A Computer Animation System for Creating Deaf-Accessible Math and Science Curriculum Materials

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Abstract

In this paper we report the development and initial evaluation of the ASL system. The ASL system is an innovative software tool that allows educators of the Deaf to add sign language translation, in the form of 3D character animations, to digital learning content. Although this first iteration of the system is designed specifically to improve deaf students' access to K-3 math educational materials, the system's open architecture allows supporting additional age groups and additional subjects. Results of an initial evaluation with educators of the Deaf and native ASL users show that the subjects were able to produce accurate and realistic animated ASL discourse using the system. However, the majority of the subjects found the system difficult to use; future work will focus on design and development of an intuitive, sketch-based user interface.

Categories and Subject Descriptors (according to ACM CCS): J.0 [Computer Applications]: General

1. Introduction

Deaf education, specifically in science, technology, engineering, and math (STEM), is a pressing national problem in the US. The project described in the paper addresses the need to improve deaf education in math with a unique approach: accurate, realistic 3D animated signing. The goal of this work was to research and develop a software system that enables educators of the Deaf to author deaf-accessible math lessons for grades 1-3. The system—dubbed ASL as in Animation Speaks Louder—provides educators with an effective means of adding American Sign Language (ASL) translation in the form of 3D character animations to digital learning materials such as interactive activities, texts, images, slide presentations, and videos.. The paper is organized as follows: in section 2 we discuss problems with Deaf education, and in section 3 we explain the potential of 3D animation technology for improving deaf accessibility to digital media. In section 4 we report the state-of-the-art in sign language animation and we discuss current limitations. The ASL system is described in detail in section 5 and results of an initial evaluation of the system are presented in section 6. Discussion and future work are included in section 7.

2. Problems with Deaf Education

Deaf individuals are significantly underrepresented in STEM fields [Bur94] and historically they have had difficulty entering higher education leading to STEM careers [CL96] A concurrent concern that magnifies the need for advancing Deaf students in STEM fields is the crisis our nation is experiencing in recruiting, retaining, and graduating a sufficient number of students in STEM fields [NRC05]. It is in response to these needs that our work is positioned.

We have identified five barriers to successful STEM education of the Deaf: (1) Deaf students' low literacy levels [VK70, Wil80]. Fewer than 12% of deaf students 16 years of age can read at a 4th grade or higher reading level -[GRI07,Hof00, Pri02]]Literacy level is fundamental as it mediates learning when curricular materials are text-based. (2) Lack of teacher preparation. As a general rule, teacher training programs in deaf education concentrate on teaching methods, curricular modification, psychosocial factors related to deafness, teaching speech and speech-reading, and theories of development and intervention in special education. As a result, 80% of teachers of the Deaf do not have degrees in content areas such as mathematics and science [ML00]. (3) Lack of adequate early interactive communication. Fewer than 10% of deaf children have both deaf parents fluent in ASL, so the overwhelming majority suffers from inadequate communication with one or both parents. The challenge facing deaf children is not acquisition of speech skills, as many assume, but acquisition of the language skills that underlie successful use of speech, signing, reading, writing, and solving even simple word problems. Significantly, there is a strong correlation between ASL fluency and English literacy [SP97, SP00]. English literacy improves as ASL skills improve and knowledge of ASL as a first language is beneficial because it taps normal capacities at appropriate developmental stages [Wil00]. (4) Low expectations. 'Traditional' deaf education teachers may rewrite hearing children's standard materials down to their deaf children's low reading levels rather than expecting grade level performance from them [Wil80]. Johnson et al. [JLE89] call this 'the cycle of low expectations' - which they suggest is the primary cause of the failure of deaf education. (5) Inaccessibility to incidental learning, i.e. exposure to media/conversations in which math/science concepts are present. Consequently deaf children's learning suffers from lack of opportunity and interaction and some math/science concepts that hearing children learn incidentally in everyday life have to be explicitly taught to deaf students.

The overall goal of our research is to overcome the above barriers and therefore improve deaf children's learning of math concepts and related ASL signs. With the ASL system, Deaf educators will be able to provide deaf students with a wider range of curriculum-appropriate math instructional content with linguistic level-appropriate sign language translation. Deaf students will be able to use the learning activities authored with the system in the classroom and at home to learn, practice and review math concepts and related signs. Hearing parents of deaf children will be able to work on the activities with their deaf children to assist them with the homework while, at the same time, they learn new signs.

