Sequential Support: 3D Printing Dissolvable Support Material for Time-Dependent Mechanisms

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ABSTRACT
In this paper, we propose a different perspective on the use of support material: rather than printing support structures for overhangs, our idea is to make use of its transient nature, i.e. the fact that it can be dissolved when placed in a solvent, such as water. This enables a range of new use cases, such as quickly dissolving and replacing parts of a prototype during design iteration, printing temporary assembly labels directly on the object that leave no marks when dissolved, and creating time-dependent mechanisms, such as fading in parts of an image in a shadow art piece or releasing relaxing scents from a 3D printed structure sequentially overnight. Since we use regular support material (PVA), our approach works on consumer 3D printers without any modifications.

To facilitate the design of objects that leverage dissolvable support, we built a custom 3D editor plugin that includes a simulation showing how support material dissolves over time. In our evaluation, our simulation predicted geometries that are statistically similar to the example shapes within 10% error across all samples.

Author Keywords: 3D printing; support material.

ACM Classification Keywords: H5.2 [Information interfaces and presentation]: User Interfaces.

INTRODUCTION
Early on in the development of 3D printing, researchers realized that building objects bottom-up, layer-by-layer comes with an inherent issue: some geometries would have nothing underneath them to hold them up. To solve this issue, researchers developed support structures to keep overhangs upright [1, 9].

Early 3D printers that had only a single extruder used one material for both the model geometry and the support structures. Once the 3D print was finished, the support was broken off to reveal the object. However, this left visual artifacts and was not suitable for support material inside small holes as users were not able to reach in and remove it.

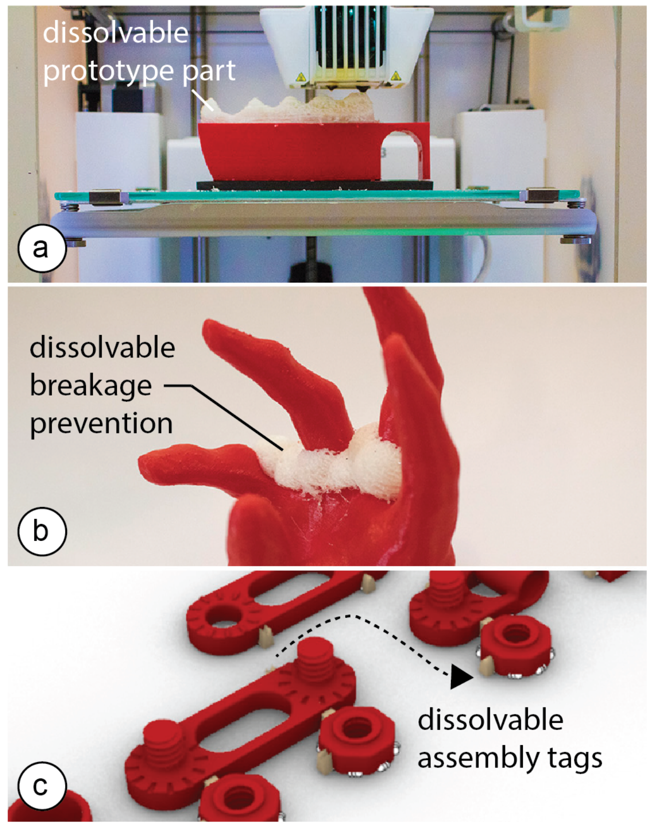

Figure 1. We leverage the transient nature of support material to create new application scenarios: (a) a dissolvable prototype part for design iteration, (b) breakage prevention that can be dissolved after transport, (c) dissolvable assembly labels that leave no marks. In addition to these discrete use cases, we also developed mechanisms that continuously dissolve over time.

Dissolvable support material [9] solved these problems: since it decomposes in a solvent, such as water, it creates smooth surfaces and leaves no visual marks. Because water can better access small holes, dissolvable structures can more easily be removed. Due to its many benefits, dissolvable support material (e.g., PVA) is now a widely used alternative to physically breaking off the support.

Since printing support structures requires extra time and material, the use of support has so far been perceived as an inconvenient necessity to extend the range of printable geometries. In this paper, we take a different approach. Rather than using support material to print support structures, our idea is to make use of its transient nature, i.e. the fact that it can be dissolved when placed in a solvent, such as water, to enable a range of new use cases.

