ENHANCED DEVICE-BASED 3D OBJECT MANIPULATION TECHNIQUE FOR HANDHELD MOBILE AUGMENTED REALITY

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DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

3D object manipulation is one of the most important tasks for handheld mobile Augmented Reality (AR) towards its practical potential, especially for real-world assembly support. In this context, techniques used to manipulate 3D object is an important research area. Therefore, this study developed an improved device-based interaction technique within handheld mobile AR interfaces to solve the large-range 3D object rotation problem as well as issues related to 3D object position and orientation deviations in manipulating 3D object. The research firstly enhanced the existing device-based 3D object rotation technique with an innovative control structure that utilizes the handheld mobile device tilting and skewing amplitudes to determine the rotation axes and directions of the 3D object. Whenever the device is tilted or skewed exceeding the threshold values of the amplitudes, the 3D object rotation will start continuously with a pre-defined angular speed per second to prevent over-rotation of the handheld mobile device. This over-rotation is a common occurrence when using the existing technique to perform large-range 3D object rotations. The problem of over-rotation of the handheld mobile device needs to be solved since it causes a 3D object registration error and a 3D object display issue where the 3D object does not appear consistent within the user's range of view. Secondly, restructuring the existing device-based 3D object manipulation technique was done by separating the degrees of freedom (DOF) of the 3D object translation and rotation to prevent the 3D object position and orientation deviations caused by the DOF integration that utilizes the same control structure for both tasks. Next, an improved device-based interaction technique, with better performance on task completion time for 3D object rotation unilaterally and 3D object manipulation comprehensively within handheld mobile AR interfaces was developed. A pilot test was carried out before other main tests to determine several pre-defined values designed in the control structure of the proposed 3D object rotation technique. A series of 3D object rotation and manipulation tasks was designed and developed as separate experimental tasks to benchmark both the proposed 3D object rotation and manipulation techniques with existing ones on task completion time (s). Two different groups of participants aged 19-24 years old were selected for both experiments, with each group consisting sixteen participants. Each participant had to complete twelve trials, which came to a total 192 trials per experiment for all the participants. Repeated measure analysis was used to analyze the data. The results obtained have statistically proven that the developed 3D object rotation technique markedly outpaced existing technique with significant shorter task completion times of 2.04s shorter on easy tasks and 3.09s shorter on hard tasks after comparing the mean times upon all successful trials. On the other hand, for the failed trials, the 3D object rotation technique was 4.99% more accurate on easy tasks and 1.78% more accurate on hard tasks in comparison to the existing technique. Similar results were also extended to 3D object manipulation tasks with an overall 9.529s significant shorter task completion time of the proposed manipulation technique as compared to the existing technique. Based on the findings, an improved device-based interaction technique has been successfully developed to address the insufficient functionalities of the current technique.

ABSTRAK

Manipulasi objek 3D merupakan salah satu tugas yang paling penting untuk augmentasi reality (AR) mudah alih terhadap potensi praktikalnya terutamanya untuk menyokong bidang pemasangan. Dalam konteks ini, teknik yang digunakan untuk memanipulasi objek 3D merupakan bidang kajian yang penting. Oleh itu, kajian ini mencadangkan teknik interaksi berasaskan peranti diperbaiki dalam antara muka AR mudah alih. Dua isu utama yang melibatkan masalah putaran objek 3D julat besar serta sisihan posisi dan orientasi objek 3D ditangani dalam kajian ini. Pertama, masalah putaran objek 3D julat besar melibatkan putaran lampau yang menyebabkan ralat pendaftaran objek 3D dan objek pada skrin yang kelihatan tidak konsisten dengan julat pandangan pengguna. Untuk menghalang putaran lampau, teknik putaran objek 3D dipertingkatkan dengan struktur kawalan inovatif yang menggunakan amplitud kecondongan dan kepencongan peranti untuk menentukan paksi dan arah putaran objek. Apabila peranti dicondongkan atau dipencongkan dengan melebihi nilai ambang amplitud, putaran objek 3D dimulakan secara berterusan dengan kelajuan sudut pratakrif per saat. Kedua, sisihan posisi dan orientasi objek 3D ditangani dengan mengasingkan darjah kebebasan (DOF) translasi dan putaran objek 3D. Seterusnya, teknik interaksi berasaskan peranti diperbaiki dengan prestasi yang lebih baik untuk masa penyempurnaan tugas bagi putaran objek 3D secara sepihak dan manipulasi objek 3D secara menyeluruh dalam antara muka AR peranti mudah alih juga dicadangkan. Ujian rintis dijalankan untuk menentukan beberapa nilai pratakrif dalam struktur kawalan teknik putaran objek 3D yang dicadangkan sebelum ujian utama yang lain dilaksanakan. Selanjutnya, sekumpulan tugas putaran dan manipulasi objek 3D direka khas dan dibangunkan sebagai dua eksperimen berasingan untuk menilai teknik putaran dan manipulasi objek 3D yang dicadangkan berbanding dengan teknik sedia ada untuk masa penyempurnaan tugas (s). Dua kumpulan berbeza yang terdiri daripada peserta yang berumur di antara 19 hingga 24 tahun telah dipilih untuk kedua-dua eksperimen dengan setiap kumpulan mempunyai enam belas peserta. Setiap peserta perlu melengkapkan sebanyak dua belas kali percubaan dengan jumlah keseluruhan sebanyak 192 percubaan bagi setiap eksperimen. Data telah dianalisa dengan menggunakan analisis sukatan berulang. Berdasarkan dapatan kajian secara statistik, membuktikan teknik objek 3D yang dicadangkan dengan ketara melebihi teknik sedia ada dengan masa penyempurnaan tugas yang lebih pendek dan signifikan iaitu 2.04s lebih pendek masanya pada tugasan mudah dan 3.09s lebih pendek masanya pada tugasan sukar selepas pengiraan masa purata ke atas semua percubaan yang berjaya. Sementara untuk cubaan yang gagal, teknik yang dicadangkan juga mencapai kejituan yang lebih tinggi dengan capaian 4.99% lebih jitu ke atas tugasan mudah dan 1.78% lebih jitu ke atas tugasan sukar berbanding dengan teknik sedia ada. Keputusan yang serupa juga dipanjangkan ke teknik manipulasi objek 3D yang dicadangkan dengan capaian 9.529s masa yang lebih pendek dan signifikan berbanding dengan teknik sedia ada ke atas semua tugasan secara menyeluruh. Berdasarkan dapatan kajian, teknik interaksi berasaskan peranti yang diperbaiki ini berjaya dibangunkan untuk menangani fungsi teknik semasa yang tidak mencukupi.

