**Proceedings of the ASME 2012 International Design Engineering Technical Conferences &**
**Computers and Information in Engineering Conference**
**IDETC/CIE 2012**
**August 12-15, 2012, Chicago, Illinois, USA**

**DETC2012-71427**

# HANDY-POTTER: RAPID 3D SHAPE EXPLORATION THROUGH NATURAL HAND MOTIONS

**Vinayak**
School of Mechanical Engineering
Purdue University
West Lafayette, Indiana 47907
Email: fvinayak@purdue.edu

**Sundar Murugappan**
School of Mechanical Engineering
Purdue University
West Lafayette, Indiana 47907
Email: cpiya@purdue.edu

**Cecil Piya**
School of Mechanical Engineering
Purdue University
West Lafayette, Indiana 47907
Email: cpiya@purdue.edu

**Karthik Ramani** *
School of Mechanical Engineering
Purdue University
West Lafayette, Indiana 47907
Email: ramani@purdue.edu

## ABSTRACT

*We present the paradigm of natural and exploratory shape modeling by introducing novel 3D interactions for creating, modifying and manipulating 3D shapes using arms and hands. Though current design tools provide complex modeling functionalities, they remain non-intuitive and require significant training since they segregate 3D shapes into hierarchical 2D inputs, thus binding the user to stringent procedural steps and making modifications cumbersome. In addition the designer knows what to design when they go to CAD systems and the creative exploration in design is lost. We present a shape creation paradigm as an exploration of creative imagination and externalization of shapes, particularly in the early phases of design. We integrate the capability of humans to express 3D shapes via hand-arm motions with traditional sweep surface representation to demonstrate rapid exploration of a rich variety of fairly complex 3D shapes. We track the skeleton of users using the depth data provided by low-cost depth sensing camera (Kinect$^{TM}$). Our modeling tool is configurable to provide a variety of implicit constraints for shape symmetry and resolution based on the position, orientation and speed of the arms. Intuitive strategies for coarse and fine shape modifications are also proposed. We conclusively demonstrate the creation of a wide variety of product concepts and show an average modeling time of a only few seconds while retaining the intuitiveness of communicating the design intent.*

## INTRODUCTION

The goal of providing greater and better affordances for natural human-computer interactions (HCI) has largely motivated computational research and technological advancements. The parallel developments of hardware and software technology have continuously provided each other with challenges as well as solutions. The invention of the mouse in 1970 by Doug Engelbart [1] is an example which gives insight about the evolution of our interaction with computers and the corresponding evolution of our way of creating, manipulating, developing and accessing digital information. The key impact of this invention was that it mapped physical human motion into a corresponding actions on a virtual user interface. Recent innovations by Apple® took a significant step forward and made more impact by further reducing the distance between the computer and the

---

*Address all correspondence to this author.

user through capacitive touch based interfaces. However, WIMP (windows, icons, menus, and pointers) paradigm is still dominant in human-computer interactions despite the development of post-WIMP since the last two decades [2]. Work presented in [3] discusses the basic themes and strategies for reality-based virtual interactions. The recent success of Microsoft® Kinect™in the gaming industry is a direct example of the importance of using human motion as an expression, in a *non-intrusive* way, to create more involving, intuitive and interesting *virtual* experiences. Wigdor and Wixon [4] discuss that reality-based systems facilitate expert human-computer interaction with little or no prior instructions to the user. To this end, we believe that conceptualization of shapes by human beings is a natural process devoid of any specific tool. Thus, the instructions and training are primarily dedicated towards learning the usage of a modeling tool rather than learning how to think about shapes. This is what drives our research wherein, our intention is to bridge the gap between human expression and digital shape conceptualization during the early exploratory phases of design.

In this paper we propose and emphasize on the metamorphosis of “*Computer-aided Design (CAD)*” to “*Design Aided by Computers (DAC)*”. Here we use the term *CAD* in a sense which is broader than that applied to engineering design. In doing so, we introduce a new paradigm for reforming the early-stage design process by developing natural user interfaces (NUIs) which facilitate cognitively simple interactions towards creative and exploratory design without the need for extensive training. The primary motivation for this paper is to bring the element of design to the forefront of the current engineering process and to eliminate disconnect between the designer and the prototype by naturalizing the design process; particularly when the designer is trying to create rough shapes in large numbers to explore several design concepts.

## Human Expression and Shape Conceptualization

Expression and description of shapes via hand and body movements is a frequent occurrence, not only in design, but even in general human communication. Recently, Holz and Wilson [5] gave an interesting and comprehensive description of how natural gesticulation is critical in description of spatial objects. While 2D artifacts like sketches and drawings are better-off being created with 2D interfaces, the creation of 3D shapes using 2D interfaces limits the capability of designers to experiment at conceptual and artistic levels [6]. Creation of organic and free-form shapes had been shown in literature using glove-based [7] and augmented reality interfaces [8]. Though these interfaces are promising in providing 3D interaction capabilities for creating a wide variety of 3D shapes, the physical interfaces are often either difficult to setup, involve wearable devices or are expensive to procure.

To this end, classification of gestures is a rich and well-studied problem in computer vision. Work in [9] used compressed 3D shape descriptors using the depth data from Zcam™for 3D hand pose recovery. Recently, Oikonomidis et al. [10] showed a robust hand pose estimation based on particle swarm optimization on the GPU using depth images from the Kinect™. Despite the vast literature, a holistic combination of computational ease, time efficiency and feasibility of *readily usable* gesture classifications and their application to shape creation is a challenging task. Further, body skeletal tracking has been applied with greater fidelity for direct use in comparison to gesture recognition at the level of detail of the hands [11]. User satisfaction being the first priority, we take an approach wherein the motion of the human body (particularly the arms) can be robustly used for shape modeling.