Our contributions include: (1) an exploration of alternative use cases of 3D printable support material in two categories: those that require controlled dissolving behavior for timing and sequencing events and those that do not need precise control and only require the support material to dissolve eventually; (2) a design interface in the form of a 3D editor plugin that facilitates designing with dissolvable support material; (3) a simulation integrated in the design interface that visualizes how the support material dissolves over time; and (4) a step-by-step procedure to characterize the simulation parameters for different environments.

RELATED WORK

Our work is related to research that repurposes fabrication tools, optimizes support material, and models time-dependent geometries.

Repurposing Fabrication Devices & Materials

Several research projects have investigated how to extend the capabilities of 3D printers by changing the standard workflow. *WirePrint* [11], for instance, extrudes in 3D space rather than layer-by-layer; *3D printed hair* [8] repurposes the stringing behavior of plastic extrusion; and *Embedded textiles* [18] embeds fabric layers during 3D printing. Finally, *Encore* [3] allows to print on top or around existing objects. These methods do not modify the 3D printer, rather they change how it is being operated.

Similar explorations exist for other fabrication processes. For stereolithography, *Cillia* [16] generates bitmaps rather than CAD models to enable high-resolution structures; and *FusePrint* [32] inserts existing objects directly into the resin to produce molds. For laser-cutting, *LaserOrigami* [12] makes 3D objects by using the laser for cutting and bending a single sheet, while *LaserStacker* [24] creates 3D objects by welding multiple sheets together. Other innovative fabrication techniques create multi-material bendable (*Foldem* [17]) and inflatable 3D objects (*BlowFab* [29]).

Optimizing Support Structures

Several research projects have developed methods to print support structures in a way that minimizes the overall amount of support required. For instance, *Branching Support* [21] and *Clever Support* [25] optimize support structures by reducing the number of its connection points to the object. *Bridging Support* [4] uses the stringing behavior of plastic extrusion printers in order to build support structures that resemble horizontal bridges. Finally, *Perceptual Support* [31] lays out support structures to minimize visual artifacts. Support structures have also been used for innovative use cases: For instance, to prevent smearing from oozed-out material, a rampart structure made of support has been shown to work well [6]. Closest to our work is *Printable Hydraulics* [10], which uses the liquid support material in inkjet 3D printing as a means of fabricating hydraulic actuators with pre-filled fluidic channels.

Modeling Time-Dependent Structures

Since we provide a simulation tool for how the support material dissolves over time, our work is also related to modeling tools for time-dependent geometries. *Transformative Appetite* [26], for instance, simulates the swelling and bending of edible 2D films that fold into 3D shapes during cooking. Similarly, *BioLogic* [30] comes with a simulation to preview how biofilms curve under humidity. Other predictive models have been developed for controlling bending angles in pneumatically actuated devices [13] and shape memory polymers that are activated by heat [14].

SEQUENTIAL SUPPORT OVERVIEW

The main idea behind *Sequential Support* is to make use of the transient nature of support material, i.e. the fact that it can be dissolved when placed in a solvent, such as water, to enable a range of new application scenarios.

Discrete vs. Continuous Dissolving

We classify our application scenarios into two categories: (1) *discrete* and (2) *continuous* dissolution.

In *discrete* dissolving, the timing and sequencing of how the support material dissolves plays no role, i.e. it is only of importance that the support material dissolves eventually. For instance, when iterating over a design, rather than reprinting the entire object, we use dissolvable support material for the part that requires iteration (Figure 1a). After dissolving the prototype part that required a change, we can print the new iteration directly on top of the object.

In *continuous* dissolving, in contrast, the timing and sequencing of how the support material dissolves does matter. For instance, we can use dissolvable support capsules to release relaxing scents on a night stand overnight in a particular *sequence* and at pre-defined *time steps* (see Figure 2). We release the scents in the order of red, blue, green and at 86 min, 115 min and 158 min respectively.

