Proceedings of the ASME 2014 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference
IDETC/CIE 2014
August 17-20, 2014, Buffalo, USA

DETC2014-35442

PROTO-TAI: QUICK DESIGN PROTOTYPING USING TANGIBLE ASSISTED INTERFACES

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ABSTRACT

In the real world, we use our innate manual dexterity to create and manipulate 3D objects. Conventional virtual design tools largely neglect this skill by imposing non-intuitive 2D control mechanisms for interacting with 3D design models. Their usage is thus cumbersome, time consuming and requires training. We propose a novel design paradigm that combines users' manual dexterity with the physical affordances of non-instrumented and ordinary objects to support virtual 3D design constructions. We demonstrate this paradigm through Proto-TAI, a quick prototyping application where 2D shapes are assembled into 3D representations of ideated design concepts. Here, users can create 2D shapes in a pen-based sketch medium and use expressive handheld movements of a planar proxy to configure the shapes in 3D space. The proxy provides a metaphorical means for possessing and controlling the shapes. Here, a depth sensor and computer vision algorithms track the proxy's spatial movement. The 3D design prototype constructed in our system can be fabricated using a laser cutter and physically assembled on-the-fly. Our system has vast implications in many design and assembly contexts, and we demonstrate its usability and efficacy through user studies and evaluations.

INTRODUCTION

Traditionally the infrastructure, knowledge, and skill required for designing and creating real-world artifacts have been confined within professional domains. As a result, large number of individuals possessing imaginative ideas but lacking technical design expertise have been unable to participate in creative design activities. One of the primary reasons for this gap is that conventional computer-aided design tools pose significant knowledge and skill related barriers that prevent convenient learning and usage of the tools. These tools also impede creative design expression and exploration due to their reliance on cognitively tedious design modeling operations through WIMP (windows-icons-menus-pointers) based paradigms [1]. However, recent advancements in affordable and light-weight computing hardware and vision-based 3D sensors have created possibilities for novel interfaces that are more conducive towards design activities. These interfaces facilitate human-computer interactions based on users' natural abilities (acquired from day-to-day human experiences) to directly express design modeling intent [2].

Leveraging on such developments, our broader goal is to explore tangible interfaces for supporting creative design activity. The elements of such interfaces are not confined within the computer desktop, but rather distributed among tangible objects that can be easily handled using natural human dexterity [3]. As a result, users can combine expressive hand movements with the physical affordances and motion constraints of tangible objects to perform design tasks in an intuitive and efficient manner. Un-

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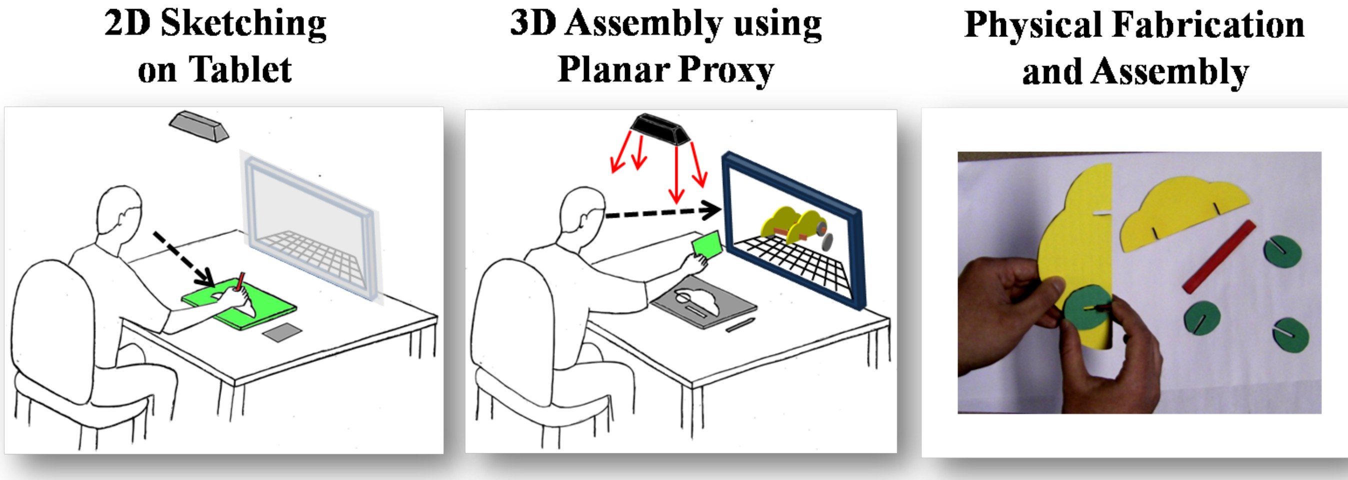

FIGURE 1. GENERAL WORK-FLOW INVOLVED IN PROTO-TAI. A DEMONSTRATION VIDEO CAN BE VIEWED THROUGH THIS LINK https://www.youtube.com/watch?v=2VF8E8kbJdk

like conventional design tools, which merely aid the design process, tangible interfaces can actually serve as integral counterparts to a user's design activity. The physical plausibility of tangible interactions enables users to quickly learn and apply the design tools based on real-life experiences and their understanding of the physical world. Additionally, such interactions also provide rich tactile feedback that enhances kinesthetic control of virtual objects and help reduce visual cognitive load.

