Developing an Accessible 3D Printing Pipeline

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Abstract

Digital technology provides an opportunity for people with disabilities to be involved in artistic activities, such as virtual sculpting whose output can be fabricated using 3D printing. Existing accessible solutions, however, present mainly a set of separate tools rather than a whole cohesive production pipeline which takes into an account the specific needs of the user group. Challenges include accessible user interfaces for all pipeline steps, suitable shape modelling operations, ”3D Print” button and model data formats that require no post-processing or clean-up operations for the Direct Fabrication step. In this paper we discuss an accessible pipeline which includes 3D modelling and 3D printing, providing an example of a 3D modelling system with developed special-purpose applications allowing children with complex disabilities to participate in sculpting activities through accessible interfaces such as eye-gaze control.

Introduction

According to the Disabled Living Foundation, there are 6.9 million people with disabilities of working age amongst a total of about 10 million adults and children with disabilities in the UK. It is often difficult for these people to be involved in artistic activities, especially those requiring physical actions. Digital technology provides an opportunity for including people with disabilities in the process of digital content creation, however, the main focus in the majority of the current accessible solutions is on the access rather than on the content. Moreover existing accessible solutions present mainly a set of separate tools rather than a whole cohesive production pipeline which takes into an account the specific needs of the user group. It is clear that the problem is not about creating an access solution alone, but it actually emcompasses the whole framework or pipeline which leads the user through different software and hardware solutions and eventually allows them to achieve the result in a most user-friendly yet efficient way.

In this paper we present the design and implementation of an accessible 3D printing pipeline, from content creation to physical print, which is a part of our ongoing Direct Fabrication approach. The key to this pipeline is a continuous and heterogeneous volume representation which, as well as offering other advantages, completely eliminates the traditional mesh-fixing step commonly required in boundary representation pipelines. At the same time on every part of the pipeline the accessibility and wide range of users of different abilities is taken into account. As a result, the process has a significantly reduced technical burden on the users and operators and allows for accessible access to modelling and fabrication technologies. Moreover, we are aiming at applications where access to hardware should not prevent users from being involved in the content creation from neither the technical point of view nor from the means of access, the result of which is that the pipeline can be used in a wide range of potential social applications. We describe the accessible pipeline design, the current implementation and planned future developments. We base this work on the accessible solutions developed in the SHIVA project [4] that produced prototype accessible virtual sculpting tools and 3D printing for children with complex disabilities to allow them to express themselves creatively.

Background and related works

This section covers several relevant areas such as issues of 3D printing pipelines, accessibility of 3D geometric modelling in general and virtual sculpting in particular, and more general issues of accessible computer technologies.

3D Printing Pipelines

The current 3D printing process requires multiple stages from 3D modelling software to final printer hardware, many steps of which are tedious and require specialist knowledge of geometric modelling. The paper [3] describes all the stages and difficulties of transformation from 3D geometric models to the fabrication of tangible artefacts. One of the reasons for the lack of a simple way of fabricating 3D models is that 3D modelling software in general currently has no way to send the model straight to a 3D printer. After creating the 3D model it must, therefore, be exported to a standard geometric format. The current standardisation level is very primitive, which reduces any geometric model to a set of disconnected surface triangles (STL format, set up by 3D Systems in the late 1980s) or one built upon it (AMF and 3MF formats). Online pipelines also exist for 3D printing service companies (such as ShapeWays, Materialise) but these are proprietary systems, do not include the content-creation stage or the ability to print using your own fabrication hardware, or meet accessibility requirements.

Geometric Modelling

Numerous approaches are available for the creation of virtual 3D models. Roughly, these may be categorised into: a manual modelling approach such as virtual sculpting; scanning or other data acquisition from the real-world source; procedural modelling from a set of instructions. A number of paradigms exist for manual 3D modelling: constructive modelling based on restricted sets of geometric primitives and operations, surface forming (e.g. creating points and polygons and joining them together), global and local carving supporting local adding and removing virtual material. It is, however, currently unclear which is the best user interaction paradigm to allow users with disabilities to model and interact in a 3D virtual space with multiple degrees of freedom. The main common feature for existing modelling tools aimed for children is that some restrictions are introduced on navigation, primitives and operations to make the modelling process more simple and intuitive. For example, a system can have a number of primitives and only one operation (attachment) with continuous (Spore Modeller) or discrete grid navigation (Tincercad), a single type of primitive and a selection of operations (Cosmic Blobs), or a single primitive (cube) and two geometric operations such as add and remove (Minecraft).