3. Computer Animation as the technology of choice

Videos of live signers and computer animated virtual signers have the potential to improve young deaf learning outcomes in math and science by making educational content deaf accessible, thus providing deaf children with the same learning opportunities as hearing students. The main benefit of video and computer animation is that they provide low-cost and effective means for adding sign language translation to digital media. However, compared to video, animation technology has 2 fundamental advantages.

Scalability. ASL discourse can be decomposed into signs and sign-to-sign transitions; signs can be decomposed into manual and non-manual components and component-to-component transitions. Seamless transitions can be computed automatically by animation algorithms, which makes sign components and signs powerful building blocks that can be rearranged to form new signs and new discourse. By comparison, concatenating ASL video clips suffers from visual discontinuity. The abrupt jumps from clip to clip greatly reduce realism and legibility of ASL. Once the domain-specific ASL lexicon, such as mathematics, has been encoded into an animation database, a virtually unlimited set of math learning activities can be translated at little additional cost. Translation for additional domains becomes progressively easier since most of the signs and sign components needed have already been created for previous domains.

Flexibility. Animation offers great control over parameters that can be adjusted to optimize ASL discourse eloquence. For example, the speed of signing motion can be adjusted to the ASL proficiency of the user, which is of great importance for children who are learning ASL. The point of view of the virtual camera that renders the signing character and the location of the character in relation to the background can be optimized to minimize hand/face occlusion and to enhance sign clarity. As a third example, the signing character can easily be changed by selecting a different 3-D model. Video ASL annotation cannot provide this level of flexibility.

Although the quality of animated ASL has improved significantly in the past few years and it shows strong potential for revolutionizing accessibility to digital media, its effectiveness and wide-spread use is still precluded by two main limitations: (a) low realism of motions and facial expressions of signing characters and low rendering quality, which result in limited legibility of animated signs and low appeal of virtual signers, and (b) lack of easy-to-use public domain authoring systems that allow educators to create animated ASL annotated educational materials.

4. State-of-the-art in sign language animation ad current limitations

Among the research groups working on computer animation of ASL, three groups in the US are focusing on research, development and application of computer animation technology for enhancing deaf accessibility to educational content: Vcom3D [Vcom07] TERC [TERC06] and Purdue University [AVW08].

Researchers and developers at Vcom 3D have been the first to reveal the potential of computer animation of ASL for improving deaf accessibility to digital content [Sim00]. Two of their commercial products are designed specifically for adding sign language to media: Signing Avatar® and Sign Smith Studio®. SigningAvatar® software uses animated 3D characters to communicate in sign language with facial expressions; has a vocabulary of over 3500 English words / concepts, 24 facial configurations, and can fingerspell words not in the sign vocabulary. Sign Smith Studio® is an authoring tool that enables digital content developers to add 3D animated signing characters to their content.

Vcom3D ASL animation is based on a system that translates high-level commands from an external application into character gestures and facial expressions that can be composed in real-time to form sequences of signs. The main problem with fully synthetic animation of ASL is its inability to capture the nuances typically portrayed by skilled ASL users. While synthetic animation can approximate sentences produced by ASL signers, the individual hand shapes and rhythm of signing are often unnatural, and the facial expressions do not convey meanings as clearly as a live signer.

Recently, Vcom 3D has teamed up with the Laurent Clerc National Deaf Education Center of Gallaudet University to research and develop a system for creating and delivering animated stories using more realistic ASL non-manual and manual signs. The goal of the project is to evaluate how the use of "Lifelike Expressive Avatars" affects the reading comprehension of Deaf students. Their proof-of-concept animation entitled "The forest" [Ste07] shows more natural facial expressions and improved fluidity of body motions. However, the animated sequence is an off-line rendered animation- i.e. it is not assembled in real-time from a database of signs, was developed using motion capture technology, and took 2 years to complete.

In 2005, TERC collaborated with Vcom3D and staff from the National Technical Institute for the Deaf (NTID) on use of the SigningAvatar® accessibility software to sign the web activities and resources for two Kids Network units. Recently, TERC has developed a Signing Science Dictionary (SSD), using the same software [SS07]. SSD has been designed to support access to standards-based science content among elementary and middle-grade students who are deaf or hard of hearing and whose first language is sign. Although both projects have benefited young deaf learners, they have not advanced the state-of-the-art in animation of ASL—they employed existing Vcom3D animation technology.

