MobiSweep: Exploring Spatial Design Ideation Using a Smartphone as a Hand-held Reference Plane

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ABSTRACT
In this paper, we explore quick 3D shape composition during early-phase *spatial* design ideation. Our approach is to re-purpose a smartphone as a hand-held *reference plane* for creating, modifying, and manipulating 3D sweep surfaces. We implemented *MobiSweep*, a prototype application to explore a new design space of constrained spatial interactions that combine direct orientation control with indirect position control via well-established multi-touch gestures. *MobiSweep* leverages kinesthetically aware interactions for the creation of a sweep surface without explicit position tracking. The design concepts generated by users, in conjunction with their feedback, demonstrate the potential of such interactions in enabling spatial ideation.

ACM Classification Keywords
H.5.2 Information Interfaces and Presentation: User Interfaces; J.6 Computer-aided Engineering: Computer-aided Design (CAD); I.3.5 Computer Graphics: Computational Geometry and Object ModelingGeometric algorithms, languages, and systems; I.3.6 Computer Graphics: Methodology and TechniquesInteraction techniques

Author Keywords
Design Ideation; Sweep surfaces; Smartphones; Mobile interactions.

Early-phase ideation is fundamental to product and industrial design processes. Ideation involves *divergent thinking* for quick externalization of ideas to help the designer understand the design problem [18, 23]. This exploratory nature of ideation demands an uninhibited flow between what a designer is *thinking* and what the designer is *doing* to communicate the thought. This is perhaps why designers still predominantly prefer a direct and physical method - sketching - to express design ideas [7, 6]. However, an unambiguous visual representation of 3D forms through sketching, necessitates multiple coordinated 2D projected views. Thus, even sketching is perceived as a challenging medium by novice designers while communicating 3D forms [9]. While systems such as *EverybodyLovesSketch* [1] cater to users untrained in sketching, they are focused towards the creation of detailed 3D sketches rather than quick design conceptualization. In this paper, we explore *spatial design ideation* through the association of physical human movement to the design outcome. Our broader goal is to explore the role of embodied interactions in enabling spatial ideation during early phase design by employing mobile spatial user interfaces (M-SUI's).

We find that computer support for quick *spatial design ideation* has received very little attention in existing literature. Tools for 3D design are not suited for ideation since they do not embody the notion of *controlled vagueness* [25] that is central to the process of idea generation. Thus, computer-aided design (CAD) tools end up supporting the creation of sophisticated artifacts *once the designer has learned the usage of the modeling tool*. The same goes for casual modeling systems such as *Paper3D* [20] where the focus is on demonstrating detailed design capabilities. The amount of time spent in merely familiarizing oneself with the tool digresses the designer's attention from the design activity. Thus, an important problem in computer-supported ideation is to determine a minimal set of modeling features that channel the designer's thinking process towards the variety of ideas while retaining expressiveness of their creations.

Klemmer et al. [11] state: "*One of the most powerful human capabilities relevant to designers is the intimate incorporation of an artifact into bodily practice to the point where people perceive that artifact as an extension of themselves; they act through it rather than on it*". Systems such as *Spatial Sketch* [28] and *PROTO-TAI* [21] are examples of embodied approaches towards the creation of physical artifacts via bodily movement. Drawing from these works, we argue that enabling the direct externalization of spatial design concepts can be effectively achieved by embedding the geometric representation of the artifact within the physicality of the creation process itself. We take a step towards this goal through *MobiSweep*, a prototype application for creation of 3D compositions comprised of swept surfaces through constrained spatial interactions with a smartphone.

As the name suggests, *MobiSweep* makes use of sweep surfaces as the underlying shape representation. In addition to being fundamental in CAD, sweep surfaces inherently lend

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themselves to the intuitive physical action of *sweeping* a planar section along a trajectory in 3D space, especially through a mobile interface. In *MobiSweep*, we utilize this spatial relationship between the physical action of sweeping and the creation of the resulting swept surface.

BACKGROUND

Mobile devices offer a unique combination of computational power, wireless data communication, 3D sensing capabilities, ergonomic manipulability, and multi-touch input mechanisms. Although mobile devices have been previously explored as spatial controllers for several virtual applications [2, 22], inertial position tracking is impractical without adding additional hardware [17]. Here, the multi-touch capability of phones and tablets provides additional affordances for both direct and indirect manipulations of the virtual objects. To this end, several works [16, 12, 24, 10] have used combinations of touch and tilt for 3D object manipulation.

