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SHIVA: Virtual Sculpting and 3D Printing for Disabled Children

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Abstract: In this paper we present the SHIVA project which was designed to provide virtual sculpting tools for children with complex disabilities, to allow them to engage with artistic and creative activities that they might otherwise never be able to access. Modern 3D printing then allows us to physically build their creations. To achieve this, we combined our expertise in education, accessible technology, user interfaces and geometric modelling. We built a generic accessible graphical user interface (GUI), a suitable geometric modelling system and used these to produce two prototype modelling systems. These tools were deployed in a school for students with disabilities and are being used for a variety of educational purposes. In this paper, we present the project's motivations, approach and implementation details together with initial results, including 3D printed objects designed by children with disabilities.

Keywords: Virtual Sculpting, Accessibility, User Interfaces, Disabilities, 3D Printing

1. Introduction

Artistic activities are an important educational subject in their own right and can also provide strong links with other core subjects and life-skills such as spatial awareness, object recognition, as well as aspects such as self-expression and building self-confidence (Rubin, 2001). However, using clay or other sculpting materials is non-trivial for individuals with complex disabilities, as well as raising practical issues such as hygiene, dust, equipment, storage, and so on. In the SHIVA (Sculpture for Health-care: Interaction and Virtual Art in 3D) project, we proposed to use ICT to extend access to artistic tools within a fully protected environment, for vulnerable groups: people in rehabilitation (through French partners in Lille and the HOPALE Foundation) and children with various types of disabilities (by the authors in the UK at Bournemouth University (BU) and Victoria Education Centre (VEC)). In this paper we present the motivations, approach and initial results of the SHIVA project's use with children.

Young people with disabilities may have a very different experience of the physical world to those without (Tumbull, 2011). This experience may be influenced by their range of movement, coarse or fine motor control, or having spent their life in a wheelchair. New technologies are helping to provide ways in which young people who have disabilities can have the experience of the physical world in a virtual sense. Thus, the aim of the SHIVA project was to enable such young people to learn about manipulating objects by providing a few basic virtual sculpting tools and then producing the objects physically with 3D printing technologies.

The primary goals for the project were to give school students the opportunity to be creative and to produce physical artefacts which would otherwise not be possible for them by developing software tools. Artistic creativity was chosen for its well documented educational applications and benefits (Rubin, 2001) and the geometric modelling approach has similar parallels to the concepts of active learning and constructivism. So, the primary research objectives were: 1) to establish the ranges of interface requirements needed by children with disabilities; 2) to develop a generic accessible user interface system to meet these requirements and 3) to develop appropriate virtual sculpting methods, built on an accessible interface, and allowing 3D printing for real-world output.

2. Previous Work

2.1 User Models and Accessible User Interfaces

User interfaces provide the software interface layer between the human user and the actual software application. Most computers currently support user input from keyboard, mouse, touchscreen and to some extent voice commands while most output modalities rely on information-rich visual displays, which can be difficult for the visually impaired. While some of the project's students can use a mouse or touchscreen, others struggle to press a single large button, or have absolutely no limb control and can only access software through an eye-gaze system.

Each individual user with disabilities has very different interface requirements which vary according to their physical or cognitive abilities and which are dynamic and liable to change, often throughout each day. The interface must store information about its users in order to be configured to their requirements. This is called a user model and can generally be stored in two ways: a medical approach, where information about the user's medical and physical capabilities is stored; and a functional approach, where the user's interface requirements are stored. The medical approach must always be interpreted by the system to translate this into actual needs of the user.

Specialist accessible interface toolkits are available to extend the limited interface adjustments available in operating systems. The Grid 2 (Sensory Software 2014) provides disabled access primarily for communication. The software covers a wide range of inputs and features, but is not open or flexible enough for a heavy-weight application such as interactive 3D modelling. The MyUI project (Peissner et al, 2012) has an adaptive interface but is targeted at elderly people for giving them access to simple utilities and consumables. The user profile is adjusted while the user is working with the system, however the actual input of profile data is not supported. Similarly, the GUIDE project (Jung et al, 2012) has a user-centred approach to create basic UIs with a large variety of input devices as well as accessibility options, but again, the project is primarily focussed on elderly users for simplifying access to entertainment and communication and the user profile which is set up by guiding the user through a simple test is somewhat limited and does not take into account input of the user data nor complex disabilities.

SHIVA was designed to build on such work for setting up the user profiles, but extending the concepts to provide more flexibility and support for heavy-weight content creation tools rather than just media consumption.

2.2 Virtual Sculpting for Disabled Users

Virtual (Digital) Sculpting is a computer-aided technology allowing for the creation of sculptural artefacts. It can be performed in various ways: using 2D/3D input with subsequent reconstruction, using a purely mathematical description, using an interactive modelling technique that employs pressure-sensitive or haptic interactions, or alternatively, using a set of virtual reality interface tools such as cybergloves or Digital Clay.

The concept of Virtual Clay (McDonnell et al, 2001) is perhaps the most natural metaphor for virtual sculpting. It is supported by a number of commercial and research products such as Geomagic Freeform and Claytools, Cubify Sculpt, Pixologic's ZBrush and Sculptris.