Purdue University Animated Sign Language Research Group [AVW08], in collaboration with the Indiana School for the Deaf (ISD), is focusing on research, development, and evaluation of innovative 3D animation-based interactive tools to improve K-6 math/science education for the Deaf. The research team is currently working on two projects: Mathsigner™ and SMILE™, The animation of the ASL signs in Mathsigner™ and SMILE, although far from being truly life-like, improves over existing examples primarily because it is based on the use of state-of-the-art optical motion capture technology, and on the development of a new blending algorithm which allows for creation of more natural transitions between signs. In a survey of adult and children signer reactions to SigningAvatar® and a prototype of Mathsigner™, Mathsigner™ was rated significantly better on readability, fluidity, and timing, and equally good on realism. Specifically, the evaluators pointed out the higher intelligibility of the individual signs, and the more fluid connections across signs.

In Europe, the main research on signing avatars has been done by Prof. John Glauert at the University of East Anglia, UK. Prof. Glauert led the ViSiCAST project [BCE*00] whose goal was to provide deaf citizens with improved access to services and facilities through animated sign language. ViSiCAST built on the initial work of Simon-the-signer. Simon-the-signer revealed that translation of text into real-time animated Signed English (SEE) is possible; however the form of language that Deaf people prefer is natural sign language. As such, the objective of the ViSiCAST project was the realization of a natural text-to-sign language animated translation through the use of innovative avatar technology. The project is now being continued by eSIGN [eSIGN04]. To date, eSIGN has produced software tools which allow website and other software developers to augment their applications with signed versions.

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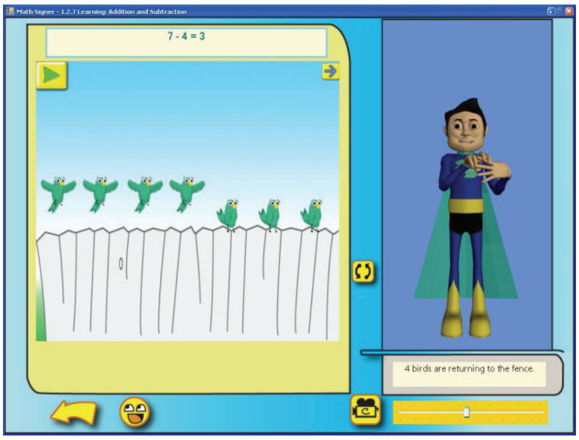
5. The ASL system

The ASL system is a sign language animation system that allows users to create life-like 3D animations of ASL signs and sentences. The animations can be embedded in digital media as sign language translation. Figure 1 shows an example of interactive learning game annotated with sign language animation produced with the ASL system.



7 - 4 = 3

4 birds are returning to the fence.

Figure 1. *Activity in the MathSigner application annotated with animation created by the ASL System.*

The animations created with the system improve on the state-of-the-art in terms of fluidity of the signing motions and character skin deformation, naturalness of character facial expressions, and rendering quality. High visual quality, i.e. fluid 3D signers that are emotionally appealing to deaf learners, is fundamental for students' learning. Research shows that the emotional aspect plays a decisive role in learning for deaf students [TFA*01].

Increased smoothness and accuracy of the signing motions is achieved primarily through an interpolation algorithm that computes fluid transitions between consecutive hand shapes, signs, and character poses. In existing 3D signing programs, transitions are implemented with cut-and-paste methods or simple interpolation resulting in robotic, unnatural, in-between movements. In addition the 3D signers show improved character skinning. In order to allow for a large number of joints, and therefore a high number of degrees of freedom for the character, and maintain the character volume during animation, the virtual signers make use of dual-quaternion skinning [KCZ*07]. This method only uses two quaternions to represent position and rotation per bone (allowing up to one hundred bones) and prevents loss of volume while only being slightly slower to calculate the skinning transformation than linear blend skinning. With this method the 3D signers are not only able to perform complex gestures and movements, but also to show realistic organic deformations during motion. Figure 2 shows the difference in deformation between the two skinning methods.