Xin et al. [29] demonstrated the use of a tablet as an augmented reality (AR) canvas for 3D sketching, akin to creating wire-sculptures. Similarly, Lue and Schulze [15] demonstrated the *3D Whiteboard* system using smartphone AR technique with fiducial markers. The use of fiducial markers has also been shown for larger environments such as rooms, for AR based virtual furnishing by Swaminathan et al. [27]. Lakatos et al. [14] demonstrated the use of tablets as *spatially-aware* hand-held controllers in conjunction with hand-worn gloves for 3D shape modeling and animation. However, their work was more focused on demonstrating general interactions for modeling scenarios rather than exploring a concrete design work-flow for shape composition. Mine et al. [17] described and discussed an immersive adaptation of the SketchUp application using a tracked smartphone in a CAVE setting. Our work differs from these works in two ways: (a) our intention is to support quick creative compositions with actual 3D surfaces in contrast to [29, 28, 15] and (b) our system does not use any additional hardware or vision based method for explicit position tracking (such as in [27, 14, 17]).

MOBISWEEP

System Setup

The *MobiSweep* interface comprises of a hand-held controller (smartphone), and the virtual environment (i.e. a modeling application running on a personal computer) (Figure 1). The virtual environment consists of a *reference plane* with a local frame of reference mapped to the phone's coordinate system.

Design Rationale

The design goal behind *MobiSweep* is to strike a balance between modeling constraints, interaction techniques, and system workflow to enable direct spatial ideation. There are mainly two fundamental aspects that we considered while designing *MobiSweep*: (a) 3D manipulation and (b) sweep surface generation. For 3D manipulation, the critical aspect under consideration is to minimize fatigue for precise manipulations and minimize the interaction time for coarse manipulations. Instead of imposing full mid-air movements, we employ touch gestures to allow controlled and precise 3D manipulation of virtual objects. In order to minimize learning time, we take advantage of the fact that most users are already familiar with multi-touch gestures for manipulating objects. Thus, we define a single *context-aware* interaction metaphor that: (a) uses known multi-touch gestures and (b) is shared between several modeling tasks.

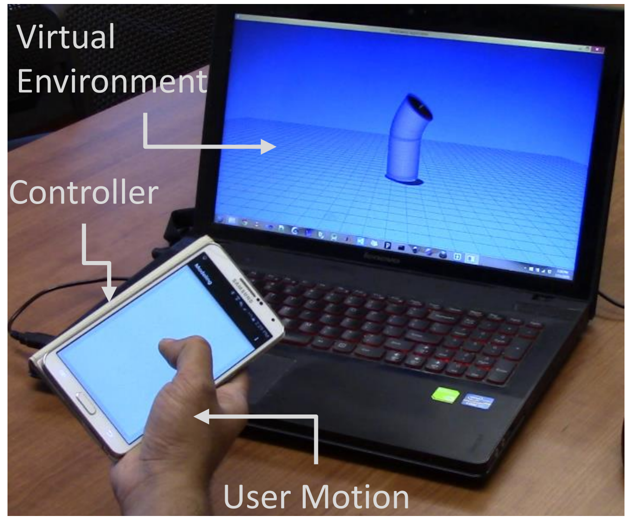

Figure 1. Setup for *MobiSweep* comprises of a visual display of the virtual environment and a smartphone that acts as a reference plane in the virtual environment.

Drawing from the key insight of Jacob et al. [8], we find that the separation of degrees-of-freedom (DoF) can be effective if the interactions for the task (sweeping a section) are synergistic with the input mode provided by the device (the smartphone). Based on this, we inspire our approach from the free plane casting method proposed by Katzakis et al. [10] by combining direct orientation control with indirect gesture based position control. We introduce an interaction metaphor - *phone as a reference plane* - that emulates the action of sweeping a sketched cross-section that is held in the user's hand (Figure 1). In doing so, we do away with the procedural specification of planes as spatial references for drawing 2D curves to define profiles and trajectories, as is predominantly done in conventional CAD systems. The key advantage of our metaphor is that in addition to creation, it naturally lends to spatial actions such as on-the-fly bending, gesture-based cross-sectional scaling, and in-situ modification of the cross-sectional shape by sketching.

