Parallel Reality: Tandem Exploration of Real & Virtual Environments

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1. Candidates declarations

I, CJ Davies, hereby certify that this thesis, which is approximately 27 words in length, has been written by me, and that it is the record of work carried out by me, or principally by myself in collaboration with others as acknowledged, and that it has not been submitted in any previous application for a higher degree.

I was admitted as a research student in [month, year] and as a candidate for the degree of PhD in [month, year]; the higher study for which this is a record was carried out in the University of St Andrews between 2011 and 2015.

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2. Supervisors declaration

I hereby certify that the candidate has fulfilled the conditions of the Resolution and Regulations appropriate for the degree of PhD in the University of St Andrews and that the candidate is qualified to submit this thesis in application for that degree.

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Abstract

- **Content -** Short, high-level summary of document.
- **What has been done -** Nothing.
- **What is left to do/how long should it take -** Write entire abstract, but should be quick to do & be done (near) last.

Acknowledgements

- **Content -** Acknowledgements.
- **What has been done -** Nothing.
- **What is left to do/how long should it take -** Short list of acknowledgements, should be quick & one of the last things to do, not overly important.

Contents

1

Introduction

- **Content -** Short (10 pages is probably far too much). High level introduction to the concepts/topics involved in the thesis, very short/broad definitions of any terms introduced in the title (eg 'simultaneous presence'), overview of the rest of the document, list of contributions/donations of this document
- **What has been done -** Nothing.
- **What is left to do/how long should it take -** Should be one of the last things to be written, maybe a few days of writing.

2

Extended Example

- **Content -** Short (10 pages is probably far too long) example or usage scenario of how the concepts investigated in the thesis have/could be used (a 'near-future usage scenario').
- **What has been done -** Nothing.
- **What is left to do/how long should it take -** Come up with a legitimate scenario, keep it short, should probably be written after the bulk of the later sections so there's a clear idea of what scenario I actually want to allude to. Perhaps a few days writing.

This section presents two use cases for simultaneous presence in real and virtual environments and illustrates the two different relationships that can exist between the real and virtual environments - whether they are *spatially equivalent* or not.

2.1 Virtual Time Windows - Spatial Equivalence

The ongoing Virtual Time Window (VTW) project is an application of simultaneous presence in real and virtual environments within the domain of cultural heritage that promises to further existing alternate reality work in the field by allowing simultaneous exploration of a real cultural heritage site and its virtually reconstructed counterpart via a tablet computer [1]. A visitor to a cultural heritage site, such as the ruins of the cathedral at St Andrews, uses a tablet computer that in effect presents a 'window' into a virtual reconstruction of the entire site as it was at an earlier point in time, such as the cathedral in its 13th century splendour.

To maintain a natural and unhindered sense of exploration VTW does not require visitors to manually control navigation within the virtual environment. Changes in the tablet's position within the site are automatically reflected by a corresponding movement of the avatar within the virtual environment, making use of a combination of location tracking technologies. The direction that a visitor faces is monitored by magnetometer and the angle that they hold the tablet at by accelerometer; this information is reflected by the direction and pitch of the camera within the virtual environment. The resulting style of interaction is similar to using a digital camera to take a photo; the screen on the back of the camera shows what the image will look like when the shutter is released, whilst with VTW the screen on the tablet shows what the site looked like in the past.

This approach addresses the vacancy problem by presenting the user with a convenient and natural manner in which to interact with the virtual environment whilst simultaneously exploring the real environment. A tablet computer is small, light and easy to carry and by controlling the position and direction of the camera by sensing the user's physical movements the user doesn't have to pay close attention to manually navigating within the virtual environment which would risk introducing vacancy from the real environment.

By using a complete virtual environment, rather than adding sparse virtual augmentations to a user's view of the real location in an augmented reality fashion, interactions between users at the site and those who are physically elsewhere are possible via the virtual environment.

With VTW, the virtual environment is based upon the real environment. Even though certain features may differ, for example where ruins stand in the real environment a complete building may stand in the virtual environment, there is a fundamental spatial equivalence between the two environments - they are both in effect the same 'location' or 'place', in an abstract sense of the terms. It is this relationship that permits the project to map a user's physical position in the real environment to an equivalent position within the virtual environment, allowing them to navigate both when in affect only controlling their navigation in one.

One might consider the 'Second Earth' concept to be the ultimate realisation of this scenario of spatially equivalent real and virtual environments. Discussed by Wade Roush in a 2007 article of MIT's Technology Review magazine [2], which is cited by Lifton in his thesis, Second Earth is theorised as the combination of the notions of virtual world technology (as in Second Life) with 'mirror world' technology (as in Google Earth); Second Earth theorises a virtual simulation/reconstruction of the entire physical world, such that for any location in the real world there is a corresponding location in the virtual world. Such a resource would allow for simultaneous presence in corresponding real and virtual environments to take place anywhere, rather than being restricted to specific real world locations for which a corresponding virtual location had been created, such as a cultural heritage site.

Furthermore, if one were to apply the concepts of cross reality to such a global virtual reconstruction, it would in effect create a complete parallel virtual Earth that would react in real-time to events in the real world via sensor infrastructure and would be able to affect the real world in real-time through actuator infrastructure.

Naturally the Second Earth concept will remain just that - a concept - likely for decades, as the underlying technologies and infrastructures are not yet available to us. In a blog post on the subject of virtual world/mirror world mashups [3], Avi Bar-Zeev estimates that the Second Life server model at the time would require 2.4 billion physical servers to host a simulation of the entire surface of the Earth, or 1400 servers just for Manhattan. In a comment on this post, Roush emphasises that his article in Technology Review was not meant to be taken as a premise for a literal Second Life/Google Earth mashup, but that they were the leading virtual world/mirror world technologies at the time and that overlap was sure to happen.

2.2 Snow Crash - No Spatial Equivalence

In the opening quote to this review, taken from Neal Stephenson's cyberpunk novel *Snow Crash*, the protagonist enquires about the location of another character, called Y.T., both in the real world and in the 'Metaverse'. For the sake of this discussion, this Metaverse can be considered analogous to a virtual world akin to Second Life, accessed via a head mounted display, and comprises an entirely synthetic virtual world whose locations have no counterparts in the real world. Y.T.'s response is that *"In the Metaverse, I'm on a plusbound monorail train. Just passed by Port 35."* whilst in reality she is at a *"Public terminal across the street from a Reverend Wayne's"*.

In this scenario there is no spatial equivalence between the real environment and the virtual environment - they are not the same 'location' or 'place' as is the case with VTW - however the concept of simultaneous presence in both can still be useful, as illustrated later in the book. Y.T. is in fact waiting for a third character, Ng, to come and collect her, which leads to the following conversation in the Metaverse between Y.T. and Ng

> *"... you're driving?"*
>
> *"Yes. I'm coming to pick you up - remember?"*

"Do you mind?"

"No," he sighs, as if he really does.

Y.T. gets up and walks around behind his desk to look.

Each of the little TV monitors is showing a different view out his van; windshield, left window, right window, rearview. Another one has an electronic map showing his position: inbound on the San Bernardino, not far away.

"The van is under voice command," he explains. "I removed the steering-wheel-and-pedal interface because I found verbal commands more convenient. This is why I will sometimes make unfamiliar sounds with my voice - I am controlling the vehicle's systems."

Ng is driving his van in the real world to come and collect the real Y.T, whilst simultaneously sitting in his virtual house in the Metaverse having a conversation with the virtual Y.T., using a series of virtual TV monitors in the Metaverse to inform him of his real surroundings and to allow him to control the van.

In this scenario there is necessarily no spatial equivalence between the real environment and the virtual environment, as the virtual environment has no spatial equivalent in the real world - the monorail and Ng's house have no real counterparts. However a lack of spatial equivalence between the real environment and the virtual environment could also arise when the virtual location does have a real counterpart, but the user isn't there. For example, in reality a user could be in London whilst in the virtual environment they could be in a location that is spatially equivalent to a real part of Hong Kong.

It is already common to see people interacting with their real location, even if that interaction is limited to just walking from A to B without bumping into too many other people or being run over by a bus, whilst simultaneously interacting with the 2D Web, social media and textual chat via mobile devices such as mobile phones and tablets. With the continued trend toward the 3D Web, it is no leap to imagine a near future in which people regularly want to interact with a 3D virtual environment that is not spatially equivalent to their current location at the same time as walking to the bus stop, thus simultaneous presence in real and virtual environments that are not spatially equivalent promises to be a desirable scenario.

3

Background, Theory & Rationale

- **Content -** Should lay out the theoretical motivations behind this work, outline the main issues that arise given these motivations & describe the approaches taken to overcome the issues. For each part of this, pertinent related work should be overviewed (eg. this is where the literature review will be situated).
- **What has been done -** Extensive literature review was written at the end of year one. This literature review needs re-writing such that the pertinent parts are included in the relevant part of the discussion of 'theory & rationale' (eg the content of the literature review will be split up & inserted where appropriate into the new 'theory & rationale' document). Literature read since the end of year one (which is substantial & includes a slight shift in focus; presence, PoSR, older VR & AR literature) needs incorporating.
- **What is left to do/how long should it take -** New document needs writing in the guise of 'theory & rationale', splitting up & inserting contents of old literature review & writing in about more recently read literature since. 30 pages of the current literature review document is far too long, needs to be substantially cut down whilst covering more literature. Substantial exercise in writing/collating/drawing links between, etc. Might want to put aside a month or so of write-up time for this alone.

"Where are you?" Hiro says.

"In Reality or the Metaverse?"

"Both."

Snow Crash, Neal Stephenson

This research centres around the design, development & evaluation of a hardware & software platform which allows its user to observe & move around their Real World (RW) environment whilst wearing a wide field of view (FOV), stereoscopic 3D, Head Mounted Display (HMD) which allows them to alternatively view an immersive Virtual Reality (VR) environment from the equivalent vantage point. This is achieved by combining a head-tracked HMD, webcams, an indoor positioning system (IPS) & a 3D game engine, into a mobile *cross reality* (XR) interface.

One of the distinguishing features of XR is that, by linking real & virtual environments more closely, it mitigates the 'vacancy problem': *"the noticeable & profound absence of a person from one world, either real* *or virtual, while they are participating in the other"*, which arises *"because people do not currently have the means to be in more than one place (reality) at a time"* [4].

Previous XR research approached the vacancy problem by integrating sensor/actuator networks into the environments, such that actions in one could manifest in the other, however direct visual engagement with the virtual environment was only possible from static interfaces at pre-determined locations within the real environment [4, 5]. The platform discussed in this document addresses this shortcoming by providing a mobile interface for visual engagement with both environments of a XR system, allowing the user to transition between viewing their real environment & a virtual environment at any time while maintaining the freedom to move around them, multiplexing visual stimuli from their real surroundings & from a parallel, virtual 'mirror world' [6].

3.1 Defining Alternate Realities

A fundamental imperative for the remainder of this review is a well defined set of criteria for classifying and differentiating between different types of alternate reality. The terms *mixed reality*, *augmented reality* and to a lesser extent *augmented virtuality* are all now relatively common in the literature, however they have too often been used in conflicting manners, or assigned vague definitions with uncertain boundaries separating them from each other. Furthermore the less well established terms *cross reality* and *X reality* (different names for the same concept) also need classifying according to the same system.

Research on alternate realities has been extensive, with the theme being explored for purposes as diverse as education [7] and new forms of data visualisation [8] to medical [9] and military training [10]. Traditionally access to implementations of alternate realities was limited by the availability and high monetary cost of the specialised hardware and software that was required to create virtual environments and computerised superimpositions [11]. However more recently the cost and availability of this hardware and software has reduced and increased respectively to the point at which we find ourselves today where alternate realities can be, and in fact frequently are, experienced by many with the equipment they already have available to them with no special considerations [12].

Hardware capable of synthesising the graphically complex three-dimensional environments that alternate realities often present has reduced in cost to the point that it is no longer considered specialist equipment, owned only by those expressing an explicit interest in the subject, and is now commonplace in 'average' consumer electronics devices, be they traditional desktop and laptop computers, games consoles, or portable devices such as mobile phones and tablets. Combined with the continued adoption of high-speed Internet connectivity [13] the potential of multi-user virtual environments is already being realised, both for traditional competitive gaming through platforms such as World of Warcraft, but also for non-competitive purposes that focus more on community, creation and commerce with 'virtual world' platforms such as Second Life [12].

Furthermore, progress toward ubiquity of sensing and actuating infrastructure in our everyday lives continues at an accelerated rate [14, 15]. Such systems are now commonplace in new buildings and also in consumer electronics, both portable devices such as mobile phones and tablets as well as home entertainment products such as games consoles. The result is that the amount of information that we can access about the physical and environmental state of a particular location at any given time is greater than ever.

The combination of these factors means that we are approaching the required dissemination of technology and public knowledge and understanding for virtual environments and integration with sensor/actuator infrastructure to begin making a larger impact on society and ultimately to be used by on a scale and in a manner similar to how the World Wide Web already is today. It is no longer preposterous to imagine a near future where a 'Metaverse' reminiscent of that in Neal Stephenson's cyberpunk novel *Snow Crash*, presenting an extension of the Web in the form of a three-dimensional virtual environment, has become a reality adopted by the majority of current Web users rather than remaining a vision of academics and cyberpunk fiction aficionados.

However although there are numerous examples of virtual environments, particularly those for competitive gaming, gaining substantial popularity [12] and augmented reality and augmented virtuality products are no longer restrained to the research lab, this review has found very little research into simultaneous presence in *complete* real and virtual environments. The term *complete* is used to emphasise that the discussion here is about real and virtual environments that are both complete unto themselves and which can thus be explored and interacted with in isolation from the other, in addition to being explored simultaneously. This is a different concept to augmented reality and augmented virtuality systems, where the augmentations are usually near meaningless when separated from the context bestowed upon them by the underlying environment that they are augmented upon.

The *cross reality* paradigm represents the most promising foray into investigation of this concept, as such a system is established through the combination of two complete environments, a real environment and a virtual environment that is based upon and mimics this real environment, which are bestowed with the abilities of mutual reflectance and influence through the use of sensor/actuator infrastructure (see section 3.3 for full discussion). Physical and environmental changes in the state of the real environment are captured by sensors and these data used to update the state of the virtual environment, whilst simultaneously changes in the state of the virtual environment manifest into the real environment via actuators. Users are free to explore and interact with either environment in relative isolation from the other, even if their interactions in one trigger changes in the other, however simultaneous interaction and exploration with both environments has largely remained without systematic investigation.