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LIST OF ABBREVIATIONS

3D	-	3 Dimension
2D	-	2 Dimension
AR	-	Augmented Reality
DOF	-	Degree of Freedom
HCI	-	Human-Computer Interaction
WIMP	-	Windows-Icons-Menus-Pointing
EMMIE	-	Environment Management for Multiuser Information Environments
UTM	-	Universiti Teknologi Malaysia
HMD	-	Head-Mounted Display
RNT	-	Rotate N Translate
RGB-D	-	Red-Green-Blue-Depth
DBI	-	Device-Based Interaction
MBI	-	Mid-air Gestures-Based Interaction
TBI	-	Touch-Based Interaction
HoldAR	-	Existing Device-based 3D Object Rotation Technique/ Control Structure
TiltAR	-	Proposed Device-based 3D Object Rotation Technique/ Control Structure
DI	-	Existing Device-based 3D Object Manipulation Technique
DS	-	Proposed Device-based 3D Object Manipulation Technique
SDK	-	Software Development Kit
CIF	-	Common Industry Format
ANOVA	-	Analysis of Variance
X	-	Roll Axis
Y	-	Pitch Axis
Z	-	Yaw Axis
cm	-	Centimeter
M	-	Mean
SD	-	Standard Deviation

LIST OF SYMBOLS

%	-	Percentage
$<$	-	Smaller Than
$>$	-	Greater Than
=	-	Equal
+	-	Plus
-	-	Minus
$^\circ$	-	Degree
x	-	Multiply
/	-	Divide
s	-	Second
$\rightarrow$	-	Clockwise Direction
$\leftarrow$	-	Counter-clockwise Direction
R_t	-	Target Rotation Pose
R_i	-	Initial Rotation Pose
R_{DEG}	-	Amount of Rotation Degrees
Q_3	-	Quatile 3
Q_1	-	Quatile 1
max	-	Maximum
min	-	Minimum
$\approx$	-	Closely Equal
p	-	Calculated Probability
Z	-	Calculated Z-score

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Augmented Reality (AR) provides a new way to interact between the physical and virtual world. AR is commonly defined as a combination of real and virtual by registering virtual objects in 3D that run interactively in real-time (Krevelen and Poelman, 2010; Mekni and Lemieux, 2014). Interaction has become the keyword in AR and the main focal point of many research studies on AR.

AR is a new direction and a new concept in the field of Human Computer Interaction (HCI). In any computer system, interaction is always the most important part because it includes the interface where the end-user communicates with the system. Interaction holds similar importance in the field of AR too. Traditionally, HCI was primarily concerned with designing and investigating interfaces between humans and machines (Rekimoto, 2014). According to Rekimoto (2014), AR is the new direction in the HCI field to enhance the ability of humans.

In AR, one of the important aspects is the creation of appropriate interaction techniques for AR-related applications that would allow end users to interact intuitively with virtual contents (Zhou, Duh and Billinghurst, 2008). Wearable inputs and interaction technologies enable a mobile person to work with the augmented world and to further augment the world around them. They also make it possible for an individual to communicate and collaborate with other handheld mobile AR users (Höllerer and Feiner, 2004). As a moiety of HCI, there are several considerations in AR that need to be focused on. As a new notion of interacting with both the physical and the digital world, traditional WIMP metaphors (Windows, Icons, Menus and Pointing) were not suitable anymore in the AR domain (Billinghurst, 2003). AR-based perceptual user interfaces and tangible user interfaces allow the creation of a new generation of interactive experiences.