Gesture Definition

In order to define the interaction work-flow for *MobiSweep*, we begin with the definition of our interaction metaphor - *phone as a reference plane*. Given a hand-held phone, we can define a reference plane in the virtual 3D space with a local coordinate frame. Subsequently, the objective is to allow the user to specify the location and orientation of the reference plane. We define the following gestures to achieve this objective:

Rotate: Here, the orientation (and hence the local coordinate frame) of the phone is directly mapped to that of the reference

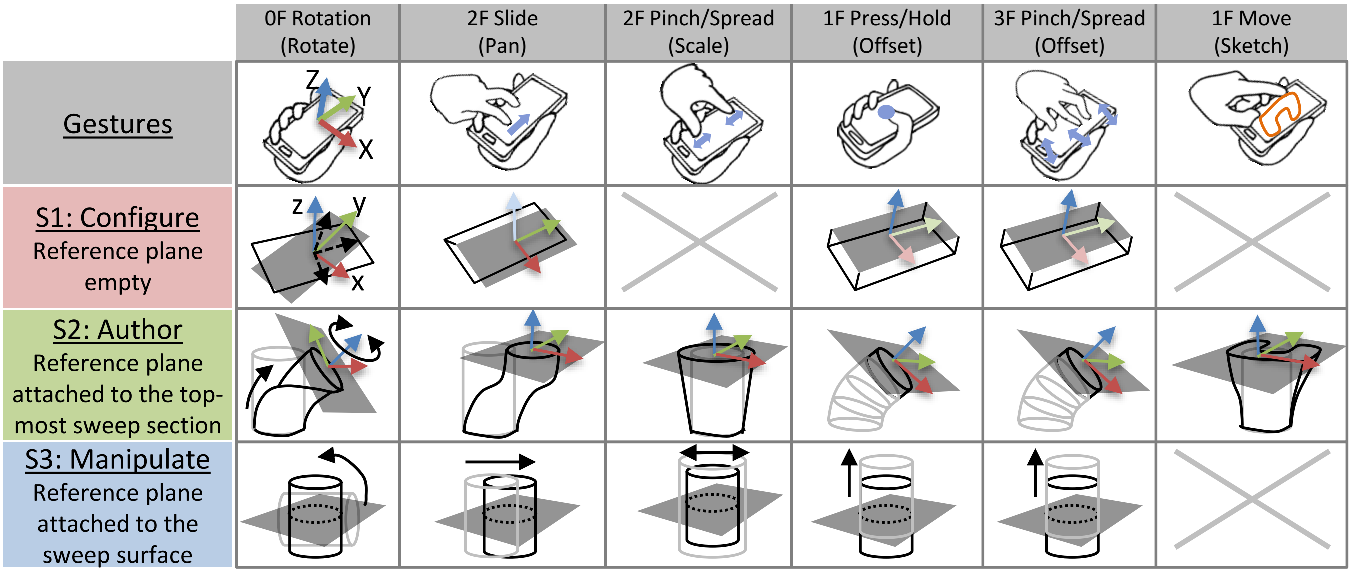

Figure 2. There are six gestures (row 1) that enable the interactions across three modeling states: Configure (row 2), Author (row 3), and Manipulate (row 4). (0F, 1F, 2F, and 3F denote 0, 1, 2, and 3 finger gestures respectively)

plane. Thus, simply rotating the phone results in the rotation of the reference plane (Figure 2: column 1, row 2).

Pan: Using the two finger sliding gesture, users can translate the reference plane on the x-y plane of the local coordinate system (Figure 2: column 2, row 2). This is similar to *in-plane* panning in the *free plane casting* interaction [10].

Scale: Users can also perform in-plane scaling by using a two finger pinch gesture. However, scaling is a context dependent operation that is allowed only when the reference plane either contains a sweep section (Figure 2: column3, row 3) or is attached to a 3D object during a manipulation task (Figure 2: column 3, row 4).

*Offset:*The use of one-finger press/hold (Figure 2: column 4, row 2) gesture allows for automatic translation of the reference plane along its normal with a predefined constant speed. Users can also offset the reference plane by applying a three-finger pinch/spread gesture (Figure 2: column 4, row 2). In this case, the magnitude of offset defined according to the area of pinching or spreading[1]. The one finger gesture provides a quick but imprecise method for offsetting. On the other hand, the three finger gesture requires more effort but allows for a more precise and bi-directional control of the reference plane.

Sketch: Users can sketch a curve on the reference plane using the traditional one finger movement. Similar to scaling, we allow sketching only when the user wants to modify the cross-section of a sweep surface.