Expression of shapes through human actions has been a focus of study in design literature. Horvath investigated hand motion language for shape conceptualization [12]. To this end, the naturalization of the process of direct interaction with digitally represented shapes has been addressed in promising field of virtual reality (VR). Recent review of VR-based assembly and prototyping [13] states that “*the ultimate goal is to provide an invisible interface that allows the user to interact with the virtual environment as they would with the real world*”. However, VR-based technologies are typically more suitable for post-design phases and are less affordable in terms of cost and setup-time. Although we inspire our approaches along the same lines, we do it primarily in the context of the early design phases where iteration of design prototypes necessitates the provision of an *affordable and non-intrusive environment* which can support exploratory thinking amongst designers. Our approach is based on a combination of one-handed and two-handed motions in 3D space towards the definition of the user’s intent in a shape exploration process. Based on the global and relative positions and orientation of each of the hands, our modeling system discerns the action which the user intends to perform. This enables our interaction strategies affordable to a first-time user with minimal training since apart from a very few gestures for extremely specific tasks (like switching between modeling modes etc) the user can relate every other motion directly to the primary task at hand - shape exploration.

## CAD and Shape Modeling

The representation of parametric shapes has been studied extensively in CAD literature. A comprehensive description of these representations can be found in [14]. Parametric surface modeling makes use of Bezier, B-Splines and NURBS for modeling complex shapes [15]. Ideas presented in [16] demonstrate the creation and modification of generalized sweep surfaces based on rational motion. Shape deformation, which is an integral part of shape-modeling, has been extensively studied in literature for parametric as well as free-form shapes. Defor-

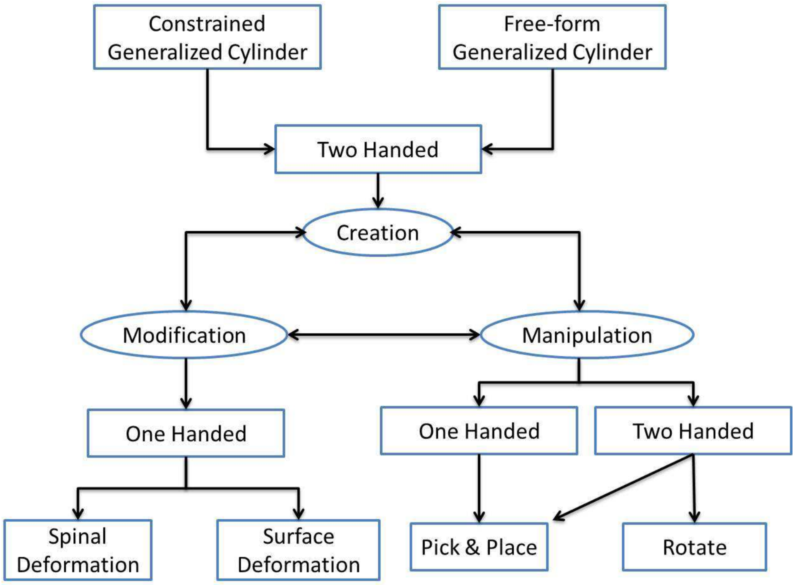


**FIGURE 1**. Components of a typical shape exploration process and the corresponding natural motions

mation of generalized sweeps have also been investigated extensively in [17, 18], towards applications in human deformation.

In this paper, we approach the shape creation process by using the idea of generalized sweep surfaces. With this approach we show that a variety of constraints can be applied for generating symmetric as well as free-form models in very low modeling time. Further, since sweeps can be represented as a set of cross-sections along a skeletal contour or "*spine*", we leverage this representation and propose a novel method for skeleton-based deformation of the shapes created using the generalized sweep concept.

## CONTRIBUTIONS

The main contributions of our work is as follows: **Natural Shape Interaction** - With this work, we have initiated the development of a framework to support natural interactions with 3D shapes in 3D space by allowing users to directly create, modify and manipulate 3D shapes without the need for extensive training. Further, we develop this framework using low-cost depth sensing commodity camera (Kinect$^{\text{TM}}$) which requires minimal setup time.

**Rapid Shape Exploration** - We demonstrate the strength of our natural interaction framework by showing high-speed creation of complex shapes which are other wise difficult to model using existing commercial CAD tools. To this end, we develop the idea of a *pottery-based* shape modeling metaphor by enabling the on-line creation and modification of *generalized cylinders* through simple and natural one-handed and two-handed human motion.

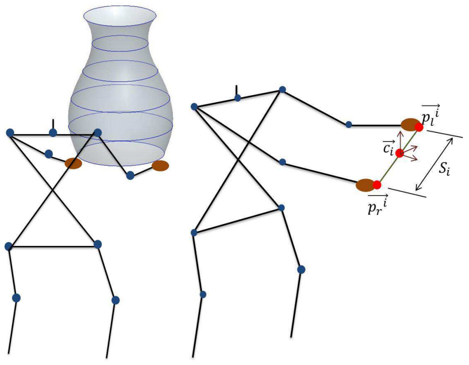
**Shape Creation Approach** - We explore novel methods for representing generalized cylinders, which have been extensively studied in literature, in the context of human shape expression capabilities. We use the representations to enable extremely quick creation of a variety of constrained and free-form shapes while retaining the aesthetic characteristics of the shapes. We categorically show that fairly complex models can be created in a matter of a few seconds without the need for training.