Design Tool including Support Material Simulation

Our design tool, implemented as a plugin to the 3D editor Rhino3D, supports both types of use cases, discrete and continuous. Users start by creating a regular 3D model, then assign either regular plastic (‘PLA’) or dissolvable support material (‘PVA’) as a shader to the different object parts. Once users have assigned the material, our design tool enables a ‘time-slider’ that when dragged provides the user with a preview of how the support material will dissolve over time. The user can change the object geometry to explore different dissolving outcomes and then choose the design which produces the desired dissolved geometry to export for 3D printing. We provide a more detailed illustration of our design tool in the next section using a variety of use cases.

APPLICATION USE CASES

In this section, we will illustrate five applications, including two continuous and three discrete examples. For each example, we will show the use of our design tool, and report on the fabrication and dissolving time as well as the simulation accuracy.

#1 Overnight Scent Release (Continuous)

As mentioned above, we can use dissolvable support capsules to release relaxing scents overnight at pre-defined time steps. For this, we printed three support material spheres and filled them with essential oils (paused the print half way through, filled the capsule, continued the print as described in *Printed Optics* [28]). We then placed the capsules in a water container on the night stand in our bed room.

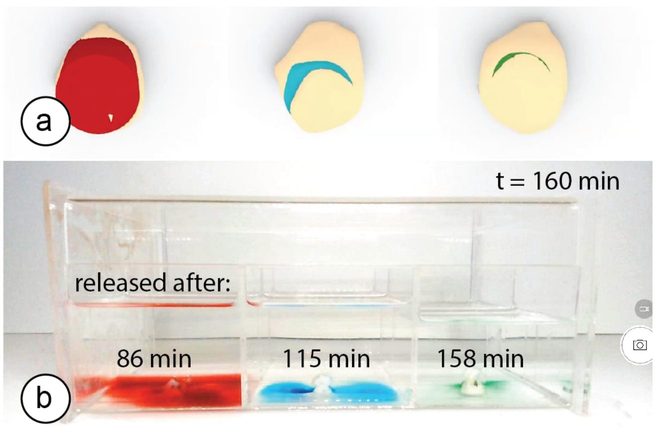

Figure 2. This nightstand box releases relaxing scents in a pre-defined sequence: the red scent first, then blue, and finally green. (a) Simulation, and (b) actual release.

Since each sphere had a different wall thickness (2.5mm, 3mm, 4mm), the scents were released one after another after 86 min, 115 min, and 158 min respectively. We had previously explored the timing using *Sequential Support's* simulation tool, which had predicted times of 86 min, 135 min, and 163 min for the red, blue, and green capsules.

#2 Animating Shadow Art (Continuous)

By leveraging the timing and sequencing prediction of our support material simulation, we can use dissolving support to create shadow art. Figure 3 shows an example: Before the support material dissolves, the shadow art shows the initial image, i.e. a figure standing under a sunny sky. Once

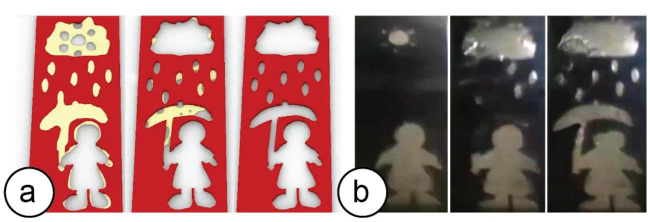

Figure 3. (a) Simulation: We time the dissolving support to first convert the sun into a cloud, then show the raindrops, and finally an umbrella. (b) Physical result.

The shadow art starts dissolving, the sun turns into a cloud, the raindrops become visible, and finally an umbrella appears above the figure. The setup that we used to create this sequence consisted of the 3D printed object submersed in a water container and a light source mounted above it.

The dissolution time predicted by the simulation was 428 min vs. 380 min for the actual dissolving; the clouds, rain-drops, and umbrella were mostly dissolved at 1/2, 3/4T and at T, respectively, for both simulation and experiment.

#3: Design Iteration Partially Replacing a Part (Discrete)

Rather than reprinting the entire object during prototyping, we can use dissolvable support material for the parts that require iteration. Figure 4 illustrates this using a Kinect handle that has been 3D printed to provide the user with a steadier grip while 3D scanning. We are unsure about the exact curvature and spacing for the grip and thus decide to print the grip part in dissolvable support.

