User-Elicited Surface and Motion Gestures for Object Manipulation in Mobile Augmented Reality

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Recent advancements in mobile and AR technology can facilitate powerful and practical solutions for six degrees of freedom (6DOF) manipulation of 3D objects on mobile devices. However, existing 6DOF manipulation research typically focuses on surface gestures, relying on widgets for modal interaction to segment manipulations and degrees of freedom at the cost of efficiency and intuitiveness. In this paper, we explore a combination of surface and motion gestures to present an implicit modal interaction method for 6DOF manipulation of 3D objects in Mobile Augmented Reality (MAR). We conducted a guessability study that focused on key object manipulations, resulting in a set of user-defined motion and surface gestures. Our results indicate that user-defined gestures both have reasonable degrees of agreement whilst also being easy to use. Additionally, we present a prototype system that makes use of a consensus set of gestures that leverage user mobility for manipulating virtual objects in MAR.

CCS Concepts: • **Human-centered computing → Mixed / augmented reality**; **Interaction techniques**; *HCI theory, concepts and models.*

Additional Key Words and Phrases: Mobile Computing; Augmented Reality; Interaction Techniques; Gesture Elicitation

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1 INTRODUCTION

Interaction with virtual content in Mobile Augmented Reality (MAR) [7] is commonly achieved using surface gestures, as seen in many commercial applications. These existing MAR interaction techniques for manipulating virtual objects often vary in design and level of control. Specifically, prior work developed 6DOF manipulation methods using only 2D surface gestures [13], however these require the use of complex multi-finger gestures, and fail to utilise the inherent 3D spatial component of AR; limiting all interactions to a 2D surface, resulting in more complex and less engaging interactions [15, 18]. Other work proposed hybrid interaction techniques, such as combining both surface and motion gestures [9, 18, 24] to simplify more complex interactions in 3D space. Notably, these interaction techniques require the use of on-screen widgets to switch between different manipulations [24], or do not support 6DOF manipulations [9, 14]. Additionally, there are few mechanisms to support both large manipulations of virtual objects (room-scale) and precise manipulations, such as aligning objects[10]. Considering this, is it possible to design a non-widget 6DOF interaction system supporting both precise and coarse manipulations in MAR? Our paper contributes: (i) an elicitation

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study investigating small and large object manipulation in MAR, (ii) a consensus set of user-defined surface and motion gestures, (iii) an example interaction technique based on our results, and (iv) directions for future work. Our example technique incorporates user mobility and positioning to enable 6DOF object manipulation. We conclude that surface and motion gestures can be combined in different ways for both precise and coarse manipulations, and that user mobility can act as an implicit indicator for degrees of freedom separation.

2 RELATED WORK

2.1 Mobile AR Interaction

Due to AR's popularity, much research has been conducted into object manipulation techniques. Several previous mobile AR works have attempted to leverage mid-air hand gestures as both a standalone input method [2, 6] and combined with touch gestures [3, 16] to support 6DOF object manipulation. These novel input methods often created engaging interactions, but suffered notable limitations in the accuracy and reliability of the mid-air hand gestures. Hürst et al. [14, 15] looked at alternative concepts for MAR input, comparing surface and motion gestures, with their results suggesting that a hybrid input method utilising both multi-touch gestures and device movement would be optimal for engagement and performance.

2.2 Surface and Motion Gestures

The use of both surface and motion gestures has been extensively explored [12, 17, 28, 31]. Work such as Ruiz et al.'s motion gesture guessability study [26] and Bragdon et al.'s analysis of surface gestures [4], examined these input methods on mobile devices. More recent work, looked at combining surface and motion gestures for mobile devices, such as Marzo et al. [23] studying the performance of surface, motion, and hybrid gestures for 6DOF manipulations in MAR concluding that the hybrid interaction was the quickest for users. Interestingly, the hybrid system used surface and motion gestures for separate tasks, and did not examine if using them in tandem would have yielded better results. Mossel et al. [24] explored this gap and developed two interaction systems: 3DTouch, which relied on the device pose and a surface gesture for input; and HOMER-S, which directly maps the device pose and movement to the object. Our work distinguishes itself from Mossel et al.'s [24], by attempting to observe when users find value in, and employ these techniques, as well as integrating these modalities into a single interaction technique for object manipulation for varying levels of precision. More recently, Dong et al. [9] elicited user-defined surface and motion gestures for 3D object manipulation in MAR, observing that users found surface gestures easier to use, but motion gestures more engaging as they provided finer control in 3D space. They proposed the Touch-Move-Release (TMR) technique, combining surface and motion gestures into one interaction system. Our study differs from this work, as not only does our proposed system support 6DOF manipulation, but instead of eliciting two explicit gesture sets, surface and motion, we explicitly follow open elicitation, with participants choosing to design a surface, motion, or hybrid gesture.