In AR, interaction can be divided into three (3) major types: 1) tangible user interaction, 2) multimodal input and 3) mobile interaction (Billinghurst, Kato and Poupyrev, 2001). In tangible user interaction, humans can use real objects to interact with digital content. In AR, users should be able to manipulate 3D objects, as the Six Degrees of Freedom (6DOF) are the basic requirements in AR; and traditional input devices such as mice and keyboards are cumbersome to wear and use, and hence reduce the AR experiences (Krevelen and Poelman, 2010). It seems that tangible user interactions will be a possibility in AR applications such as the Digital Desk Project. This project, which can be considered to be a very relevant example of a tangible user interaction experience, is a system which uses computer-vision techniques to track the position of paper documents and the user’s hands on an augmented table (Wellner, 1993). This interaction method has good potential and attempts have been made to use it in various other AR experiences, such as the augmented dining table invented by Mitchell, Papadimitriou, You and Boer (2015), which aims to enhance social dining experiences.

These kinds of tangible interfaces allow for seamless interactions because a single physical device represents each interface function or object, unlike traditional graphical user interfaces or 3D virtual reality interfaces, in which the designer determines most of the interface layout in advance. In this context, AR tangible interfaces, such as Tiles proposed by Poupyrev, Weghorst, Billinghurst and Ichikawa (2002) for example, provide an unrestrained AR experience.

Other than using physical objects to interact with AR content, there are also other input modalities such as the addition of speech and gesture inputs (Billinghurst, Kato and Myojin, 2009). Gesture-based interactions have been widely studied since early 2004, until Buchmann, Violich, Billinghurst and Cockburn invented a gestures-based direct manipulation AR system which used human fingers and hands as markers to interact with 3D objects in AR. A set of user-defined gestures for AR was then proposed by Piumsomboon, Clark, Billinghurst and Cockburn (2013) using knowledge of user preferences and behaviors for gestures in AR.

Multimodal input is another type of AR interaction, which shares a similar meaning with hybrid AR interfaces. Multimodal input refers to the usage of a combination of more than one more of input, such as vision and speech, gesture and speech and so on. These kinds of interactions require the user to change sets of inputs, outputs and even the interaction techniques mutually when involved. In its early stages, Butz, Hollerer, Feiner, MacIntyre and Beshers (1999) introduced EMMIE (Environment Management for Multiuser Information Environments), also referred to as a hybrid interface combining multimodal inputs such as 3D widgets and physical objects. In 2005, Sandor, Olwal, Bell and Feiner (2005) proposed another hybrid user interface in AR, where an AR overlay was presented on a head-tracked, see-through, head-worn display that provided overlaid visual and auditory feedback. Recently in 2015, Ismail, Billinghurst and Sunar reviewed multimodal interactions in the AR system that can be divided as: 1) gesture recognition, 2) facial recognition and 3) speech recognition.

Recently, the research trend, even for AR technologies, has shifted from desktop computing to mobile computing. Handheld mobile devices have become the growing platform to be implemented with AR technology. The popularity and mobility of handheld mobile devices, usually smartphones, can be used as a potential platform to bring AR technology into the mass market. Thus, handheld mobile interaction becomes another focus in AR. Figure 1.1 represents the research area. The final focus area is shown, along with all open issues in AR.

In studying AR for handheld mobile devices, several important differences have been noted between using a handheld mobile device's interface and a traditional desktop interface. These include: 1) limited input options (no mouse or keyboard), 2) limited screen size (Billinghurst et al, 2009) and 3) limited activity time due to the limited battery capacities of handheld mobile devices. Meanwhile, compared to a traditional head-mounted display-based AR system, the display and input devices in handheld mobile AR are connected. This means that interface metaphors developed for desktop and head-mounted display-based systems may not be appropriate in the context of handheld mobile devices (Billinghurst et al, 2009). These apparent differences derived from different interaction techniques concentrated on handheld mobile AR.