This is largely because users exploring and interacting with the real environment do not have a convenient manner of also exploring and directly interacting with the virtual environment, as such interaction usually relies upon the use of software run on a desktop or laptop computer which is not conducive to mobile use. Using a laptop computer whilst walking around is far from convenient and using a desktop computer obviously limits the user's interaction with the real environment to that immediately around the location of the computer and results in a disjoint relationship between their physical position in the real environment and the location of their avatar in the virtual environment when they navigate their avatar away from the respective position of their computer. This situation has been called 'the vacancy problem'; an apparent vacancy from one environment whilst engrossed in the other (see section 3.3.3 for full discussion).

Interested in the promise of simultaneous presence in complete real and virtual environments, particularly those that are able to mutually affect each other via sensor/actuator infrastructure and the cross reality paradigm, this literature review investigates how academic studies have treated such themes. The conclusion of this investigation is that the theme of simultaneous presence in real and virtual environments is still discussed only marginally in the scholarly literature and that this situation warrants attention as the benefits proposed by such interactions between real and virtual environments are extremely promising.

3.1.1 Milgram & Kishino's Reality Continua

Paul Milgram, Herman Colquhon and Fumio Kishino addressed this issue in detail and can in fact be accredited with introducing the terms *augmented virtuality* and *mixed reality* to the literature in the first instance, prompted by their identification of the need for more encompassing terms to supplement the existing definitions of *augmented reality* [16, 17]. Their discussion at times takes on a hint of the philosophical, as it rightly discusses what exactly it is that we mean by 'real' and 'virtual' and whether it is in fact reality or virtuality which is being augmented. However despite these thorough and well-reasoned definitions being published originally in 1994, much of the subsequent literature studied for this review has adopted conflicting, or at least confusing and misleading, definitions.

One of the overbearing concepts that Milgram et al. introduced is that whilst both purely real and purely virtual environments do exist they should not be considered discrete alternatives but rather poles lying at opposite ends of a linear scale called the *Reality-Virtuality continuum.* The location of an environment along this continuum coincides with its location along a parallel *Extent of World Knowledge continuum* where 'world knowledge' refers to the amount of quantitative information that is associated with the content being presented, or in other words how much of the environment is being 'modelled' by a computer. These continua are included as figure 3.1.

With a purely virtual environment, the entire viewport must necessarily be computer modelled in order to be rendered and as such there is complete quantitative information about all objects and between all objects being presented. At the opposite end of the spectrum with a completely real environment where

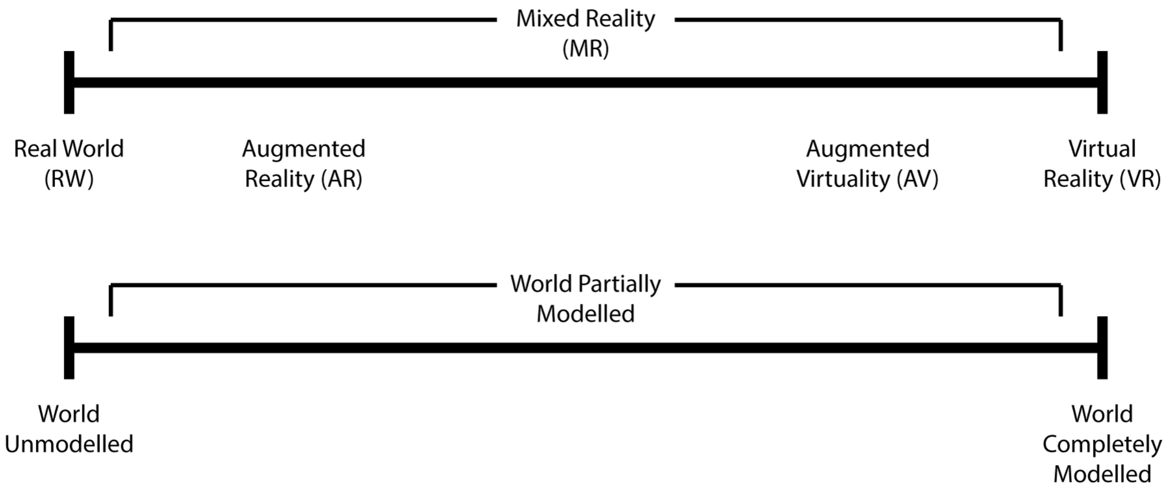

Figure 3.1: *Reality-Virtuality continuum* (top), parallel with *Extent of World Knowledge continuum* (bottom).

none of the viewport is computer modelled there is no quantitative information associated with the content being displayed. At any point between the extremes the environment consists of a mixture of some modelled and some non-modelled content; with the computer associating quantitative information to, and between, the virtual objects, but not to the real objects or between the virtual and real objects.

Carrying the continuum concept further, Milgram et al. illustrate their understanding of the existing term *augmented reality* and also introduce two related new terms; *augmented virtuality* and *mixed reality.* In this fashion, *mixed reality* is used to describe any environment that is not completely real or completely virtual; that is, it encompasses all positions on the continuum between the extremes. *Augmented reality* is used to describe a real environment upon which virtual objects are overlain and *augmented virtuality* is used to describe a virtual environment upon which objects sampled from the real world (such as video feeds) are overlain. It is also shown here that *mixed reality* encompasses both *augmented reality* and *augmented virtuality.*

One obvious question raised from studying this figure is at what point toward the centre of the continuum an environment changes from being *augmented reality* into *augmented virtuality* or vice-versa. The answer lies with consideration of the quantitative knowledge associated with the objects that comprise the viewport.

For example, if one were to take a viewport depicting a purely real environment and then incrementally add more and more virtual objects, the environment's classification would progress rightward along the continuum. Eventually the entire viewport would be obscured by virtual objects and the obvious conclusion would be to classify the environment as being purely virtual. However this would only be true if there was complete quantitative information associated with, and between, all of the virtual objects within the real 3D space of the viewport, which is unlikely to be the case.

Likewise if one were to take a viewport depicting a purely virtual environment and incrementally replace the entire viewport with sampled real objects we could not classify the resultant environment as purely real as there would be associated quantitative knowledge with and between the sampled objects, meaning that the environment isn't completely unmodelled and thus can't be classified as purely real.

Thus, Milgram et al. conclude, it is not necessarily true that an environment is purely virtual simply because all of the visible objects are computer modelled, nor is it necessarily true that an environment is purely real simply because all of the visible objects are sampled from the real world.

3.1.2 Waterworth & Waterworth's Three Dimensions of Virtual Experience

Haven't actually mentioned anything about presence in the review so far, have we?

The virtuality continuum is here considered to be analogous to the *locus of attention* axis of Waterworth & Waterworth's *three dimensions of virtual experience* model [18]; the combination of these models is shown by figure 3.2. In this model, locus of attention represents the environment where the stimuli that the user is perceiving originate from; focus of attention represents the balance between conceptual/abstract reasoning & perceptual/concrete processing, where complex conceptual reasoning results in little attention being paid to processing environmental percepts (whether originating from real or virtual stimuli) thus reducing presence[1] in that environment toward its antithesis – absence[2]; and sensus of attention represents the level of conscious arousal (or 'wakefulness' [19]) of the user, whether directed toward percepts originating from real stimuli, virtual stimuli, a mix, or not directed toward any percepts in the case of completely 'absent' conceptual reasoning.

3.1.3 Reality Matrix

Another useful method of illustrating the relationships between the different categories of alternate realities was put forward by Roy Want in his introductory article for a 2009 issue of IEEE Pervasive Computing dedicated to the *cross reality* paradigm [20]. Here he presented a 2x2 matrix categorising the different terms according to whether the experience and overlay data are real or virtual (see figure 3.3).

Whilst this is a useful representation, some of the definitions and criteria depicted do not match with those of Milgram et al. or even with those of other authors in the same issue of IEEE Pervasive Computing, let alone other publications concerning alternate realities. Thus this review presents a modified version of Want's matrix, that is better in fitting with the consensual definitions built from reviewing the literature on alternate realities, as figure 3.4.

Where Want has *cross reality* occupying the upper left quadrant at the congruence of 'experience virtual' and 'overlay data real' this review instead places *augmented virtuality.* Referring to Milgram's continuum 'experience virtual' relates to a position somewhere on the right half, while 'overlay data real' relates to presentation over this virtual environment of sampled real world data resulting in a partially modelled environment, leaving us in the area of the continuum occupied by *augmented virtuality.*

Want's matrix also features the term *embodied virtuality* in the upper right quadrant, at the congruence of 'experience real world' and 'overlay data real'. Want explains that this is an alternative term for *ubiquitous computing* which is *"essentially the opposite of VR"*; this review instead reasons that the opposite of *virtual reality* is simply *reality* and that *ubiquitous computing* does not constitute an alternate reality but simply a different model of human-computer interaction that can be implemented in either *reality* or *augmented reality*, depending upon how the computing infrastructure presents information to users.

A *ubiquitous computing* system is necessarily a real environment, as it is by definition the integration and dissemination of computational infrastructure into our real surrounds [21]. However whether this real environment is augmented by virtual objects is not restricted by the concept. Thus *ubiquitous computing* can exist in an environment that is either on the left extreme of the continuum, where no virtual objects are employed and the environment remains completely unmodelled, or somewhere to the right of the left extreme in the region of *augmented reality*, where virtual objects are employed and the environment is partially modelled.

This line of reasoning is supported by an almost complete lack of further mention of *ubiquitous computing* elsewhere in the literature about alternate realities studied for this review. Furthermore the term *embodied virtuality* is not used by any other author in the studied literature.

[1]**Presence** in this context is defined as a state of heightened perceptual processing of environmental stimuli (*"a psychological focus on direct perceptual processing"* [18]) accompanied by lessened conceptual reasoning, whether these environmental stimuli originate from a real environment, a virtual environment, a mixed reality environment, or even from multiple discrete environments.

[2]**Absence** is defined as *"a psychological focus on . . . conceptual processing"* [18].

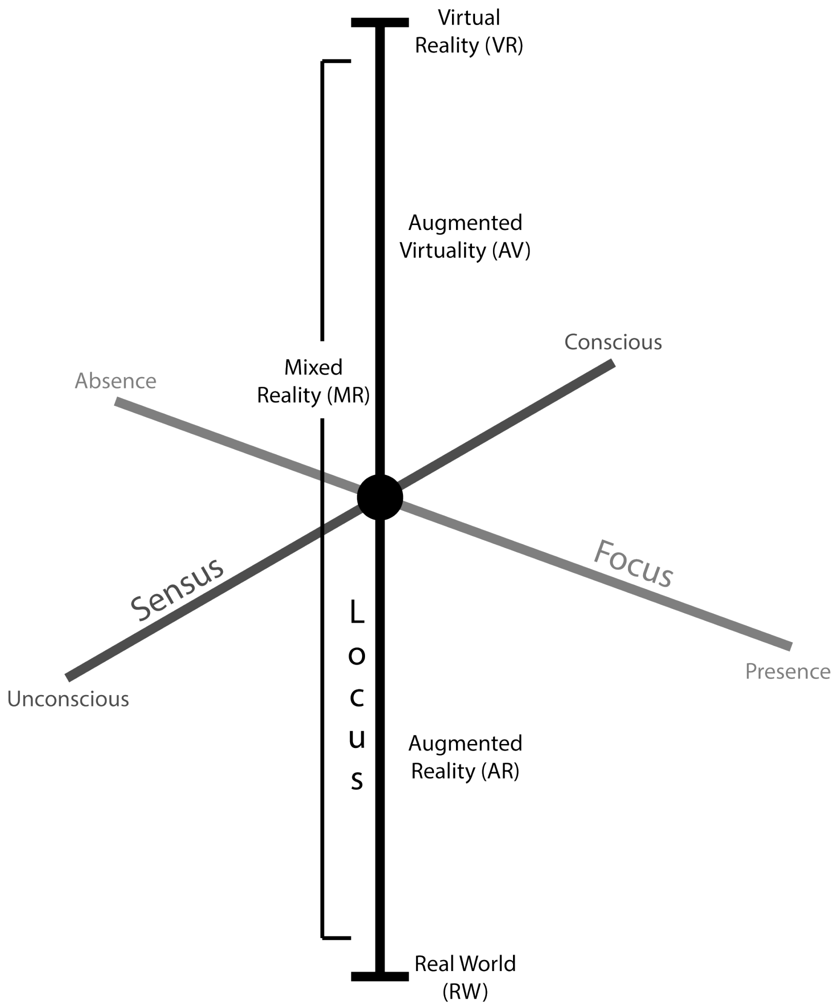

Figure 3.2: The combined virtuality continuum/three dimensions of virtual experience model.

Finally this review has removed the central *mixed reality* section from Want's original matrix, as its position could be misleading. As the boundaries formed between the categories by the different colours could be construed as meaning that there are discrete boundaries between the different categories, rather than a linear scale as depicted by Milgram's continuum, the reader could be led to believe that a purely *virtual reality* or a purely *embodied virtuality* environment can be considered *mixed reality*, which is incorrect. If one wishes to picture the position of *mixed reality* in relation to the modified matrix, it would cover the same area as enclosed by the union of *augmented virtuality* and *augmented reality*.

3.1.4 More Reality Continua

As one of the most prominent academics in the development of the cross reality paradigm (see section 3.3) it is also worth comparing Joshua Lifton's definitions for the different categories of alternate realities and the relationships between them [4] in the current context.

Lifton's definitions, or more accurately his relationships between, the terms *reality*, *augmented reality*, *mixed reality* and *virtual reality* do not perfectly match the consensus that this review has observed. Lifton defines the terms individually in agreement with the consensus, however doesn't proffer the conclusion that

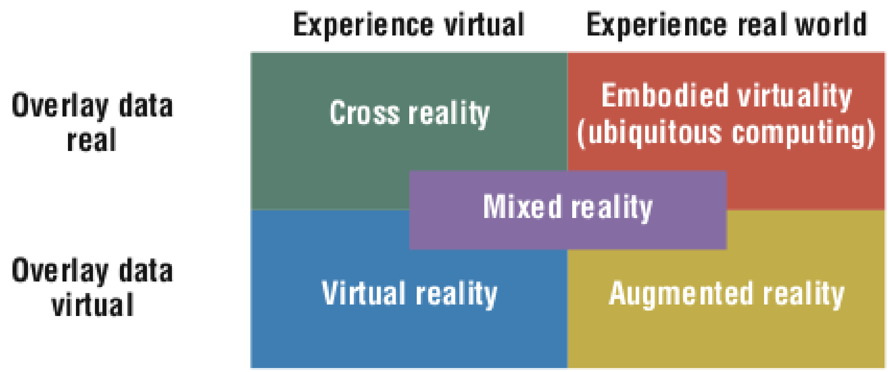

Figure 3.3: Want's original virtuality matrix.