Interactive local modifications can also be performed using different sculpting metaphors. In the Augmented Sculpture Project by the SHIVA team (Adzhiev et al, 2005) a specific interactive environment with embedded sculptural means was created. The user experiences an immersion into a virtual space where they can generate new shapes using either metamorphosis between several predefined sculpture models or the virtual carving tool with such operations as subtraction, offsetting and blending. Finally the resulting sculpting artefacts were 3D-printed to produce new physical sculptures. The project had both artistic and educational merits and the tools and lessons learned fed directly into the SHIVA project, especially the use of the group's scalar field or Function Representation (FRep) based modelling system due to its feature set and natural 3D printing suitability.

3. Approach

3.1 Accessible Graphical User Interface (GUI)

To achieve the objectives of the SHIVA project a new accessible interface was needed which could cater for the broad interface requirements of users with complex disabilities. A functional user modelling approach was determined the most suitable because it directly maps the user's interface needs with the software settings. The input mode and specific settings are stored in a user profile which is created for each individual student and which can also be transferred between different software prototypes that use the interface.

The user's physical needs were identified in a way that focussed on the direct interface requirements and their ranges. This informed the development of a generic graphical user interface (GUI) system to map all sculpting features to on-screen 'buttons'. All interface devices and modalities could then be successfully employed. Single button access is possible with switch-scanning (Colven & Judge 2006), where each GUI button is highlighted in turn until the user presses their switch to select the current element. This approach gives full access, regardless of physical input requirements.

The final SHIVA GUI system features include: switch-scanning with adjustable timing, direct progression with multiple switches; mouse or touchscreen control; button debouncing; key-mapping with activation on trailing or leading edges; basic 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 across multiple profiles; visual adjustment in themes and profiles; configurable graphics for buttons, symbols, text, including sophisticated colour replacement in graphics.

3.2 Shape Modelling System Core

The third research objective was to allow the users to sculpt virtual objects and in our system we use a geometric representation in implicit form through Function Representation (Pasko et al, 1995). This allows us to describe a vast number of geometric primitives and perform many operations in a simple and efficient way compared to other traditional representations, such as polygonal meshes. Easy formulation allows us to work with traditional geometric primitives such as a sphere, box and cylinder. Beyond this, more complex geometric primitives such as polygonal meshes can be represented efficiently in the form of signed distance fields (Sanchez et al, 2012) which is a natural subset of Function Representation. Traditionally, the disadvantage of such a representation is that the geometry cannot be rendered using the standard interface for graphics hardware. In our system we visualise objects with real-time ray-casting on graphics hardware (Fryazinov and Pasko 2008).

The objects and operations are represented in the form of a tree that generates the defining function for the model. In the leaves of such a tree we have the geometric primitives and objects, while in the nodes we have operations over other nodes and leaves (Pasko et al, 1995). This allows us to perform operations in the modelling system by modifying the structure of the tree itself by adding and removing nodes.

As an intermediate format for the geometry we are using the volumetric object format developed by the Norwegian company Uformia. This supports most of the operations and primitives existing in the current state of the art in modelling with geometry represented in an implicit form. For 3D printing we must convert to a polygonal mesh.

4. Applications

4.1 Metamorphosis Prototype

The first prototype software developed by BU in collaboration with VEC and using the accessible GUI was a metamorphosis exercise, specifically for younger or less cognitively able students. Here, the user chooses two objects and can produce an intermediate shape that is a blend between the two objects. Interaction for this is through a slider and the blended shape is displayed to the user and updated interactively. The user can then rotate their object and apply a colour to it. The relatively simplistic interface is shown in Figure 1.

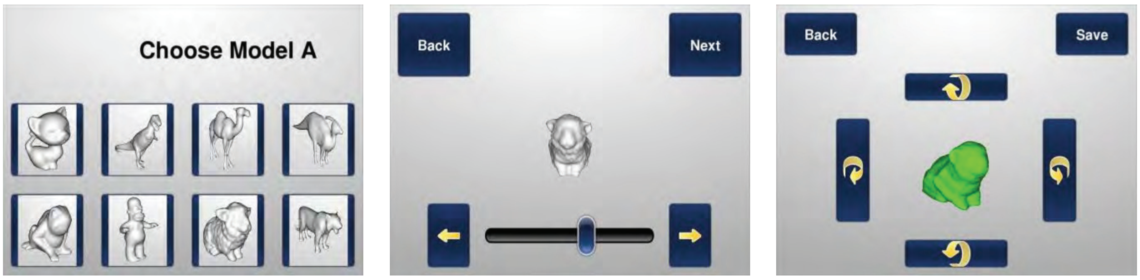

Figure 1. The metamorphosis prototype, with button layouts designed with VEC participation. The student chooses two models, can make a blend between them, and then colour the resulting shape. A blend between a sheep and a frog model is shown.

From the geometric point of view, in the application we perform metamorphosis operations over two FRep objects which can be seen as a linear interpolation between the values of the scalar field for the initial object and the target object, and we have tried more complex metamorphosis operations (Sanchez et al 2013). We used polygonal meshes of existing real-world objects converted to scalar fields as sources for the input shapes. The output of the application is the solid object representing the intermediate stage of the metamorphosis between two objects. The resulting object is a solid model and can be used for fabrication (3D printing).