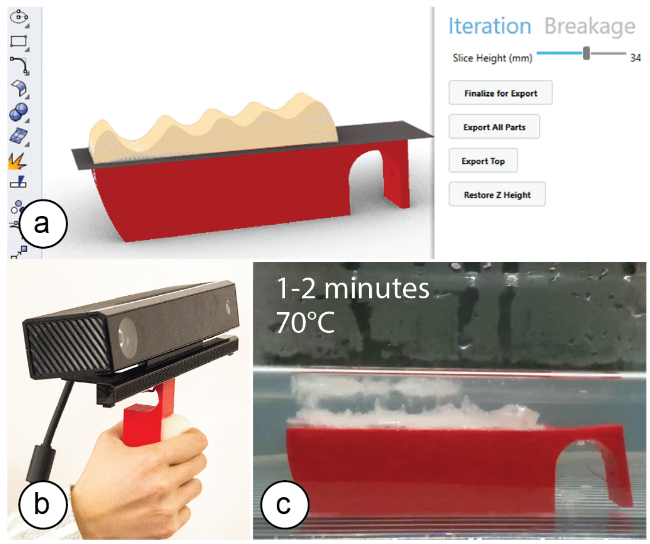

Figure 4. (a) Splitting the model, (b) testing, (c) dissolving the top part before fabricating the next version.

We use *Sequential Support's* user interface to split the model into two parts (bottom: red PLA, top: white dissolvable PVA) using the 'slicing height' slider. After printing and testing, we notice that the handle does not allow for a firm grip. We thus place it into hot water (70°C), which dissolves the top part within 1-2 minutes (note that discrete scenarios work with a higher water temperature (70°C vs. 45°C, thus dissolving faster). We return to the 3D editor, modify the 3D model, then export again. To reprint the top portion of the grip, we place the previously printed bottom part onto the build plate (using a custom mount and double sided tape) and print the new part directly on top.

Printing the new part took only 1h 41 min vs. 5h 16 min for printing the object from scratch (68% faster), and only took 16g material vs. 54g (71% less material). We test the handle again and now it feels right. We dissolve the top one more time and reprint it in red PLA to produce the final version of the design.

#4 Breakage Support: Dissolvable Packaging (Discrete)

To prevent fragile regions from breaking during transport, we use support material to reinforce them. Figure 5 shows an example: We print this phone stand in a FabLab but are afraid it might break as we transport it home. (a) After clicking *Sequential Support's* 'stress analysis' button, we see that the phone stand is likely going to break in the regions close to the fingers. (b) By dragging the 'support level' slider, the regions identified by the stress analysis (FEA) are covered in additional dissolvable material.

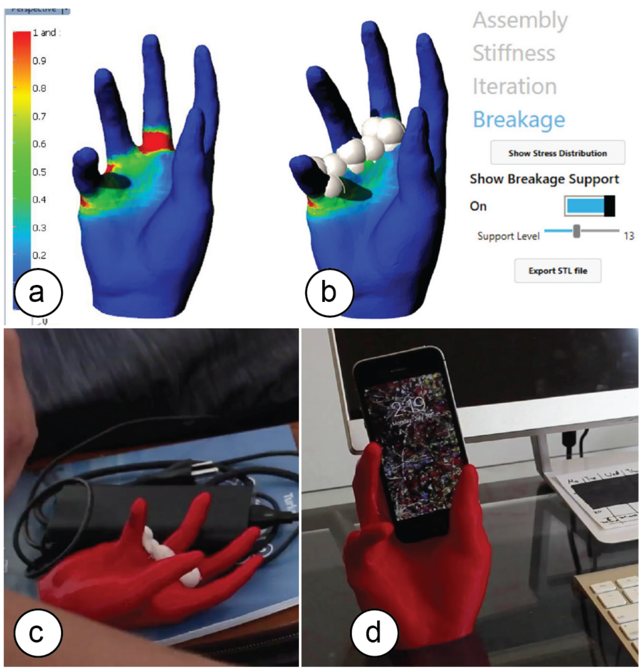

Figure 5. (a) Stress map, (b) breakage support. (c) Transporting the object, and (d) after dissolving the support material on arrival use the phone stand.