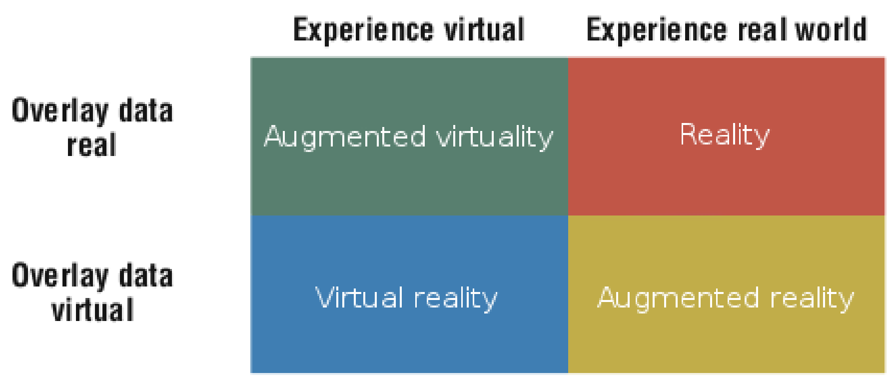

Figure 3.4: Want's virtuality matrix after modification by this review; note removal of *mixed reality*, *cross reality* and *embodied virtuality* and addition of *reality* and *augmented virtuality*.

mixed reality is a broad term that includes augmented reality. He also doesn't mention augmented virtuality, even though the Dual Reality Lab project (see section 3.3.5) does implement it. Finally his diagram that alludes to Milgram's continua and is included as figure 3.5, situates mixed reality at an incorrect position, implying that Lifton's definition of mixed reality is of a discrete state to that of augmented reality, even though his textual definition of mixed reality hints that it logically encompasses augmented reality. This review presents a modified version of Lifton's diagram to illustrate these differences as figure 3.6.

Lifton does however explain that while such a taxonomy can be successfully applied to most alternate reality efforts, it does not well address the concept of cross reality where there are two complete realities, one real and one virtual.

3.2 Adopted Definitions of Alternate Realities

This review has discovered differing (and in some cases conflicting) definitions for the different categories of alternate realities and for the criteria for differentiating between them. What follows in this section represents the definitions and differentiating criteria that this review has adopted after concluding them the

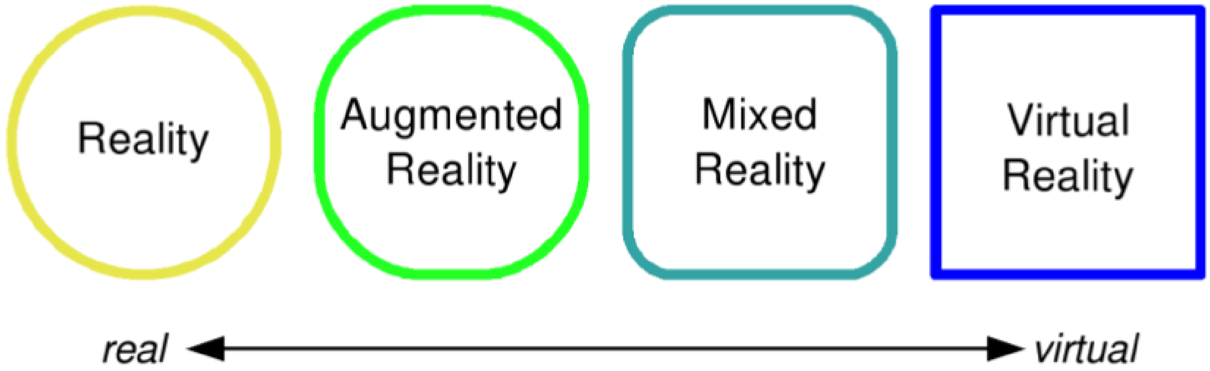

Figure 3.5: The *"virtual worlds taxonomy as viewed on the real-virtual axis"* presented by Lifton.

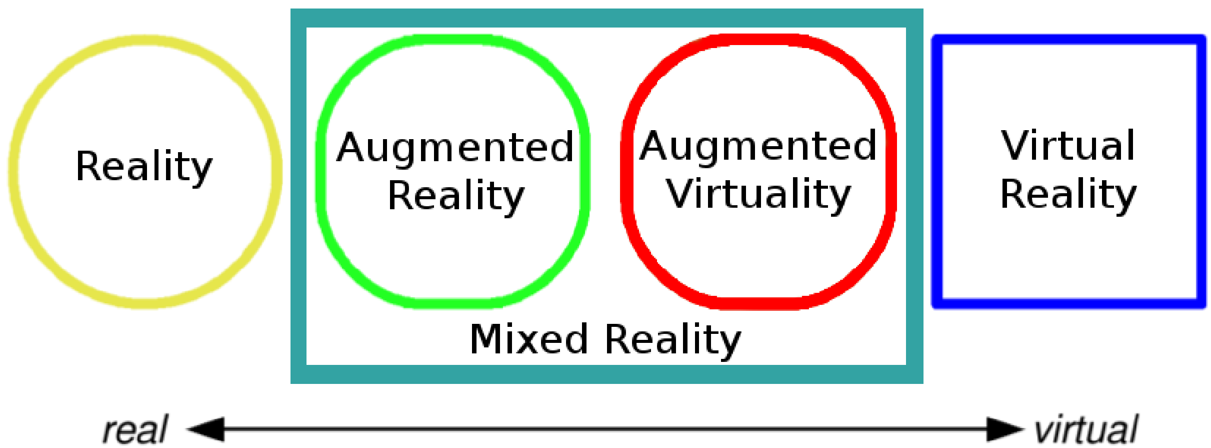

Figure 3.6: Lifton's taxonomy as modified by this review.

most widely accepted and well reasoned.

3.2.1 Reality

Occupying the left extreme of Milgram's continuum and the upper right quadrant of the modified Want matrix, *reality* refers to an environment that is entirely unmodelled, with the viewport containing no virtual objects and no computer-based quantitative information is associated with any of the (necessarily real) objects. In fact, there may be no computer infrastructure involved in the situation whatsoever. This is the situation that we are most familiar with, as it is where the vast majority of us spend the vast majority of our time.

3.2.2 Virtual Reality

The polar opposite to *reality*, a *virtual reality* environment occupies the right extreme of Milgram's continuum and the lower left quadrant of the modified Want matrix. A *virtual reality* environment consists solely of virtual objects, with computer-based quantitative information associated with all of them and between all of them, creating a completely synthetic world entirely discrete and separate from the real world; a new world that exists solely within the data structures of a computer.

Traditional definitions of *virtual reality* require the environment to be completely immersing; that is, when involved with such an environment the user is completely unaware of the real environment that surrounds their real bodies, often making use of Head Mounted Displays (HMD) and head &/or body tracking techniques to improve the sense of immersion by removing the need to interact with interfaces logically anchored to the real world such as keyboards, mice and joysticks [11].

However this review believes that taking the concept to a lesser extreme, the virtual environments presented by video games such as World of Warcraft can be construed as *rudimentary* implementations of virtual reality; they are completely modelled environments that exist entirely separate to the real world, however interaction is not completely immersing due to the use of 2D monitors and traditional interface devices, largely due to the lack of common ownership of HMDs and advanced body tracking systems.

3.2.3 Mixed Reality

Occupying any position between the extremes on Milgram's continuum, the term *mixed reality* refers to a broad range of environments that arise from the merging of real and virtual environments to some extent such that the result is neither entirely real nor entirely synthetic, where real and virtual objects co-exist. As alluded to previously, under this definition both *augmented reality* and *augmented virtuality* are included under the broader classification of *mixed reality.*

This is one definition where Want is lacking, claiming *mixed reality* to be *"some combination of the others"* where 'others' refers to all of *virtual reality*, *augmented reality*, *embodied virtuality* and *cross reality.* This review disregards this definition as it relies upon Want's previously refuted definition of *embodied virtuality* being the polar opposite of *virtual reality* and because it also depends upon Want's definition of *cross reality* which this review will also go on to refute.

3.2.4 Augmented Reality

An *augmented reality* environment occupies a position within the 'left half' of Milgram's continuum, the lower right quadrant of the modified Want matrix and within the broader classification of *mixed reality.* Thus an *augmented reality* environment comprises a real environment that has had virtual objects added to or overlain upon it; a common approach for achieving this addition/overlay is superimposing virtual objects over a direct or indirect view of the real environment using Head Mounted Displays &/or cameras [22].

A commercial example of *augmented reality* is the Layar browser for mobile phones, which overlays various forms of data onto the view captured by a phone's camera after determining its location and orientation using GPS, accelerometer and magnetometer readings [23]

3.2.5 Augmented Virtuality

Logically opposite to *augmented reality*, an *augmented virtuality* environment occupies a position within the 'right half' of Milgram's continuum, the upper left quadrant of the modified Want matrix and again lies within the broader classification of *mixed reality.* Thus an *augmented virtuality* environment comprises a virtual environment, akin to *virtual reality*, upon which sampled real objects are overlain, perhaps through the use of cameras [24].

A simple commercial example of augmented virtuality is the EyeToy accessory and associated software for Sony's Playstation 2 games console (and later the Playstation Eye for the Playstation 3), a digital camera that captures images of players and their surroundings and integrates them into the gaming experience presented on the screen.

3.3 Cross Reality

The discussion of the literature pertaining to the *cross reality* paradigm warrants its own section of this review, as it is not only one of the youngest categories included under the umbrella term *alternate reality* but also the closest existing concept to lend to the simultaneous exploration of real and virtual environments.

3.3.1 Overview of Cross Reality

Cross reality is the ubiquitous mixed reality situation that arises from the fusion of real-world sensor/actuator infrastructure with virtual environments, such that augmented reality and augmented virtuality manifest simultaneously and facilitate synchronous multi-directional exchange of media and control information between real and virtual environments. Sensors collect and tunnel dense real-world data into virtual environments where they are interpreted and displayed to dispersed users, whilst interaction of virtual participants simultaneously incarnates into the real world through a plenitude of diverse displays and actuators [25].

The principle features that distinguish cross reality from other alternate realities that this review has thus far covered are;

1. a shift from single- to bi-directional information flow between real and virtual environments [26]
2. that both environments are complete unto themselves (but are enriched by their ability to mutually reflect, influence and merge into one another). [27]

This thesis presents systems that focus on the second aspect above & extends it by permitting both environments to be experienced at any time & position.

3.3.2 MIT Media Lab Responsive Environments Group

The Responsive Environments Group at MIT's Media Lab, under the direction of Joseph Paradiso, deserve the accolade for the inaugural work in establishing cross reality as a field of research. In their own words, the group *"explores how sensor networks augment and mediate human experience, interaction and perception"* [28] and since 1995 they have produced prolific research in the domain of sensor architecture and wireless sensor clusters [29–39] and perceptive spaces [40–43], establishing a prime research environment, both in terms of experience and available technologies, for a concept such as cross reality to emerge.

The path to cross reality began with the 'Plug' project that created a sensor network comprising power strips imbued with sensing, computational and communicative abilities [44]. By basing the nodes on power strips the platform was ideally suited for broad and unobtrusive deployment in environments where people work and live as power strips already exist in such environments with ubiquity. In addition to sporting a number of different sensors, each Plug node was also able to individually control the output of the four 120Vac sockets, allowing the nodes to act as both input (sensing) and output (actuating) devices.

Parallel to the development of the Plug platform the group also developed two mobile platforms for interacting with the network of nodes. The Tricorder project [45], based around a Nokia 770 Internet tablet, presented users with a two-dimensional map centered and oriented about the Tricorder's physical position and allowed *"real-time point-and-browse"* functionality to browse the sensor data from nodes within the vicinity. The Ubicorder [46] project made use of a tablet laptop computer and allowed users to graphically define, and recursively combine, rules for translating sensor data to higher order and potentially more meaningful events.

The true birth of cross reality at the Media Lab came from the combination of the Plug platform with the Second Life virtual world in the Dual Reality Lab project which is comprehensively covered in Joshua Lifton's PhD thesis entitled 'Dual Reality: An Emerging Medium' [4] and summarized in [27]. The term 'dual reality' would later evolve into what we now know as 'cross reality', an association confirmed by Lifton himself [47].

3.3.3 Dual Reality: An Emerging Medium

Perhaps the most interesting and topical discussion within Lifton's thesis for the purposes of this literature review is the discussion of what he calls *'the vacancy problem'*, defined as

> *"the noticeable and profound absence of a person from one world, either real or virtual, while they are participating in the other. Simply put, the vacancy problem arises because people do not currently have the means to be in more than one place (reality) at a time. In the real world, the vacancy problem takes the form of people appearing completely absorbed in their virtual reality, to the exclusion of everything in the real world. In the virtual world, the vacancy problem takes the form of virtual metropolises appearing nearly empty because there are not enough avatars to fill them."*

Lifton identifies that this vacancy problem is a fundamental characteristic of the current generation of virtual worlds and proposes dual reality, more closely linking the real world with the virtual world, as an approach to mitigate the problem.

3.3.4 IBM Virtual Universe Community

IBM was influential in the 2006-2009 wave of virtual worlds,their involvement starting through grass roots interests on internal blogs and on Second Life [48–50] from people such as Ian Hughes, at the time an IBM Software Strategist, and eventually expanding to include around 8000 employees (including the CEO at the time) and the creation of an Emerging Business Unit (EBO) - IBM's way to venture capital new ideas and see how they fit. A number of impressive projects were undertaken, the most high profile of which were the Wimbledon projects of 2006, 2007 and 2008 [51, 52]. Journalist Rita King provided a good write-up of the entire story of the 'Virtual Universe Community' at IBM [53] and various projects were featured by both Businessweek [54] and the BBC [55].