**Shape Deformation Approach** - In contrast to the common inverse kinematics based skeletal deformation methods, we propose a novel spinal-deformation scheme for enabling users to bend generalized cylinders during shape deformation.

## SHAPE EXPLORATION APPROACH

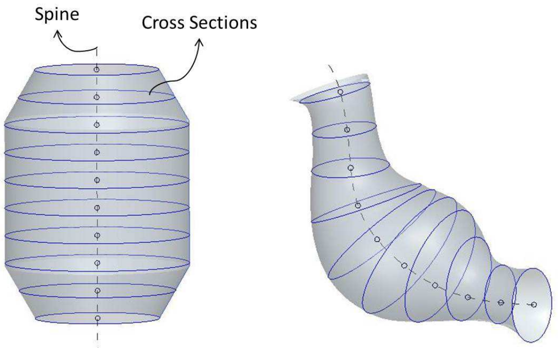
We categorize the shape exploration process into three distinct components, namely, (a) shape creation, (b) shape modification and (c) shape manipulation (Figure 1). By shape creation, we mean the use of hand and arm motions to create a shape from scratch within an empty working volume. Shape modification refers to interactions with shapes with the intention of changing the geometric characteristics of the shape. Shape manipulation refers to the pick-place-orient operations, i.e. rigid body translations and rotations. The following sub-sections give a detailed description of our technical approach towards the shape exploration process.

The process of 3D interactions is divided into *hand and arm motion* and *hand and arm gesture*. Motion is the temporal vari-



(a) (b)

**FIGURE 2**. (a)Shape modeling metaphor inspired by pottery (b)Interpretation of hand locations for shape creation



(a) (b)

**FIGURE 3**. Generalized cylinders (a)Constrained (CGC) (b)Free-form (FFC)

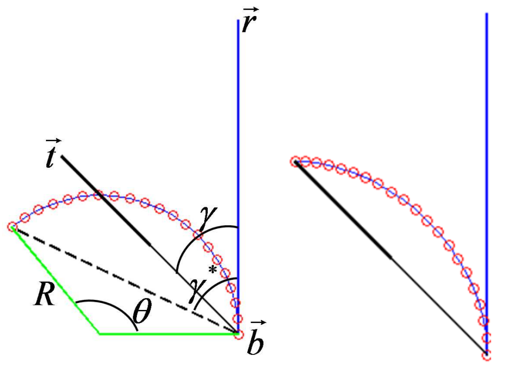
ation of the spatial configurations of the hand and the arm, i.e. it deals with the dynamic articulations of the hand and arm by obeying some kinematic constraints. In the context of this paper, we define gesture as an interpretation of dynamic hand and arm movements to convey a certain meaningful shape. A typical sweep operation, for instance, can be succinctly defined as a physical process of sweeping a curved piece of wire in 3D space. To this end, we use the *pottery* metaphor for the creation and modeling of sweep surfaces wherein the user moves both hands defining a side profile of the swept surface (Figure 2(a)).

## Shape Creation

In this paper, shape creation is enabled by generalized sweep surfaces i.e. "*generalized cylinders*" (GC). Given a 2D cross-sectional curve and a 3D skeleton curve, [16] defines a GC as the sweep surface of the cross-sectional curve moving along the skeleton curve. The cross-sectional curve may change its shape dynamically. However, in most conventional methods, the cross-sectional plane is restricted to be orthogonal to the tangent direction of the skeleton curve. GC's have been well-studied in literature since they have the combined potential of being able to represent fairly complex and free-form shapes and still retaining their parametric nature. In a discrete setting, we define a GC as a surface created by a sequence of sections represented as planar poly-lines along a 3D trajectory or *spine* represented as 3D poly-lines. A given GC can be described by the position, orientation and size of each of its cross-sections. We use the locations of the hands, $\overrightarrow{p}^i_r$ (right) and $\overrightarrow{p}^i_l$ (left) at a given $i^{th}$ instance to evaluate these three parameters. Given a cross-section, the distance between the hands, the orientation of the line joining the two hands and the mid-point of the line joining the two hands specify the size, orientation and position of the cross-section respectively (Figure 2(b)). Thus, the temporal variations of the locations of the two hands in 3D space completely define the evolution of the GC for a given cross-sectional shape. Given a planar cross-section $C$ which tightly fits within a bounding square of unit-length, we represent a GC, $G$, as a set of scaling factors, $s_i$, their corresponding center locations, $\overrightarrow{c}_i$ and orientations represented as $3 \times 3$ rotation matrix $\theta_i$ (equation 1).

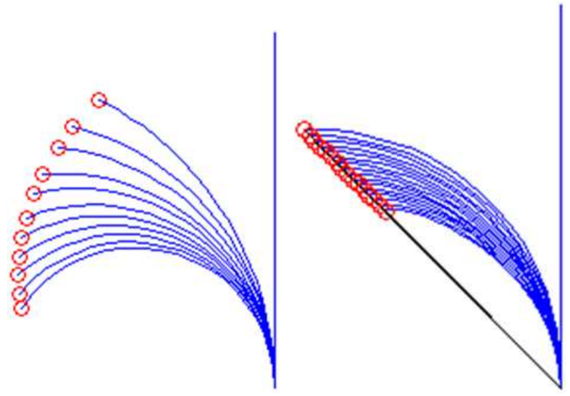
$$
\begin{aligned}
G &= \{C_i | C_i = s_i \theta_i C + \overrightarrow{c_i}, 1 \le i \le n\} \qquad (1)\\
s_i &= \| \overrightarrow{p}^i_r - \overrightarrow{p}^i_l \|_2\\
\overrightarrow{c}_i &= \frac{\overrightarrow{p}^i_r + \overrightarrow{p}^i_l}{2}\\
\theta_i &= Rot(\alpha_i, \beta_i)\\
\alpha_i &= \text{angle of azimuth of} \overrightarrow{p^i_r p^i_l}\\
\beta_i &= \text{angle of elevation of} \overrightarrow{p^i_r p^i_l}\\
n &= \text{Number of sections}
\end{aligned}
$$