Adding the support increased printing time by only 19% (17h51 vs. 15h01) and required only 6g of support added to 107g PLA. After transporting the object home, softening the support using hot water (70°C) took only 4 minutes; we then wiped off the rest by hand and were ready to use the object within 15 minutes.

#5 Assembly: Temporary Labels (Discrete)

In our final use case, we use support material to simplify assembly. Here, we design a lamp that consists of 10 different parts. First, we use *Sequential Support's* user interface and attach matching labels to the parts of the object that belong together using the 'label' buttons (Figure 1c).

Next, we create 'stickers', i.e., small support structures that can be used to connect two parts together (Figure 6a). These structures work as temporary adhesives to put parts that belong together close to each other (e.g., a nut that belongs to a particular threaded protrusion). Users can break them off during assembly and dissolve the rest later together with the labels (ca. 2-3 min in 70°C).

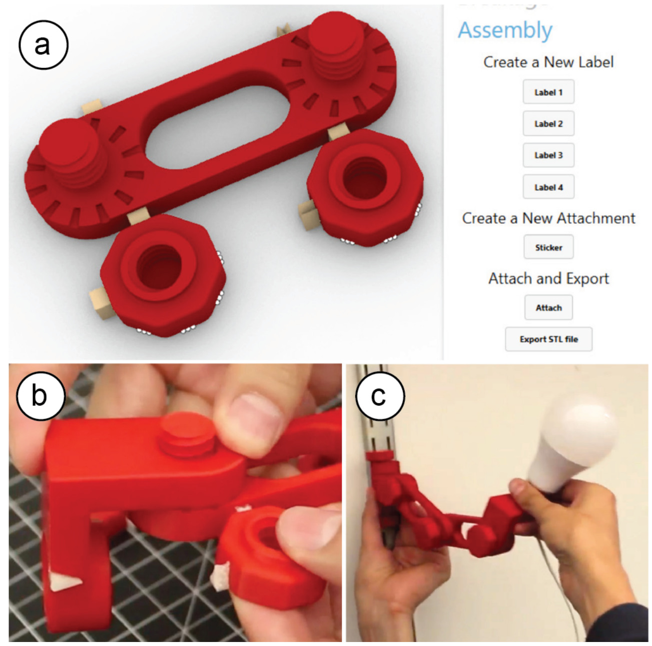

Figure 6. (a) Small support structures can be used as connectors, to hold parts in place for (b) later assembly. (c) Mounting the assembled lamp onto the wall.

SIMULATION OF DISSOLVING SUPPORT MATERIAL

In the next section, we describe the algorithm used in our support material simulation that enables the continuous-time application scenarios. Our simulation takes into account different factors involved in dissolving support material, which we primarily base on related research on dissolving crystals in solvents [2, 5, 15].

Step #1: Voxelizing the Model

As soon as the user assigns support material ('PVA') as a shader to a part of a 3D model, we begin pre-processing the part to enable the simulation. We begin by voxelizing the part: We first compute the part's bounding box and then fill it with voxels of size N (we use: side length = 0.3mm; the higher the resolution the more accurate the simulation, however, this comes with the trade-off of increased computational complexity that limits interactive exploration in the design interface). We then keep all voxels that intersect with the part's surface and discard the rest.

Step #2: Dissolution Probability for Number of Faces

Each remaining voxel can have one of two states: dissolving in the current time step or not dissolving. To determine the probability that a voxel will dissolve, we use the following equation (initially proposed by Gilmer et al. [5] and extended by Briese et al. [2]):

$$P_d = v^{-\frac{f\phi}{kT}}$$

As can be seen in the formula, the probability that a voxel dissolves increases exponentially with the *number of faces f* exposed to the solvent. A voxel that is attached on only one side and thus has 5 faces exposed to the solvent, has a much higher chance of dissolving than a voxel with only one exposed face (Figure 7). This is why support structures on a model's surface dissolve faster than those in small inlets (e.g., screw holes), and why sparse structures dissolve faster than solids.