Ian Hughes confirmed via email to this review the extent toward a cross reality system that these investigations progressed

> *"The control mechanisms worked two ways generally. There was a physical lab that had devices that were controlled by a pub/sub mechanism based on the light weight protocol MQTT. Those devices subscribed to various messages. So initially web pages controlled them. The web page generated the message that was broadcast to everything that was interested, sending on/off messages. Equally the objects generated messages when they were physically switched on and off. As SL had an RPC interface it was possible (using another software component outside of SL) to subscribe to the same messages and send requests into SL to change states of object. Likewise it was simple to make an object when clicked or some other event in SL send a message back out. So there were lights, blinds, proximity detectors and even the tilt sensors on the laptops that were instrumented with these messages."*

So whilst Lifton and the other researchers at the Media Lab cannot necessarily be credited with 'inventing' cross reality or performing the very first implementation of it, they deserve the accolade for being the first to perform an in-depth academic investigation into the concept, framing it as a new area of research interest.

3.3.5 Shadow Lab

The most impressive creation of the MIT Dual Reality Lab project was the 'Shadow Lab', *"a space in Second Life modelled after the third floor of the MIT Media Lab's Wiesner building, where the Plug sensor network is most often deployed", 3.7.* This comprised a to-scale two-dimensional floor plan of the entire third floor of the building and a three-dimensional reconstruction of the Media Lab itself.

Around the Shadow Lab were distributed a number of 'data ponds' that each represented the data from a single Plug node. Each pond consisted of a number of waving stalks growing out of a puddle of water on the ground, with the different types of data affecting the appearance of different features; light affecting the pattern of the stalks' skin, temperature affecting their colour, motion affecting the stalks' motion, sound affecting the size of the puddle and electrical current (of devices drawing power from the 120Vac sockets of the Plug node) affecting the intensity of ethereal foxfire rising from amongst the stalks. These virtual data ponds allowed for the real-to-virtual, augmented virtuality aspect of the system. Inversely real world versions of the data ponds, each comprising a desk fan shrouded with lightweight plastic, allowed for the virtual-to-real, augmented reality aspect of the system. The airflow through the shroud, and thus the height and sound produced, could be controlled by pulse width modulating the output of the 120Vac sockets of the Plug nodes.

Figure 3.7: Side view of the final Shadow Lab structure, showing the two-dimensional floor plan of the third floor of the Wiesner building, three-dimensional reconstruction of the Media Lab, virtual data ponds and a human-sized avatar.

3.3.6 Ubiquitous Sensor Portals

This is getting closer to what this thesis is about, as we now have simultaneous visual interaction of both constituent environments, although only from pre-determined/fixed positions & a more abstract virtual environment rather than the Shadow Lab of before (the stacked/time-travel image that has been removed from this document).

Following on from the Dual Reality Lab, and now dropping the title dual reality in favour of cross reality, the Ubiquitous Sensor Portal project situated 45 I/O rich 'portals', shown in figure 3.8, throughout the Media

Lab, each with a corresponding extension in Second Life. Each portal comprised a myriad of environmental sensors (passive infrared (PIR) motion, light, sound, vibration, temperature and humidity) in addition to multimedia abilities via a camera, mounted on a motorised pan/tilt platform and capable of capturing still images as well as DVD-quality video, microphone and small touch screen display. They also featured active IR links that allowed them to communicate with various wearable badges in development by Media Lab researchers to identify users stood at a portal, and in addition could be used as reflection proximity sensors to detect the presence of unbadged users. When a user is present at a real portal, a white ‘ghost’ is displayed by the corresponding virtual portal if they cannot be identified by badge, and their name displayed if they can. Video and audio from the real portal can be streamed into Second Life and a stream from a Second Life client streamed to the screen of the real portal.

Figure 3.8: A Ubiquitous Sensor Portal.

However in stark contrast to the Dual Reality Lab, the virtual portals were not situated in a simulation of the real Media Lab in situations corresponding to their physical location, but instead used a more abstract virtual representation with a geometric layout; this design, shown in figure **??**, reflected intellectual affiliation as opposed to real-world location and also allowed for intuitive browsing of past still images and videos captured by the real portal.

The ability of a person to walk about the real building and for their presence in front of different portals to be reflected in Second Life addressed the vacancy problem to some extent by allowing the user to explore the real environment in a normal fashion but for their position to occasionally be updated in the virtual environment. However the abstract layout of the virtual environment presents a method of virtual environments exploration disjoint to the physical layout and relationship between the portals themselves, which is not ideal for all applications.

3.3.7 Doppellab

This isn't really cross reality by anybody's definition & is just a neat 3D visualisation of sensor network data.

The current cross reality project undertaken by the Media Lab is the ongoing Doppellab, *"an immersive, cross-reality virtual environment that serves as an active repository of the multimodal sensor data produced by a building and its' inhabitants"* [5, 56]. Doppellab uses the Unity3d game engine to allow users to visualise current and historic sensor data captured by a wide range of sensors distributed throughout the Media Lab in a three-dimensional virtual reconstruction.

However despite claiming to be a cross realtiy project, there is no evidence in the associated literature of any virtual-to-real, augmented virtuality data flow, which is a requirement of a cross reality system. Furthermore with regards to the vacancy problem, Doppellab *"focuses on encouraging and enriching individual users' experiences of sensor data in 3-d environments"* and as such is of only passing interest to this review, as simultaneous presence in real and virtual environments must inherently support multiple users present in the same real and virtual surroundings to be of any great use.

3.3.8 X-Reality

Marie Kim, Hwang Jae Gak and Cheol Sig Pyo at The Electronics and Telecommunications Research Institute, Korea, produced a Universal Sensor Network (USN) middleware, COSMOS, to address the issue of heterogeneity of sensor/actuator infrastructure that leads to difficulty in integrating them with virtual environments to establish a cross reality, or as they write it 'X-reality', system [26].

The matter of standards with relation to cross reality is discussed further in section **??** however Kim et al.'s article is mentioned here as its introduction section frames and explains the cross reality paradigm well in terms of the principle features

> *"The important point of X-reality is a paradigm shift from single-directional information flows to bidirectional information flows between two worlds."*

and also how it can be employed for simultaneous presence in real and virtual environments

> *"The differential characteristic of X-reality is that it can augment user's engagement in the experiences of virtual presence and virtual world. Ultimately, it results in the human life span extension from the only real world to both worlds."*

This quote is good for this thesis.

3.3.9 IEEE Pervasive Computing - Cross Reality Environments

The July-September 2009 issue of IEEE Pervasive (volume 8, number 3) was entitled 'Cross Reality Environments' and serves both as attestation to the research promise of the paradigm and as a good survey of the state of the art in cross reality research at the time of publication. The issue is introduced by Roy Want [20], whose definitions and matrix representation of the different categories of alternate realities were discussed in section 3.1.3, whilst the guest editor's introduction is provided by Joseph Paradiso, director of the Responsive Environments group at the MIT Media Lab [25], whose work was discussed in section 3.3.2.

Paradiso's introduction frames the background of cross reality very well, explaining the constituent technologies whose evolution will see the paradigm come to be, realising that it promises to serve as an extension of human perception and interaction and contrasting it with other alternate realities

> *We call the ubiquitous mixed reality environment that comes from the fusion of these two technologies cross-reality. Sensor networks can tunnel dense real-world information into virtual worlds, where this data is interpreted and displayed to dispersed users. Interaction of virtual participants can incarnate into the physical world through a plenitude of diverse displays and actuators. We*

can envision a user's interface into this environment as an extension of human perception and interaction, augmenting our five senses well beyond the canonical "here and now" and redefining the meaning of presence."

Beth Coleman's article [8] starts promisingly by further confirming that the terms cross reality and X-reality are interchangeable and then summarising the Eolus One project, an example application of cross reality, as further discussed in section 3.3.10.

Lifton and other members of the Media Lab also have an article in the issue [57], which primarily serves to summarise their current cross reality endeavours (including Plug, Shadow Lab, Ubiquitous Sensor Portals, Tricorder and Ubicorder), but also provides an interesting background to and future visions of the concept from their perspective, leading to this somewhat colourful quote

> *"We see cross-reality precipitating when diverse and ubiquitous sensor and actuator networks meet pervasively shared online virtual worlds, where phenomena freely tunnel between real and contrived continua at a multitude of "wormholes" opened by densely deployed networked devices, seamlessly adapting the level of immersion to match a variable ecology of available interfaces and user context or preference."*

Gotta keep this 'wormholes' quote...

3.3.10 Eolus One

A project from Swiss construction, building services and real estate company Implenia, involving creative minds from SAP, Wago and Zumtobel, as well as some crossover with IBM, that ran for 2 years exploring concepts including building automation, energy monitoring, alert management and preventive maintenance [8, 58]. Eolus One connected real-time data collection and distributed control mechanisms of smart buildings in the real world to a Virtual Command Center (VCC) hosted in Second Life. This connection was facilitated by a hardware and software platform that they created and dubbed the Virtual World Communication Interface (VWCI), which mediated communication between Second Life and various protocols in Building Automation Systems (BAS) including ZigBee, CANOpen and Modbus.

3.3.11 IBM and Implenia

In 2008, during the height of their investigation into virtual worlds, IBM announced their 3-D Data Center technology to allow the recreation of data centres in secure virtual worlds, bringing real-time data from different facilities into a 3D environment to visualize hot spots, data flow, server utilization and more to reduce cost, save time and help reduce carbon footprints [59, 60].

Implenia made use of these solutions to extend the functionality of their existing VCC (see section 3.3.10) by using IBM's virtual world integration middleware, Holographic Enterprise Interface (HEI), to add data from datacentre equipment to their existing virtual world models. Before the advent of this IBM technology Implenia's knowledge of the state of their data centres comprised only of information from the BAS and their VWCI, with no information from the servers themselves.

> *"Until working with IBM we only knew the state of our data center from the information we got through the building automation system and our virtual worlds communication interface. We didn't know the state of the server and information that was readily available to us until it was made more accessible via the 3-D visualizations that IBM built for us. We think that by combining this information with the information we had from the building automation side we can, from a building management standpoint, control the data much better and take action to be more efficient."* [60]

3.4 Position of Cross Reality

3.4.1 Position - *Milgram & Kishino*

The position of XR in relation to other alternate realities studied by Computer Science can be visualised using Milgram & Kishino's *virtuality continuum* that stretches from an entirely real environment at one extreme to an ontologically parallel but entirely virtual environment [61] at the other. The explanation herein distinguishes between environments themselves (depicted in figures 3.9 to 3.12 by solid ellipses) & where the stimuli that the user is perceiving originate from (depicted by dashed ellipses).

Of particular importance is to appreciate the distinction between a XR system & an *augmented reality* (AR) system, as both concepts involve user engagement with both real & virtual content. Whilst an AR system features a single environment, comprised of the user's RW overlain by some virtual content, with the user perceiving stimuli from this single augmented environment (figure 3.9), a XR system instead features two discrete environments, one real & the other virtual, each complete unto itself (figure 3.10).

Whilst AR falls within the realms of Mixed Reality (MR), a XR system can be considered as occupying the two extremes of the continuum outwith the MR region. However, XR systems that allow simultaneous interaction with both of their constituent environments blur this definition; using a XR platform such as that discussed in this document, a user can transition between perceiving stimuli from each of these environments (figures 3.11 & 3.12) in a manner that allows them to engage with each environment without becoming wholly vacant from the other.

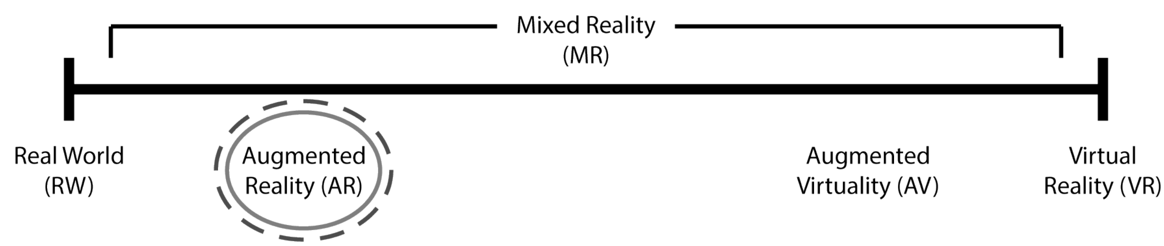

Figure 3.9: AR visualised using the virtuality continuum.

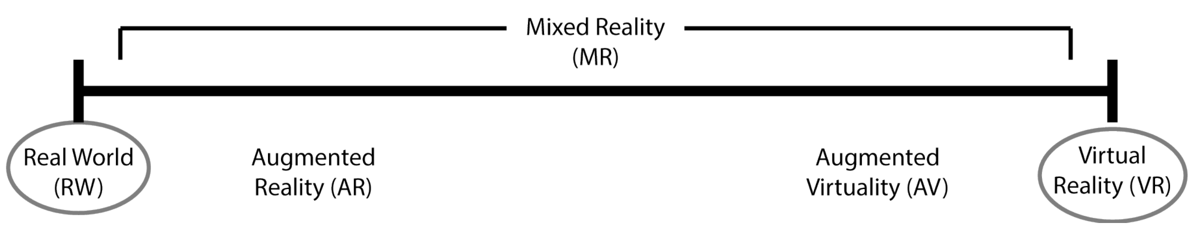

Figure 3.10: The two environments that comprise a XR system.

Is it worth pointing out on the diagram that a true XR system would have a constant bi-directional stream of data between the two environments? And that without this, we have something like parallel reality?

3.5 Informing Mobile XR Implementation / On Presence

The novel aspect of the Mirrorshades platform is the ability it imparts upon its user to switch their locus of attention between equivalent vantage points in RW & VR environments whilst walking around. This is

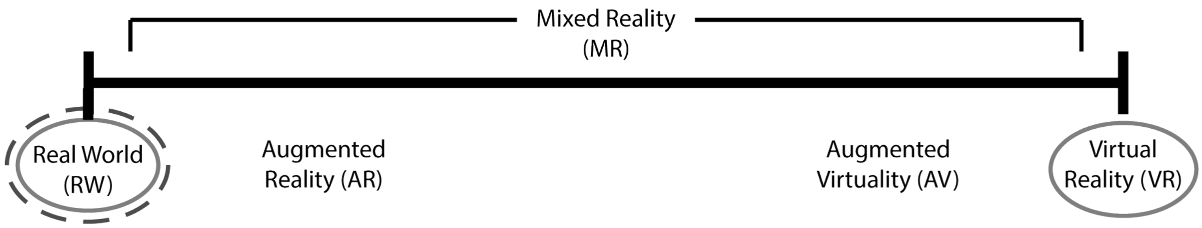

Figure 3.11: A XR system with the user attending to RW stimuli.