2.3 3D Object Manipulation on a 2D Surface

Interacting with 3D objects on a 2D surface has proven to be a difficult challenge to solve, with many interaction methods being proposed [1, 21, 22]. Hancock et al. [13] proposed 6DOF manipulations of 3D objects using 3-fingered surface gestures. However, not only do these techniques require undesirable complex multi-fingered surface gestures, but they also require specialist hardware, making it unsuitable for use on common smartphones. Notably, Buchanan et al. [5] found that users instinctively prefer familiar surface gestures for object manipulation, while other work has called for alternate gestures to be designed for mobile devices [8, 11, 27]. Liu et al. [20] compared a simple two-finger surface gesture against other existing multi-finger interactions [13], and found their technique to be more effective on mobile devices, suggesting that simpler surface gestures are optimal for object manipulation. However, none of these previously designed techniques are designed for MAR. Our work aims to combine the insights of surface-based object manipulation with the spatial mobility enabled by MAR to allow 6DOF manipulations at varying levels of precision.

3 GESTURE ELICITATION STUDY

We follow previous elicitation methodology [9, 18, 25, 31] to collect user-elicited motion and surface gestures for 3D object manipulation on smartphones. Specifically, we follow an open elicitation methodology where participants are unrestricted on the design of the gestures. Our elicitation focusses on 4DOF gestures as we intended to combine the elicited gestures with user's spatial mobility to enable degrees of freedom separation for manipulations, ultimately allowing for 6DOF interactions.

3.1 Participants, Apparatus, and Tasks

A total of 8 participants were recruited for the study, 3 identified as female and 5 as male, all were over 18 with an average age of 27.75 ($\sigma = 12.6$). 6 participants were right-handed and 2 were left-handed and all ranged in ability and experience with both mobile games and AR applications. The experiment used a custom Unity application running the ARFoundation API. We recorded users' touchscreen input data, users' subjective gesture ratings, and their responses to semi-structured interview questions. Our study differs from previous research [9, 18, 26, 31], as participants used their own devices instead of using a device provided by the experimenter (for a total of 6 unique devices). This ensured that gestures were not influenced by participant's lack of experience with a device, and avoided bias to one particular device/device-size, which Liang et al. noted as a possible limitation in single device studies [18].

Participants were instructed to design gestures for a total of 6 manipulation tasks (Table 1). For the tasks, we surveyed some of the most common object manipulations within popular mobile AR applications and also adapted tasks included in previous research [9, 18, 19, 25, 31]. While we focus on 4DOF manipulations for elicitation, our rotational tasks omits the z axis as we intended to use spatial movement as a means to separate degrees of freedom in the final prototype. Omitting the z-axis was also done by Liang et al.'s study [18] and we intended for participants to use the same gesture for manipulations on the z-axis and so focused on *vertical* and *horizontal* rotations/translations. Both translation and rotation tasks were separated into two types: *small* and *large* manipulations. *Small* translations defined by the target being visible from the user's starting position, and *small* rotations defined as a 45°rotation. *Large* translations defined by the target being outside the device's field of view, described and contextualised to participants as moving a virtual object to the 'other side of the room'. *Large* rotation tasks were defined as a 180°rotation.

Category	Sub-Category	Task Name
Manipulation	Translation	Short distance (Within device FoV)
		Large distance (Outside device FoV)
	Rotation	Large vertical axis rotation (180°)
		Small horizontal axis rotation (45°)
	Scale	Uniform scale (2x larger)
	Mixed	Move a short distance, rotate horizontally a small amount, and scale uniformly