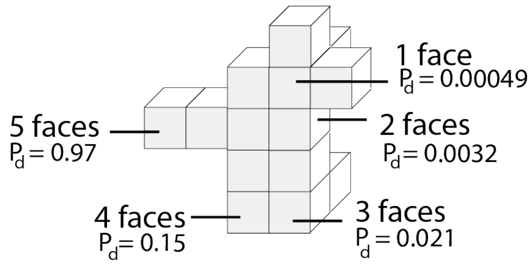

Figure 7. The more faces of a voxel are exposed to the solvent, the higher the probability that it dissolves.

In the formula, *T* is the temperature of the water in Kelvin (constant at 318K or 45°C), *k* is Boltzmann's constant (1.38064852 × 10^{-23} $m^2 kg/s^2 K$), and *v* and *φ* are constants that influence the speed of dissolution. We determined *v* and *φ* for our setup as described in section 'Characterizing simulation parameters' (*v* = 6.5, *φ* = 1.9).

Inserting all values into the formula, and varying the numbers of faces *f* from 1-5 gives us the probability for a voxel to dissolve based on its number of faces: f_1 = 0.00049, f_2 = 0.0032, f_3=0.021, f_4=0.15, f_5=0.97 (Figure 7).

Step #3: Drawing a Random Sample

We then use these probabilities as inputs to a kinetic Monte Carlo simulation as described in Briese et al. [2].

We start by drawing a random number n from a uniform distribution on the interval [0,1]. This number is then compared to the probability that each voxel will dissolve. If the random number is smaller than the dissolution probability of the voxel, the voxel is dissolved. If not, it stays put.

After removing all dissolved voxels in the current time step, new surface voxels are generated to ensure that the voxel layer remains 1 voxel thick. We then repeat step #2 and #3. Figure 9 shows some results from our simulation.

Step #4: Rendering

We then convert the voxel model into a continuous surface using the Laplacian smoothing algorithm from the *Weaverbird* [27] Grasshopper add-on to render a more visually compelling result.

CHARACTERIZING SIMULATION PARAMETERS

Next, we explain how we determine the two input parameters *v* and *φ* for the dissolution formula experimentally.

Factors v (global dissolve speed) and ϕ (local speed)

The factor *v* represents the *global* dissolve speed independent of the number of faces. The factor *φ,* in contrast, represents the *local* speed with which each voxel dissolves based on the number of its exposed faces *f.*

For instance, consider the effect of varying v and *φ* on a 'star' shape. If *φ* is small, the number of faces exposed to the solvent has less of an effect on the probability of dissolution of each voxel. As a result, voxels at the tips of the star (containing more exposed faces) will be dissolved at rates similar to those voxels composing the flat sides of the star (fewer exposed faces). Therefore, with small *φ,* the star will remain star-shaped. In contrast, if *φ* is large, the number of faces exposed will play a greater role and the tips of the star will dissolve faster than the flat sides of the star, leading the star to become sphere-like.

Collecting Test Data

To determine the parameters v and φ, we printed different shapes (sphere, star, cube). We dissolved them in water and captured images using a front view camera (Figure 8). The shapes measured: *cube* length: 15mm, *sphere* diameter: 15mm, and *star* outside diameter: 24mm.

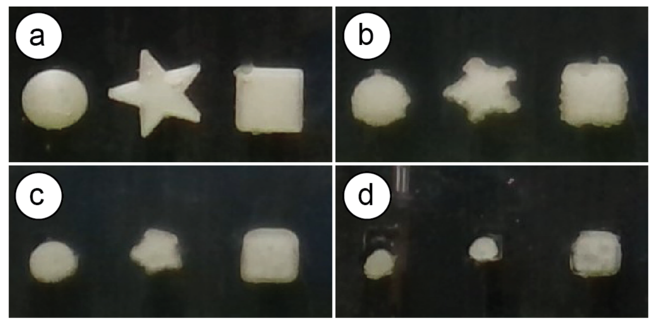

Figure 8. Dissolving shapes over time.

We used a 3-liter water tank and heated the water to a temperature of 45°C. This was the highest temperature chosen based on a trade-off between faster dissolution times and a tendency of the solvent to become cloudy at elevated temperatures, preventing us from recording the experiment.