In this paper, we confine to closed poly-line sections and open poly-line spines and we consider the creation of *constrained generalized cylinder* (CGC) and *free-form generalized cylinder* (FFC) (Figure 3). We envisage a CGC as a surface being created by motion of two hands along a *straight spine* wherein a cross-section varies in size, retaining a constant orientation and shape. On the other hand, creating an FFC is enabled by additional capabilities of defining the orientation of each section dynamically and *curvilinear spines*. Thus, from a representational standpoint, the only distinction between CGC and FFC is the level of controllability of $s_i$, $\overrightarrow{c}_i$ and $\theta_i$. We implement this controllability by defining *snapping* of these parameters within prescribed limits with respect to the extent of the motions of the user.



(a) (b)

**FIGURE 4**. Procedure for spine deformation (a) circular bending (b) angular error minimization



(a) (b)

**FIGURE 5**. Bending of a unit-length spine for $\theta = \pi/3$ and $0.75 \leq d_{bt} \leq 0.95$ (a) circular bending (b) final bending

## Shape Modification

In this work we support parametric global shape modifications by providing *spinal deformation* of a GC. As seen in the previous section, the general representation of a GC requires only 1D curves for the cross-section and spine. Thus, the general modeling strategy that we follow for the proposed deformations involves the application of 1D parametric functions defined on the curves representing the spine (trajectory)of a given GC. In the following sections, we will demonstrate that the use of parametric functions does not, in any way, curb the designer to conceptualize free-form surfaces. On the contrary, we show that the use of parametric functions allows for free-form deformations while retaining the aesthetic and symmetric characteristics of the shapes modeled. Spinal deformation entails the bending of the trajectory of the GC. In this paper, we consider bending schemes which preserve the *total* length of the spine. As mentioned earlier, the spine of the GC is represented as a poly-line i.e. a sequence of points in 3D space. Given such a spine, the user holds one end and drags it to a location of choice. Assuming one end of the spine to be fixed at the *base point* ($\vec{b}$), the problem is to find a set of rotations of each of the line segments or *links* of the spine such that the location of the last point moves from the *source point* ($\vec{r}$) to the location of the user's hand which we call the *target point* ($\vec{t}$). This is a typical inverse kinematics (IK) problem for a serial manipulator and has been very well-studied in literature [19, 20]. We propose a novel method of the problem as described in the following paragraph. For simplicity, we assume that the spine is vertical in its initial configuration and the bending happens only on a plane defined by the base, source and target points.

First, we compute the distance, $d_{bt} = \|\vec{t} - \vec{b}\|_2$, and the angle $\gamma = \angle(\overrightarrow{tb}, \overrightarrow{rb})$. Then we bend the spine to a circular arc taking $d_{bt}$ as a chord such that its arc length is equal to the length of the spine (Figure 4(a)). Obtaining the circular bend requires the determination of the radius $R$ of the circle and the angle corresponding to the chord-length satisfying the constraint preserving the length of the spine (equation 2).

$$R = \|\overrightarrow{rb}\|/\theta \tag{2}$$

$$\theta = \underset{\theta \in [0,2\pi]}{\arg\min} \left( \left| \frac{\sin(\theta/2)}{\theta} - \frac{d_{bt}}{2\|\overrightarrow{rb}\|} \right| \right)$$

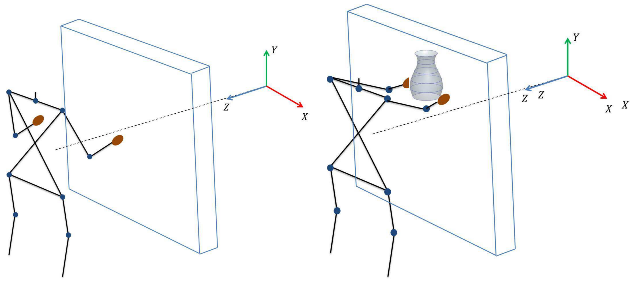
It can be observed in figure 4(a) that the *bending angle* $\gamma^*$ is different than the desired angle $\gamma$. Thus, in the final step, we minimize the angular error ($|\gamma - \gamma^*|$) by compensating for this error in a peicewise manner according to the hyperbolic tangent function. Equations 3, 4, 5 and 6 give the complete mathematical formulation for the computation of the final coordinates, $q_i^*$, of the the $i^{th}$ point $q_i$ of the bent spine (Figure 4(b)). Figure 5 shows a set of spinal deformations for a bending angle of $\pi/3$ and varying target points.

$$w_i = \frac{\tanh(1/i)}{\sum_{i=1}^{n} \tanh(1/i)} \tag{3}$$

$$n = \text{Number of sections in the surface}$$

$$\phi_i = \sum_{j=1}^{i-1} \{\phi_j + w_j(\gamma - \gamma^*)\} \tag{4}$$

$$\phi_0 = 0$$



(a) (b)