We demonstrate this concept through *Proto-TAI*, a quick prototyping tool that employs tangible assisted interfaces in early-stage design tasks. This tool emphasizes the ability to quickly represent the general forms of design ideas without focusing too much on fine level details. Here, 2D shapes are first created on a pen-and-touch sensitive electronic surface. A physical planar proxy, tracked by a depth sensor, is then used as a means for metaphorically possessing and spatially assembling the 2D shapes to form meaningful 3D objects (Figure 2). Such minimalistic representations enable designers to quickly illustrate the underlying 3D structure of design ideas without the use of complex geometric operations. *Proto-TAI* provides a multimodal design environment that exploits users' inherent ability to create 2D sketches and to spatially manipulate and configure physical objects with their hands. Additionally, this tool also takes advantage of low-cost laser cutting technology to physically fabricate design prototypes created by users. Figure 1 illustrates the overall workflow involved in *Proto-TAI*. We envisage this tool to enable a wide range of users to creatively externalize their design ideas in a quick, fun, and engaging manner. A demonstration of this system's usage can be viewed through the link in Figure 1

We showcase the usability and efficacy of *Proto-TAI* through user studies conducted on participants who had no prior experiences with tangible interfaces. The results of the studies indicated that users can conveniently learn the tool and begin applying it in creative design activities with minimal training. They can also create interesting design prototypes quickly and without too much effort.

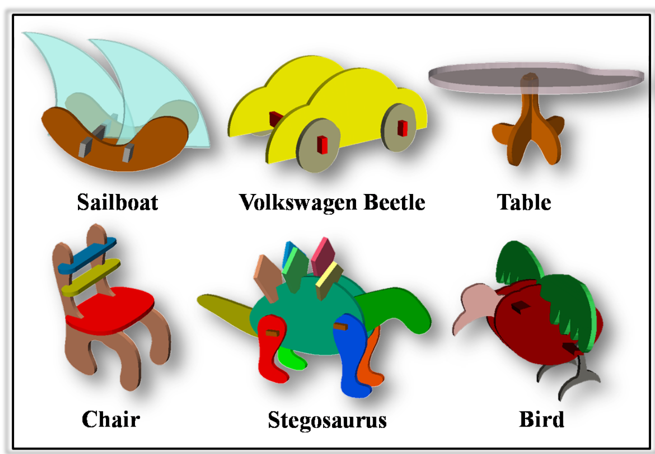

FIGURE 2. 3D OBJECTS CREATED USING THE PROTO-TAI INTERFACE. HERE, 2D COMPONENTS ARE SKETCHED ON A PEN-BASED SKETCH MEDIUM AND ASSEMBLED USING TANGIBLE INTERACTIONS.

Our Contributions

(i) Non-Instrumented Tangible Spatial Interactions: We introduce a novel interaction method for providing direct and expressive spatial inputs using a physical planar proxy that is independent of external addendums such as electronic sensors or fiducial markers. This proxy is easily acquirable since it can be selected from a wide range of ordinary objects. The simplicity in the proxy's geometry allows it to be robustly tracked using low-fidelity vision-based sensors and algorithms, and also makes it resilient against self-occlusions. Since the proxy provides consistent tactile feedback, it can be conveniently handled using our innate manual dexterity at a low cognitive level.

(ii) Multimodal Interactions for 3D Design Prototyping: We present a 3D design prototyping environment where each design task is performed in an appropriate virtual or physical medium (e.g. sketching on a planar surface, 3D assembly in mid-air, physical fabrication using laser cutters etc.) that provides ideal capabilities and affordances for the task. The entire system is implemented in a common computational framework facilitating real-time exchange of design information across different media. It also enables users to seamlessly transition from one design mode to another.

(iii) Low-Cost and Efficient Design Iterations: *Proto-TAI* enables designers to quickly build and modify virtual 3D prototypes using minimalistic but coherent representations. Here, higher-order iterations of multiple design concepts can be performed in a virtual environment prior to physical fabrication. Thus, designers can fully explore all design possibilities without bearing additional material and operational costs.

(iv) Democratized Design Tool: The physically plausible interactions in *Proto-TAI* enable novice designers from diverse age-groups to conveniently learn and apply the tool in 3D design prototyping. Additionally, its use of automated spatial constraint recognition and joint creation capabilities precludes tedious geometric operations that require training and practice. The physicality involved in *Proto-TAI* also enriches user experiences by making it enjoyable to use.

RELATED WORKS

The emergence of low-cost and portable motion sensing devices and computer vision hardware has inspired innumerable works involving design of spatial interactions that facilitate direct and intuitive modeling of virtual 3D prototypes. These works are classifiable based on their input modalities.

Free-hand Gesture based methods employ users' hand gestures, tracked by a vision sensor, as the input mechanism for 3D modeling. The interactions presented in 6D Hands [4] and Handle-bar [5] enable virtual 3D shape manipulations using metaphorical bimanaual gestures. However, they can only be used for constructing 3D assemblies from pre-existing components, but not for creating new shapes. Handy Potter [6] and Shape-it-Up [7] demonstrate how a small set of simple hand gestures can define and modify the physical forms of virtual objects based on generalized cylinders. In contrast, Kang et al. [8] use a more extensive gesture set to create complex and structured 3D shapes in a procedural manner. Despite their physical plausibility, free-hand gesture based methods suffer from the effects of hand occlusions and are also unable to estimate hand orientations required for fine level unimanual interactions. Additionally, they also lack a means to provide tactile feedback required for kinesthetic control of virtual shapes.