Accessibility

Disability is a complex topic and a full discussion is beyond the scope of this paper. The ICF-CY [8] framework can be used for measuring the health and disability levels of young people. The framework is very detailed, but sections pertinent to this research can be used to illustrate the functional levels of the target group. This will help to build a profile of the target group and also demonstrate some of the barriers that they face.

The requirements of software designed for accessibility stem primarily from the physical interface needs of the users. However, such software must also satisfy the practical requirements of support staff, which in many cases is impossible to completely remove from the process. Within the context of accessible design, the typical workflow presents a number of key challenges, such as: 1) Most of the software tools involved in the process were not designed with accessibility in mind; 2) For experienced practitioners it is fairly straightforward to learn a new piece of software; however, for newcomers to the field of 3D modelling or AM processes there can be a steep learning curve, especially for users with a wide range of disabilities [1]; 3) There are many steps involved in the process, leading to further complexity; providing an accessible method of quickly switching between different software packages, which may have radically different interface paradigms, is unlikely to be easy or to lead to a positive user experience.

The aim of this research is to develop a pipeline which overcomes these key challenges to allow acces-

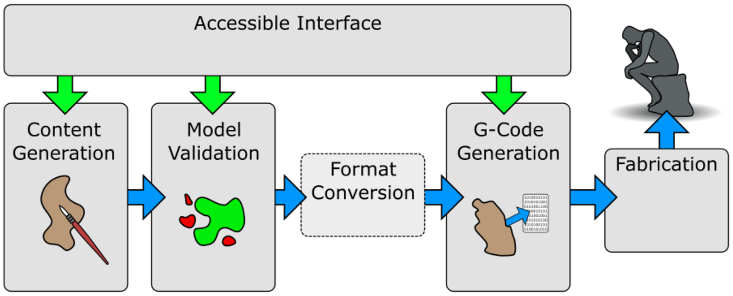


Figure 1 : *Design of our accessible 3D printing pipeline.*

sible access to modelling and fabrication technologies.

An Accessible Pipeline Design and Implementation

Based on previous projects offering accessible virtual sculpting tools and 3D printing for users with wide range of disabilities including very complex ones [4], we can conclude that accessible interfaces for virtual sculpting as well as a highly reconfigurable GUI system are a key for a pipeline which provides solution for challenges stated above. Core to this pipeline is an accessible interface in most steps including 3D printing, which therefore is specifically designed to accommodate accessible interfaces. The scheme of this pipeline is shown in Figure 1 and the steps are discussed in detail below.

Accessible Interface

The primary requirement in the accessible pipeline is for a heavily customisable accessible interface because each individual has potentially very different requirements and even the same individual will have different requirements at different times (especially for progressive conditions).

In the SHIVA project the generic accessible GUI system (see Figure 2) was designed allowing flexibility and the ability to store specific settings for each user's needs in their corresponding user profiles. To achieve these, some of the features that were implemented include: switch-scanning support with adjustable timing parameters, direct progression with multiple switches; mouse or touchscreen control; button debouncing options; key-mapping options with activation on trailing or leading edges; eye-gaze support with adjustable dwell time and configurable rest zones; fully configurable GUI layouts which can be saved and loaded from user profile; visual styling in themes for use across multiple profiles; visual adjustment in themes and profiles; basic symbol set based on feedback from a speech therapist and prior experience; configurable graphics for buttons, symbols, text, including sophisticated colour replacement in graphics.

Content Generation Stage: Shape Modelling

The main idea of the project is to allow users to virtually sculpt models, i.e. undertake operations over the virtual representation of real world objects and geometric primitives in a virtual environment. Therefore manipulations over the geometry is an important part of our project. One of the application prototypes created in the SHIVA project was a Totem exercise: a basic 3D modelling application where the students could stack primitive shapes and then apply simple modelling operations on the stack such as scaling, rotating, moving items and drilling holes. This application was shown to be successful among school students for being easy to understand and yet powerful enough to create a variety of 3D shapes.

It is clear that to make the core of the system extensible and applicable for different purposes in various prototypes, the layout that works with the representation and manipulations of the geometry should be universal. In our system, we use geometric representation in an implicit form using Function Representation (FRep) [5]. This representation allows for describing a vast number of geometric primitives and performing