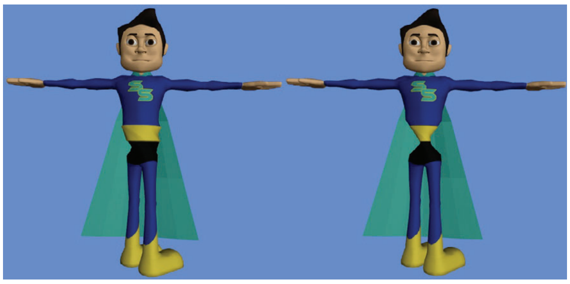


Figure 2. *From the left: character skinned with dual quaternion skinning; character skinned with linear blend skinning. In both images, a rotation of 120 degrees has been applied to the character's waist joint.*

Improved naturalness of character facial expressions is accomplished through the use of multiple target morphing, which enables the user to combine different facial deformations (targets) to represent a large variety of facial articulations (see Figure 6) that always look different. In current signing systems the animation of the character's face is based on a limited set of pre-modeled facial expressions that cannot be combined. The result is animated characters that show mechanical repetition of identical, often symmetrical, and therefore unrealistic, facial expressions.

Improved rendering quality is achieved by adding three effects that enhance the readability of the signs: motion blur, ambient occlusion, and depth of field (these effects are described in the Rendering Support Component section).

In the next paragraph we describe how the ASL system works. In order to gain a better understanding of the functionality of the system, we encourage the reviewers to view the video demonstration available at http://idealab.tech.purdue.edu/ASL/About.htm . High-resolution images and screenshots of the system are available at: http://idealab.tech.purdue.edu/ASL/Images.htm The system includes 3 components:

3D Model Support Component (Figure 3). This component allows importing 3D models of characters that sign messages and background 3D scenes. A character 3D model describes "bone" and "skin" structure as well as facial deformations using morph targets (Figure 5). Currently the system provides a database of 3 characters, each with 30 facial morph targets. The database can be easily expanded.

Animation Support Component. This component enables the user (i.e. educator) to (a) import previously created animated signs, (b) create new signs, (c) create facial articulations, (d) smoothly link signs and facial articulations in ASL continuous discourse, and (e) write an ASL message in ASL gloss and automatically generate the signing sequence including manual and non-manual signs.

(a) *Database of signs*. We have produced an initial database of approximately 200 animated signs for K-2 mathematics that can be loaded into the ASL animation software and applied to the selected character; more signs can be added to the library. Each individual sign was produced by a skilled animator/ASL signer using keyframe animation technique; all signs were reviewed for accuracy and realism (and subsequently refined) by two Deaf educators. The animated signs are stored in a database as individual clips accessed at run-time. The application dynamically determines which signs are required for a particular ASL message, loads the required signs into memory, and unloads the signs that are no longer needed. Keeping a small subset of signs in memory at a time allows for a very large database of signs and therefore a large ASL vocabulary.

(b) *Creation of a new sign in the ASL system*. If a needed sign is not available in the database, it can be created within the ASL system. The process of creating a new sign involves defining character handshapes and limb/body poses by setting joint angles using both IK (inverse kinematics) and FK (forward kinematics) approaches.

(c) *Facial Animation.* Realistic facial articulations are achieved through vertex tweening using multiple target morphing. Vertex tweening is the process of interpolating between two vertices, generating intermediate vertices to produce a smoothe transition. Morph target blending uses vertex tweening to interpolate, or morph, between the vertices of two facial deformations. Morph targets are stored in a database and are loaded into the ASL system together with the avatar. Different facial deformations with varying weights are then combined in real-time to produce a facial expression. The strength of multiple-target morphing is that it allows for creating a large range of facial expressions that never look identical. In order to assist the user in creating facial articulations, basic controls are given that directly manipulate different regions of the face (see Figure 6)

Facial expressions can also be imported from a database of pre-made facial articulations. The database consists of a collection of images visualizing the facial expressions and encoding the deformation weights that comprise the facial expression. Realistic facial animations are created by setting keyframes for each facial pose; keyframes are then interpolated at run-time using spline curves.