Modeling States

The gestures defined for manipulating the reference plane form the basis of *MobiSweep's* work-flow. For any given state in the work-flow, the input gestures (Figure 2: row 1) remain the same but the reference plane takes a different meaning according to the context of the states (Figure 2: rows 2-4) as defined below:

Configure (S1): In this state, the reference plane is detached from all existing shapes (if any). This empty plane can be manipulated to a desired location and orientation in 3D space using the gestures described above (Figure 2: row 1). Such as manipulation may occur either during the creation of the first shape of a composition or during in-situ composition where a user is directly creating one shape on an existing shape. Alternately, users can also move the reference plane in order to select an existing shape in the virtual environment.

Author (S2): In this state, the reference plane is attached to the top-most section of a sweep surface. Users can (a) create a swept surface by offsetting (Figure 2: columns 4-5, row 3), (b) bend and twist a sweep surface by rotating the phone (Figure 2: column 1, row 3), (c) pan and scale a section using two-finger gestures (Figure 2: columns 2-3, row 3), (c) modify a section's shape by sketching on the phone (Figure 2: column 6, row 3).

Manipulate (S3): This state involves rigid transformation of a swept surface for composing through assembly. Here, the reference plane serves as a container for the swept surface through which users can translate, rotate, or scale the surface. Additionally, users can also copy an existing shape and reuse a transformed version of the copy within the composition.

Modeling Work-flow

In the *MobiSweep* work-flow, the configure state (**S1**) is the base state from where users can transition to either the authoring state (**S2**) or the manipulation state (**S3**). The transition between these states are enabled using a combination of menu and gestures. The controller interface for *MobiSweep* is a single-screen Android application that allows for two distinct modes of interactions: (a) *multi-touch input* for reference plane manipulation, sketching, and state transition and (b) *menu navigation* for state transitions and general software

[1]See supplementary material for details.

tasks. Below, we describe the three canonical examples for creation, modification, and manipulation of swept shapes.

Shape Creation

The creation of a swept surface involves the transition from the **configure** (**S1**) to the **author** state (**S2**) (Figure 3(a)). For this, the user selects the "**Add Shape**" button on the menu, thus expressing the intent to begin the creation of a sweep surface. Once the user has expressed the intention to add a shape, the visual representation of the reference plane changes to a default circular section. The user can now sweep the section by using the *one finger press-hold* (or *three-finger pinch-spread*) gestures. This corresponds to the *offsetting* operation occurring along the reference plane normal. By continuously re-orienting the phone during the sweeping process, users can create curved sweeps. Users can also modify the swept surface as described in the following section. Once the user has created a desired shape, the swept surface can be detached from the reference plane using the *double-tap* gesture effectively bringing the user back to the **configure** state.

Shape Modification

Once the user has created a swept surface, the authoring state allows users to modify it *as long as the user has not detached the reference plane from the surface*. The reference plane is attached to the top-most section of the sweep surface (Figure 2: column 3). Hence, all interactions performed by the user affect the top most section only and correspondingly changes the remaining sections of the sweep surface (Figure 3(b)). For instance, simply re-orienting the smartphone results in the rotation of the top-most section effectively allowing the user to bend and twist the swept surface. Similarly, using the two-finger gestures allows for panning and scaling the top-most section of the swept surface.

The modification of the shape of the top-most section involves three steps. The user first selects the "**Sketch Section**" button on the menu to activate the sketching mode. Once in sketching mode, the user simply sketches a desired curve on the smartphone. In our current implementation the user is required to sketch the section in a single stroke. Every time the user finishes drawing a sketch, the sweep surface is immediately modified according to the new sketched section. Thus, the user can simply keep over-drawing the sketch in order to explore different varieties of shapes. Once satisfied with the modified section, the user finalizes the modification using the "*Confirm Section*" button on the menu. Similar to shape creation, the swept surface can be detached from the reference plane by using a *double tap* gesture.