Digital Controller based methods include hand-held or hand-worn devices that facilitate direct spatial interactions with virtual 3D shapes. Commercially available hand-held controllers (e.g. Razer Hydra™ and Playstation Move™ etc.), which utilize accelerometer based 3D motion sensing and click button functionalities, have been successfully employed in 3D design prototyping [9, 10]. However, such devices are not intuitive to use and lack physical expressiveness. In contrast, hand-worn multi-sensory devices, such as those used by Nishino et al. [11] and Surface Drawing [12], enable users to provide meaningful gestures to sculpt free-form 3D designs. As demonstrated in 3D Mockup-builder [13] and ErgoDesk [14], digital controllers have also be used in conjunction with a sketch medium where precise inputs can be provided. The main disadvantages of digital controllers is that they have inflexible hardware requirements and impose consistent wearing or holding of unweidly devices that completely occupy users' prehensile capacity.

Functional Proxies are physical objects that directly embody either the 3D design model components or the modeling tools. Their inherent affordances suggest their appropriate usage in a design activity. For example, Timba [15] demonstrates how rectangular proxies with fiducial markers can be spatially configured to build virtual architectural models. Similarly, Flexm [16] provides a digitally instrumented hub and strut construction kit for creating 3D geometries. Sheng et al. [17] introduce a virtual sculpting interface where finger based manipulations of a deformable proxy indicate sculpting operations. In contrast to these methods, KidCAD [18] enables designers to geometrically combine multiple proxies by imprinting them on a malleable gel. It is apparent that existing works using functional proxies are dependent upon electronic sensors or fiducal markers, which users might not be able to setup as per the interface requirements.

Our work is also related to interactive 3D modeling involving 3D assembly of planar components. Existing works in this area have used either traditional input devices [19] or pen-based sketch media [20, 21] to define the shapes of the planar components. However, these methods lack a means for directly assembling the components in 3D space and thus rely on non-intuitive WIMP based modeling software. More recently, Mueller et al. [22] introduced an interface where the components are directly fabricated using a laser pointer. Despite its efficiency, it does not allow users to edit or modify the shapes and can cause material wastage. Additionally, all of these methods require users to pre-define joint locations between adjoining components, which impedes rapid design modifications and creative explorations.

SYSTEM IMPLEMENTATION

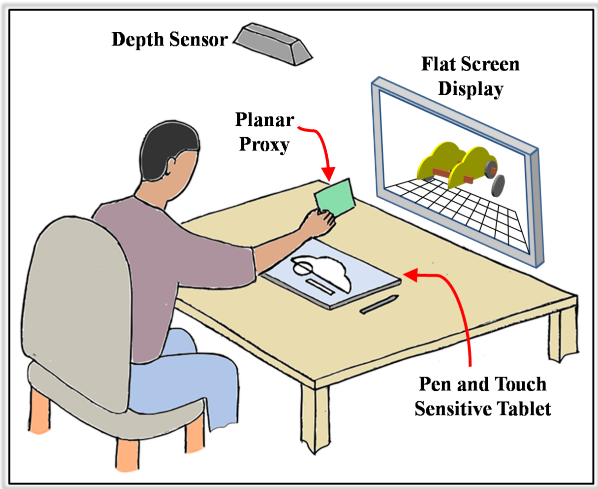

FIGURE 3. PHYSICAL SETUP OF PROTO-TAI INTERFACE.

We observe that different virtual design tasks require distinct interaction capabilities and physical affordances. For example, while sketching is best performed with a pen on a planar surface, 3D assembly is primarily a mid-air gestural activity. With this in view, we have implemented a virtual design interface that is receptive to both pen based 2D inputs and 3D spatial interactions. As illustrated in Figure 3, this interface can be easily configured on a physical desktop, where users can perform design activities in a seated position. Here, a pen and touch sensitive tablet PC (Microsoft Surface Pro^{TM}, 4GB RAM, Intel HD Graphics 4000) serves as both the sketching medium as well as the central computing system. A depth sensor (Microsoft Kinect^{TM}) is mounted above the desktop such that it is facing vertically downwards with the user's hands in its field of view. This sensor tracks real-time spatial parameters of a hand-held planar proxy used for 3D interactions. Any flat planar object with rectangular dimensions over 3x5 inches can serve as the planar proxy. In our implementation we use a simple cardboard cutout. We also included a handle at its based for convenient holding and manipulation. While the sketching interface (Figure 7) is directly displayed on the tablet, an OpenGL based virtual 3D scene (Figure 8) that provides visual feedback to the assembly tasks can be viewed on a flat-screen monitor. Tapping and touching gestures on the tablet using the non-dominant hand (the one not holding the proxy) or the digital pen can also utilized for specifying certain input commands.

3D Workspace Calibration

The free region hovering directly over the desk surface in Figure 3 represents the 3D workspace wherein spatial inputs through the planar proxy can be provided. The bounds of this workspace can be adjusted to fit the ergonomic needs of different users. For this purpose, we provide a simple calibration interface that displays the image of the physical desktop as observed by the RGB camera in the Kinect sensor. Users can draw a rectangular box over this image to indicate the region within which all mid-air motions of the planar proxy will be construed as user-intended spatial inputs.