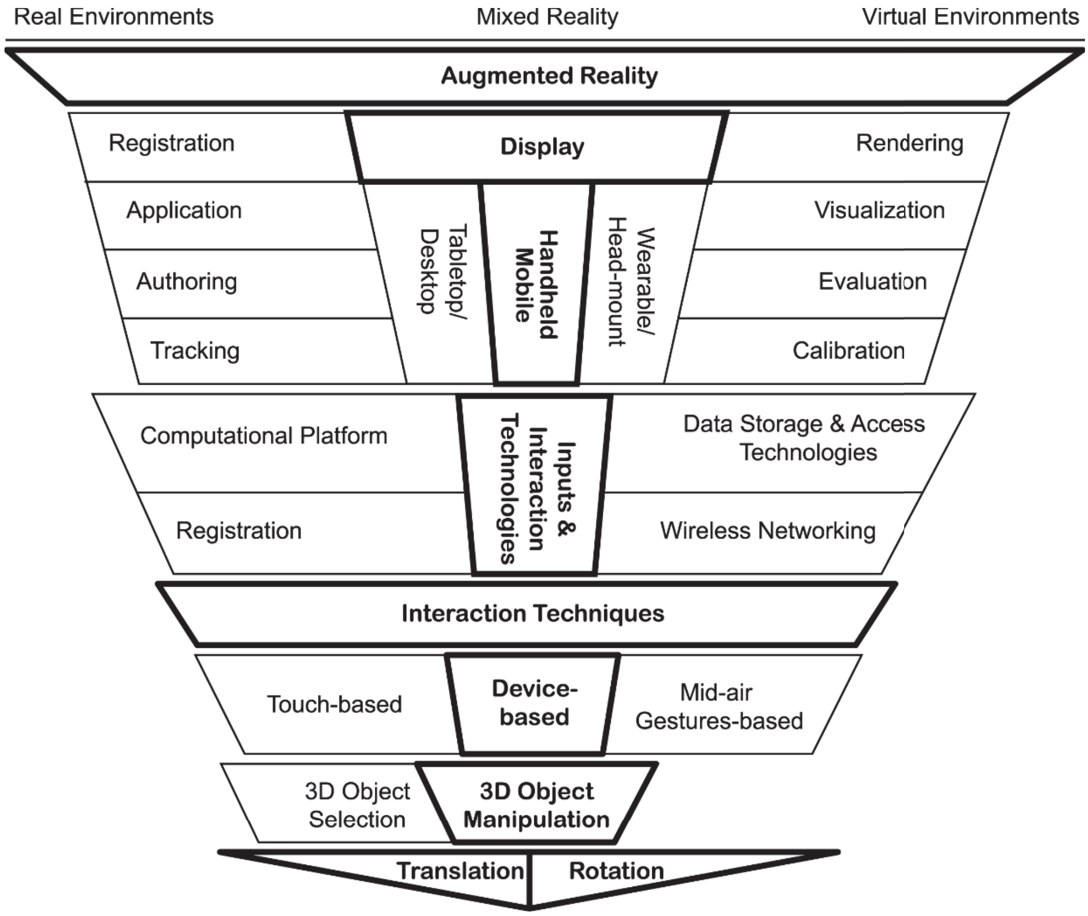


Figure 1.1 Research focus area

Although several interaction techniques focused on handheld mobile AR have been introduced, there are several other remaining issues related to handheld mobile AR that should be considered and looked into, with the aim of enhancing AR experiences. Issues in 3D object manipulation for user interaction still need to be improved to enable decent AR in handheld mobile platforms, which mostly refer to smartphones and tablets, which are limited to small screen sizes to display AR (Hancock, Carpendale and Cockburn, 2007; Martinet, Casiez and Grisoni, 2012a; Polvi, Taketomi, Yamamoto and Dey, 2016). Another limitation of the handheld mobile devices is that users need to hold the devices with their single hand and stretching out another hand to interact may cause the fatigue phenomenon (Yusof, Bai, Billinghurst and Sunar, 2016).

As stated in Bowman, Kruijff, LaVoila and Poupyrev (2005) and Hancock et al (2007), the selection and manipulation of 3D objects including translation and rotation in handheld mobile AR are the fundamental tasks in 3D interaction. Currently, many of the existing handheld mobile AR applications are not considered very practical due to their insufficient functionality and failure to respond appropriately to the needs of the users (Olsson and Salo, 2013; Grubert, Langlotz and Grasset, 2011). Many design and technical challenges remain, and 3D object manipulation (including 3D object translation and rotation) is one of them. For handheld mobile AR to be widely accepted, users must be able to create AR content by positioning and rotating virtual objects in a real environment (Kurkovsky, Koshy, Novak and Szul, 2012; Langlotz, 2013). In this context, the basic 3D object manipulation (Bowman et al, 2004) of virtual objects is fundamental in handheld mobile AR's content creation, and this leads to the introduction of various interaction techniques focusing on 3D object manipulation tasks within handheld mobile AR interfaces.

On the foundation of these concepts, interaction techniques in handheld mobile AR focusing on 3D object manipulation, becomes the emphasized discussion in this research.

1.2 Problem Background

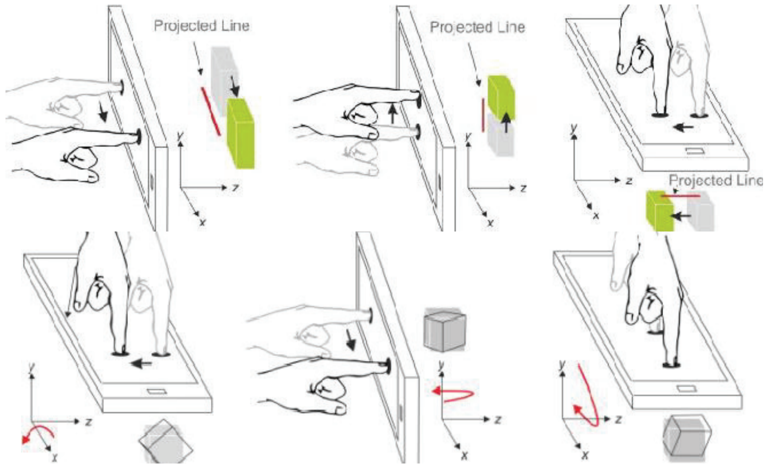
The selection and manipulation of 3D objects, which includes translation and rotation, in handheld mobile AR interfaces is considered the fundamental task in 3D interaction (Bowman et al., 2005). 3D object manipulation is commonly performed using touch-based interaction techniques (Figure 1.2a), because of the widespread use of touchscreen smartphones and tablets (Mossel, Venditti and Kaufmann, 2013; Marzo, Bossavit and Hachet, 2014; Yusof et al., 2016). The drawback in handheld mobile displays is that they only allow 2D touching on the screen (Hürst and Wezel, 2013).