We also created a mild current by using a 20mm magnetic stirrer at 600rpm. The reason we use stirring is that when support material dissolves, the resulting particles stay close to the location where they dissolved, i.e., close to the object's surface. The more particles are floating close to the surface, the slower the support material dissolves.

After immersing the objects in water, we took pictures every 8 minutes (Figure 8). We collected the same data from our simulation, i.e., we ran our simulation with an initial set of parameters for factor *v* and *φ* on the three test shapes and took screenshots from the same angle that the physical camera took photos of the real objects (Figure 9).

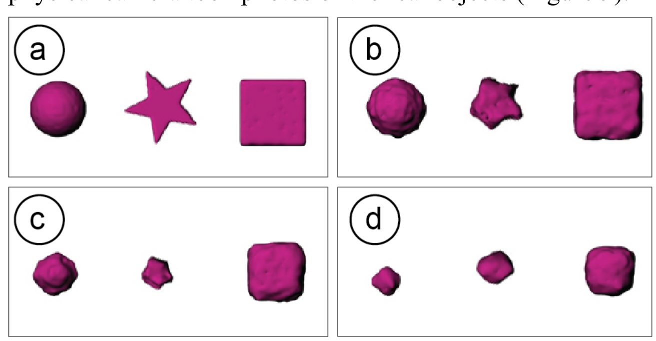

Figure 9. Simulation pictures.

Extracting & Comparing Shape Contours

We used OpenCV to extract and then compare the shape contours. We first thresholded the images and then extracted huMoments to gain a feature vector describing the contours in a translation-, rotation-, and scale-invariant manner. We applied the same procedure to both the photos and the screenshots to gain a feature vector for each.

Computing Error and Adjusting Simulation Parameters

We then used the two feature vectors to compute the error (Euclidean distance) between the actual physical behavior and our simulation. This error is thus based on the compared 2D images (photos and simulation screenshots), which we use as a proxy for the difference between the full 3D shapes.

We then chose another set of simulation parameters v and φ, re-ran our simulation with the new v and φ and compared the error to the error from the previous parameters (we always first picked φ, and then adjusted the corresponding v (global speed) until the probability for a voxel that has 5 faces (f_5) was 97%). The results for each set of φ and v can be seen in Figure 10.

We found that $\varphi = 1.9$ and $v = 6.5$ lead to the best results across the three different shapes (lowest average error between the feature vectors over all time steps). Figure 10 summarizes the result for dissolving the same objects (star, sphere, cube) twice. We found that the error between the two experiments differed by less than 10%.

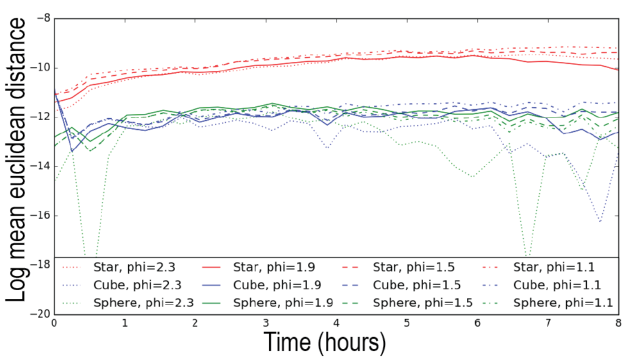

Figure 10. **Graph of feature vector errors over time.**

IMPLEMENTATION

Both the simulation and the use-case specific features in our design tool are implemented as a *Grasshopper* plugin for the 3D editor *Rhino 3D*. We used the *HumanUI* library for the user interface elements.

Design Iteration: Splitting the Model & Off-Setting It

To split the model in half at the desired height, we use the Grasshopper *SplitBrep()* function. On export of the .stl files, the two parts are merged into a closed solid using the Grasshopper *Cap* function. After splitting and capping, the two geometries are baked to a new layer in Rhino using the function *GH_Bake()*. We use a custom script to export each geometry on the *GH_Bake* layer as individual .stl files (both are regular closed meshes, i.e. the parts can have sparse infills but will be separated by a solid layer).

When printing a new iteration, the system only exports the top geometry as an .stl file. We then run a python script in the background that offsets the gcode commands in the Z direction by the height of the PLA part.