Hand-held Planar Proxy Tracking

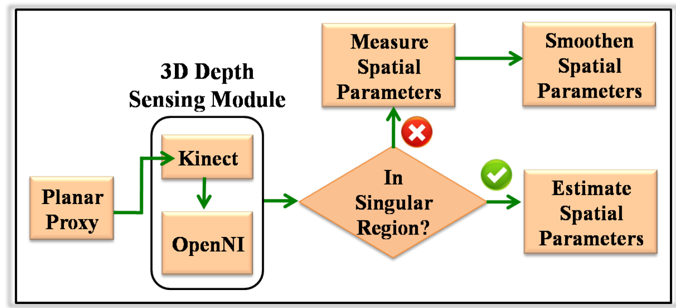

FIGURE 4. PLANAR PROXY TRACKING PIPELINE

We utilize the OpenNI API to obtain 3D data from the physical workspace and to track the motion of the planar proxy. While working with the interface, users can explicitly indicate to the system when to start tracking the proxy by holding it and gently shaking it in mid-air. To stop tracking the proxy, users simply need to place it down flat on the desktop. While being tracked, the proxy's real-time position and 3D orientation get measured by the system. The position is directly provided by the OpenNI tracking function and is represented as a single point located approximately at the proxy's center. We estimate the proxy's orientation by applying principal component analysis (PCA) on the 3D data acquired from its surface. Our system extracts this data by first creating a 250x250x150 mm axis-aligned bounding box around the proxy's 3D position. It then isolates all data points lying inside this box from the rest of the physical workspace. Since, the resulting data set contains points belonging to both the proxy and the hand holding it, a RANSAC based plane fitting algorithm is used to separate the proxy data from the hand data. The PCA algorithm then computes the normal and major directions of the proxy data to define the proxy's 3D orientation. To avoid planar orientation ambiguity, the system checks the angular displacement between successive proxy normals. If this displacement is greater than a pre-defined threshold, the proxy's orientation is flipped to make it compatible to the previous measurement. The system also performs the following tasks to enhance the tracking process.

a) Spatial Parameter Smoothing: To reduce the effects of inherent measurement noise within the Kinect depth sensor [23], we apply single exponential smoothing (equation 1) on the planar proxy's spatial parameters.

$$\vec{v}_{smooth,t} = \alpha \cdot \vec{v}_{raw,t} + (1-\alpha) \cdot \vec{v}_{smooth,t-1} \quad (1)$$

Here, a parameter's smoothened value at time t ($\vec{v}_{smooth,t}$), is obtained as a linear combination of its measured values at successive times before t ($\vec{v}_{raw,t}$). α is the smoothing factor that ranges between 0 and 1. In our implementation we set α to 0.3. When smoothing the proxy's parameters, its 3D position can be directly applied in equation 1. However, the proxy's orientation must first be represented as a quaternion with respect to its previous orientation. Equation 2 defines the quaternion between two successive orientations, where θ and $\vec{w}$ are the angle and axis of rotation between the orientations.

$$\vec{q} = \left[cos\left(\frac{\theta}{2}\right), sin\left(\frac{\theta}{2}\right) \cdot (w_x\vec{i} + w_y\vec{j} + w_z\vec{k})\right] \quad (2)$$

Typically spherical linear interpolation (equation 3) is used for smoothing the measured quaternions. But since the incremental angle between successive proxy orientations is small, equation 3 becomes identical to equation 1.

$$\vec{q}_{smooth,t} = \frac{\sin(\alpha \cdot \theta)}{\sin(\theta)} \cdot \vec{q}_{raw,t} + \frac{\sin\left[(1-\alpha) \cdot \theta)\right]}{\sin(\theta)} \cdot \vec{q}_{smooth,t-1} \quad (3)$$

b) Spatial Parameter Estimation: During its usage, the planar proxy can occasionally get roughly aligned with the depth sensor's line of sight, causing our system to lose track of its spatial parameters. If the sphere in Figure 5 represents a Gauss map containing all possible orientations of the proxy, the region bounded by the red circles includes orientations where such alignment could occur. This singular region extends 10 degrees in both directions of the plane containing the sensor's line of sight. Whenever the proxy attains an orientation within this region, our system linearly extrapolates the proxy's position, orientation, and velocity based on their last 30 measurements. If the proxy remains inside the singular region even after its estimated orientation has come out, then the system understands it is being held stationary in that region. In such cases, the proxy's orientation is set to coincide with the sensor's line of sight and its position is adjusted to the last measured position.

Spatial Parameter Mapping

If the planar proxy is in possession of a vitual planar shape, its measured or estimated spatial parameters at each instance are directly mapped to the virtual shape. Figure 6 illustrates such mapping at two consecutive instances. It can be seen that the normal and major axis directions of the proxy define the orientation of the shape. A virtual shape's major axis direction is pre-defined as the direction from its centroid to the location of its first profile vertex.

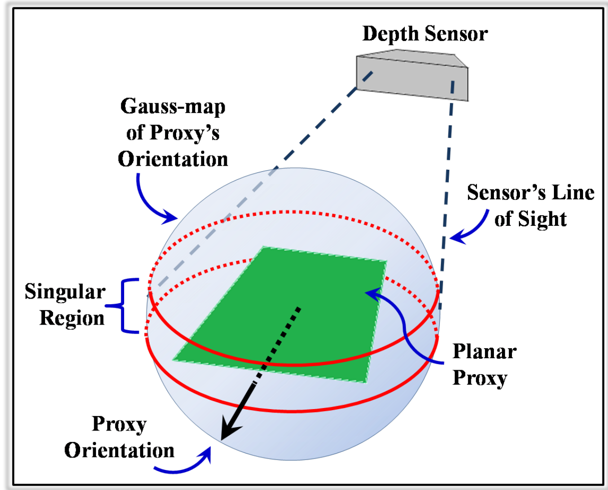

FIGURE 5. SINGULAR ORIENTATIONS OF THE PLANAR PROXY, WHERE ITS SPATIAL PARAMETERS ARE ESTIMATED.