Table 1. The list of tasks grouped by sub-category

3.2 Procedure

Our study follows a similar procedure outlined in previous work [9, 18, 25, 31], with each participant designing and performing a gesture for each task in Table 1. Participants were instructed to design a gesture they felt best suited the task using either a surface gesture, a motion gesture, or a gesture which utilised them both. For each task participants were presented with a textual description of the manipulation and a 3D animation demonstrating the effect. Participants were encouraged to vocalise their gesture design process and were also free to move the device and themselves. Once participants arrived at a gesture they were satisfied with, they performed this gesture in view of a video camera. All participants were asked to rate the gestures they designed on two 7-point Likert scales for both *goodness* (which was conveyed as how suitable participants felt their gesture was for its intended purpose), and *ease of use*. A semi-structured interview was conducted post hoc, allowing participants to provide additional insight into their gesture designs. Participants were advised to disregard any potential input recognition issues and conflicting gestures across tasks. Notably, due to COVID-19 restrictions, our study was conducted in two phases with the first being in-person (5 participants) and the second being completed online over a video call (with the remaining 3 participants). To ensure consistency across the two phases, the only difference in procedure was remote participants were instructed to perform gestures in front of a webcam, rather than the experimenter recording the gesture. We believe this difference had a negligible impact on the remote participant's gesture design.

4 RESULTS

The elicitation study produced a total of 48 gestures across the 6 tasks. To construct the final user-defined gesture set of 9 unique gestures, the *consensus set* [30], we grouped *similar gestures* [25] together and chose the largest group for each task. We define *similar gestures* as gestures that consist of the same basic motion and are classified the same in our taxonomy. Our *open elicitation* method produced a number of repeated/conflicting gestures, which were assigned based on the frequency they were performed [31]. For conflicting gestures that were performed the same amount in two different tasks, we then considered the average 'goodness' and 'ease of use' ratings and assigned gestures to manipulations for which they were scored the highest. This resulted in small translation being assigned its second most popular gesture (which used two fingers). We also included large translation's second most popular gesture for the consensus set (which also used two fingers), to help increase the distinctiveness of translation and rotation gestures (rotation, one-finger; translation, two-fingers). This reflects previous works which also included additional gestures to improve the consistency and distinctiveness of various manipulations [9, 18, 25].

4.1 Taxonomy of Gestures

Wobbrock et al.'s [31] four-dimensional taxonomy was adapted to examine the characteristics of the gesture set. Removing the metaphorical and world-independent categories, as no gestures of these types were observed, whilst adding the screen-dependent category in the binding dimension, and adding Buchanan et al.'s [5] proxy gestures as a category in the nature dimension, as participants were frequently observed using both. A total of 48 gestures were recorded and classified using the taxonomy, producing a set of 16 *similar* gestures.

4.1.1 Level of Agreement. To evaluate the level of consensus amongst participants an agreement score was calculated for each task using Equation 1 defined by Vatavu et al. [29]. Where AR is the agreement rate of an individual gesture (r) between 0 and 1, P is the total amount of gestures performed within task, and P_s is a subset of P that contains *similar* gestures. Whilst the agreement scores for some tasks were middling, particularly for *large rotation* (35.7%) and *small*

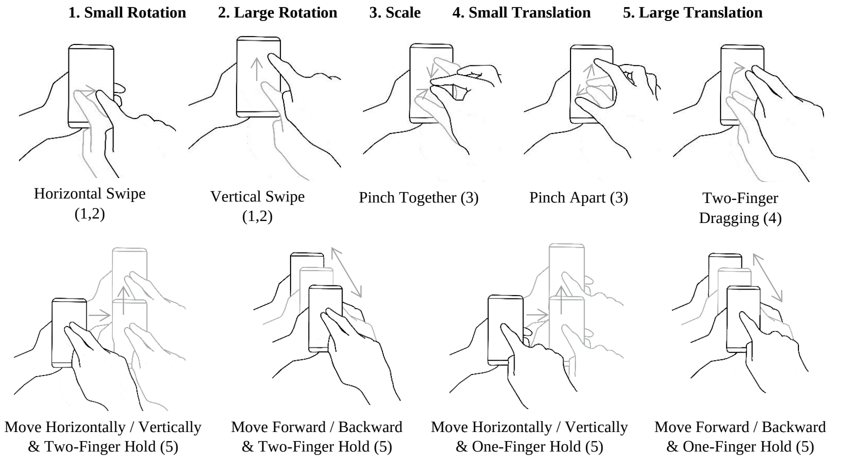


Fig. 1. Consensus set of user-defined surface and motion gestures, the gestures depicted are an example set of *similar* gestures. The diagrams for large translation demonstrate different ways the motion gesture can be applied, but are all classified as one gesture.