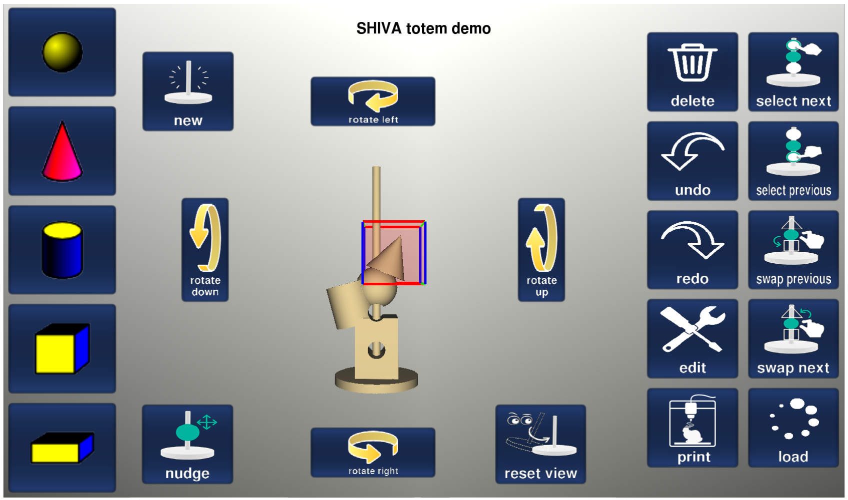


Figure 2 : *Interface of the SHIVA sculpting software. Layout is fully customisable and accessible with switch-scan or eye-gaze tracking inputs as well as keyboard, mouse and touch-screen. Appearance can be adjusted to cater for visual impairments. Note 3D print button as a part of the interface.*

many operations over them in a simpler and more efficient way when compared with other established representations, such as polygonal meshes. Traditional geometric primitives such as a sphere, box and cylinder are easy to use. More complex geometric primitives such as polygonal meshes can be represented efficiently in the form of signed distance fields [7] which is a natural subset of Function Representation. The main disadvantage of such a representation is that the geometry of the object cannot be rendered using the common API for graphics hardware. Instead for direct visualisation in our system we use real-time ray-casting of the objects, which is accelerated with graphics hardware [6].

Model Validation

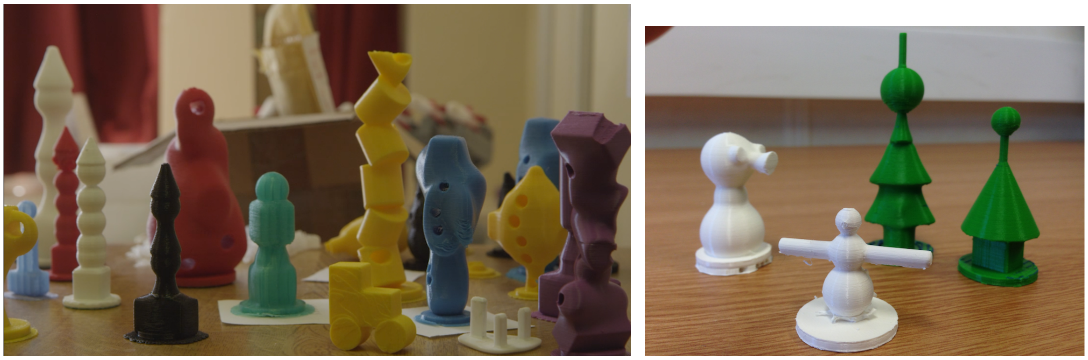
The objects which can be produced in the software should be validated before being sent to the printer or exported as a mesh. As we are working with implicitly defined geometry, we can directly work with that to ensure printability.

On the first step of the validation process, we analyse the number of disjoined components that the model has, which can be done by the method presented in [2]. In that approach a solution based on reliable spatial enumeration using interval analysis allows us to check how many components the object represented by a continuous function has. In our pipeline the simplest check that the model has more than one component allows us to prevent students from modelling objects which will break during printing. Further steps of validation can include balancing and a thickness analysis.

Format Conversion and Fabrication

The usual object format used in the current software for 3D printing is a polygonal mesh, normally as a .stl file. As the model is represented by a continuous scalar field, it has to be converted to the polygonal mesh first, or to polygonise. A large number of methods exist to perform such a task, with marching cubes as one of the most well-known methods. One of the main advantages of keeping continuous scalar fields and use of polygonisation is that the resulting meshes are manifold, meaning that they do not require any extra post-processing to ensure the mesh is suitable for the printing software. The process of polygonisation can be fully automated and therefore the step of mesh generation does not require user's interaction.

As an alternative to the polygonisation process, an approach of direct fabrication can be used. Here, by



(a) (b)

Figure 3 : *a) a gallery of resulting sculptures produced within SHIVA project; b) models created by school students with disabilities for design and technology unit with a topic "Christmas"*

using the continuous scalar field, we can obtain a set of slices and then use these slices to generate G-code for each particular printer. As not many 3D printing hardware manufacturers allow for producing the G-code directly, this approach is currently less feasible and limits the choice on the user's side.