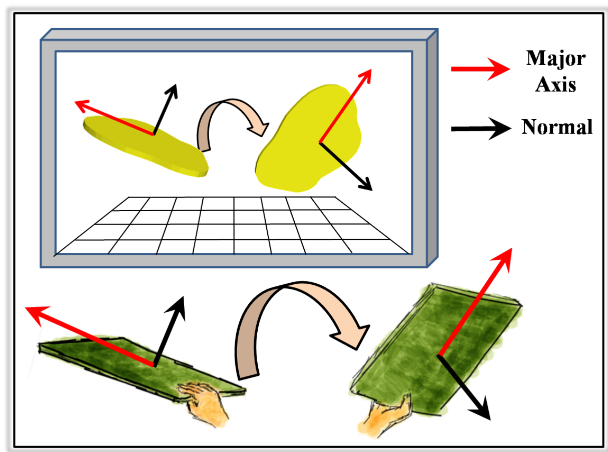

FIGURE 6. MAPPING OF THE PLANAR PROXY'S SPATIAL PARAMETERS ONTO A POSSESSED VIRTUAL SHAPE.

USER INTERFACE AND MODELING INTERACTIONS

The *Proto-TAI* workflow comprises of three modeling stages: (i) creating planar shapes, (ii) assembling those shapes into a 3D object, (iii) physically fabricating the 3D object. Here, the design tasks in each stage are carried out in an appropriate medium that best suit the tasks. Since the first two stages contribute towards a common virtual design activity, users can freely switch between them at any given instance of interface usage. A demonstration video can be viewed through the link provided in Figure 1

Creating Planar Shapes

Planar shapes required for constructing the 3D design prototype are created on a sketch medium using a digital pen. In the absence of a pen, users can also employ a finger-based touch gesture on the sketch surface. The following operations are performed during this process.

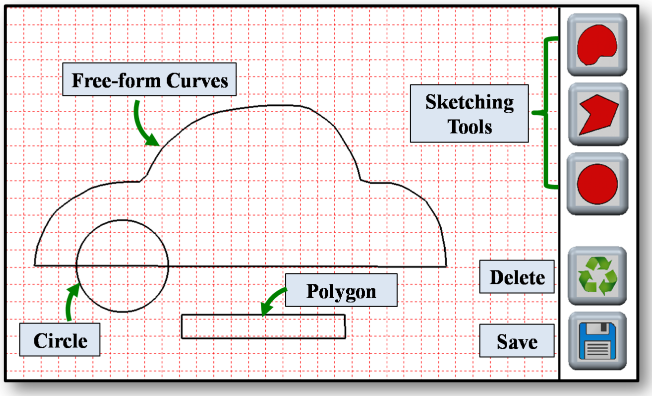

FIGURE 7. SKETCHING INTERFACE USED IN PROTO-TAI.

a) Draw: Users can draw closed curves to define the geometric profile of the planar shapes. As shown in Figure 7, *Proto-TAI* facilitates creation of three types of profiles: free-form curves, polygons, and circles. Our user studies indicated that these three profile types can alone support creation of a wide range of 2D shapes conceivable by users. Each sketched profile gets automatically subjected to a uniform resampling process to maintain even spacing between adjacent vertices. Additionally, median filtering gets applied on the vertices of the free-form curves to enhance their smoothness. If a free-form curve drawn is not closed, the system creates a straight line between its end points.

b) Compare and Edit: The sketched profiles can be moved around, rotated and scaled within the 2D workspace. This enables users to position different profiles relative to one another such that their size and geometric compatibility can be directly compared and adjusted before 3D assembly. For example, in Figure 7 the wheel and the axle of the car are placed in close proximity to the body such that their relative proportions are directly observable. The sketched profiles can also be deleted. The edits made in the profiles are directly reflected on their counterparts in the virtual 3D scene.

c) Extrude and Save: The sketched profiles can be saved for use in the assembly of the 3D design prototype. To provide the profiles with a volumetric structure, they are first extruded by a pre-defined distance equal to the thickness of the material that will be used in their physical fabrication. The extrusion is created by simply offsetting a copy of the profiles' vertices above the sketch plane. The extruded volume is represented as a 3D triangular mesh. The saved planar shapes are laid out on the horizontal surface of the virtual 3D scene (Figure 8) and can be "picked up" during assembly.

Constructing Virtual 3D Prototypes

The setup of the virtual scene (Figure 8) that displays 3D assembly activities is analogous to the physical workspace. It comprises of a horizontal desk that represents the physical desktop the user is working on. All planar shapes saved in the sketching interface get laid out on this desk and are available for selection during assembly. The 3D object being constructed is suspended in the 3D region above the virtual desk. The spatial movement of the hand-held proxy within the physical workspace is analogously mapped into the virtual scene. The proxy's movement is represented by the planar shape it is possessing or a 3D spherical cursor if it is not possessing any shapes. The following interactive operations are performed during the construction process.