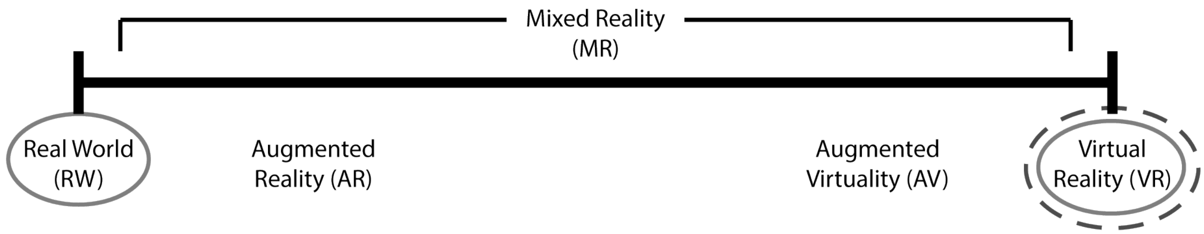

Figure 3.12: A XR system with the user attending to VR stimuli.

achieved by the user performing transitions between RW visual stimuli & VR visual stimuli, both presented via their HMD. This extends existing XR research by allowing the user to engage with the visual stimuli of the VR component of a XR system from any position & at any time.

In order to achieve the highest quality of experience with this style of interaction with XR systems, it is vital to determine how best to implement these transitions; that is, to mitigate the increased cognitive load (manifesting as increased conceptual reasoning & reduced perceptual processing, see section **??**) required to comprehend these transitions, as this increased cognitive load will detract from engagement with the environments & reduce the user's willingness to perform these transitions.

Whilst some researchers support the notion that in systems where more than one environment competes for the user's locus of attention there is an 'all or nothing' Gestalt switch between awareness of one environment & the other [62], which would result in a substantial increase in cognitive load upon each transition, Mirrorshades has been developed in support of the contrary opinion; that switching locus of attention from the stimuli of one environment to those of another does not completely overrule the user's awareness of the former, that both environments can be perceived at the same time (albeit one to a lesser extent) [63] & that when engaging with VR content a user's focus can even be said to typically be *shared* between VR & RW [18].

This latter position is particularly apt for situations wherein the RW & VR environments share the same fundamental layout & dimensions, as those in a XR system often do, as the inherent familiarity between the two environments reduces the cognitive load associated with transitioning between them. Furthermore, the notion of experience of presence as changing continually from moment-to-moment [64, 65] lends confidence to the successful mitigation of the cognitive load associated with these transitions to manageable levels. One might even liken this 'switching' between RW & VR to the 'cycling through' behaviour observed in users of virtual communities, which stemmed from the 'window' concept of modern computer operating systems [66].

However, no matter how smooth the transition the process is expected to always result in some heightened cognitive load, a temporary *break in presence*[3] (BIP), as the user comes to terms with the new environment

[3] The definition of **break in presence** adopted herein is the second from Waterworth & Waterworth [18] (p205): a movement along the focus axis away from presence in the real or a virtual environment & toward absence. This differs to Slater & Steed's original definition in [67] as they considered presence only in terms of attending to stimuli from a virtual environment, with a break in presence as a Gestalt switch to instead attending to stimuli from the real environment. Waterworth & Waterworth's

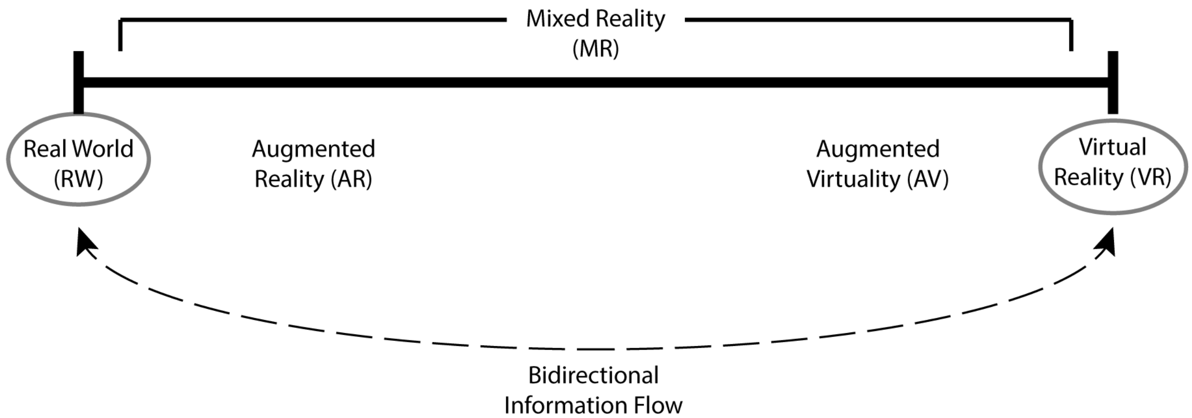

Figure 3.13: The two environments that comprise a XR system, plus the bidirectional information flow between them.

presented to them & comprehends its relation to the other environment that they were just perceiving.

Transitions can be performed in multiple different manners & it is hypothesized that users will prefer different styles of transition in different situations, surroundings & scenarios (where 'preference' toward a particular style of transition is expected to correlate strongly with a less severe BIP being experienced upon its execution).

To this end, several different transition methods have been developed & this investigation will endeavour to identify & quantify preferences toward them, to infer which approaches to transitioning between RW & VR visual stimuli are more or less appropriate for the different situations that arise where a platform like Mirrorshades may be deployed. In particular, it is hypothesized that there will be a strong correlation between participant movement (or lack thereof) & choice of particular transition style.

3.5.1 Transitions using the Combined Model

Visualised using the combined model (see section **??**) as figure 3.14, these transitions are an oscillation along the locus axis, between a RW environment at one position & a VR environment at the other.

Heightened cognitive load required to comprehend a transition is a temporary movement upon the focus axis from presence toward absence (a BIP). With the ability of a wide FOV, stereoscopic 3D, head-tracked HMD to produce immersive VR visual stimuli that require fairly limited cognitive processing & our inherent ability to engage with our RW surroundings without significant cognitive load, focus is expected to be high (toward the presence extremum) when attending to stimuli from either RW or VR.

Sensus is expected to be largely task dependent, however when performing a task that involves actively engaging with the visual stimuli from either/both of RW or VR it is expected to be high (toward the conscious extremum). Upon triggering a transition, sensus is expected to increase, as the user centres their attention upon relating the visual stimuli from the new environment to those they were just perceiving from the other environment

Reviewing the literature on the domain of alternate realities this research finds that there is a gap in the scholarly investigation of simultaneous presence in real and virtual environments and the associated 'vacancy problem'. This review proposes that a better understanding of the extension of human presence from only

model considers presence in terms of attending to stimuli from either the real *or a virtual* environment, with a break in presence representing absence in the sense of heightened conceptual load & the resultant reduced perceptual processing of environmental stimuli originating from *either* the real or a virtual environment. This definition better fits the situation invoked by the Mirrorshades platform, which is concerned with intentionally & willingly switching engagement between stimuli from both real & virtual environments, rather than engaging with stimuli from only a virtual environment in a scenario where stimuli from the real environment are considered a 'distraction'.

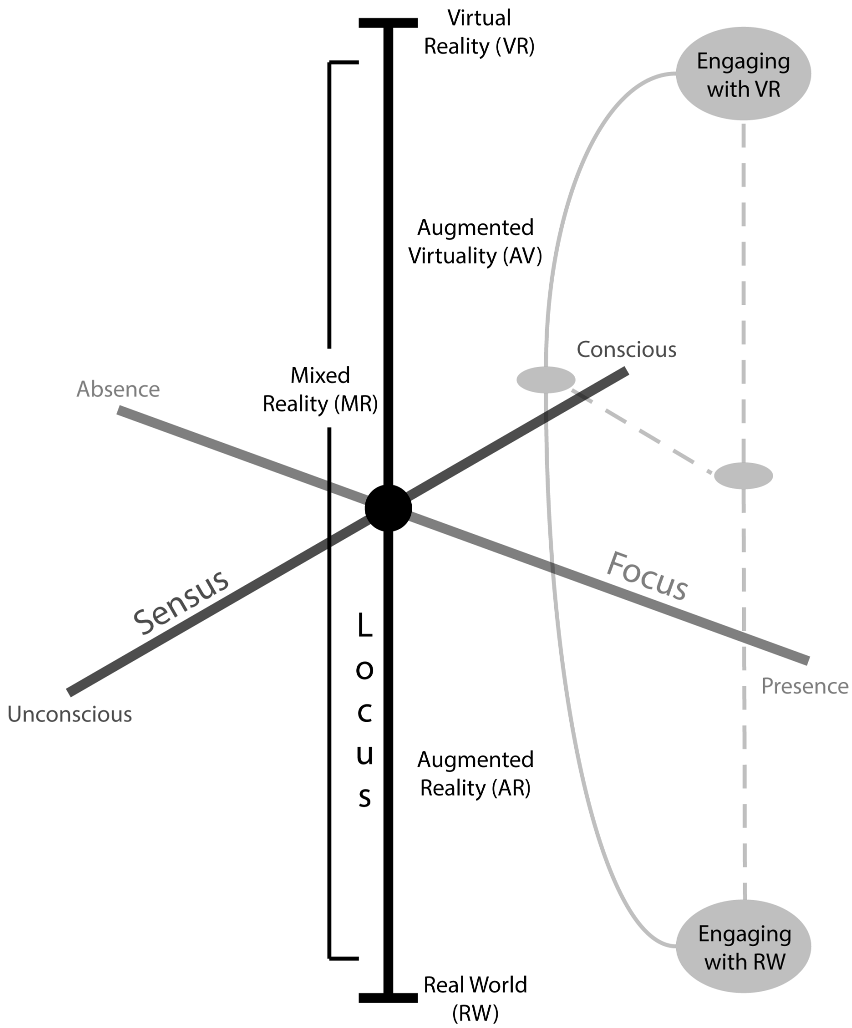

Figure 3.14: Operation of the Mirrorshades platform represented upon the combined model.

one of the real world or a virtual environment to simultaneous presence in both will permit the introduction of novel systems in a variety of fields in which simultaneous interaction and exploration of both real and virtual environments is possible. Such systems will likely be formed by expansion of research into *cross reality*, an alternate reality comprised of complete real and virtual environments able to mutually reflect and influence each other via sensor/actuator infrastructure, and are likely to be in high demand as progress toward 3D extension of the Web continues.

3.6 Conclusions

We are rapidly approaching a situation in which ubiquitous sensor/actuator infrastructure allows us to access vast amounts of information about any location at any time and additionally to act upon this information and affect these locations. The continuing adoption of fast Internet connections, the increasing ability of commodity hardware including portable devices such as mobile phones and tablets to render complex three-dimensional graphics, and the development of 3D multi-user virtual environments that place an emphasis on notions of community, creation and commerce instead of competitive gaming, all point toward a continuing natural progression toward 3D extension of the Web on a large scale.

It is already common to see people spending substantial amounts of time immersed in the 2D textual/graphical Web whilst simultaneously interacting with the real world around them. This desire to maintain a Web presence whilst simultaneously interacting with the real world is set to remain as interaction with the Web evolves from 2D to 3D. Thus it is prudent to investigate approaches for implementing and applications for exploiting the concept of simultaneous presence in real and virtual 3D environments, whether spatially equivalent or not.

This review has unearthed a plenitude of research on numerous alternate realities, either experienced in isolation from other realities (reality, virtual reality) or by mixing limited amounts of one with another (augmented reality, augmented virtuality) however has discovered a comparative lack of research attention focussed on the concept of simultaneous presence and interaction with two complete environments, one real and the other virtual. Cross reality is the closest existing concept, however the vast majority of the research in this field has used statically located computers to access the virtual environments, preventing users from exploring or interacting with the real environment that is not immediately surrounding them; the true notion of simultaneous presence in real and virtual environments requires freedom of movement and interaction with both environments, perhaps by adopting a manner of interaction with the virtual environment similar to that of the VTW project.

This deficiency of research into simultaneous presence in real and virtual environments warrants addressing with further academic investigation, as it represents a style of interaction that is bound to become commonplace as progress toward 3D extension of the Web continues at an accelerated pace.

4

Virtual Time Window

Widespread adoption of smartphones and tablets has enabled people to multiplex their physical reality, where they engage in face-to-face social interaction, with Web-based social networks and apps, whilst emerging 3D Web technologies hold promise for networks of parallel 3D virtual environments to emerge. Although current technologies allow this multiplexing of physical reality and 2D Web, in a situation called PolySocial Reality, the same cannot yet be achieved with 3D content. Cross Reality was proposed to address this issue; however so far it has focused on the use of fixed links between physical and virtual environments in closed lab settings, limiting investigation of the explorative and social aspects. This paper presents an architecture and implementation that addresses these shortcomings using a tablet computer and the Pangolin virtual world viewer to provide a mobile interface to a corresponding 3D virtual environment. Motivation for this project stemmed from a desire to enable students to interact with existing virtual reconstructions of cultural heritage sites in tandem with exploration of the corresponding real locations, avoiding the adverse temporal separation caused otherwise by interacting with the virtual content only within the classroom. The accuracy of GPS tracking emerged as a constraint on this style of interaction.

4.1 Introduction

The rapid adoption of smartphones and tablets and their popularity for social interaction via the mobile Web [68] has led to people increasingly mixing their online and 'real life' behaviours, multiplexing traditional face-to-face social interaction with Web-based social networks and apps. The pervasive provision of these devices provides a new mechanism for people to take physical space for granted, to cerebrally occupy a Web-based location whilst their bodies are simultaneously established in a physical location [69]. The term PolySocial Reality (PoSR) has been proposed to describe these multiplexed mixed realities [70], wherein individuals interact within multiple environments [71], and to identify the extent and impact of shared and unshared experience in such situations [72]. Whilst current technologies allow PoSR involving 2D Web content to manifest, attempting the same with 3D content is marred by the 'vacancy problem': the inability to immerse oneself in 3D content whilst maintaining awareness of one's physical surroundings [4], or put another way the inability to simultaneously experience a sense of presence in both grounded and synthetic realities. With the majority of players of popular Massively Multiplayer Online games (MMOs) wishing they could spend more time playing, over a fifth even wanting to spend all of their time in game [73], and with social roles and the community aspect constituting key aspects of these game's popularity [73, 74], exploring approaches for achieving 3D PoSR is prudent as demand for access to 3D social environments will only increase as 3D Web technologies further develop and more increasingly appeal to general social Web users and to educators in addition to gamers.