**FIGURE 6.** Virtual slab for sweep creation (a) Slab definition (b) Interaction within the slab

$$T_i = \begin{bmatrix} \cos(\phi_i) & \sin(\phi_i) \\ -\sin(\phi_i) & \cos(\phi_i) \end{bmatrix} \quad (5)$$

$$q_i^* = T_i q_i' \quad (6)$$

## 3D INTERACTION APPROACH

To provide naturalistic interaction with minimal training, our approach uses one-handed and two-handed motions of the user to define what the user intends to do at a given instance during a shape exploration process (Figure 1). For each of the three components of shape exploration, we contextualize the motions of the hand in the following manner. In case of shape creation, we define a *thick* virtual slab at a specified distance from the global coordinate frame (Figure 6(a)). When both the user's hands are within this slab, the modeling tool starts creating the generalized cylinders described in the previous section ((Figures 6(b) and 7(a))). While in shape modification and manipulation modes, we use both one-handed and two-handed motions in conjunction with a nearness threshold of the hands with specific parts of the objects. For instance, touching the top face of a generalized cylinder with one hand activates spinal deformation (Figure 7(b)). Holding an object (when either or both the hands are within a prescribed distance threshold of the surface of the object) in manipulation mode with two hands enables the user to translate and rotate the object in 3D space, while only translation is possible when holding an object with with one hand (Figure 7(c)).

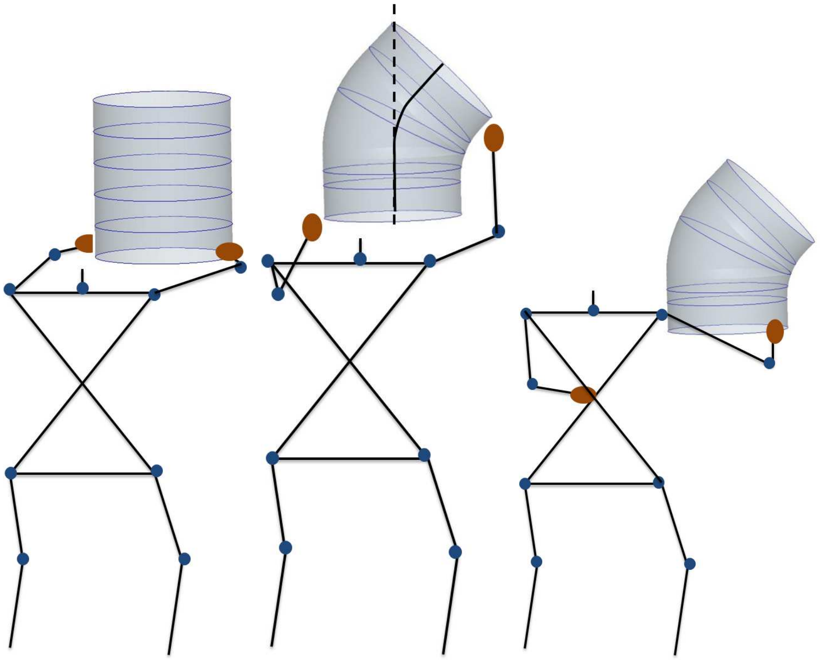
Being able to shift between the three components of shape exploration is also an important aspect for a complete experience of shape modeling. Since the prime focus of this paper is the demonstration of the main functionalities of creative shape exploration, defining and implementing the gestural strategies to achieve the inter-mode iterations is out of the scope of the current work.

## IMPLEMENTATION

To demonstrate the natural shape exploration framework with the pottery metaphor, we developed a modeling tool to support the creation of GC's. In our current prototypical implementation we assume the the shape of the cross-section to be given apriori. We particularly experimented with circular, square and hexagonal cross-sections to create shape models. The development of the tool was done using C++ and openGL was used for the real-time visualization of the results. We use an off-the-shelf Kinect$^{\text{TM}}$camera in conjunction with the skeletal tracking capability provided by the openNI$^{\text{TM}}$library to track the hand locations of the user. The pipeline for the implementation is shown in figure 8. The interface developed in this tool is very simple, in the sense that the user only sees the global frame of reference and a working volume wherein the user can create the GC's. Taking into account the spatial extent within which a user would typically feel comfortable working, we define the virtual slab at a distance of 1.5 m away from the Kinect$^{\text{TM}}$camera and we define the thickness of the slab to be 30 cm which is about double the size of the palm. Figure 9 shows a typical interactive session using the interface developed.

## RESULTS AND DISCUSSION

Figure 10 shows general shapes shapes corresponding constraints for the creation of GC's. We show three varieties of GC's, (a) fully constrained, wherein the scale of the GC changes with the hand motions while the spine is kept vertical and orientational variations of cross-sections is not allowed, (b) partially constrained wherein the spine can take a free-form on 3D space while the orientation is still constrained and (c) a completely free-form mode wherein the spine, orientation and the section scales can be varied as per the wish of the user. We were able to create these shapes within 2 to 3 seconds which is a significantly low modeling time. However, a better understanding of 3D interfaces for shape modeling warrants a detailed user-study involving the performance of our system and its comparison with traditional CAD tools. Our modeling metaphor being "pottery", we show a collection of pots which were modeled using the constrained mode (Figure 11). The average time taken per model was about 2.6 seconds. Figure 12 shows a rich variety of shapes and the corresponding time taken to model each shape. The authors would like to stress here that the primary goal of the proposed research is to enable the designer to externalize rough design prototypes for the purposes of exploration in the early phases of design. Thus, it can be appreciated that the description of shapes in the examples shown, involves only the interpretation of what the designer wants to create through his/her own body motion. Moreover, since the actual dimensional details of a shape can always be specified as a post-process by standard parametric CAD techniques, the 3D shape creation process demonstrated in this paper is more intuitive and natural to use.