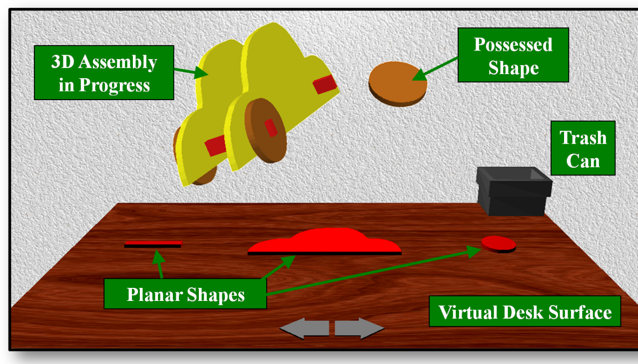

FIGURE 8. VIRTUAL 3D SCENE FOR ASSEMBLING PLANAR COMPONENTS.

a) Shape Selection: To select a planar shape from the virtual desk or the prototype being constructed, the 3D cursor is first brought close to the shape. Change in the shape's color indicates adequate proximity required for shape selection. A single tapping gesture on the tablet surface (with the non-dominant hand or the digital pen) is then used for specifying selection of that shape. As shown in Figure 6, this shape gets anchored to the planar proxy allowing users to control its spatial movement. Multiple copies of the same shape can be selected for use during 3D assembly.

b) Shape Manipulation: A planar shape possessed by the proxy can be spatially manipulated in the following ways:
(i) Free-form Manipulation: The spatial parameters of the proxy are directly transferred over to the possessed shape, giving users the ability to concurrently translate and rotate the shape to a

desired 3D configuration.
(ii) Constrained Manipulation: Users can also translate a planar shape in 3D without changing its orientation or rotate it about its face normal at a fixed position. The intent for constrained manipulations can be expressed during shape selection by using a double tapping gesture (for translation only) or a touch-and-hold gesture (for rotation only) on the tablet. Here, only the relevant spatial parameters get mapped from the proxy to the planar shape.

c) Shape Assembly: The 3D object being assembled is incrementally created by adding one planar shape at a time. A single tap gesture is used to indicated placement of a shape at a specified location. A possessed shape can be placed in the assembly with either a user-defined orientation or constrained to a pre-existing shape. Such constraints are automatically enforced based on the following contexts.

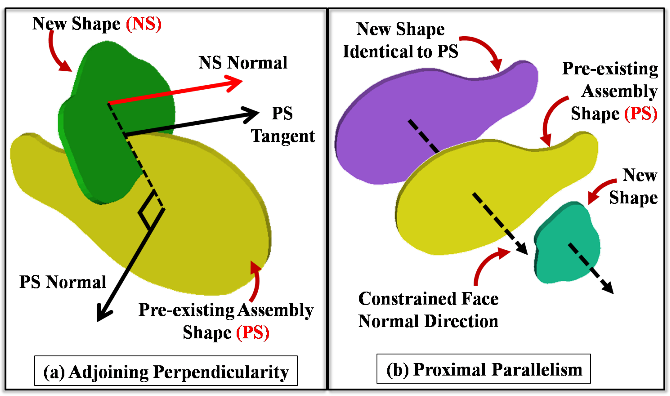

FIGURE 9. AUTOMATICALLY ENFORCED ASSEMBLY CONSTRAINTS BETWEEN SHAPES THAT ARE ADJOINING OR IN CLOSE PROXIMITY.

(i) Adjoining Perpendicularity: If a newly added shape adjoins to a pre-existing assembly shape, its orientation is adjusted such that the planar faces of the two shapes are perpendicular. Additionally, the face normal of the new shape is made parallel to the profile tangent of the pre-existing shape at the point of intersection. These constraints are required to ensure manufacturability and structural integrity in the resulting 3D object. Figure 9(a) illustrates this constraint.
(ii) Proximal Parallelism: If a new shape is placed close to a pre-existing shape such that their planar faces are approximately parallel (within 20 degrees), they are snapped into parallelism. Additionally, if the two shapes are identical, then they are also aligned along their 2D profiles as shown in Figure 9(b).

d) Assembly Rotation: At any point during 3D interactions (even when a planar shape is being held), the assembly can be rotated to adjust its viewing direction or to gain access to a specific location on it. This can be done by taking the cursor away from the assembly, applying a touch-and-hold gesture, and moving the planar proxy to indicate rotational direction.

Creating Physical Prototypes
This process converts the virtually constructed 3D objects into physical prototypes. It comprises of two stages.

a) Automated Joint Creation: *Proto-TAI* facilitates automated notch joint creation between adjoining planar shapes in the 3D object. These joints essentially comprise of rectangular grooves cut out from one shape such that others can be snuggly fit into it. Upon completing the assembly, the planar proxy can be directly used for specifying which shapes in the 3D object will contain these grooves. The groove geometry between a pair of adjoining shapes is determined by first computing the intersecting area between a planar face on the grooved shape (GS) and the entire volume of the non-grooved shape (NGS). This area is then removed from across the thickness of the GS. If the NGS lies entirely within the 2D profile of the GS, the intersecting area is extended upto the closest vertex of the GS profile.