In order to maintain interactive rates on a variety of computer hardware, three methods of facial morphing can be used: hardware morphing, software morphing, and a hybrid approach that combines hardware and software morphing. Hardware facial morphing blends facial deformations entirely on the GPU. While this allows for high interactive rates, the drawback is that only a limited amount of facial deformations can be combined at one time to form a facial expression (when combined with skeletal animation a maximum of eight targets can be used). This results in simplified facial articulations that are not able to convey the subtle details of the human face. Software facial morphing is able to blend a virtually unlimited amount of facial deformations at a time on the CPU at a cost of speed (i.e. interactive rates are much lower; therefore transitions between consecutive facial expressions do not appear smooth). Hybrid morphing combines both methods to enable a virtually unlimited number of morph targets to be combined to form a complex facial articulation, while maintaining fast execution. With this method, the first eight morph targets are computed on the GPU while additional morph targets are computed on the CPU. The avatars in the ASL system use hybrid morphing because it allows for high visual quality and fast real-time performance.

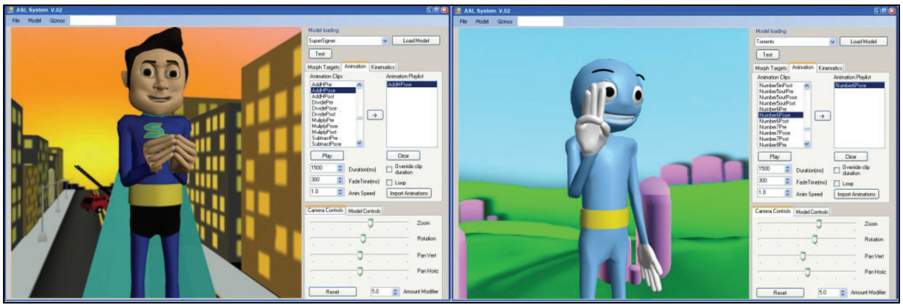
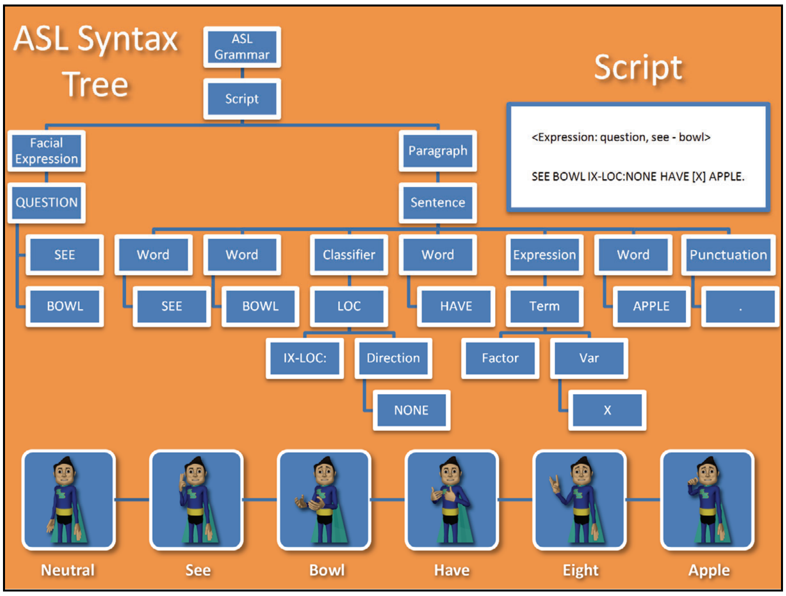


Figure 3. *From the left: 3D Model of 'SuperSigner' imported in the ASL system with 'City' background scene (the character is signing 'add'); 3D Model of 'Torrents' imported in the ASL system with 'Fields' background scene (the character is signing 'six').*



<Expression: question, see - bowl>

SEE BOWL IX-LOC:NONE HAVE [X] APPLE.

Figure 4. *Visualization of the ASL syntax tree generated by the script compiler. Top right: example of ASL script including ASL sentence and facial expression persisting from the word "See" to the word "Bowl". Bottom: output animation sequence generated by the compiler.*

(d) *Animation Blending.* The quality of the blending motions between individual animation clips and keyframes drastically affects the realism of the sign animations. Simple linear interpolation-based blending can result in mechanical, non-fluid movements. In the ASL system, motions within and across signs are generated in real-time using spline-based interpolation, which allows for extending/reducing, pausing, and adjusting ease-in and ease-out variables to enhance the quality of the movements. Utilizing spline curves virtually eliminates visual recognition of keyframes and transitions between animations, thus the motion appears smooth and not jerky. Fluidity of motion is also achieved through the use of spherical linear interpolation, which is employed to blend between joint rotations. This type of interpolation ensures that angular velocity remains constant (and therefore smooth) between keyframes. In addition to these interpolation techniques, ease-in and ease-out variables are used to amplify or retard an animation time curve, i.e. to simulate natural acceleration and deceleration in hand movement. Finally, the animations can be stretched and paused for a user-defined quantity of time. Pausing, extending, and reducing animation significantly enhances the rhythm of the ASL discourse.