(a) (b) (c)

**FIGURE 7**. 3D Interaction approach (a) Creation (b) Modification (c) Manipulation

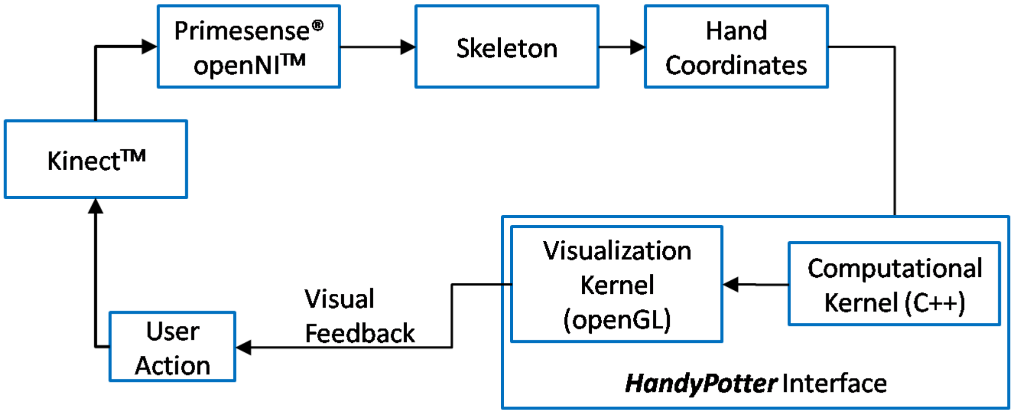
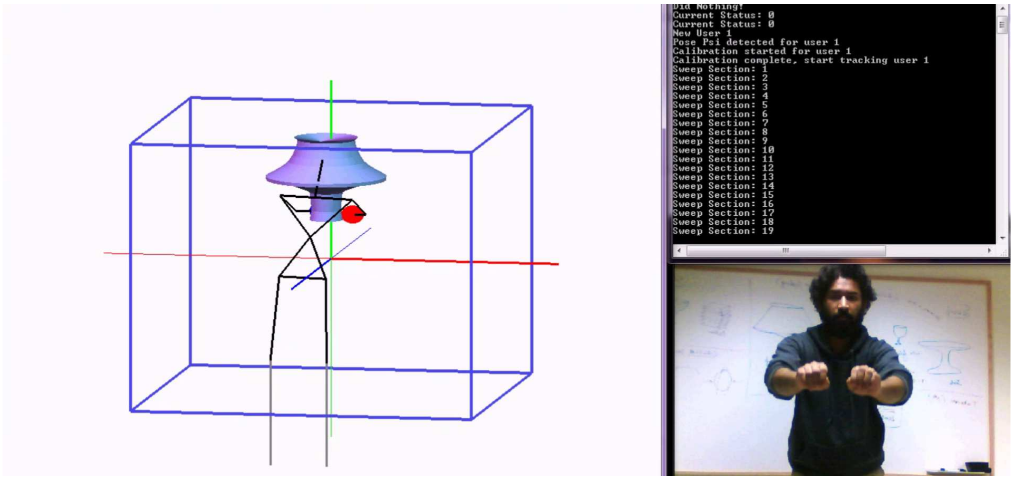


**FIGURE 8**. Pipeline showing the flow of information from the user to the Handy-Potter system and back

## CONCLUSIONS & FUTURE WORK

We present "*Handy-Potter*", an interactive system for rapid 3D shape exploration through natural hand and arm motions. Our work contributes the paradigm of natural and exploratory shape modeling through novel 3D interactions for creating, modifying and manipulating (the three components of shape exploration) 3D shapes in 3D space. The developed framework is easy to setup and low-cost with only humans as the actors. We showcased the strength of our modeling framework through high-speed creation of shapes, the stress being on the capability that is provided to the designer to quickly explore a wide variety if shapes with almost negligible training. We present the idea of pottery-based shape modeling metaphor which enables online creation and modification of 'generalized cylinders through simple human-arm motions. The examples shown in the paper demonstrate that humans can express 3D shapes naturally and intuitively and the description of such shapes involves only the interpretation of what the designer wants to create.

*Handy-Potter* offers only a glimpse at the variety of rich spatial interactions enabled by depth camera for 3D shape explo-



```
Did Nothing!
Current Status: 0
Current Status: 0
New User 1
Pose Psi detected for user 1
Calibration started for user 1
Calibration complete, start tracking user 1
Sweep Section: 1
Sweep Section: 2
Sweep Section: 3
Sweep Section: 4
Sweep Section: 5
Sweep Section: 6
Sweep Section: 7
Sweep Section: 8
Sweep Section: 9
Sweep Section: 10
Sweep Section: 11
Sweep Section: 12
Sweep Section: 13
Sweep Section: 14
Sweep Section: 15
Sweep Section: 16
Sweep Section: 17
Sweep Section: 18
Sweep Section: 19
```