Shape Manipulation

Manipulation of an existing shape involves two steps (Figure 3(c)): *hover* (**S1**) and *selection* (**S3**). Translating the center of the reference plane inside a swept surface is defined as *hovering* on the surface. The user can select an object by first hovering on the object followed by a *double tap* gesture on the phone. Similarly, using the *double tap* on a selected object reverts the state to *hover* again. Thus, *double tap* acts as a toggle between the attachment and detachment of a shape from the reference plane. The use of *double-tap* enables users to perform selection without looking at the controller. *Selection*

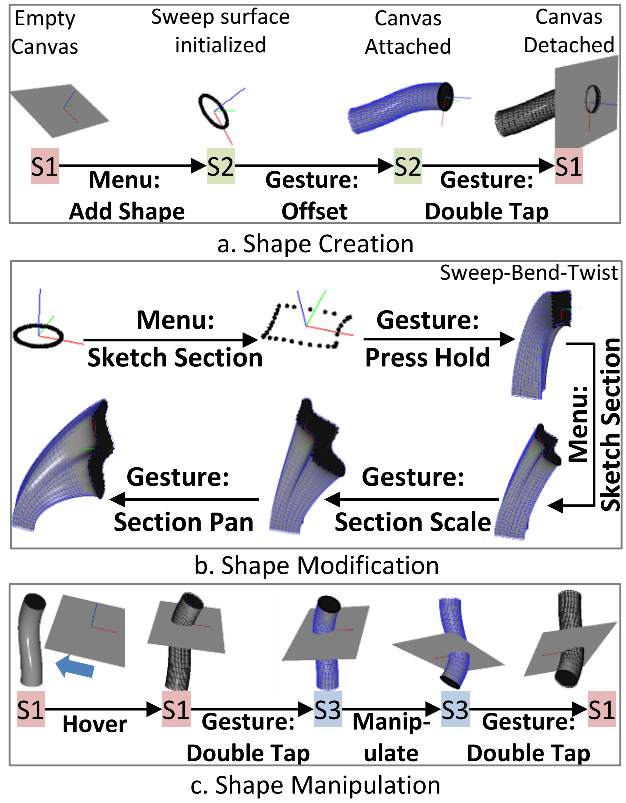

Figure 3. For shape creation (a), the user selects the Add Shape menu item and creates a sweep surface using one or three finger offsetting gesture. For manipulating a shape (b), the user first hovers on a desired sweep surface and selects the shape using the *double-tap* gesture. In the shape modification example (c) the user modifies the initial section by sketching, creates a sweep surface, and modifies the final section by sketching, scaling, and panning.

signifies the attachment of a 3D object with the reference plane, i.e. all rigid transformations applied on the reference plane are transferred to the selected object. In addition to manipulation, the *hover* state can also be used to perform operations such as copying, deleting, and coloring a shape by using the menu.

IMPLEMENTATION

Hardware & Software

Our hardware comprises of a ThinkPad T530 laptop computer with Dual Core CPU 2.5GHz and 8GB RAM, running 64 bit Windows 7 Professional with a NVIDIA NVS 5400M graphics card, and the Samsung Galaxy Note 3 as the handheld controller. We implemented a one-way Bluetooth serial port communication to stream input data from the controller (phone) to the *MobiSweep* application (running on the PC). The input data packet consisted of device orientation, touch coordinates, menu events and multi-touch gestures. Our controller interface was implemented using the Android SDK and the application was developed in C++ with openGL Shading Language for rendering [2].

[2] See supplementary material for details on menu and calibration implementations

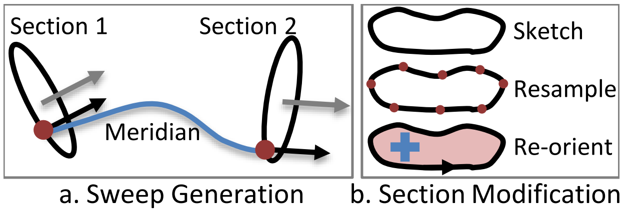

Figure 4. Algorithms for (a) sweep generation and (b) section sketching.

Algorithms

Sweep Surface Generation

The sweep surface is represented as a stack of cross-sections. Once the users starts the offsetting interaction, the sweep surface is incrementally generated in three steps: (a) adding a new section and (b) translating the top-section along the reference plane normal at until a stipulated time has elapsed, and (c) repeating addition and translation as long as the user is offsetting the reference plane. This process of incremental generation provides the visual continuity of sweeping to the users and the translation time defines the distance between consecutive sections.

In this work, we implemented a variant of the control-section based sweeping technique [5] wherein every sweep surface consists of two control sections at the two ends of the sweep surface. Each control section comprises of equal number of points and the information about its local coordinate frame (i.e. the frame of the reference plane). Hence, there is a one-to-one point correspondence between the control sections. For a given pair of control sections, we interpolate each meridian of the sweep surface by using the cubic hermite basis functions (Figure 4(a)). The interpolation requires four boundary conditions, namely, the position and tangents at the end points. These are conveniently provided by the vertices and the normal of the section's local coordinate frame respectively. Our approach removes the need for explicit computation of the individual section transformations and avoids frame rotation minimization and section blending. This simplifies the operations (bending, twisting, panning, scaling and section modification) in the authoring state.