(e) The ASL Script (gloss) Editor. There is no generally accepted system of "written ASL" and it is not possible to translate English into ASL word-by-word. Therefore, to write ASL signs and sentences, linguists and educators use glossing. In ASL gloss, every sign is written in CAPITAL LETTERS, i.e. PRO.1 LIKE APPLE. Gestures that are not signs are written in lower-case letters between quote marks, i.e. "go there". Proper names, technical concepts and other items with no obvious translation into ASL may be fingerspelled, which is glossed either as fs-MAGNETIC or m-a-g-n-e-t-i-c. Upper body, head and facial articulations that are associated with syntactic constituents are shown above the signs with which they co-occur, with a line indicating the start and end of the articulation. For instance,

$\overline{\text{\qquad wh-q}}$ $\qquad$ $\overline{\text{\qquad\qquad wh-q}}$
YOUR NAME? or YOUR NAME WHAT?
'What is your name?'

where 'wh-q'indicates a facial articulation with lowered eyebrows [Wea08].

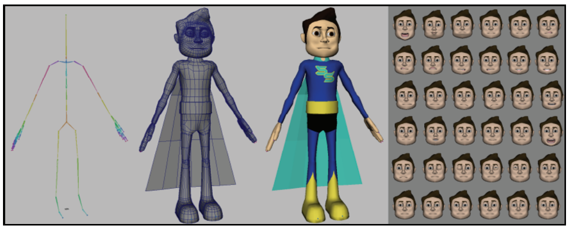


Figure 5. *From the left: bone structure, polygon mesh, skin with textures and facial morph targets*

To speed up the generation of real-time sign animation sequences, the ASL system includes a tool that understands ASL gloss: the ASL Script Editor. The ASL script editor enables a user with knowledge of ASL gloss, to type an ASL script including both ASL gloss and mathematical equations; the script is then automatically converted to the correct series of animations and facial expressions. The ASL script editor dynamically compiles an ASL script into an ASL syntax tree. Multiple passes are executed over the tree to generate the correct sequences of animation. First, the parser determines whether the script is of correct ASL gloss syntax. Once the script is determined to be of correct syntax, an animation selection pass iterates over the script to dynamically build an animation sequence. The compiler searches the database of existing signs and automatically generates the correct animation – signs not found in the database need to be created by the user. Once all signs have been retrieved from the database, the compiler searches over the script for additional modifiers, which include spatial directions and temporal pauses. These modifiers are converted into additional animation layers that modify the sign to which they are attached. Facial expressions are also queried from the database and are inserted into user-defined segments in the script. The user is able to specify the duration of a facial expression and can also give a word range over which the expression will persist. Punctuation is also interpreted into relevant facial animations, such as question expression for question marks, inserting pauses in place of commas, etc. Once the animation is generated, the user is then able to modify time curves, clip length and insert pauses to adjust the rhythm of the ASL discourse. Figure 4 shows the process of generating a sign animation sequence using the ASL script editor.

Rendering Support Component. This component implements advanced rendering effects such as, ambient occlusion, motion blur, and depth-of-field in order to enhance visual comprehension of signs. Ambient occlusion adds realism to the character model by improving upon diffuse shading and taking into account how light reacts with surfaces in real life. For example, two extended fingers that touch each other are delimited by a visually salient dark line, that is accurately conveyed by ambient occlusion. Motion blur is used to bring the user's focus to the hands of the character by simulating how human eyes react to fast moving objects. This effect improves the readability of the trajectory of fingers and hands during rapid signing motion by visualizing several intermediate positions in a single frame, the same way the human eye or a camera blends several positions of a rapidly moving object. Without motion blur the visualization is discontinuous and the information conveyed by important intermediate positions is lost. Depth-of-field is used to bring focus to the signing character itself by blurring out of focus secondary objects. Depth of field can be seen in the middle and right frames of Figure 3; the characters are in focus while the background 3D scenes are slightly blurred.