Stress Analysis using Finite Element Analysis

To create the stress analysis for our model, we use Rhino's *Scan&Solve* plugin. The plugin comes with a function called *AddFaceVectorLoad(),* which we give a set of input forces with a uniform load of 100N pointing from the top to the bottom. To display the resulting stress distribution we use the function *SolutionDisplayEnable()*. We then get the points of the highest stress using the function *QuerySolutionValue(),* which returns a list of stress values at all points on the model. We sort this list using a custom python script and then create a number of spherical support structures to cover the stress points commensurate with a value chosen using the slider in the user interface.

Assembly Instructions

To set up the snap locations on both the object and the instruction labels, we generate 'point' objects in Rhino. When the user connects two parts, we call Rhino's *orient()* function to snap the instruction label onto the reference point. We use the same approach for the *attach* option.

Scent Release and Shadow Art

Both examples use the simulation described previously in section 'Simulation of Dissolving Support Material'.

LIMITATIONS

While our approach enables new application scenarios, it is subject to the following limitations: *(1) single-use only:* once the support is dissolved, we cannot repeat the functionality. Thus, using support material works best for scenarios that require functionality only once, such as during assembly, product configuration, or transportation. *(2) Simulation Precision:* Since our set of sample shapes was small and the parameters were only optimized over a narrow range, the simulation should be fine-tuned in future work using additional shapes. *(3) Speed:* While the process of dissolving is fast at high water temperatures and for small amounts of support (only a few minutes for thicknesses in the vicinity of 1mm), it can take hours at low temperatures and when a lot of support material needs to dissolve. Thus, our work is limited to application scenarios with an extended time span, such as the overnight scent release or the slowly changing shadow art piece that could be displayed in a public plaza. (4) *Overhangs:* The support material cannot be used to print support structures for overhangs if those interfere with the main dissolving geometry. (5) *Adherence:* Current PVA support material is challenging to print since it does not adhere well to the regular PLA printing material. Printing on large flat surfaces (e.g. as in the design iteration case) facilitates adherence, while more complex geometries, such as the phone stand, are more difficult to print.

DISCUSSION

In this paper, we provided a first exploration into how support material can be used for different application use cases. However, for each individual use case, a more extensive exploration is required to analyze the trade-offs of using support material vs. traditional approaches.

For instance, using support material in the design iteration use case can accomplish the same function (i.e. replacing a part of the object geometry) as by using a milling machine (see *Patching Physical Objects* [22]). Compared to using a mill, our approach has the benefit of not requiring additional hardware and being faster when a high temperature bath is used (minutes of dissolving vs. hours for milling). However, when using a mill, the user can decide which part to replace *after* printing, whereas in our approach the user needs to decide which part requires iteration *before* printing. In both processes, alignment and delamination are challenges that need further investigation. In contrast to approaches that use joints to connect parts [7, 20] or rafts / brims, our method does not require modifying the model.

Similar trade-offs need to be explored for the other use cases, such as the breakage support. For instance, the benefit of our approach compared to traditional packaging is that it reinforces the object locally at its most fragile locations; this is different from packaging foam, which provides aggregate protection across the entire object. In addition, our approach provides additional breakage support even after being removed from the main packaging and during handling, until dissolved by the end user. On the other hand, if the amount of protective support is large and requires a long time to print, the high speed of traditional wrapping techniques might outweigh the advantage of local support. Finally, depending on the circumstances, the soluble support packaging may need to be protected against humidity as this could weaken the structure over time.

CONCLUSION

We presented *Sequential Support,* a system that enables users to use support material in 3D printing as a feature and not as a time- and material-consuming necessity. We showed how *Sequential Support* allows users to create a variety of objects for different application scenarios, such as dissolvable prototype parts, breakage support, assembly labels, and time- and sequence-dependent shadow art and scent release mechanisms. For future work, we plan to run a qualitative study in which we will investigate how our method changes participants' design practices. We will also use this study to explore additional application scenarios with participants. In particular, we are interested to further explore use cases in fabrication in which objects have a limited life-span such as those outlined in *Mobile Fabrication* [19], which include temporary tools and short-term fixes to everyday objects.

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