Section Modification

Currently, we allow single stroke sketching in our implementation and the number of points in each section of the sweep surface is constant and pre-defined. For a sketch input, we first determine if the sketch is an open or a closed curve based on a simple distance threshold between the two end-points of the sketch input. For a closed curve, we implemented a three stage processing of the sketch input (Figure 4(b)). First, we perform an equidistant curve re-sampling [13] to match the number of points on the sketch to the initial control section of the sweep surface. Subsequently, we determine if the orientation of the curve is the same as that of the initial control section. This involves the comparison between the signs of the areas enclosed by the sketched curve and the initial section. If the initial and sketched sections have opposite orientations, we correct the sketch orientation by reversing the order of vertices in the re-sampled sketch input. Finally, we minimize the twist between the sketch input and the initial section [3].

USER EVALUATION

The goals for our study, were to (a) understand how users perceive the interaction workflow embodied by *MobiSweep*, and (b) explore and characterize user ideation and creation enabled our system.

Participants

We recruited a total of 14 (11 male, 3 female) participants in the range of 19 – 40 years. Our user population consisted of 9 mechanical engineering students (with 1 user with expertise in CAD and design practices) and 5 students from other fields including engineering, liberal arts, and sciences. All participants were dominantly right handed and owned a smartphone.

Procedure

The length of the study varied between 60 to 75 minutes. In the beginning of the study, each participant was given a verbal description of the setup, the purpose of the study and functionality of the *MobiSweep* application. Each participant was taken through a guided composition process wherein the participant used *MobiSweep* to create an abstract tree concept. The goal was to introduce the participants with features and constraints of the system in an organized manner. During this phase, the participants were encouraged to think-aloud, ask questions and were provided guidance when required.

After the practice session, each participant was given 1 among 3 pre-determined product contexts (tea-kettles, jars, lamps). The task was to generate as many concepts as possible in a fixed time duration of 15 minutes. Once the participant was satisfied with a composition, they would clear the virtual environment and start with a new composition. Although the duration of time was fixed, we allowed the users to complete their last composition that was started before the end of the specified duration. Finally, the participants were asked to complete an online questionnaire for evaluating: (a) effectiveness of interactions and gestures and (b) the usefulness of *MobiSweep* towards ideation and creation activities in early design. For assessing the usefulness of *MobiSweep* for design ideation, we used the creativity support index [4].

Results

We found that almost all users were able to rapidly generate ideas in the product contexts provided to them (Figure 5). With an average practice time of 19 minutes (min: 11, max: 30), users generated between 3 to 4 (min: 1, max: 6) concepts within an average ideation time of 15.7 minutes (min: 6, max: 21). Typically, each concept comprised of at least 2 and at most 4 parts (sweep surfaces). As expected, the number of concepts reduced for compositions with more geometric detail at the part level. In the context of these results, we will discuss our observations and users' feedback regarding interactions, creative support, and perceived utility of *MobiSweep*.

Interactions

A significant majority of the ratings were positive across interaction types and workflow states (Figure 6). The two main problems users faced were (a) manipulation of a shape/part (**S3**) using the offsetting operation with one finger press and (b) controlling the reference plane orientation (**S1**). Interestingly,

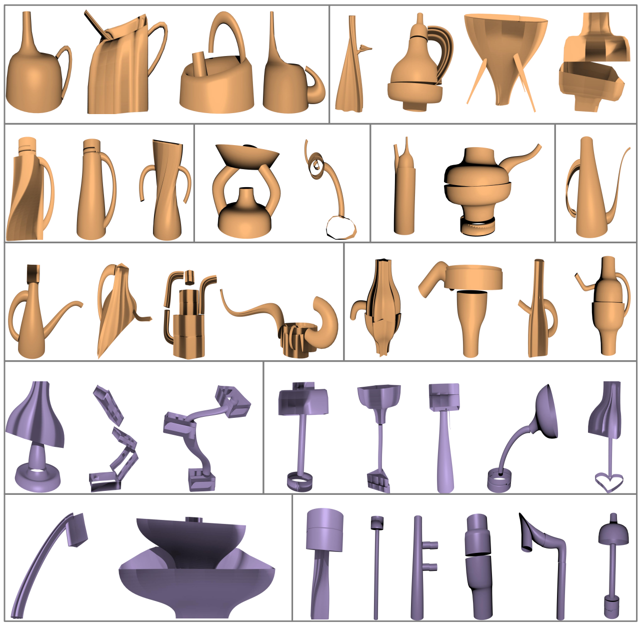

Figure 5. Design concepts generated by the users are shown (kettles and jars are shown in the top three rows and lamps in the bottom two rows). Each box represents concepts generated by one user.