The capacity of 3D environments to provide extensible collaborative platforms for the reconstruction of cultural heritage sites and the potential of such reconstructions to promote understanding of and engagement with cultural heritage content both in public and classroom settings has been demonstrated [75, 76]. This research tested various deployment scenarios, leveraging different control methodologies (traditional keyboard and mouse, Xbox controllers and gesture recognition via Kinect) and display options (regular 24" desktop monitors, larger 40" televisions and still larger 150" projection) along with voice interaction with actors playing the parts of historical figures. These scenarios support three deployment modes; a network of reconstructions accessible via the Internet as part of the OpenSim hypergrid; portable LAN exhibitions where multiple computers are connected to a server via local network suitable for classroom use; and immersive installations combining projection and Kinect for use in museums and cultural heritage centers. In all these scenarios a recurrent theme has been the relationship between the virtual reconstruction and the physicality of the corresponding physical site. Frequently projects have involved interactions with the reconstruction and subsequent visits and tours of the physical site; however the temporal separation between these activities makes it harder to appreciate the sometimes complex relationships between the two. To overcome this temporal separation of experiencing the virtual and the real it is necessary for the virtual representation to be accessible in tandem at the physical site by overcoming the vacancy problem.

The cross reality concept [4, 25] was proposed as an approach to address the vacancy problem and describes the mixed reality situation that arises from the combination of physical reality with a complete [27] 3D virtual environment. Previous cross reality experiments did not address the explorative nor social elements of the paradigm as they focused on static locations at which the two environments were linked within closed lab surroundings [69]. The project described in this paper addressed these omissions with the Pangolin virtual world viewer [77] that uses a tablet computer with location and orientation sensors to provide users with a mobile cross reality interface allowing them to interact with 3D reconstructions of cultural heritage sites whilst simultaneously exploring the corresponding physical site, providing a sense of presence at both the physical site and in the reconstruction. The primary difference between this style of interaction and the more widely explored Augmented Reality (AR) concept is that cross reality concerns systems in which the virtual content constitutes a complete environment, as opposed to the sparse and discrete objects that AR positions upon a view of the real environment. This allows the virtual environment of cross reality systems to be accessed in absence of the real environment and allows for more encompassing graphical content.

4.2 Scope

The amount that the real and virtual environments that constitute a cross reality system spatially relate to each other is an important design decision which largely prescribes the style of interaction of the system as a whole. If the two environments have a high degree of spatial equivalence, that is to say that even if their visual appearances differ substantially that their fundamental layout and dimensions are the same such that navigating freely in one will never result in a collision with an object in the other (an allusion to the 'mirror world' concept [2, 3, 6]), then monitoring a user's movements within the real environment provides a method for controlling their avatar within the virtual environment without the need for concious manual control. This approach substantially lightens the cognitive load of maintaining a presence in a virtual environment, which is one of the main contributors to the vacancy problem.

This paper presents a cross reality project in which there is a high degree of spatial equivalence between the real and virtual environments, as it deals with bringing together virtual reconstructions of cultural heritage sites with their corresponding real locations. The backdrop for many of the experiments is the impressive ruins of the St Andrews cathedral, while the virtual environment is a 'distorted' [27] OpenSim simulation of the same location that presents a historically accurate reconstruction of the cathedral as it would have stood at the peak of its former glory [76, 78] (see figure 4.1). This is a large reconstruction, over 400m by 600m, of a complex multi-storey building and thus represents a challenge for a mobile device to render and consequently is considered a good platform for testing.

The same pioneering collaborations between computer scientists, educationalists and historians that led to the creation of the St Andrews cathedral reconstruction have also led to the creation of reconstructions of; a 6th Century Spartan Basilica, Virtual Harlem (1921), Linlithgow Palace (1561), Brora Salt Pans (1599), Featherstone Fishing Station (19th century), Eyemouth Fort (1610), an Iron Age Wheel House and Caen Township (1815). These reconstructions provide a platform for interactive historical narratives, a

Figure 4.1: OpenSim reconstruction of the St Andrews cathedral.

stage for visitors to play upon and engage in both serious (and not so serious) games both alone and with other users, and serve as a focal point for educational investigations into local history and culture [9, 18]. The reconstructions have been widely used in a range of real world educational contexts. In the formal sector they have been a vehicle for investigative research, part of degree accredited university modules and used in both primary and secondary education. They have also been used as the content for interactive museum installations, art installations and community groups. This has involved further collaborations with Education Scotland, Historic Scotland, SCAPE Trust, Timespan cultural center, the Museum of the University of St Andrews (MUSA), Madras College, Linlithgow Palace and Strathkiness Primary School.

The project described in this paper furthers this previous work by developing a mobile interface to allow students to explore both a physical site and its virtual reconstruction in tandem, rather than having to explore the reconstruction from a computer in the classroom and trying to relate what they had seen to a visit to the physical site at a later date. Figure 4.2 shows how small the spatial separation between the classroom and the physical site was during a session with students at St Andrews' Madras College. This project, introduced in [1], developed a modified version of the Second Life viewer called Pangolin, which through use of sensors allows movement of the avatar and camera to be implicitly controlled by sensing the physical position and orientation of the tablet computer which the user carries and upon which the viewer executes. Figure 4.3 depicts the system in use at the St Andrews cathedral.

Figure 4.2: Aerial photograph of St Andrews demonstrating the distance between Madras College (left ring) and the cathedral itself (right ring). The distance between the two sites is roughly 650m, with the photograph being approximately 1km across.

Figure 4.3: The Pangolin viewer running on a tablet computer at the St Andrews cathedral, with the camera orientation of the viewer synchronised to the physical orientation of the tablet, the view of the virtual reconstruction corresponding to that of the physical ruins.

This system promises to augment exploration of cultural heritage sites by allowing convenient navigation of the 3D reconstruction and stimulating reflection through the close juxtaposition of the remains and an accessible interpretation. The use of a complete virtual environment also allows for the possibility of interaction between individuals and groups at the site with remote participants, including domain experts, who are connected to the reconstruction from a distant physical location.

4.3 Methods

4.3.1 Virtual Environment

The 3D virtual environment component of the Pangolin system was implemented using the Second Life/OpenSimulator (SL/OpenSim) platform, which provides a 3D social-oriented multi-user non-competitive virtual environment which focuses on the community, creation and commerce [12] aspects of many users interacting within a shared space through the abstraction of avatars, rather than the competitive natures of games and the solitary environments commonly afforded by simulation and visualization platforms. The distributed client/server model of SL/OpenSim, wherein 3D content is stored on a grid of servers operated by a multitude of organizations and distributed to and navigated between by dispersed clients on demand when they enter a particular region rather than being pre-distributed as is the norm for games, simulations and visualizations, is analogous to the manner in which 2D social Web content is served from Web servers to client browsers and apps. This style of content delivery is necessary when considering the dynamic and ephemeral nature of consumer-generated media which constitutes the majority of the current 2D social Web and will make up the majority of expanding 3D social Web content.

Whilst SL/OpenSim encapsulates many of the desirable architectural features for 3D PoSR experiments it does not support execution upon familiar mobile platforms (Android/iOS) nor does it provision for avatar control from sensor data. However the open source nature of the SL viewer allowed modifications to be effected, enabling control of the avatar and camera from real time data collected from position and orientation sensors connected to a tablet computer. This ability to control navigation within the 3D virtual environment without explicit conscious input of keyboard/mouse/touch commands is integral to reducing the cognitive load required to maintain a presence within a virtual environment which is a key requirement for overcoming the vacancy problem and achieving successful mobile cross reality.

As the SL viewer is only available for x86 platforms the choice of user hardware platform for the experiments was limited, with the MSI WindPad 110W presenting the most promising solution: a 10” tablet computer sporting an AMD Brazos Z01 APU (combining a dual-core x86 CPU and Radeon HD6250 GPU) [79].

The user's position was monitored using GPS, a solution which is well suited to applications of the system within the use case of cultural heritage; such sites often constitute outdoor ruins at which a clear view of the sky allows for good GPS connectivity. For use cases where a similar modality of interaction is desired whilst indoors then an indoor positioning system would be used; a roundup of such technologies is available in [80].

To reduce computational load on the 110W, the OpenSim server was run on a separate Lenovo ThinkPad X61s laptop computer during the experiments. Due to the limited range of the laptop's wireless interface, the laptop was connected by RJ45 ethernet cable to a Linksys WRT54G wireless router to allow the 110W to access the OpenSim server wirelessly from anywhere within the experiment area. The router was powered from a 12V sealed lead-acid battery. This setup is shown in figure 4.4.

Figure 4.4: Lenovo ThinkPad X61s laptop, Linksys WRT54G wireless router and sealed lead-acid battery providing OpenSim server via wireless to the 110W.

4.3.2 GPS Configuration

The 110W features an AzureWave GPS-M16 [81] GPS receiver; however poor API provision and meager documentation lead to use of a separate u-blox MAX-6 GPS receiver [82] outfitted with a Sarantel SL-1202 passive antenna [83]. The MAX-6 is of higher operational specification than the GPS-M16 and supports Satellite Based Augmentation Systems (SBAS) which improve the accuracy of location data by applying additional correction data received from networks of satellites and ground-based transmitters separate to those of the GPS system. These networks include the European Geostationary Navigation Overlay Service (EGNOS) that covers the UK where the experiments took place.

The product summary for the MAX-6 claims accuracy of 2.5m Circular Error Probable (CEP) without SBAS corrections and 2m CEP with SBAS corrections "demonstrated with a good active antenna" [84]. This means that, in an ideal situation with SBAS correction data available, there would be 50% certainty that each position reported by the GPS receiver would be within 2m of its actual position. The SL-1202 antenna used is passive, however as the distance between antenna and the MAX-6 IC itself in the hardware application is only a few millimeters there would have been negligible benefit from using an active antenna. However whether the SL-1202 constitutes 'good' for achieving the headlining performance characteristics of the MAX-6 is debatable as the definition of 'good' was not provided in the product summary.

The MAX-6 was operated in 'pedestrian' dynamic platform model, use of SBAS correction data was enabled and frequency of readings was set to the maximum of 5Hz.

To determine the real world accuracy attainable with the MAX-6 outfitted with the SL-1202 in situations akin to those of the cultural heritage case study, a walking route around the St Andrews cathedral ruins, akin to the route that an individual visitor or school group might take, was planned and then walked with the MAX-6 connected to a laptop computer via an Arduino operating as a Universal Asynchronous

Receiver/Transmitter (UART) feeding the raw National Marine Electronics Association (NMEA) messages into the 'u-center'GPS evaluation software version 7.0 which logged the messages for later evaluation. Simultaneously for comparative purposes a mid-range consumer Android smartphone was used to record the same track; a HTC One S [85] containing a gpsOne Gen 8A solution within its Qualcomm Snapdragon S4 processor [86] and using Google's 'My Tracks' app version 2.0.3 to record the data. The three sets of positional data (planned route, MAX-6 recorded route and smartphone recorded route) were entered into a PostgreSQL database [87, 88] and the PostGIS database extender's ST_HausdorffDistance algorithm [89] was used to calculate the Hausdorff distances between the recorded routes and the planned route and between the recorded routes themselves. In this scenario, the Hausdorff distance represents the furthest distance needed to travel from any point on the route recorded by the GPS receiver to reach the nearest point on the planned route. Because of the substantially greater inaccuracies identified in the latter part of the recorded tracks, separate Hausdorff distances were calculated both for the complete tracks and also for truncated first and second sub-tracks.

4.3.3 GPS to OpenSim conversion

Translating real world positions, obtained via the GPS receiver as latitude and longitude pairs, into corresponding OpenSim (X,Y) region coordinates is achieved using the haversine formula [90] from spherical trigonometry. The prerequisites for this approach are that the OpenSim model is aligned correctly to the OpenSim compass as the real location is aligned to real bearings (although provision to specify an 'offset' within the Pangolin viewer for non-aligned models would be a trivial addition), that the model was created to a known and consistent scale and that a single 'anchor point' is known for which both the real world latitude/longitude and corresponding OpenSim (X,Y) region coordinates are known.

Using the haversine formula the great-circle (or orthodromic) distance between the latitude of the anchor point and the latitude of the new GPS reading is calculated, then applying the scale of the model results in the equivalent distance in OpenSim metrics between the Y coordinate of the anchor point and the Y coordinate of the position corresponding to the new GPS reading. Repeating the same calculations with the longitude of the new GPS reading provides the distance between the X coordinate of the anchor point and the X coordinate of the position corresponding to the new GPS reading. Adding or subtracting these distances as appropriate to the OpenSim coordinates of the anchor point provides the OpenSim coordinates that correspond to the new GPS reading, to which the avatar is then instructed to move.

The anchor point is specified using global coordinates, not local coordinates. This allows navigation to operate across region boundaries and within mega regions (it is not limited to a single 256x256 meter OpenSim region) and there are no restrictions for the placement of the OpenSim component of the anchor point (it can be anywhere in any region, movement of the avatar can be in any direction from it (positive and negative), it does not have to be at the center of the model or even in a region that the model occupies).

Calculating a global coordinate is simply a case of multiplying the position of the region by 256 and then adding the local coordinate. For example, for an anchor at local coordinate $(127, 203, 23)$ within a region that is at $(1020, 1042)$ the global X coordinate is calculated as $(1020 * 256) + 127 = 261247$ and the global Y coordinate as $(1043 * 256) + 203 = 267211$. Elevation (Z) is ignored due to a combination of the relatively low accuracy of these data attainable via GPS (when compared to the longitudinal/latitudinal accuracy) and as the case study explored involved users navigating outdoor ruins remaining at ground level.

4.3.4 Orientation

To control the SL camera in the required fashion, sensor data is collected for the direction that the user is facing (in terms of magnetic compass bearing) and the vertical angle (pitch) at which they are holding the tablet. Magnetic compass bearing is sensed using a magnetometer and pitch by an accelerometer. Roll data is also captured by the accelerometer, however it was expected that users would keep the tablet in a roughly horizontal fashion when interacting with it, thus using these data to control the SL camera's roll was not deemed to be beneficial and was not implemented.

The 110W does not feature a magnetometer and its tilt sensor is rudimentary (only useful for differentiating between discrete cases of landscape and portrait orientation for screen rotation). Several alternative sensors were auditioned, including the MMA8452, ADXL335, HMC5883L and eventually the HMC6343 which was adopted for the experiments. The HMC6343 combines a 3-axis magnetometer, 3-axis accelerometer and algorithms to internally apply the accelerometer's readings to tilt compensate the magnetometer's readings; tilt compensation is necessary for an accurate compass bearing when the device is not held in a perfectly level orientation, such as when the user tilts it up or down to view content above or below their eye level.