translation (25.0%), individual gestures often had high agreement scores that spanned multiple tasks, for instance a 1-finger swipe accounted for 62.5% of all small translation gestures.

$$AR(r) = \frac{|P|}{|P|-1} \sum_{P_s \subseteq P} \left(\frac{|P_s|}{|P|} \right)^2 - \frac{1}{|P|-1} \quad (1)$$

4.1.2 Characteristics of the Consensus Set. Our consensus set (Figure 1) primarily consists of *legacy* surface gestures, with gestures also exhibiting both a high degree of consistency and reversibility [31]. Consensus set gestures are unanimously continuous, predominately physical (83.3%) and object-centric (66.7%), and most commonly being one-point path (33.3%); With the *swiping*, *holding*, and *pinching* surface gesture primitives accounting for 66.6% of consensus set gestures and 100% of the surface gestures. Interestingly users applied, without prior knowledge, Dong et al.'s TMR motion gesture technique [9] for large translation tasks, suggesting that the TMR technique is somewhat intuitive.

4.1.3 Subjective Ratings of the Consensus Set. Participants were asked to rate their gestures using 7-point Likert scales for both 'goodness' and 'ease-of-use', producing ratings of 6.27 and 6.54 respectively in the consensus set and 5.93 and 6.60 in the discarded set. The discrepancy in the 'ease-of-use' rating between the consensus and discarded set is not wholly unexpected, as the need to eliminate conflicting gestures meant that more difficult gestures were included in place of conflicting gestures. Both 'goodness' and 'ease-of-use' scores were predominantly rated the same by the participants, however participants favoured designing gestures that were *easy* to perform, rather than those they felt best matched the manipulation. Specifically, participants felt 'uncomfortable' using gestures that did not rely on familiar gesture primitives, even if more complex gestures could offer finer control. Individual gestures with high agreement were rated highly by participants particularly familiar 1 finger gestures, i.e. *swiping* and *dragging* gestures. However, agreement scores did not necessarily correlate with the ratings of the gestures designed for the task. For instance, large rotation had the highest average 'goodness' and 'ease-of-use' scores (at 6.5 and 6.75 respectively), despite being the task with the lowest agreement score. Interestingly, the only hybrid gesture (large translation), produced the lowest average ratings for both 'goodness' and 'ease-of-use' (5.625 and 6 respectively), suggesting that surface gestures were preferable to motion or hybrid gestures.

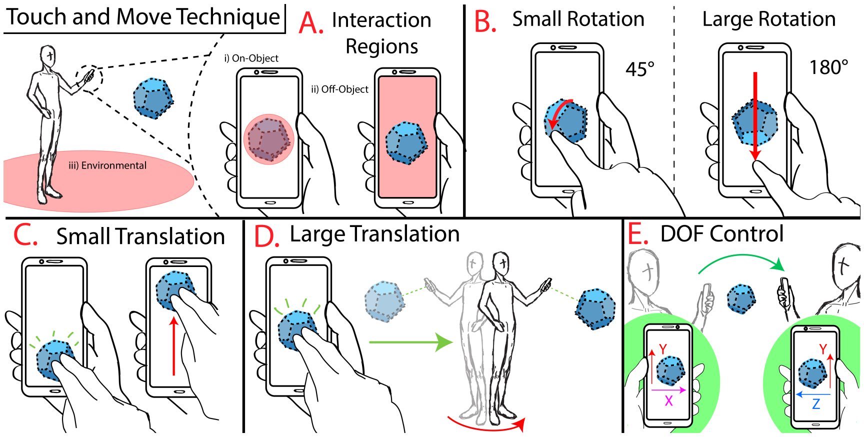


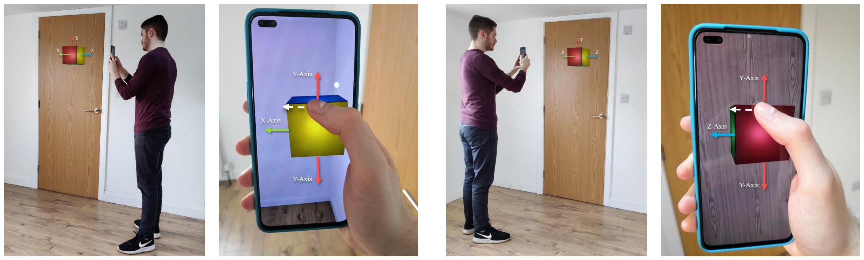
Fig. 2. Our proposed interaction technique. *A)* 3 regions of interaction, *B)* large and small rotational interaction, *C)* small and *D)* large translational interaction, and *E)* DOF separation via user mobility.