Since the user needs to place his/her finger on the handheld mobile device's screen for performing the manipulations, occlusion may occur and the user would fail to have a comprehensive view on the virtual object on the display screen. Besides this, there is also a general lack of intuitiveness as this method of interaction is not considered a natural way to interact (Mossel et al, 2013; Marzo et al, 2014; Yusof et al, 2016).

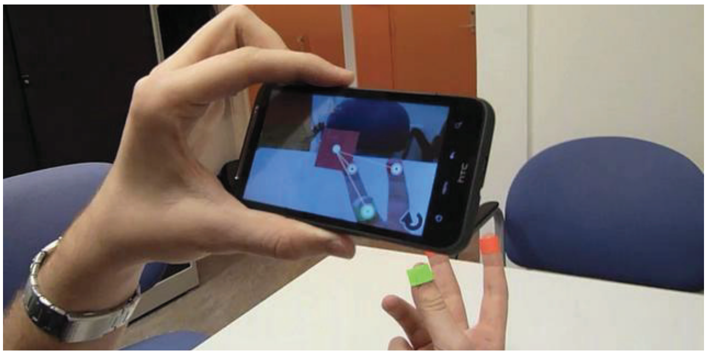
In order to increase intuitiveness in manipulating 3D objects, the mid-air gestures-based interaction technique category (Figure 1.2b) has been introduced (Hürst and Wezel, 2013). By using the 3D gesture tracking method, users can interact with the 3D object naturally. In the earliest study of mid-air gestures-based interaction, Henrysson, Marshall and Billinghurst (2007) used a fiducial marker attached to the index fingertip and tracked at the front of a mobile phone, which was used to control a 3D painting application. In mid-air gestures-based interaction, users hold the handheld mobile device with one hand and use the other hand to handle the 3D object using an AR marker. In some cases, the hand represents as the AR marker to manipulate the 3D object directly within the respective camera's field of view. However, this technique contains some inferiorities such as the occlusion problem as well as the 3D object's position and orientation deviations (Hürst and Wezel, 2013). When users hold the 3D object in mid-air, it is difficult to release it at a precise position because of occlusion. Detection of the user's hands or fingers becomes difficult when they appear in an occluded manipulation area.

Furthermore, this technique has been shown to achieve high error rates (Hürst and Wezel, 2013). Besides this, 3D object manipulations performed using mid-air gestures-based technique are also constrained by the person's reach of the hand to perform 3D object translation. The rotation of the hand is also limited by the movement around the wrist joint, making it almost impossible for the users to perform large-range 3D object translations and rotations.

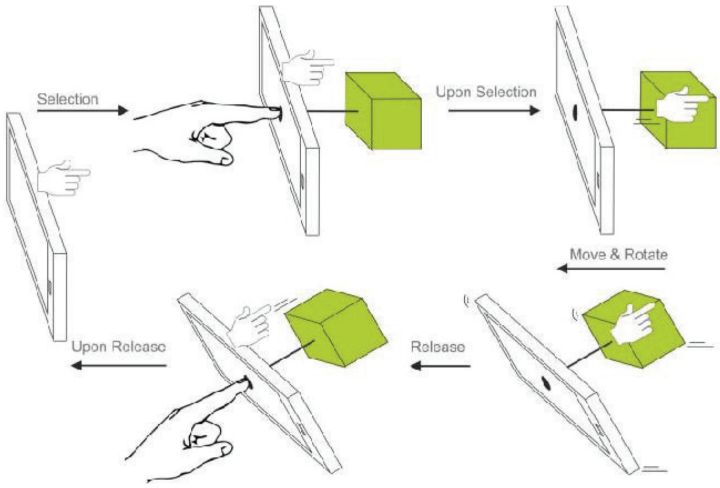
Figure 1.2 shows examples of different interaction techniques used for 3D object manipulation in handheld mobile AR to apprehend the basic concepts of each interaction technique category.



(a) Example of touch-based interaction technique (Mossel et al, 2013)



(b) Example of mid-air gestures-based interaction technique (Hürst and Wezel, 2013)



(c) Example of device-based interaction technique (Mossel et al, 2013)

Figure 1.2 Examples of interaction techniques in different categories for 3D object manipulation in the handheld mobile AR interfaces

Apart from touch-based and mid-air gestures-based interaction, a device-based interaction technique category (Figure 1.2c) has been recently introduced for handheld mobile AR interfaces, that is based on video see-through AR. This technique uses information from the handheld mobile device's own attributes such as the built-in camera's position and orientation information, as inputs to capture the primitive data from the diversification of the handheld mobile device's physical poses, to perform the 3D object manipulation, that consisted of 3D object translation and rotation (Mossel et al, 2013; Marzo et al, 2014; Tanikawa, Uzuka, Narumi and Hirose, 2015; Samini and Palmerius, 2016; Samini 2018). In short, the 3D object is manipulated to achieve the desired position and orientation when the user translates or rotates his/her handheld mobile device, which acts as a holding tool or adhesion agent to manipulate the 3D object, while the 3D object is diversified following the movement of the handheld mobile device.