Magnetic declination information was entered into the HMC6343 for the position of the cathedral and the date of our experiments. The HMC6343's hard-iron offset calculation feature was used each time the hardware configuration was altered. The sampling frequency of the HMC6343 was set to its highest value of 10Hz. Orientation was set to 'upright front' to match the physical orientation of the IC in the experiments.

4.3.5 Interfacing GPS/Orientation hardware with SL

The MAX-6 and HMC6343 were connected to an Arduino (the setup used throughout the experiments is shown in figure 4.5) and a 'sketch' (the name given to programs that execute upon the Arduino platform) written to receive the data from the ICs, perform simple processing upon them and relay them to the tablet via USB connection [91]. The TinyGPS library [92] was used to abstract processing of NMEA messages from the MAX-6 to obtain the required latitude and longitude values.

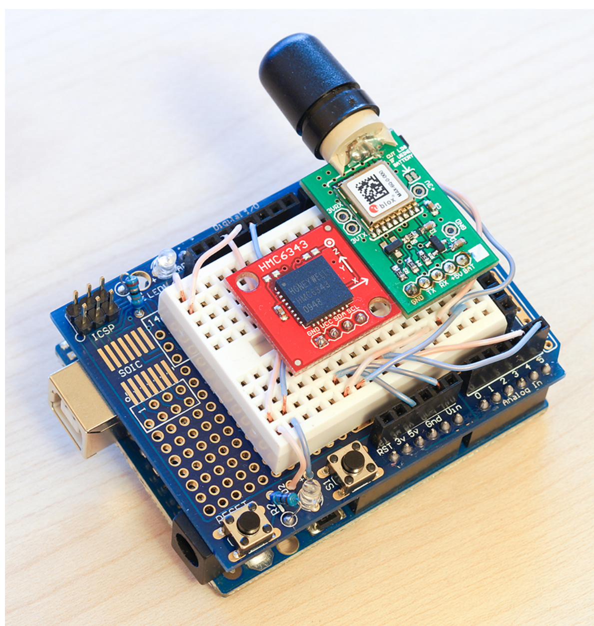

Figure 4.5: The HMC6343, MAX-6 and SL-1202 connected via a breadboard prototyping shield to the Arduino, in the setup and configuration that was then attached to the rear of the 110W for the experiments.

Leveraging standard SL avatar/camera control interfaces was explored by programming the Arduino to mimic a standard USB HID joystick via the Lightweight USB Framework for AVRs (LUFA), sending messages that the viewer interpreted as coming from a joystick and allowing the use of the standard joystick options. However the granularity of control attainable via this method was not sufficient and thus the viewer was modified (giving rise to the Pangolin viewer) to make use of the Boost.Asio C++ library to support receiving data via serial port and to use these data to control the movement of the avatar and camera by directly interfacing with the control functions at a lower level of abstraction. Receipt of messages is performed in

Figure 4.6: The setup from figure 4.5 attached to the rear of the 110W. The sensors are configured such that (in the orientation of this photograph) the X axis is positive pointing straight down, Y is positive pointing straight right and Z is positive pointing perpendicular out of the rear face of the tablet.

an asynchronous non-blocking fashion, with the viewer's main loop processing the most recently received message in each iteration. Messages follow the format

$\langle bearing \rangle$ $\langle pitch \rangle$ $\langle roll \rangle$ $\langle latitude \rangle$ $\langle longitude \rangle$

The viewer's GUI was modified with the addition of a dialogue that allows the user to specify the path of the serial device, separately enable or disable sensor-driven camera and movement control, as well as providing numerous controls for fine-tuning its behavior, including the ability to specify high-pass filters for avatar movement and specify the smoothing applied to camera control. This GUI also presents the necessary fields for input of the anchor point details and fields for diagnostic output of the received information. Figure 4.7 shows this GUI within the Pangolin viewer.

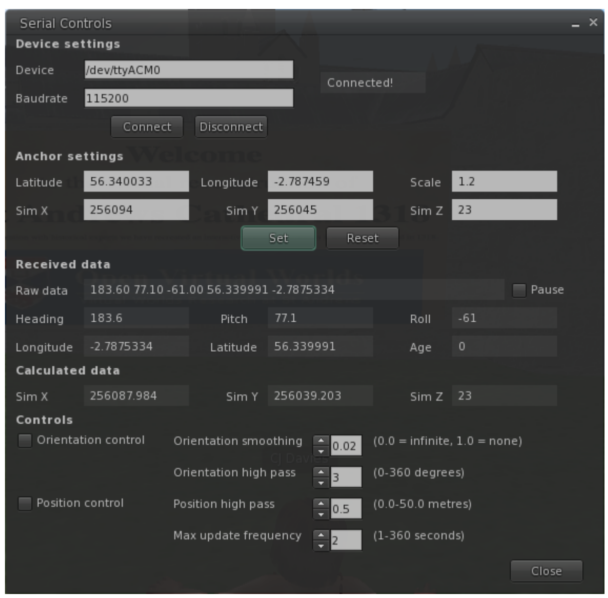

Figure 4.7: The GUI within the Pangolin viewer that allows administration of the position and orientation control of the avatar. In this screenshot Pangolin is connected to the Arduino and is receiving position and orientation data.

4.4 Results

Two plausible modalities of interaction were identified for this system, with each presenting different requirements with regards to accuracy of position tracking.

The first modality is one in which a number of locations that represent points of particular interest are identified. This is already a common practice at cultural heritage sites, with such locations often bearing signs or placards presenting text and/or images explaining what can be observed from the position. With Pangolin, when a user walks within a certain range of such a point, their avatar can be moved to the corresponding location within the reconstruction (and a sound played to alert the user to the fact that there is something of interest to observe) from which they can then move the tablet around them to examine their surroundings in the reconstruction. This modality is similar to audio tours employed by many museums and cultural heritage sites, but replaces the requirement to follow a static route or type in numbers of locations with the ability to freely navigate the real environment with access to additional information being triggered automatically once within the required range of a point of interest.

The second modality is one of free roaming exploration, in which the movements of the user's avatar within the reconstruction mimic the user's movements within the real world as closely as possible. The first modality can be scaled to function with different accuracies of position tracking; as long as the distance between any two points of interest is at least as much as the worst case performance of the position tracking then distinguishing correctly between different points will always succeed. The second modality requires extremely accurate position tracking, arguably surpassing the capabilities of mainstream GPS technology even in ideal situations.

During the experiments the MAX-6 was unable to maintain reception of the additional correction data required for SBAS operation; when left stationary for several minutes reception was possible however subsequent movement of only a few meters at walking pace broke the connection. This reduced the theoretical maximum performance of the unit to 2.5m CEP, with observed performance being lower. Figure 4.8 depicts an aerial view of the St Andrews cathedral ruins; the blue line represents the planned route, red the route recorded by the MAX-6 receiver and green the route recorded by the smartphone for comparative purposes, both while walking the planned route.

Figure 4.8: Aerial view oriented North upward of the St Andrews cathedral ruins; the blue line represents the planned route, red the route recorded by the MAX-6 and green the route recorded by the smartphone whilst walking the planned route.

The Hausdorff distance between the planned route and that recorded by the MAX-6 was $1.02e^{-04\circ}$. The 'length' of a degree of latitude and a degree of longitude depends upon location upon the Earth; around the location of the St Andrews cathedral 1° of latitude is equivalent to 111347.95m and 1° of longitude to 61843.88m. Thus the Hausdorff distance of $1.02e^{-04\circ}$ can be visualized as ±11.3m of North/South inaccuracy or ±6.3m of East/West inaccuracy (or a combination of both N/S and E/W inaccuracy not exceeding a total displacement of $1.02e^{-04\circ}$ from the planned route).

The MAX-6 did achieve better performance than the smartphone, which recorded a Hausdorff distance of $1.33e^{-04\circ}$ ($\pm$14.8m N/S, $\pm$8.2m E/W). The Hausdorff distance between the routes logged by the MAX-6 and the smartphone was $1.14e^{-04\circ}$ ($\pm$12.7m N/S, $\pm$7.0m E/W), which represents a low correlation between the inaccuracies recorded by the two receivers even though they are of similar magnitudes from the planned route.

The maximum inaccuracies were recorded when walking along the South wall of the cathedral's nave. This wall is one of the most complete sections of the building with stonework reaching some 30ft above ground level and providing an effective obstruction to line-of-sight to half of the sky (and substantially impairing reception of signals from GPS satellites) when in close proximity to it. When considering just the sub-route shown in figure 4.9, which terminates before this wall begins to significantly obstruct view of the sky, the Hausdorff distances are notably smaller; the MAX-6 achieved a Hausdorff distance of $7.23e^{-05\circ}$ ($\pm$8.05m N/S, $\pm$4.47m E/W) throughout this sub-route, with the smartphone still behind with $8.99e^{-05\circ}$ ($\pm$10.01m N/S, $\pm$5.56m E/W). Again the Hausforff distance between the receivers showed low correlation between the inaccuracies, at $6.43e^{-05\circ}$ ($\pm$7.12m N/S, $\pm$3.98m E/W).

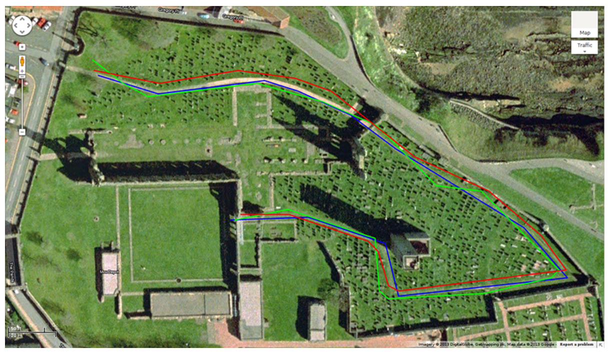

Figure 4.9: Aerial view oriented North upward of the St Andrews cathedral ruins; the blue line represents the first sub-route of the planned route, red the sub-route recorded by the MAX-6 and green the sub-route recorded by the smartphone whilst walking the first planned sub-route.

When analyzing the tracks in the vicinity of the nave (see figure 4.10) it is shown that although the MAX-6 outperformed the smartphone in terms of Hausdorff distance this relationship can be considered misleading as the smartphone track corresponded more closely in shape to the planned route even if it did stray further at its extreme. The discrepancy in the behavior of the two receivers in this situation is attributed to different implementations of dead-reckoning functionality between the receivers. Dead-reckoning is the process used when a GPS receiver loses reception of location data from satellites and extrapolates its position based upon a combination of the last received position data and the velocity of travel at the time of receiving these data.

Pangolin's camera control from orientation data does not have as stringent performance criteria as the movement control from position data. Unlike augmented reality where sparse virtual content is superimposed upon a view of a real environment and the virtual objects must be placed accurately in order for the effect to work well, cross reality presents a complete virtual environment that is viewed 'separately' or side-by-side with the real environment and thus discrepancies between orientation of real and virtual environments have a less detrimental effect to the experience. Although the accuracy of the camera control during the experiments was reported as being sufficient, the speed at which the camera orientation moved to match physical orientation was reported as being too slow, resulting in having to wait for the display to 'catch up' to changes in orientation. This is attributed to the 10Hz sampling rate of the orientation sensors which, particularly after readings are combined for smoothing purposes to reduce jerky movement, resulted in too infrequent orientation updates. Frame rates within Pangolin whilst navigating the route averaged between 15 and 20 frames per second with the viewer's 'quality and speed' slider set to the 'low' position.

The style of explorative interaction with virtual content that this system employs is more resilient to input lag and low frame rates than other scenarios of interaction with virtual content such as fast paced competitive

Figure 4.10: Aerial view oriented North upward of the St Andrews cathedral ruins; the blue line represents the second sub-route of the planned route, red the sub-route recorded by the MAX-6 and green the sub-route recorded by the smartphone whilst walking the second planned sub-route.

video games including First Person Shooters (FPS) [20], but overall user experience would nonetheless be improved by a faster sampling of orientation data and a higher frame rate. Additionally it should be noted that the cathedral reconstruction was created with relatively powerful desktop computers in mind as the primary deployment platform and has not been optimized for use on less powerful mobile platforms such as Pangolin. Performance of Pangolin on a less graphically complex OpenSim region (Salt Pan 2 [17]), that also depicts a reconstruction of a cultural heritage site, was better at 20 to 25 frames per second at the 'low' position and between 15 and 20 frames per second at 'high' (see figure 7).

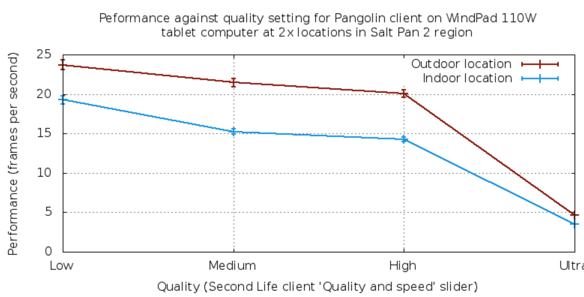

Figure 4.11: Plot of Pangolin's performance (measured in frames per second) against different graphical settings (selected via the 'Quality and speed' slider of the viewer) in two positions within the Salt Pan 2 region.

4.5 Interpretations

The positional accuracy of $1.02e^{-04\circ}$ attained by the MAX-6 is sufficient for the first modality of interaction (that of distinguishing and navigating between multiple points of interest). This value of $1.02e^{-04\circ}$ (analogous to a combination of ±11.3m of North/South inaccuracy or ±6.3m of East/West inaccuracy) represents a constraint on the granularity of the content; it is the minimum distance required between any two points of interest for them to be correctly differentiated between. This same value is not sufficient for the second modality of interaction (that of free roaming exploration with avatars mimicking their users' movements as closely as possible). This modality would require the use of additional position tracking techniques to improve accuracy to around 1m CEP (analogous to $8.98e^{-06\circ}$ latitude or $1.62e^{-05\circ}$ longitude around the location of the St Andrews cathedral).

Use of a GPS receiver that is lower performance than the MAX-6 used by Pangolin, but more common due to being of the calibre integrated into smartphones and tablets such as that used in the experiments, is still sufficient for the first modality but with a larger minimum distance required between any two points of interest. The Hausdorff distance of $1.33e^{-04\circ}$ recorded by the smartphone used in the experiments is analogous to ±14.8m N/S or ±8.2m E/W around the location of the cathedral.