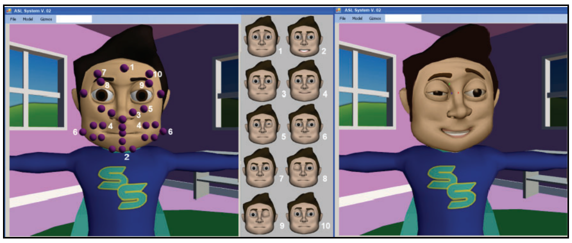


Figure 6. *From the left: character's face in neutral pose; facial controls provided with the existing system; morph targets (i.e. facial deformations) manipulated by facial controls 1-10; final facial expression resulting from manipulating and combining controls 1-10.*

6. Initial evaluation

The system has been developed with continuous formative feedback from native ASL users. A group of Deaf adults have been actively involved, early and continually, in the design, evaluation and iterative refinement of the system. An initial evaluation session with 5 Deaf educators age 35-50 (4 females and 1 male) was carried out in November 2009. 4 subjects had very little computer expertise; 1

subject was very familiar with computers and input devices. The subjects were asked to use the system to produce individual signs and signed sentences. They were then directed to fill out a web survey with rating questions focusing on system usability, on perceived quality (i.e. accuracy and closeness to real signing) of the ASL animations created with the system, and overall usefulness of the system.

Results showed that while the animations produced with the system were perceived as being accurate and fluid, the system was found difficult to use. Several signers were unable to accomplish certain tasks (i.e. animate specific signs) because of difficulties with the user interface. In particular, some participants were unable to pose the character's body and hands using the provided joint body controls. All subjects agreed that the ASL system is a useful tool that shows great potential for improving young deaf children accessibility to digital learning content.

7. Discussion and future work

The immediate benefit of this research is to drastically improve access to K-3 math educational materials for deaf children, and therefore improve deaf students' learning of mathematical concepts. We view learning as a process of domain-specific knowledge construction. This view is grounded in research on human cognition and cognitive development [GB04] and the belief that children are active learners [Bru96, Pia55]. For children to learn domain-specific conceptual structures and processes, they must actively interact with materials designed to help them acquire core ideas and ways of thinking. Currently, such activities are not deaf-accessible; thus, interaction and subsequent learning do not occur. The proposed work will increase deaf students' interaction with materials (math in grades K-3), and hence their domain-specific learning, by developing and implementing a novel technology that will enable existing (and new) materials to be annotated with signed translations at language levels appropriate to their linguistic comprehension. Age-appropriate fantasy characters help teach concepts, ask questions, and provide feedback through the most natural communication channel for deaf children. The proposed research also has the important side benefit of helping the young children learn ASL and learn to read.

A consideration of paramount importance in the design of the proposed system has been scalability. First, the system is intended for educators with limited computer literacy and with no technical background. Second, the system's open architecture allows supporting additional age groups and additional subjects at decreasing cost, by leveraging previous efforts.

[CL96] Caccamise, F. & Lang, H. (1996). *Signs for science and mathematics: A resource book for teachers and students*. Rochester, NY, National Technical Institute for the Deaf, RIT.

In order for the potential of the system to be fully realized, it must move from laboratory development and testing to field testing and use. Thus, future work will focus on ensuring the successful transition of the system from deal research laboratory and expert user conditions to an actual education institution for the Deaf (i.e. the Indiana School for the Deaf) where the system is desperately needed and where it is ready to make immediate and considerable impact. Looking ahead, this initial deployment will pave the way for mass deployment and society-level impact.

Successful transition from the research laboratory to the classroom will be contingent on the design of an intuitive system user interface with a near-zero learning curve. Thus, future work will include the development of a user interface that will provide support for sketch-based manipulation of the character's handshapes, body poses and facial articulations. Manipulation via sketch-based interfaces has a near zero learning curve and does not require artistic talent, technical knowledge, or the memorization of complex nested conventional menu interfaces or key press combinations.

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References

[AVW08] Adamo-Villani, N. & Wilbur, R. (2008). Two Novel Technologies for Accessible Math and Science Education. *IEEE Multimedia – Special Issue on Accessibility*, October -December 2008, pp. 38-46.

[BCE*00] Bangham, J.A., Cox, S.J., Elliott, R., Glauert, J.R.W., Marshall, I. (UEA), Rankov, S., Wells, M. (2000). An Overview of ViSiCAST. *IEE Seminar on "Speech and language processing for disabled and elderly people"* , London, April 2000.