The two (2) common issues faced in 3D object manipulation within handheld mobile AR, which are occlusion and fatigue phenomenon, have guided us to select the device-based interaction technique category to be explored in this research.

Occlusion is an issue discussed in many previous studies and has become the main focus in touch-based and mid-air gestures-based categories (Jung, Hong, Park and Yang, 2012; Bai, Lee and Billinghurst, 2012; Mossel et al, 2013; Kim and Lee, 2016; Hürst and Wezel, 2013; Chun and Höllerer, 2013; Bai, Lee, Ramakrishnan and Billinghurst, 2014; Bai, Gao, Billinghurst and El-Sana, 2013c). Several solutions have been suggested for touch-based interaction and mid-air gestures-based interaction technique categories, such as (Vogel and Baudisch, 2007; Paudisch and Chu, 2009; Jang, Noh, Chang, Kim and Woo, 2015). However, in many instances, these suggestions have led to other problems. An example is the callout display method suggested by Vogel and Baudisch (2007). Although it may have contributed in solving occlusion of the finger touch-point area, but occlusion still occurred in other areas. In this context, device-based category is the only category that provides an occlusion-free interaction technique for the user to perform 3D object manipulation (Tanikawa et al, 2015; Samini and Palmerius, 2016; Mossel et al, 2013; Marzo et al, 2014). None of the touch points on the handheld mobile device screen or mid-air gestures need to be tracked for 3D object manipulation. The 3D object displayed on the handheld mobile device screen is not occluded since the manipulation of 3D object is based on the handheld mobile device's physical attributes themselves, such as device movement or device poses.

The fatigue phenomenon is linked to the ability of the user to hold the handheld mobile device with both hands when interacting. In Yusof et al (2016), fatigue phenomenon was highlighted and supported with Benko and Feiner (2007). The researches stated that holding the device with one hand and using another hand for interaction might cause fatigue to the user (Benkoand Feiner, 2007; Hincapié-Ramos, Guo, Moghadasian and Irani, 2014). In touch-based interaction, the user needs to hold the handheld mobile device and free up one hand to perform finger touch actions on the display screen. When multi-touch actions are required for 3D object rotation for example, finger fatigue occurs (Boring, Ledo, Chen, Marquardt, Tang and Greenberg, 2012). In this context, device-based interaction technique appears to be more robust because the user can interact by holding the handheld mobile device with both hands while interacting in handheld mobile AR environments. As was mentioned by Benko and Feiner (2007), interactions that utilize both hands can effectively reduce fatigue compared to single-handed interaction.

Against this backdrop, this study concludes that the device-based interaction technique is highly suitable to perform 6 DOF for 3D object manipulation since this technique does not involve the problems stated previously, and hence is proven to improve efficiency and provide a high precision in performing the 3D object translation task within the handheld mobile AR interface (Mossel et al., 2013; Marzo et al., 2014; Samini and Palmerius, 2016). Additionally, this technique also provides an intuitive way to interact apart from using real hand and fingers like in mid-air gestures-based interaction technique, since the user holds the handheld mobile device as a holding tool to handle the 3D object, which can enhance the users' AR experience (Mossel et al, 2013; Marzo et al, 2014; Tanikawa et al., 2015; Polvi et al, 2016; Samini and Palmerius, 2016).

1.3 Problem Statement

Currently, the existing device-based interaction technique maps the position and orientation of the handheld mobile device with the 3D object; when the user moves and rotates the handheld mobile device, the 3D object is also moved and rotated. The existing technique was proven effective when used for 3D object translation as stated in previous studies (Mossel et al, 2013; Marzo et al, 2014; Samini and Palmerius, 2016), until it was used in the comparison process for 3D object translation within a handheld mobile AR interface (Polvi et al, 2016).

However, there are two (2) problems in the category of device-based interaction technique that need to be given serious attention. One of the problems is related to large-range 3D object rotation. In several related works (Mossel et al, 2013; Marzo et al, 2014; Samini and Palmerius, 2016, Samini, 2018), 3D object rotation had been discussed and stated as being the main problem in device-based interaction. At certain rotation angles, particularly on the x (roll) and y (pitch) axes, the AR marker may not be within the trackable area, thereby causing a 3D object registration error when the user over-rotates the handheld mobile device. Over-rotation may also cause the 3D object displayed on the screen to inconsistently appear within the user's range of view. Meanwhile, the AR marker may be in the trackable area but not visible within the user's range of view for some rotation angles. Furthermore, when the user performs 3D object rotation on the z (yaw) axis, he/she is required to move or rotate the handheld mobile device around the z axis and slow down the rotation speed.

The second problem is that the existing device-based 3D object manipulation technique suffers from 3D object position and orientation deviations which slow down the manipulation speed. This happens because the existing technique maps the device movements with the translation and rotation of the 3D object integrally. While the solution to this had been suggested by Mossel et al (2013) which suggested separating the 3D object translation and rotation and controlling them via different interaction techniques within different categories through a hybrid technique. They suggested using the touch-based technique to control 3D object rotation and using the device-based technique to control 3D object translation.