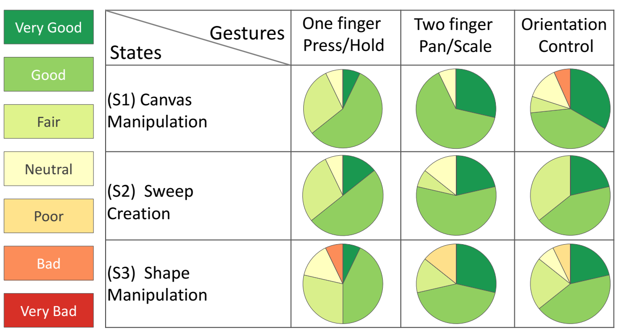

Figure 6. User feedback for interaction ratings in the context of the work-flow states.

many users actually moved their hands along the trajectory of a sweep surface during shape authoring despite having the knowledge regarding the lack of explicit position tracking. One user commented: *"I felt 3D objects [were] alive while I was sweeping and manipulating them."* This corroborates the proprioceptive nature of these activities, making the case for spatio-kinesthetic awareness for mapping spatial motion of smartphone-based controllers for 3D shape creation.

For the reference plane offset operation, we asked users to compare the one finger press, with the three finger scale on ease of use, physical comfort, intuitiveness, and controllability. All but three users indicated that the three finger press was better in terms of controllability. However, we found no significant preference towards ease-of-use, physical comfort, or intuitiveness. Users commented that the three finger pinch was more controlled, however it took some practice to understand how to apply the gesture correctly. They also perceived the one finger press as simple and natural, but only controllable in one direction (upwards). This is a useful insight that could

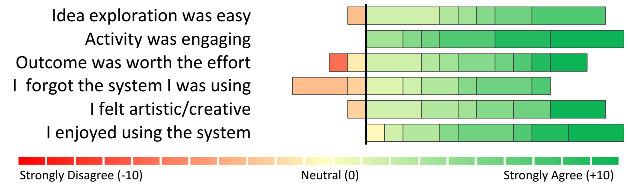

Figure 7. User feedback for creativity support in *MobiSweep*.

be used to improve the offset operation by introducing auto-rotation features based on the ergonomics of wrist movements in one-handed manipulations.

Users found the sketching mode to be an intuitive and direct method for specifying cross-sections. A user commented: "*Section sketching granted me quite a lot of flexibility in producing the desired shapes. I also found that section sketching allows me to select even the end sketch giving even more flexibility*" The default circular section was also considered useful by users. One user pointed out that *"Having the circle as a default was very helpful, as more often than not, I wanted a circular cross-section. When I didn't need a circle, I felt it was simpler to just sketch the shape. Having other options (polygon selection, for instance), may have been annoying."*

One of the main observations we made was the split visual attention between the smartphone and the computer screen displaying the virtual environment. The maximum switching of gaze between the phone and screen occurred during the modification of the sweep section. This was expected since drawing the curve necessitated looking at the phone while verifying the resulting change in the swept surface required looking at the screen. We also observed significant shifting of gaze at the beginning of shape creation task and was generally true for activities that required the use of the smartphone menu. On the other hand, the shifting of gaze was less pronounced during the creation of sweep and modification tasks such as scaling, panning, bending, and twisting.