Case studies and user feedback

The implementation of the system which succeeds the SHIVA project was tested in two special schools in the UK by children with a wide range of disabilities starting from cognitive disabilities and to severe physical disabilities. Some of the practical results are shown in Figure 3. It is worth mentioning that both schools have used different approaches to accessible interfaces because of the different levels of knowledge of technology assistant. Thus, in one school eye gaze was used for students with physical disabilities as an input device, whilst in the other school camera tracking was used for similar types of disabilities.

One of case studies of the pipeline applied in a special school was a Christmas-themed project. Students were asked to model Christmas-themed objects regardless of their artistic abilities. Some of these examples are shown in Figure 3b. The presented accessible pipeline allowed students to create these models in a way which did not require any special technical efforts neither from students nor from supporting staff. As a result, the participating children were especially happy to see the physical 3D printed form of their designs.

Feedback from users and staff is used to inform and direct the subsequent work. A number of key points have arisen from this. First, symbol support was deemed critically important for the interface. The target users are often illiterate so the meaningful symbols attached to each button together with a text do greatly help user independence and autonomy when using the software. Unfortunately there is no one standard set of symbols for assistive technology and a significant proportion of the modelling and software features have not been encountered before in this context. An initial symbol set was chosen for this work based on our prior experience, but the question of which are the optimal symbols remains open.

Secondly, a number of models were designed by users which did not reach the final printing stage because they would have been unprintable with disconnected components or parts that were too thin. While the process still fulfilled the goals of the sessions, primarily recreation and artistic expression, the project goal was to allow the models to be fabricated. This emphasises the importance of the model validation pipeline stage, especially in allowing us to easily identify such models.

It was also observed that students felt a discontinuity in the process between model creation and physical fabrication, which would typically involve a delay of a week or more. This was due to staff time limitations and compounded by the multi-step process required to take the model from the software to the physical printing stage. Again, this emphasises the importance of a pipeline with fewer stages to improve workflow.

Conclusions and Discussion

In this paper we have outlined a novel approach to construction and implementation of a full-scale 3D printing production pipeline embracing all the phases of content creation specifically tuned to the needs of people with disabilities. The main emphasis has been made on reducing the technical burden on the users with specific needs. All the phases of a practical pipeline have been addressed, including modelling, 3D printing and the in-between stage which is usually neglected as being considered strictly established. Introducing a ”3D Print” button along with the special model data format allows for a smooth cohesive process for the most problematic stage of the production.

Our work presents only a prototype of the design system working within the accessible 3D printing pipeline. Several problems which currently exist in the state of the art were identified, but not fully integrated into the framework. Those problems include user semi-automatic and automatic control over unprintable objects. We are able to detect unprintable objects but to find the right way to inform users and the way to improve the model is a topic which requires extra research. Likewise the problem of balancing and reducing post-processing process, such as removal of the support material, requires more investigation. Finally, to achieve the goals set in the Direct Fabrication approach, the mesh representation can be completely removed from the pipeline by going from the continuous scalar fields representation straight to the G-code. This process, however, also needs more investigation.

Acknowledgements

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References

[1] A.M. Cook and J.M. Polgar. *Assistive Technologies: Principles and Practice*. Mosby Elsevier, 2014.

[2] Oleg Fryazinov and Alexander Pasko. Reliable detection and separation of components for solid objects defined with scalar fields. *Comput. Aided Des.*, 58(C):43–50, January 2015.

[3] Marco Livesu, Stefano Ellero, Jonas Martnez, Sylvain Lefebvre, and Marco Attene. From 3d models to 3d prints: an overview of the processing pipeline. *Computer Graphics Forum*, 36(2):537–564, 2017.

[4] L. Mcloughlin, O. Fryazinov, M. Moseley, M. Sanchez, V. Adzhiev, P. Comninos, and A. Pasko. Virtual sculpting and 3d printing for young people with disabilities. *IEEE Computer Graphics and Applications*, 36(1):22–28, Jan 2016.

[5] A. Pasko, V. Adzhiev, A. Sourin, and V. Savchenko. Function representation in geometric modeling: concepts, implementation and applications. *The Visual Computer*, 11:429–446, 1995.

[6] Tim Reiner, Gregor Mückl, and Carsten Dachsbacher. Interactive modeling of implicit surfaces using a direct visualization approach with signed distance functions. *Comput. Graph.*, 35(3):596–603, June 2011.

[7] M. Sanchez, O. Fryazinov, and A. Pasko. Efficient evaluation of continuous signed distance to a polygonal mesh. In *SCCG '12, Proceedings of the 28th Spring Conference on Computer Graphics*, pages 101–108. ACM Press, 2012.

[8] World Health Organization. *International Classification of Functioning, Disability, and Health: Children & Youth Version : ICF-CY.* Nonserial Publication. World Health Organization, 2007.