5 TECHNIQUES

To explore the effectiveness of the consensus set, we developed a MAR interaction technique combining the user-defined consensus set gestures and our proposed implicit spatial modality allowing users to rotate, translate, and scale a virtual model. As previously discussed, the large translation gesture in our consensus set made use of Dong et al.'s [9] TMR technique, and as such we built upon Dong et al.'s work [9] by implementing TMR into our interaction system. Furthermore, by taking inspiration from Liang et al. [18], we mapped the interaction space into three regions: *on-object*, *off-object*, and *environment* (Figure 2). However unlike Liang et al., our *environment* region represents the mobility of the user in the AR space. In this case, the confluence of regions and our consensus set allows users to change the precision of a manipulation 'on-the-fly', depending on the locale of the surface gesture or the users position and device movement. For example, gestures performed in the *environment* region result in a less precise/coarser manipulations than gestures performed in the *on-object* region. To facilitate 6DOF manipulation, we implemented an implicit spatial modality by comparing the orientation of an object to the user's device. This orientation determines which axes the user can manipulate the object on at a given time, e.g. X and Y, akin to 3DTouch [24]. By doing so, this allows the user's position to act as a marker for the separation of the degrees of freedom (Figure 3), with the manipulable axes reflecting what the user perceives as the 'vertical' and 'horizontal' axes. To change the manipulable axes, the user must physically move around the virtual object which ensures that gestures can be repeated across different axes reducing the number of distinct gestures in the technique.

6 DISCUSSION

The elicited surface gestures were primarily comprised of *legacy* gestures, mirroring those found in previous works [9, 18], with the common gesture primitives of *swiping*, *dragging*, *pinching*, and *holding* accounting for all of the surface gestures in consensus set. However, the prevalence of minor gesture variations such as using a pinch or a two-thumb gesture for scaling, illustrates that users apply these primitives in slightly different ways. Similar to Liang et al. [18] findings, our participants were reluctant to design gestures that were complex in nature or that did not rely on one of the common surface gesture primitives - favouring familiar 1-finger gestures. Participants combined surface and motion gestures when manipulations were beyond the device field of view, e.g. *large translation* gestures where simple



(1) Translate along X or Y axis

(2) Translate along Z or Y axis

Fig. 3. Example of the implicit spatial modality technique showing the user's position in relation to the object. Image (1) and (2) show the available manipulation axes from the user's POV. Moving the finger left/right in (1), leads to a translation on the x-axis, whereas moving the finger left/right in (2) leads to a translation along the z-axis.

surface gestures (*holding*) were coupled with motion (the object following the device's movement). Additionally, hybrid gestures can simplify surface interactions, by leveraging the device position to reduce the number and complexity of gestures required for 6DOF manipulation. When considering precise manipulations, we found that users employed more surface gestures for small movements and more motion gestures for large movements. Both surface and motion were utilised in varying amounts depending on the task and precision required. Our interaction technique supports 6DOF manipulations, unlike Dong et al. [9], contains fewer gestures than traditional 6DOF interaction techniques [13, 22], and due to the non-conflicting nature of our consensus set, does not require the use of UI widgets present in other techniques [24]. Additionally, we enhanced components of both the TMR [9] and 3DTouch [24] techniques, by utilising user mobility as an implicit spatial modality which can offer a more engaging experience [9, 15]. Moreover, we reinforce Dong et al.'s [9] and Mossel et al.'s findings through our user elicitation, as participants reproduced TMR gestures. Finally, we successfully integrate components of 3DTouch with TMR [9] and combine with other techniques found through elicitation to produce a novel interaction technique.

6.1 Limitations and Future Work

A clear avenue for future work is to further consolidate our consensus set with more participants. Additionally, several conflicting gestures were produced resulting in replacement gestures with lower 'goodness' and 'ease-of-use' ratings being used in the proposed interaction technique. Future work could follow *closed elicitation* [25] to eliminate conflicting gestures or yield additional gestures which could prove to be more effective than the current replacement gestures. While we assert that our interaction technique could perform better than pre-existing techniques, a clear next step is to evaluate this hypothesis through a comparative evaluation. Specifically comparing against previous work such as 3D-Touch [24] and popular commercial MAR interaction methods.

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