[Bru96] Bruner, J. (1996). *The culture of education*. Cambridge: Harvard University Press.

[Bur94] Burgstahler, S. (1994). Increasing the representation of people with disabilities in science. *Journal of Information Technology and Disability*, 24(4).

[eSIGN04] eSIGN (2004). Available at:
http://www.visicast.cmp.uea.ac.uk/eSIGN/index.html

[GB04] Gelman, R., & Brenneman, K. (2004). Science learning pathways for young children. *Early Childhood Research Quarterly, 19,* 150-158.

[GRI07] GRI Demographics (2007). Available at: http://gri.gallaudet.edu/Demographics/

[Hof00] Hoffmeister, R. (2000). A piece of the puzzle: ASL and reading comprehension in deaf children. In C. Chamberlain, J. P. Morford, & R. I. Mayberry (eds.), *Language acquisition by eye*, pp. 143-164. Mahwah, NJ: Lawrence Erlbaum Associates.

[JLE89] Johnson, R. E., Liddell, S. K., & C. J. Erting (1989). *Unlocking the curriculum: Principles for achieving access in Deaf education*. (Available from Gallaudet Research Institute, Gallaudet).

[KCZ*07] Kavan, L., Collins, S., Žára, J., O'Sullivan, C. (2007). Skinning with dual quaternions. *Symposium on Interactive 3D Graphics.*

[ML00] Meath-Lang, B. & Lang, H. (2000). Words Upon a Window Pane: Opening Doors for the Deaf College Student. Available at: http://www.pepnet.org/pdf/conference/009-016-LANGLANG. Pdf.

[NRC05] National Research Council (2005). Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future.

[Pia55] Piaget, J. (1955). *The construction of reality in the child* (Trans. M. Cook). Routledge and Kegan Paul.

[Pri02] Prinz, P. (2002). Crosslinguistic perspectives on sign language and literacy development. In R. Schulmeister & H. Reinitzer (eds.), *Progress in sign language research: In honor of Siegmund Prillwitz*, pp. 221-233. Hamburg: Signum.

[SS07] Signing Science, (2007). Avaialble at: http://signsci.terc.edu/

[Sim00] Sims, E. (2000). SigningAvatars. Final Report for SBIR Phase II Project, U.S. Department of Education

[SP97] Strong, M. & Prinz, P. (1997). A study of the relationship between ASL and English literacy. *Journal of Deaf Studies and Deaf Education*, 2: 37-46.

[SP00] Strong, M. & Prinz, P. (2000). Is American Sign Language skill related to literacy? In C. Chamberlain, J. Morford & R. Mayberry (eds.). *Language acquisition by eye* (pp. 131-141). Hillsdale, NJ: Lawrence Erlbaum Associates.

[Ste07] 'The forest' by Jason Stewart (2007). Available at: http://www.vcom3d.com/vault_files/forest_asl/

[TERC06] TERC (2006) Available at: http://www.terc.edu/

[TFA*01] Toro, J., J. Furst, K. Alkoby, R. Carter, J. Christopher, B. Craft, M. Davidson, D. Hinkle, D. Lancaster, A. Morris, J. McDonald, E. Sedgwick & R. Wolfe (2001). An Improved Graphical Environment for Transcription and Display of American Sign Language. *Information* 4(4): 533-39.

[Vcom07] Vcom3D (2007). Available at: http://www.vcom3d.com/

[VK70] Vernon, M. & Koh, S. D. (1970). Early manual communication and deaf children's achievement. American Annals of the Deaf, 115: 527-536.

[Wea08] Weast, T. P. (2008). Questions In American Sign Language:A Quantitative Analysis Of Raised And Lowered Eyebrows. Phd Thesis, The University Of Texas At Arlington, May 2008

[Wil80] Wilbur, R. B. (1980) Syntax guidelines. In J. Shulman & N. Decker (eds.), *Readable English for hearing impaired students: Multi-level guidelines for linguistically controlled reading materials*. Boston, MA: The Caption Center, WGBH Educational Foundation.

[Wil00] Wilbur, R. B. (2000). The use of ASL to support the development of English and literacy. *Journal of Deaf Studies and Deaf Education*, 5: 81-104.