useless, but some users who don't know about Grasshopper know its function through the guidance of the diagram. So, the qualitative data here is about the display of geometric elements. Although usability testing is about users, one tester was very curious and asked what genetic algorithm was written in the Python battery. So, this part is more technical for the usability test and is not useful.

Theme B: Promote

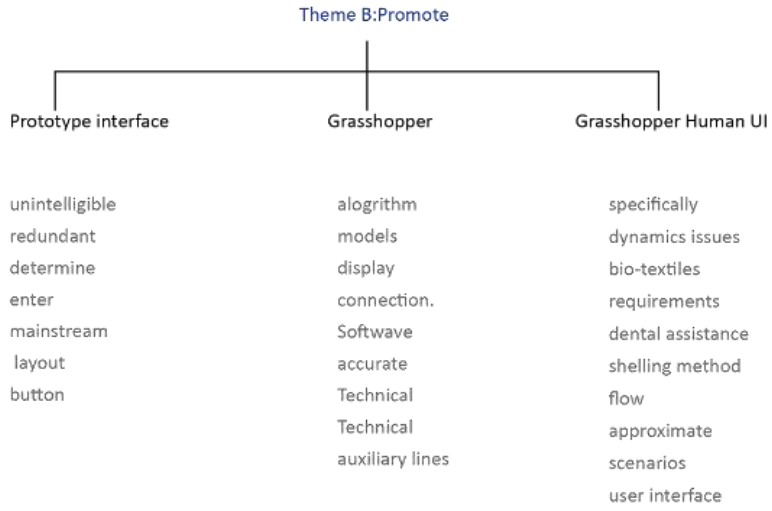


Figure 16: Theme B: Promote analysis

The following conclusions were drawn through the analysis of another keyword, Promote. Conduct usability testing in stages. Human The researchers refined certain suggested categories (nouns and verbs). The interface prototype showed that suggestions have input and output processes. Users wanted confirmation during input. And parameter data was needed. After all, designers and engineers didn't know how to set up 4D printing and hoped to have a reference parameter to control deformation. In addition, the interface needs to deformation parameters and does not require too many parameters. It is mainly used for ease of operation. As for Grasshopper, the suggestions are more on the technical level, such as how the geometric elements of points, lines, and surfaces describe the entire shape, and the accuracy is not very high. During the user interviews, the researcher learned about 4D printing, and one of the users, who worked as a product manager in a 3D design company, asked more about materials and process flow, and whether it could be added to the software for testing. In conclusion, the user suggestion is more based on the user station's technical aspects. So, the next step requires quantitative analysis.

Discussion for result

The usability test used the cognitive walkthrough method for feedback. Usability testing is also about whether the user's usage scenario meets user needs. traditional use of software, Grasshopper, and human UI, plus implementation. But, for Grasshopper, most people could not analyse and experiment to improve. So, what the Grasshopper is for, could not be known. Grasshopper is too much of a technician. But although it is more about technology, showing a process, the software can report many errors. Although some aspects are not particularly perfect, the overall usability is satisfactory, and the software quality needs to be improved, not for usability. Most designers and users think it is better in human UI implementation

It involves whether to model and whether to do it online. Online is suitable for the basic module subdivision template function, and offline is flexible, such as the SolidWorks sketch pulling, digging, and shelling method—an assistant system for Rhino based on the most used software. The issue is whether the software can be expanded. In addition, Rhino includes Grasshopper, which can be implemented quickly. On the contrary, some engineering software plug-ins require programming and a long cycle time.

In addition, the implementation of Grasshopper's human UI is feasible and relatively complete. A software implementation was carried out. The implementation is relatively complete and easily recognised by users. Grasshopper's human UI could be easily achieved, and the software implementation. It can also be implemented in software. For example, combined with the settings of Cura, the slicing software for 3D printing. The assistant software functions as a CAD tool for 4D printing differentiation.

In addition, usability testing was conducted on 18 participants, and usability was measured using a 5-point for 20 SUS scale. The test yielded a score of 4.25/5, indicating that the system is useful. Regarding the interface, the authors found that the main thing is that you can input all the factors of 4D deformation. But first, there are many deformation factors, and users need more input data to know how to set the parameters. In addition, excessive input can make it difficult for users to understand cognitive review, as they need the data to be reasonable. This depends on the specific scenario in which 4D printing is applied. It may be necessary to customise the interface according to the specific 4D printing scenario, which is based on user needs (Benyon, 2019), and for user-centred customisation for 4D printing deformation. Based on the interface validation, this method is considered usable.

Conclusion

In conclusion, deformation is an important factor, and different temperatures affect deformation results. Both thermometers and infrared devices play important roles.The general thermometer has an easily inaccurate hysteresis measurement, and the infrared measurement is more accurate. The experimental setup is useful to some extent for detecting 4D print distortion. The main finding is that the study experimentally demonstrated that using deformation software to predict 4D printing could help software.

The process is not too smooth. Mainly using a thermometer to measure the temperature, resulting in holes. Accidentally finding 4D printing (through 3d printing heating deformation) is possible in the artwork and industrial products. In the experiments on 4D printing deformation for estimation, it was observed that heating-induced deformation, due to 3D printing, shows a proportional relationship between temperature and strain. The deformation is primarily driven by thermal expansion and contraction, with more pronounced bending occurring due to the interaction of heat and material density. The experimental results confirmed that both temperature and strain are proportional, consistent with preliminary qualitative conclusions. The two primary factors influencing bending are temperature and material print density, both of which are strongly correlated. While 4D printing shows great potential, especially for artistic and industrial applications, its accuracy still poses a challenge, largely depending on the user and the specific application. Therefore, while 4D printing is viable in certain fields, achieving high precision remains a limitation for the user in 4D printing deformation. The main purpose is to demonstrate the effectiveness of the interface system.

Limitation

This study was conducted using a standard 3D printer with a limited range of available materials, which may introduce certain constraints on the types of materials tested. Additionally, the strain transducer may lose its ability to generate electricity when submerged in water, impacting performance. Another challenge is the uneven heating from hot melt guns, which can prevent the deformation from achieving the desired outcomes. Furthermore, the fact that this has been repeatedly validated through 4D printing experiments can be demonstrated using data, and the visualised design illustrates how it can be incorporated into 4D printing decision-making.

Next step

The next step is to improve the accuracy of the algorithms, the design of the interface to go with the algorithms, and the design of the application of the product to be printed in 4D printing and improve the accuracy of the algorithms, the design of the interface to go with the algorithms, and the design of the application of the product to be printed in 4D and a prototype interface with algorithms to help users with 4D printing. The interface will tell the user the distortion of the 4D print. The interface is a direct 4D printing method for users (designers and engineers). There is also the application of 4D printing in design to address the designer's use of the process. Some irregular distortions can also be utilised in art and design. Use 4D printing to develop a product design if it meets the user's needs (designing the product and engineering the needs). The user evaluation was done using a cognitive walkthrough and algorithm improvements.

Acknowledgements

N/A

a. Funding

No

b. Conflicts of interest/Competing interests

No

c. Authors' contributions

Jinghao Bai for the research Experiment and write

Availability of Data and Materials

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

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