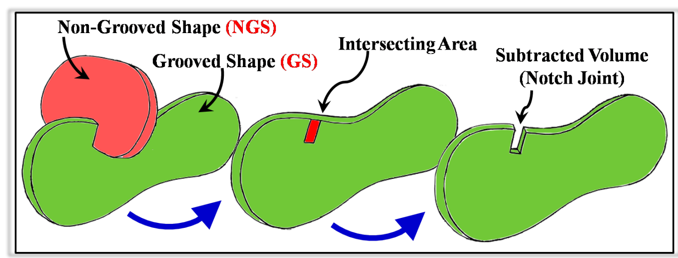

FIGURE 10. THE PROCESS OF NOTCH-JOINT CREATION BETWEEN ADJOINING PLANAR SHAPES.

b) Physical Fabrication: The virtual 3D objects can be fabricated using a wide range of rapid prototyping techniques. In our implementation, we use a laser cutter (90 Watt Pro LF Series) because of its ability to precisely create complex planar shapes from low-cost and ordinary materials such as cardboard and plastic sheets. Figure 11 provides an example of a 3D design prototype constructed in *Proto-TAI* and fabricated with regular corrugated cardboard (color paper was pasted over the laser cut shapes).

USER EVALUATION
We conducted a user study to understand what kinds of design prototypes novice designers could construct using *Proto-TAI* and to evaluate the following attributes of the interface: (i) system usability, (ii) workload imposed on users by the system, (iii) user experiences during design activity. There were 15 par-

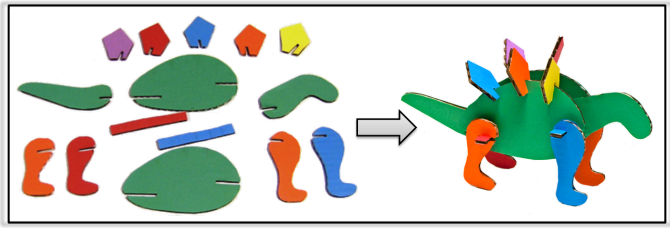

FIGURE 11. PHYSICAL FABRICATION OF 3D DESIGN PROTOTYPE CREATED IN PROTO-TAI, USING A LASER CUTTER.

ticipants (12 male and 3 female) in this study, all of whom had no prior experience with tangible interfaces or spatial gesture based 3D modeling. But about half of them were familiar with conventional CAD software. Each user study session involved one participant and lasted about 60 minutes. During the first 15 minutes, participants were introduced to the *Proto-TAI* interface and the concept of quick prototyping by assembling planar components. Two tasks, with a time limit of 15 minutes each, were then assigned to the participants. In the first task they were asked to construct a chair with a design of their choosing. This task allowed them to create a simple and familiar object and get accustomed to our system. In the second task, participants were asked to conceptualize and construct any 3D design of their choice. This task allowed us to evaluate creative design explorations enabled by the interface. Participants were also asked to fill out post-study surveys that helped document their experiences.

Effectiveness of Interface

All participants were able to complete both tasks within the 15 minute time limit. On average they spent about 13 minutes in Task 1 and 14 minutes in Task 2. Given the fact that they had only received 15 minutes of training with the system, the participants were able to gain functional proficiency rather quickly. Figure 12 illustrates some examples of chairs constructed in Task 1. It can be seen that *Proto-TAI* allows wide variations in the design of the same object. Figure 13 shows some examples of 3D prototypes created in Task 2. Here, each participant came up with a unique design idea and was able to successfully construct it using *Proto-TAI*.

Usability of Interface

We employed the well-known System Usability Scale (SUS) [24] to assess the usability of *Proto-TAI*. This method entails a 10 item questionnaire pertaining to the system's learnability, ease of use, and general appeal. Based on users' feedback from this questionnaire, *Proto-TAI* attained a score of 73.2 out of 100. A score above 60 indicates that the interface has high usability. Additionally, most of the participants indicated in the post study interview that *Proto-TAI* was fairly easy to learn and use, and

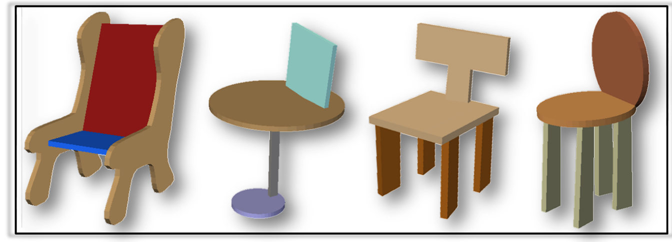

FIGURE 12. EXAMPLES OF 3D CHAIR MODELS CREATED BY PARTICIPANTS USING THE PROTO-TAI INTERFACE.

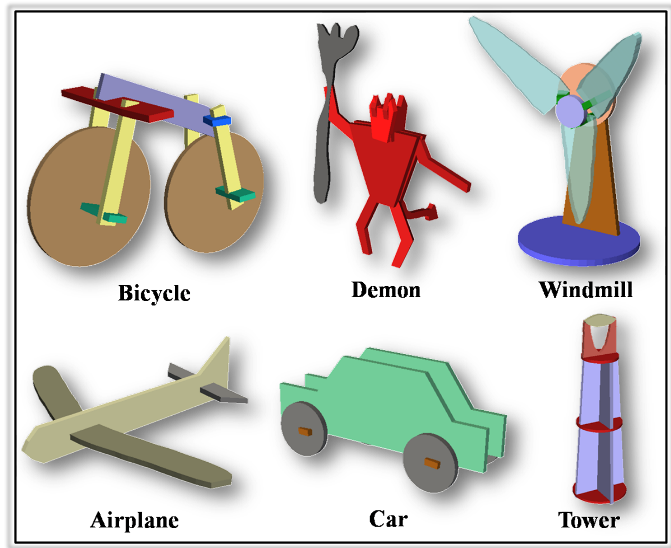

FIGURE 13. EXAMPLES OF 3D MODELS CONCEPTUALIZED AND CREATED BY PARTICIPANTS USING THE PROTO-TAI INTERFACE.

that they would frequently utilize a system like it.