Creative Support

A large majority of users responded favorably in terms of the exploration capability, expressiveness, engagement, and enjoyment provided by *MobiSweep* (Figure 7). In particular, the user feedback strongly validated our primary goal – quick design ideation in 3D space. As a user pointed out: *"Quickly sampling ideas in 3D shortens the discussion on any subject that requires a solution and closes the gap between individuals who can't explain what they see in their heads and individuals who can't visualize what is explained to them. Normally such discussions would end with - I'll have to show you later."* In context of quick ideation, another user stated: "*This tool can be very useful for people who are afraid to make mistakes and can also help people to formulate spatial perceptions.* "

Utility

Users confirmed *MobiSweep's* utility in real design problems in individual and team settings. In particular, users with mechanical engineering and design experience found such a tool particularly useful in the context of their design projects. One user commented: "*I can see myself using this tool for a quick mock-up of ideas, something to do right after the sketching* *stage. Assuming that a future version of the system will allow me to navigate my creation in 3D (instead of offering a single-port view as it does currently), I would be able to use this to mock up an idea in 3D to discuss issues like space, access, scale etc. with my team.*". Most participants with prior design experience perceived our system as a useful mode of coarse design followed by fine refinement using a professional CAD tool. One user with expertise in CAD and professional engineering design experience stated: "*I can see a multi-user scenario of this system, where you can perform 3D modeling versions of the C-sketch or Gallery methods of ideation. It would make for a fun activity, with each user using their own device to move between ideas and interact with shapes.*"

Limitations

One user who was focused on precise manipulations, mentioned: "*[it is] hard to keep a steady orientation when manipulating*". We believe this can be rectified using simple measures such as smoothing the smartphone orientation data and snapping the reference plane orientation along primary axes. Another user mentioned that: "*depth is so hard to perceive on screen.*". Improving visual feedback and allowing view manipulation would allow for better assembly of shapes. The use of cubic-hermites in our implementation constrains the control of the spine of the sweep surface. Our early experiments showed that this was a necessary constraint to achieve controllability while maintaining reasonable design flexibility. Extending our interactions for piecewise will help improve the expressiveness of ideation at the part level. Our indirect multi-touch control for 3D translations provided low-fatigue interaction and was effective in terms of controllability. Although users commented that 3D position tracking will improve the their efficiency in translation, their primary reason was the repetitive nature of the two-finger panning while moving long distances rather than unintuitive interaction design. One user commented on the offsetting gesture: *"I would still prefer on occasion to use the single tap for coarse movement, and the three-finger touch for fine movement."* This strongly indicates that the allowing users to customize interaction parameters such as the offsetting speed and panning sensitivity will significantly improve user performance in 3D translation allowing for both coarse and fine translations. Finally, the addition of two-sided tactile modalities demonstrated by Stewart et al. [26] could significantly reduce the split in visual attention by providing secondary feedback to users.

DISCUSSION

The primary motivation behind *MobiSweep* was to adapt existing parametric geometry representations in a design ideation work-flow using mobile spatial interactions. In this respect, the creative outcomes, observations, and feedback from our user evaluations make a strong case in favor of the underlying reference plane metaphor presented in our work-flow. Fundamentally, there are two aspects of the metaphor that played a central role: the offsetting operation and the sketching modality. Even though it is theoretically possible to span the whole 3D space using in-plane panning in conjunction with the orientation (free-plane casting [10]), the offsetting interaction turned out to be a critical aspect in enabling the direct connection between the physical action of sweeping and the creation of a sweep surface. Second, enabling users to provide sketch inputs for 2D curve creation proved to be equally essential for allowing them to specify and modify the shape directly on the desired location. Extending these arguments, the main aspect of our work was the combination of two fundamental interactions pertinent to geometric design: sketching and spatial configuration. Sketch-based 3D modeling has been extensively investigated for early phase design due to its accessibility and natural interface [19]. However, the two-dimensionality of the interactions involved in sketching interfaces necessitates additional interactions to achieve a complete 3D modeling work-flow. We believe that the combination of reference plane interactions with sketch-based modeling is a simple but powerful idea that could lead to several new design work-flows.

FUTURE DIRECTIONS AND CONCLUSIONS

We explored an embodied approach for spatial design ideation through a sweep-based shape composition work-flow using a smartphone. At its core, *MobiSweep* allowed for two important geometric modeling interactions: rigid transformations and curve creation (both 2D and 3D). Our goal in the immediate future is to perform a quantitative evaluation of the reference plane metaphor for these three operations. In particular we want to understand how user perception and performance changes for manipulation tasks with and without the offsetting operation. We will also study how experience, performance, and creative outcomes will change with respect different user groups such as artists, engineering designers, and young participants. Finally, it will be interesting to see how the interactions behind *MobiSweep* could be extended to animation and analysis scenarios (e.g. kinematics simulations, stress analysis) in educational and collaborative settings. *MobiSweep* revealed an untapped design space that emerged from the combination of M-SUI and CAD towards novel work-flows for creative shape conceptualization in early phase design.

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