Although there are several suggestions proposed for the large-range 3D object rotation problem as well as the 3D object position and orientation deviation problem, these solutions still suffer many drawbacks. These suggestions and their drawbacks are explored below:

(a) Incomplete large-range 3D object rotation in handheld mobile AR can be done entirely through the suggestion given by Samini (2018). However, the user needs to repeat the device pose adjustment and the 3D object holding and releasing actions frequently until the 3D object is well rotated to its desired pivot point depending on the complexity of the rotation's amplitude. Only a slight amount of rotation angle is changed each time the device is adjusted, which slows down the 3D object rotation speed. The slow rotation on z-axis is still retained, including the limitations of the roll (x) and pitch (y) axes, thereby slowing down the 3D object rotation speed (Mossel et al, 2013; Marzo et al, 2014). Moreover, the solution suggested by Samini (2018) still failed to prevent the user from over-rotating the handheld mobile device, causing a 3D object registration error and inconsistent visibility of the 3D object on the display screen.

(b) The combination of device-based and touch-based techniques requires separation between 3D object translation and rotation to prevent 3D object position, and orientation deviations that require the user to switch the interaction mode between these techniques, which may degrade the user's AR experience. This is contradiction to the aim of AR as a new user interface, which is to provide natural and intuitive, even seamless interaction experiences for the users (Yusof et al, 2016). Hybrid interaction may also decrease intuitiveness when the user interacts within the handheld mobile AR interface. Additionally, the drawbacks of the touch-based interaction technique such as occlusion are also retained and unsolved.

(c) Despite encouraging efficiency, it is obvious that the device-based interaction technique can perform faster virtual object translations with high precision (Mossel et al, 2013; Marzo et al, 2014; Samini and Palmerius, 2016; Polvi et al, 2016; Samini, 2018). However, this result was spoiled when working together with the 3D object rotation task since it is hard to rotate a 3D object without moving it (Samini and Palmerius, 2016; Samini 2018). Furthermore, in Mossel et al (2013), users reflected that the existing device-based technique is not suitable for 3D object rotations. It is therefore essential to enhance the existing technique in order to improve its performance based on speed while at the same time retaining its precision.

1.4 Research Goal

This study aims to propose an improved device-based interaction technique consisting of an enhancement of the 3D object rotation technique unilaterally and a restructuring of the 3D object manipulation technique comprehensively with better performance on task completion time.

1.5 Research Objectives

In order to achieve the above-mentioned goal, the following objectives must be accomplished:

(a) To enhance the current device-based 3D object rotation technique with a proposed control structure in performing large-range 3D object rotation tasks within the handheld mobile AR interface.

(b) To restructure the device-based 3D object manipulation technique to perform 3D object manipulation tasks without position and orientation deviations within the handheld mobile AR interface, with a combination of two (2) different control structures based on the taxonomy of DOF separation for 3D object translation and rotation.

(c) To propose an improved device-based interaction technique with better performance on task completion time for 3D object rotation unilaterally and 3D object manipulation comprehensively within the handheld mobile AR interface by benchmarking with the current technique.

1.6 Research Scope

The proposed device-based 3D object rotation technique is implemented in a handheld mobile AR interface consisting of a single scaled 3D object with a wireframe-like appearance representing the final rotation pose, each time a participant performs a 3D object rotation task. No selection stage is assimilated in the task design since this research focuses on 3D object rotation, not selection, which requires multiple objects.

For the 3D object manipulation tasks designed to evaluate the proposed device-based 3D object manipulation technique, a 3D object selection using the Raycast selection method is included. The ray point setting is at the middle of the display screen to avoid the selected object appearing to be held near the corner of the display screen, which may affect the 3D object manipulation process. A single scaled object with its wireframe appearance that represents the final allocation as well as its complement are displayed each time the task starts.

In this research, the handheld mobile device refers to a smartphone with Android operating system. Moreover, both 3D object rotation and manipulation techniques have only been developed for a single user scenario, since a multi-user scenario would require the preparation of multiple handheld mobile devices as well as the supportive network service, which is another research field altogether (Höllerer and Feiner, 2004). Additionally, evaluations of the proposed device-based 3D object rotation and manipulation techniques applied in handheld mobile AR interfaces are conducted in an indoor environment due to the lighting factor. Lighting is always one of the main issues in AR. To ensure that the results of this research are valid and reliable, the lighting condition has been considered, and as such, the participants involved in this research performed the experimental tasks under the same lighting conditions. Since lighting is uncontrollable in outdoor situations, all the research tasks are performed indoor and the participants involved are given the research tasks in the same room to minimize the effect of the lighting factor.

This research focuses on the interaction technique and not the tracking system; therefore, it only includes the basic requirements of an AR interface, which consist of a printed feature-based AR marker and a smartphone that is treated as the tracking system, rendering system as well as the display system. For the purpose of this research evaluation, only two (2) sets of 3D objects have been stored in the handheld mobile AR interface. These include one (1) 3D chair with its wireframe visualization used in 3D object rotation tasks, and two (2) 3D screws (with rounded cap and rectangle cap) and 3D chair backrest with their wireframes and complements used in the 3D object manipulation tasks. Both sets of objects are formed in. fbx format while no primitive objects are read. This format (.fbx) is chosen since it is suitable use here, due to its ability to provide interoperability between digital content. It also consists of 3D assets that facilitate higher-fidelity data exchange within an AR application.