Workload Imposed by Interface

Workload represents the physical and cognitive demand placed on users by a system. We utilized the NASA Task Load Index questionnaire [25] to evaluate workload imposed by *Proto-TAI*, as perceived by the users. Figure 14 illustrates the six factors used for measuring workload and the cumulative score each factor received in our studies. This score ranges between 0 and 10, with 10 being the least favorable situation. It can be seen that the scores in all factors lie below the 50th percentile, which indicates comfortable and ergonomic working conditions during interface usage. Comparatively, physical load seems to be higher than the rest, but it is still below 50%. This indicates that users are physically engaged but not worn out while using *Proto-TAI*.

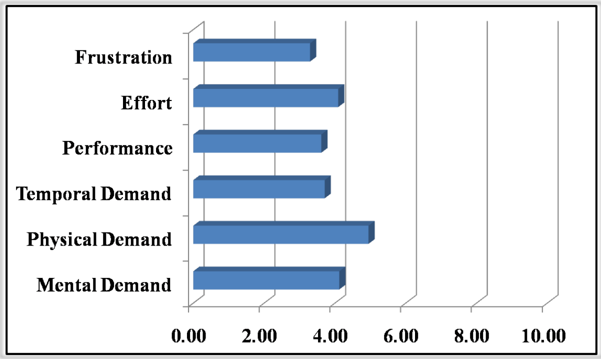

FIGURE 14. CUMULATIVE SCORES OF WORKLOAD EVALUATION FACTORS. A SCORE OF 10 REPRESENTS THE LEAST FAVORABLE SITUATION.

User Experience
We base our evaluation of user experiences provided by *Proto-TAI* on the five factors introduced by Carroll et al. [26], as shown in Figure 15. The scores for each factor ranges between 0 and 10, with 10 being the most favorable experience. Our studies showed that the participants consistently scored each factor above the 70th percentile, indicating positive user experiences. In fact, they seem to unanimously agree that the design prototyping process was highly enjoyable.

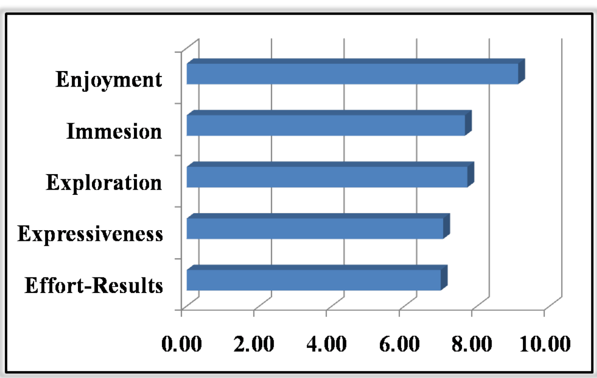

FIGURE 15. CUMULATIVE SCORES OF USER EXPERIENCE EVALUATION FACTORS. A SCORE OF 10 REPRESENTS THE MOST FAVORABLE SITUATION.

CONCLUSION AND FUTURE WORKS

In this paper we demonstrated *Proto-TAI*, a design prototyping tool that enables diverse users (irrespective of their design proficiency) to quickly represent ideated design concepts by assembling planar shapes into meaningful 3D objects. Here, we employed tangible interactions such as (a) pen-based sketching for creating planar shapes and (b) hand-held manipulations of a non-instrumented planar proxy to spatially control and configure these shapes. In the *Proto-TAI* workflow, the design prototypes are initially constructed, explored, and iteratively refined within a virtual environment and subsequently fabricated using a laser cutter. The key contribution made in this work is the use of designers' innate manual dexterity (acquired through day-to-day experiences) and physical awareness to support creative design activities at a low cognitive level. In addition, we also provide separate but seamlessly interconnected interaction spaces whose unique affordances cater to specific design tasks. We motivated our work by positing that such attributes would minimize learning and practice time taken by users to become adept with the design construction process. Our efforts were also intended to explore easy-to-use design tools that emphasize creativity without the need for high-level design knowledge.

We showcased the strength of *Proto-TAI* through a user-study where participants, having no prior experience in tangible interactions, constructed creative design prototypes with minimal training and within short time frames. Feedback from these studies revealed high usability and low workload levels imposed by the system on users. We believe that this performance is a direct result of augmenting natural human dexterity and the affordances of physical objects within virtual design prototyping. Additionally, we also observed that the physicality of the interactions enabled the design activity to become less of a chore and more of a fun and exciting creative endeavor.

Given the efficacy of *Proto-TAI*, we find that there is scope for technical expansion and enhancement of the ideas presented. Firstly, our immediate goal is to conduct comparative user studies that directly assess the performance of our interface with respect to both conventional design tools and the more recently introduced tools mentioned in the Related Works section. We expect these studies to reveal new insights that can possibly motivate research in novel directions. Secondly, we intend to employ this framework to create more complex design prototypes entailing non-planar parts with advanced geometric features and interconnectivity constraints. Finally, we believe that the general idea of using physical objects in design prototyping has immense potential for further research. Using a wider variety of physical proxies such as cylinders, cubes, and spheres is one interesting direction towards such generalized approach.

ACKNOWLEDGMENTS

This work was supported by the NSF Award No. 1235232 from CMMI-EDI (A-DRIVE). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. We also thank Vinayak for providing us with his OpenGL based library for 3D scene rendering and visualization.

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