**FIGURE 9**. Pipeline showing the flow of information from the user to the Handy-Potter system and back

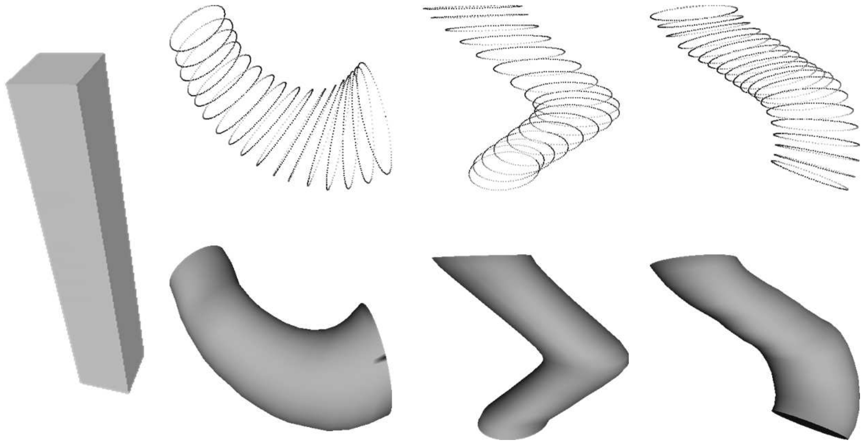


**FIGURE 10**. Fully constrained, partially constrained and free-form generalized cylinders using Handy-Potter

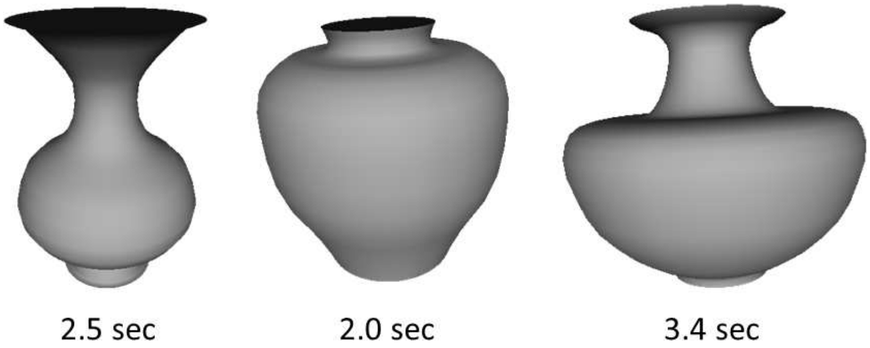
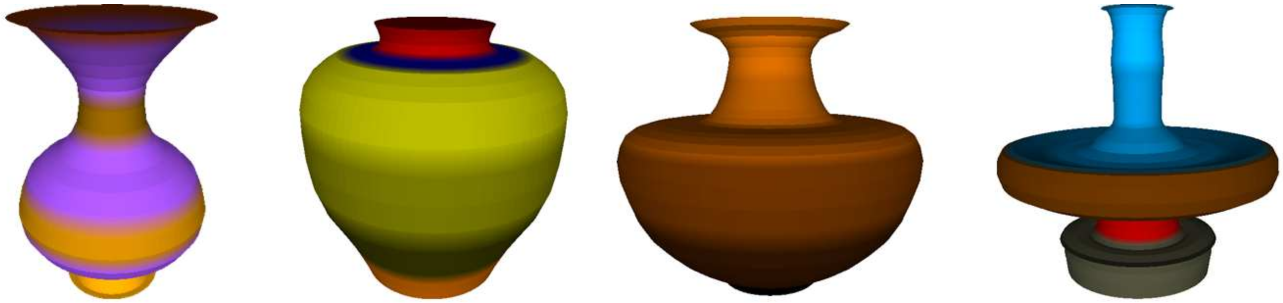
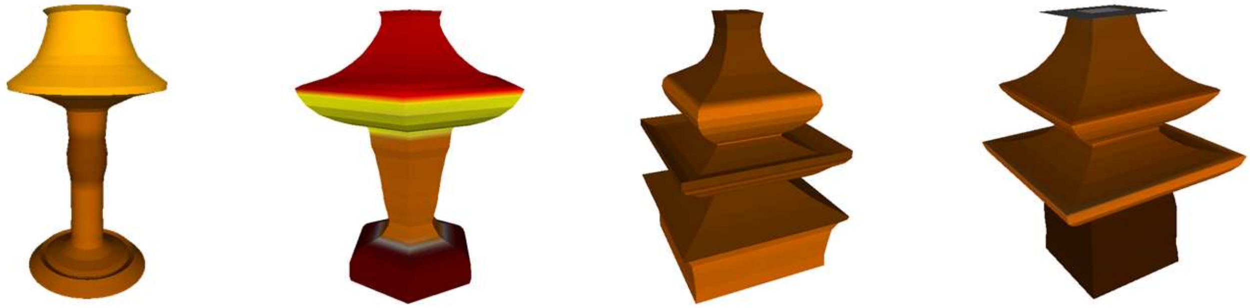


**FIGURE 11**. Pot concepts modeled using Handy-Potter



Pot1 (2.5 sec) Pot2 (2.0 sec) Pot3 (3.4 sec) Fountain (5.3 sec)



Lamp1 (3.7 sec) Lamp2 (5.1 sec) Pagoda1(4.9 sec) Pagoda 2 (4.9 sec)

Table (4.4 sec) Bowl (1.9 sec)

**FIGURE 12**. Product concepts modeled using Handy-Potter

ration. For the interface to be really natural, the designer must be able to seamlessly transition between the three components of shape exploration. Unlike shape modeling with the 2D interaction paradigm, where a significant research effort has been put, 3D interactions for shape modeling are yet to be fully developed and understood from the point of view of usability, ergonomics, efficiency of modeling and visualization. With this in view, the authors see a rich scope for future work in three primary areas. Firstly, designing appropriate gestural interactions and strategies for inter-mode transitions is an important future work for a complete immersive experience. Secondly, in the particular context of the generalized cylinders, naturally inspired methods for a variety of spinal and surface deformations and specification of a rich variety of cross-sectional shapes is the future work which the authors plan to carry out. Finally, a comprehensive user study is required to support simple 3D interactions for designing more complex digital artifacts with fluidity. This work shows the potential to move the interactions from a conventional desktop based CAD environment to an NUI enabled spatial environment where the emphasis is on design and the computers become invisible.