4.2 Totem Prototype

Figure 2. The totem-pole prototype interface. Left: main construction screen with buttons to add primitive geometric shapes to the stack, navigation buttons and a designed shape showing primitive stacking, blending and drilling. Right: drill operation screen with cross-hair controls for drill location and controls to rotate the object.

The second software prototype from BU was a 'totem-pole' exercise, which provides a more complex sculpting environment. Here, the user stacks a small number of objects together and then performs simple modelling operations such as affine transformations on individual objects within the stack, or operations such as blending and drilling on the entire stack. For this application the accessible UI is necessarily more advanced (Figure 2). We currently allow the user to choose from a number of simple geometric shapes as an input: sphere, box, cylinder and cone. The set of operations over these objects include: Boolean operations (union, and subtraction), smooth union blending between objects, and affine transformations. From the implementation point of view the operations are achieved by modifying the tree representing the object.

5. Results

Figure 3. Designs by children with disabilities, produced using the SHIVA totem-pole exercise and printed at the Victoria Education Centre on a BFB 3D printer. The children used largely touch-screen interaction or eye-gaze tracking.

Some students were invited to try the software during the development phase in 2013. This was introduced to them in a careful and controlled manner because their reaction to potentially unstable prototype software was unknown. In reality, the students were extremely enthusiastic and took particular delight in the discovery of software bugs which was useful to the development team and gave the students a sense of value in their participation. Overall student engagement has been exceptionally high, with all participating students showing a great deal of enthusiasm. The software prototypes were installed at VEC and used by eleven students including two eye-gaze users. Students successfully produced a range of objects (Figure 3), validating the software and the process.

The SHIVA software has been successfully used to help teach students about spatial relationships between objects and general spatial awareness, including concepts such as 'up' and 'down', 'behind', 'rotate' and so on. This has also been useful to check comprehension and helped to identify two eye-gaze users who had similar difficulties with the concept of a 'stack' of objects. Teachers used a physical stack of objects and asked the users to reproduce the stack using the software. In the SHIVA Totem software objects are added in a stack which starts from the bottom, adding one object on top of the other. However, both eye-gaze users would consistently try to start the stack from the topmost shape first. It is unclear if their approach was a result of the way the task was presented to the students, but we hypothesise that because these users have simply never had the experience of physically placing one object upon another, the concept was quite new to them. Regardless of the causes, the identification of this has helped the teachers in their understanding of which fundamental spatial concepts need to be taught and reinforced with such students.

The software is used to help students understand how the shape of an object may be constructed from a set of simple primitive shapes and understanding the differences between and representations of 2D and 3D shapes. One popular teaching exercise is for the student to reproduce a drawn shape using the SHIVA software. Emphasis is placed on enjoying the experience rather than producing a ‘correct’ result and some students have already shown progress – one student who started with creating random objects is now creating identifiable objects such as a cat or a teddy-bear.

Speech therapists at VEC have successfully used the software with students in their regular activities to help with speaking and listening and cognitive development by working on concepts of sequencing, following instructions, communicating ideas and collaborative work. Early observations suggest the students’ enthusiasm for the software will lead to good results.

The SHIVA software is now being used in regular scheduled art lessons at VEC. A 'shoe-box landscape' project inspired by the work of British sculptor Andy Goldsworthy involves students creating sculptural arches as viewing windows similar to some of his famous works.

Therapists are also starting to use the software as a tool from the point of view of an aid in improving manual dexterity, or through a touch-screen interface to gradually encourage students to increase their range of movement by allowing them to reach for more distant input controls.

6. Conclusions and Future Work

In this paper we presented the SHIVA project, which was designed to allow disabled children to produce virtual sculptures and then use 3D printing technologies to fabricate these. To achieve this, we established research questions to identify and address interface requirements and to identify and develop appropriate virtual sculpting.

The interface requirements were identified and described with a functional user model, resulting in user profiles that stored each individual's interface settings for a new purpose-built GUI system. We coupled this with a Function Representation (FRep) modelling system to develop two prototype software applications aimed at different cognitive levels, which gave virtual sculpting capabilities to users with disabilities through the accessible GUI.

While formal user-studies and longer term developmental studies will be useful to quantitatively identify any educational benefits, from the perspective of the school simply giving a child with no limb control the ability to create a physical sculpture for the first time in their life is a far more powerful incentive and one where the real emotional and motivational benefits are far greater yet not as easy to measure.

Moving forwards for future work, the SHIVA software prototypes provided a small subset of modelling features. A more flexible system would be desired for more advanced users including adults. The SHIVA GUI represented a state-of-the-art prototype system, but a number of open questions remain, including: lower requirement on technical staff for profile creation; automatic user adaptation; support for further input modalities: brain computer interface, gesture, multi-touch, tablet; and flexible input mapping from multiple modalities. The inclusion of all these aspects would allow the software to be used by individuals with a broader range of disabilities and would make setting up and maintaining the software easier.

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