Since the number of handheld mobile device users is large, this research has been constrained by involving only students from the School of Computing, Faculty of Engineering, Universiti Teknologi Malaysia (UTM). These participants were all self-recommended through an open invitation and each of them was compensated with a small gift for their time. The invited participants ranged from 18 to 24 years old since the young people in this age range form the largest group of smartphone users compared with others (33% of total 1244 respondents), based on the Nielsen smartphone user segmentation study conducted in Malaysia in 2015. It is also to be noted that most of the previous similar studies also chose university students as their participants. The number of participants involved in this study were decided based on similar studies conducted previously by other researchers which were counter-balanced with the experimental trials for each participant in those studies.

1.7 Significance of the Study

It is expected that the proposed device-based techniques will overcome the challenges that exist in this interaction category based on 3D object rotation and manipulation. These proposed techniques attempt to answer the remaining problems in the device-based interaction category in the form of an enhancement in performing 3D object rotation tasks unilaterally and 3D object manipulation tasks comprehensively.

The state-of-the-art device-based 3D object rotation technique showed some encouraging results. Although it was implemented to solve the incomplete 3DOF of large-range 3D object rotation issue, the handheld mobile device's over-rotation problem still existed, causing difficulties in tracking and visibility of 3D objects. Regarding the 3D object position and orientation deviations, they still remain unsolved in the current device-based 3D object manipulation technique. The motivation for conducting this PhD study is to propose optimized and innovative techniques to prevent both, the handheld mobile device's over-rotation as well as the 3D object position and orientation deviations simultaneously, with a better performance measure for task completion time.

In light of the above-mentioned issues, the results of this research will contribute to what is currently known about device-based interaction techniques for 3D object manipulation within the handheld mobile AR interface.

1.8 Thesis Organization

This thesis is organized as follows. The rest of the chapters begin with a brief description highlighting the aim of each chapter, and end with a short summary. Each chapter is developed to be self-contained, but there is a cohesion among the chapters to ensure the free flow of the presentation and understanding of the thesis content.

Chapter 2 provides an in-depth overview of relevant literature on existing techniques for performing 3D object manipulation in handheld mobile AR, which incorporates an analysis of existing literature in relation to the subject of this study. The review covers most of the techniques categorized as touch-based, mid-air gestures-based and device-based that are used to manipulate 3D objects within handheld mobile AR interfaces.

Chapter 3 presents a clear roadmap of this study to guide the reader to achieve a quick grasp of the detailed research framework. The details of the experiments and the tasks designed for this study are emphasized. The layout of the entire research framework, strategies, and procedures is also highlighted.

Chapter 4 discusses the detailed design and development of the proposed device-based 3D object rotation and manipulation techniques which include: the registration of all 3D scaled objects used in the 3D object rotation and manipulation tasks, the design of the innovative device-based control structure for 3D object rotation, the combination of two (2) control structures for 3D object manipulation based on DOF separation; design and development of the 3D object rotation and manipulation tasks, and the design of the experiments.

Chapter 5 provides details of the implementation of the experiments, experimental results, detailed analysis, and discussions. It explains the implementation of the proposed techniques into the experimental tasks within handheld mobile AR interfaces in the form of mobile applications. It then explains the quantitative measurements that were carried out for performance evaluations. In relation to this, a series of experiments were conducted based on the tasks designed, and the results of these experiments are interpreted and discussed in detail here, based on the remaining issues stated in Chapter 1. Additionally, the performance of the proposed techniques is benchmarked against present device-based techniques found in the literature to date.

Chapter 6 concludes the study by emphasizing the major contributions, significant findings, and recommended future directions of the present study.

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2. **Goh, E.S.,** Sunar, M.S. and Ismail, A.W. (2019) 'Device-based 3D Object Manipulation Technique with Different Control Structures to Separate DOF of Translation and Rotation for Handheld Mobile AR', *International Journal of Human-Computer Studies (Elsevier).* **(ISI: Q2, IF: 2.006). In review with revised manuscript.**

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1. **Goh, E.S.,** Sunar, M.S. and Ismail, A.W. (2018) 'An Inertial Device-based User Interaction with Occlusion-free Object Handling in a Handheld Augmented Reality', *International Journal of Integrated Engineering*, 10 (6), 159-168. https://doi.org/ 10.30880/ijie.2018.10.06.023. **(Indexed by SCOPUS)**

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1. **Goh, E.S.,** Sunar, M.S. and Ismail, A.W. (2019) 'Tracking Techniques in Augmented Reality for Handheld Interfaces', *Encyclopedia of Computer Graphics and Games,* 1-10. https://doi.org/10.1007/978-3-319-08234-9_364-1. **(Indexed by Springer). Accepted and will be published by Springer International Publishing in 2020.**

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1. Directional Time-Based 3D Virtual Object Rotating Technique for Device-based Interaction in Handheld Augmented Reality. **No.: UTM.J.14.01/27.13/1JLD128(46) on 2/1/2018.**