## ACKNOWLEDGMENT

We would like to acknowledge the support for Professor Ramani by the Donald W. Feddersen Chair professorship. In addition the work in this paper was partly supported by the NSF Partnership for Innovation 3DHub Grant No. 0917959 from the Industrial Innovation and Partnership Division. Any opinions, findings, and conclusions or recommendations expressed in this mate rial are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

## REFERENCES

[1] Engelbart, D. C., 1970. *X-Y Position Indicator for a Display System, US 3541541*. USA, November.

[2] van Dam, A., 1997. "Post-wimp user interfaces". *Commun. ACM, **40***, February, pp. 63–67.

[3] Jacob, R. J. K., Girouard, A., Hirshfield, L. M., Horn, M. S., Shaer, O., Solovey, E. T., and Zigelbaum, J., 2008. "Reality-based interaction: a framework for post-WIMP interfaces". In Proceedings of the twenty-sixth annual SIGCHI conference on Human factors in computing systems, CHI '08, ACM, pp. 201–210.

[4] Wigdor, D., and Wixon, D., 2011. *Brave NUI World: Designing Natural User Interfaces for Touch and Gesture*, 1 ed. Morgan Kaufmann, Apr.

[5] Holz, C., and Wilson, A., 2011. "Data miming: inferring spatial object descriptions from human gesture". In Proceedings of the 2011 annual conference on Human factors in computing systems, CHI '11, ACM, pp. 811–820.

[6] Varga, E., 2008. "Using hand motions in conceptual shape design: Theories, methods and tools". In *Product Engineering*, D. Talaba and A. Amditis, eds. Springer Netherlands, pp. 367–382.

[7] Schkolne, S., Pruett, M., and Schröder, P., 2001. "Surface drawing: creating organic 3d shapes with the hand and tangible tools". In Proceedings of the SIGCHI conference on Human factors in computing systems, CHI '01, ACM, pp. 261–268.

[8] Fuge, M., Yumer, M. E., Orbay, G., and Kara, L. B., 2011. "Conceptual design and modification of freeform surfaces using dual shape representations in augmented reality environments". *Computer-Aided Design*, June.

[9] Suryanarayan, P., Subramanian, A., and Mandalapu, D., 2010. "Dynamic hand pose recognition using depth data". In Proceedings of the 2010 20th International Conference on Pattern Recognition, ICPR '10, IEEE Computer Society, pp. 3105–3108.

[10] Iason Oikonomidis, N. K., and Argyros, A., 2011. "Efficient model-based 3d tracking of hand articulations using kinect". In Proceedings of the British Machine Vision Conference, BMVA Press, pp. 101.1–101.11. http://dx.doi.org/10.5244/C.25.101.

[11] Shotton, J., Fitzgibbon, A. W., Cook, M., Sharp, T., Finocchio, M., Moore, R., Kipman, A., and Blake, A., 2011. "Real-time human pose recognition in parts from single depth images". In Proceedings of the 24th IEEE Conference on Computer Vision and Pattern Recognition, CVPR 2011, Colorado Springs, CO, USA, pp. 1297–1304.

[12] Horváth, I., 2004. "On some crucial issues of computer support of conceptual design". In *Product Engineering*, D. Talabă and T. Roche, eds. Springer Netherlands, pp. 123–142.

[13] Seth, A., Vance, J., and Oliver, J., 2011. "Virtual reality for assembly methods prototyping: a review". *Virtual Reality, **15***, pp. 5–20.

[14] Mäntylä, M., 1987. *An introduction to solid modeling*. Computer Science Press, Inc., New York, NY, USA.

[15] Rogers, D. F., and Adams, J. A., 1989. *Mathematical Elements for Computer Graphics*, 2nd ed. McGraw-Hill Higher Education.

[16] Chang, T.-I., Lee, J.-H., Kim, M.-S., and Hong, S. J., 1998. "Direct manipulation of generalized cylinders based on b-spline motion". *The Visual Computer, **14***(5/6), pp. 228–239.

[17] Hyun, D.-E., Yoon, S.-H., Chang, J.-W., Seong, J.-K., Kim, M.-S., and Jüttler, B., 2005. "Sweep-based human deformation". *The Visual Computer, **21***(8-10), pp. 542–550.

[18] Yoon, S.-H., and Kim, M.-S., 2006. "Sweep-based freeform deformations". *Comput. Graph. Forum, **25***(3), pp. 487–496.

[19] Han, L., and Rudolph, L., 2006. "Inverse kinematics for a serial chain with joints under distance constraints". In Proceedings of Robotics: Science and Systems, G. S. Sukhatme, S. Schaal, W. Burgard, and D. Fox, eds., The MIT Press.

[20] Han, L., and Rudolph, L., 2007. "A unified geometric approach for inverse kinematics of a spatial chain with spherical joints". In 2007 IEEE International Conference on Robotics and Automation, ICRA 2007, 10-14 April 2007, Roma, Italy, pp. 4420–4427.