Observed accuracy of the orientation tracking is sufficient for both modalities of interaction; the accuracy of orientation tracking required does not change with different positional accuracy and the accuracy of orientation attained in the experiments is sufficient for an acceptable user experience, however the experience would benefit from better graphical quality and higher responsiveness to changes in user orientation.

4.6 Conclusions

Manifestations of PoSR involving 2D content are commonplace, but whilst the social allures and educational benefits of 3D environments have been recognized the ability to forge PoSR situations involving 3D content remains elusive. As development of 3D Web technologies furthers, the demand for 3D PoSR will grow. The cross reality concept, when freed from static linking between physical and virtual environments, provides a technique to address this shortcoming. This technique has been investigated by the Pangolin virtual world viewer as a mobile, location and orientation aware cross reality interface to spatially related 3D virtual environments. Pangolin aimed to provide a platform for furthering previous use of such 3D environments, for allowing students to learn from reconstructions of cultural heritage content, by allowing them to interact with such reconstructions whilst simultaneously exploring the corresponding physical environments.

Performance of position tracking by GPS emerged as a constraint upon the modality of interaction possible in such systems, with commercially available non-assisted GPS receivers, of the quality built into smartphones and tablets, capable of sufficient accuracies for the 'points of interest' modality to function correctly but not for the free roaming exploration modality.

These conclusions hold for today's commodity technology. We can expect the resolution, processing power and rendering capability of mobile phones and tablets to continue to increase for any fixed price point. Similarly, augmented positioning systems providing greater positional accuracy are likely to emerge. Thus we conclude that the benefits of having accurate virtual interpretations of historic locations available at the sites in a mobile fashion will be available for school visits, cultural heritage investigation and tourists of the future. As mobile 3D cross reality technology becomes common place and matures, applications in education, entertainment, business and the arts will emerge that will surprise us all.

5

Mirrorshades - Design/Implementation

5.0.1 The Case for Mobile XR

A XR system that presents the user with visual stimuli from both its constituent environments (RW & VR) allows that user to engage with both real & virtual content in a manner that is similar to, but has a number of advantages over, a traditional AR system;

- the XR system is less critical of registration (the accurate positioning/alignment) between real & virtual, as the virtual objects are seen as part of a larger virtual environment instead of being rendered atop a view of the real environment;
- the XR system can make use of existing VR content without the overhead of decanting/extracting a subset of the virtual components into an AR framework (e.g. manually selecting which objects within the VR environment are to be displayed over the RW environment);
- the use of a complete VR environment allows the virtual content to be more encompassing & immersive, as presenting a complete VR environment allows total control over lighting, shadows, reflections, particle effects, etc. which would be difficult or impossible for an AR platform to render atop a view of a RW environment.

Thus, such a XR platform is well suited to situations in which interaction with both real & virtual visual stimuli is required & where one or more of the following hold true;

- in lieu of accurate registration between real & virtual, there is a strong focus on the virtual environment's atmosphere & immersion [93];
- there is existing VR content;
- the visual differences between real & virtual environments are so substantial that an AR system would resort to augment (&/or diminish [94]) almost the whole RW view. While AR *"smears an informational coating over real space"* [95], XR presents a complete, discrete virtual environment. AR is beneficial where one wishes the juxtaposition of virtual objects upon what is already present in the RW environment, however VR is better suited to situations where one wishes to present a complete virtual alternative.

5.0.2 Example Application - Cultural Heritage

The field of cultural heritage has seen widespread applications of both AR [96–110] & VR [93, 111–116]. AR has been used to add artefacts, actors & reconstructed architecture to views of present day sites that bear traces of their original status, whilst VR has been used to host more complete reconstructions of entire buildings & settlements for interaction via screen, HMD & CAVE, including where the present day site bears no evidence of the past status or is inaccessible for some reason (due to latter development, change in landscape, etc.).

In situations where VR content exists in cultural heritage contexts, it is experienced from a static position that causes both spatial & temporal separation from the RW location that it relates to; in order to perform comparisons between RW & VR content, users must interact with one & *subsequently* the other. A mobile XR platform will allow VR content in cultural heritage contexts to be experienced in tandem with the real site (where accessible), combining the immediate juxtaposition of real & virtual content of AR with the immersive & atmospheric qualities of HMD based VR, all without requiring alterations to the VR content (for example to make it compatible with an AR framework).

5.0.3 Case Study - St Salvator's Chapel

Founded in 1450 but internally stripped of its medieval fittings during the Protestant Reformation (1517 - 1648), St Salvator's chapel in St Andrews looks markedly different in the present day than it did upon its completion. An existing VR reconstruction of the chapel as it stood in the period 1450-1460 & the marked differences between the internal appearance of the VR building & the current building (including the replacement of the original stone roof with a wooden one & drastically different dividing of the internal space) make this chapel an ideal candidate within the context of cultural heritage for a mobile XR system to be applied. Figure 5.1 shows the 1450-1460 layout of the chapel (including the paths that the IPS has been prepared upon).

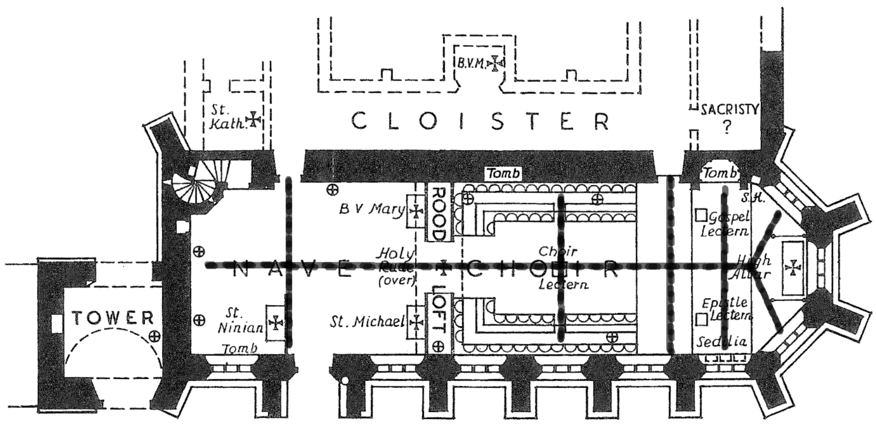

Figure 5.1: Floor plan of St Salvator's chapel, with IPS routes.

5.1 The Mirrorshades Platform

Figure 5.2 presents a high level architectural overview of our mobile XR platform, dubbed Mirrorshades[1].

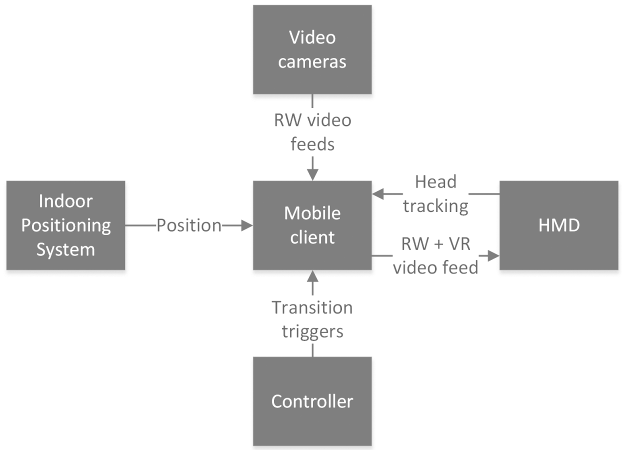

Figure 5.2: Overview of the Mirrorshades platform.

5.1.1 Implementation

Figure 5.3 presents an overview of the implementation of the Mirrorshades platform design for use in the chapel investigations.

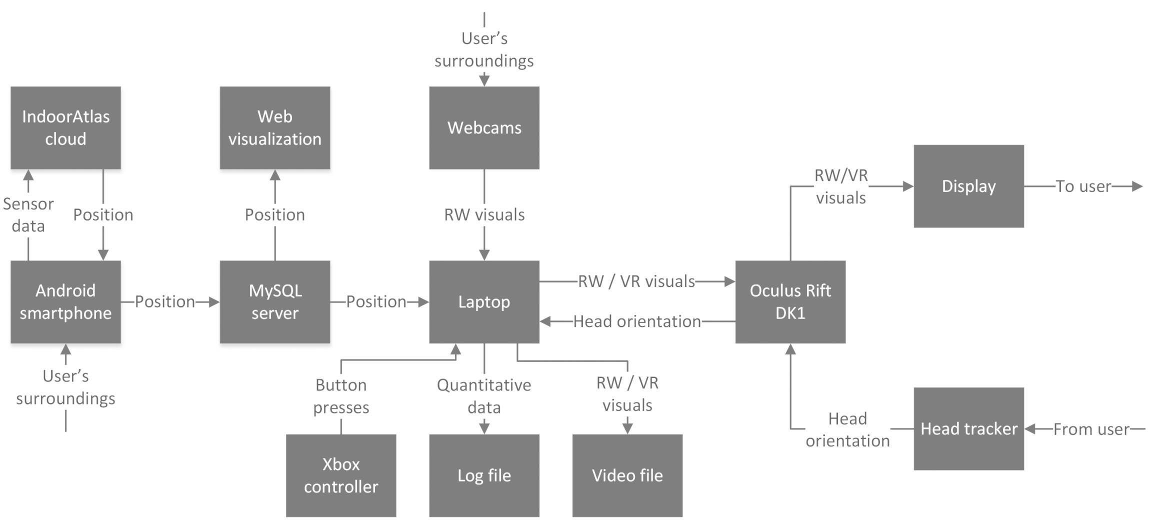

Figure 5.3: Implementation of Mirrorshades platform.

[1]**Mirrorshades: The Cyberpunk Anthology** (1986) is a defining cyberpunk short story collection, edited by Bruce Sterling.

5.1.2 Hardware Components

The hardware of the implementation comprises;

- an Oculus Rift DK1 HMD, including a 9-axis (3dof rotational) head tracker sampling at 1000Hz & mounted with a stereo camera solution comprising 2x Logitech C310 webcams modified with M12 lens mounts & 2.1mm lenses to provide approximately 87 degrees horizontal FOV of the RW environment (see figure 5.4);
- a USB battery pack, to power the HMD;
- a small laptop computer, with an Intel i7-3632QM processor, Nvidia GT 650M graphics card & 16GiB system memory;
- an Android smartphone, running Android 4.4.4;
- an Xbox 360 wireless controller, with USB receiver.

Figure 5.4: HMD with stereo camera solution.

5.1.3 Software Components

The software of the implementation comprises;

- an Android application that runs on the smartphone, determines the location of the phone within the building that it is in using the IndoorAtlas IPS [117] (figure 5.1 shows the paths within the chapel upon which the IPS has been configured) & submits these location data via PHP to a database server;
- a MySQL database server that stores location data for the phone & allows these data to be accessed both by the Unity application running upon the laptop & by a web visualisation;
- a Unity application that runs on the laptop.

5.1.4 Integration of Components

The Unity application hosts the VR representation of the chapel & takes in feeds from both webcams, the HMD head tracker & the Xbox controller. It also polls the database server for the most recent position data. All of these inputs are combined together to form the visual output for the HMD to display to the user.

As the user moves their head, the visuals that are presented to them upon the HMD's display change accordingly; the RW visuals change due to the webcams being physically fixed to the HMD & the VR visuals change due to data from the head tracker being used to change the orientation of the in game 'cameras' accordingly.

As the user changes their position by walking, the visuals that are presented to them upon the HMD's display also change accordingly; again the RW visuals change due to the webcams' position upon the HMD whilst the VR visuals change due to the user's position, as reported by the smartphone & the IndoorAtlas solution, being used to move the position of the in game cameras to the equivalent position within the VR representation.

As the user presses buttons or pulls triggers upon the Xbox controller, the visuals that are presented to them upon the HMD's display transition between RW & VR in different styles depending upon which button/trigger was activated.

5.2 Investigation 1 - The Case for Mobile XR

This first investigation will compare interaction with the RW & VR chapel using Mirrorshades to interaction with the same content separately, the latter being the approach usually adopted for dissemination of VR content in cultural heritage contexts. Participants will complete a task that will promote active comparison & contrast of the RW & VR environments, whilst navigating a set route. This investigation will gauge through experimentation whether the Mirrorshades platform provides any value over the traditional manner in which the same VR content might be disseminated at a cultural heritage site.

5.2.1 Setting & Task

This investigation comprises two phases;

1. Participants will experience the RW & VR chapels separately. They will navigate the VR chapel from a stationary position, as one might expect to see a VR installation at a cultural heritage site, using the Xbox controller to move around the VR environment observed via the HMD. The HMD will obscure their view of the RW chapel around them. Subsequently, they will navigate the RW chapel without the HMD or any associated equipment.

2. Participants will experience the RW & VR chapels in tandem using the Mirrorshades platform. They will wear the HMD, holding the Xbox controller in their right hand & the smartphone in their left, with the laptop & battery pack in a satchel worn over one shoulder. One style of transition will be available to the participants during this phase.

In all 3 scenarios (phase 1 VR, phase 1 RW, phase 2 RW + VR) the participant will navigate the same route & will be instructed to identify a particular feature/object within the chapel (see figures **??** & **??**), situated somewhere upon the set route, that differs in its appearance &/or location between the RW & VR chapels. The order in which the two phases are completed will be randomised between participants, as will the features that they are told to observe in each phase. Participants will have a maximum length of time to navigate the route & will be allowed to stop before this time has elapsed should they wish.

5.2.2 Evaluation Techniques

Evaluation will be performed via a short structured interview & completion of the System Usability Scale (SUS) [118].

5.2.3 Hypothesis

SUS responses are expected to average fairly low due to the cumbersome nature of the platform's implementation. Participants who are able to overcome this cumbersomeness are expected to respond favourably to the platform, with those who cannot overcome it responding in favour of the traditional 'separate' approach instead.

5.2.4 Transition Methods

Attending to visual stimuli from the RW environment via the webcams is required for the user to safely move around. Delay in the IPS reporting their position & inaccuracies in these position data (see figure 5.5 for a set of example position data) mean that moving around while attending only to visual stimuli from the VR environment would not be safe for the user, even with unchanging RW obstacles with perfectly accurate representations in the VR environment. Furthermore it is actually likely that RW obstacles will not have equivalent VR representations, such as in a scenario where XR is used to compare & contrast changes to a building's interior over extended periods of time (such as with the chapel investigations).

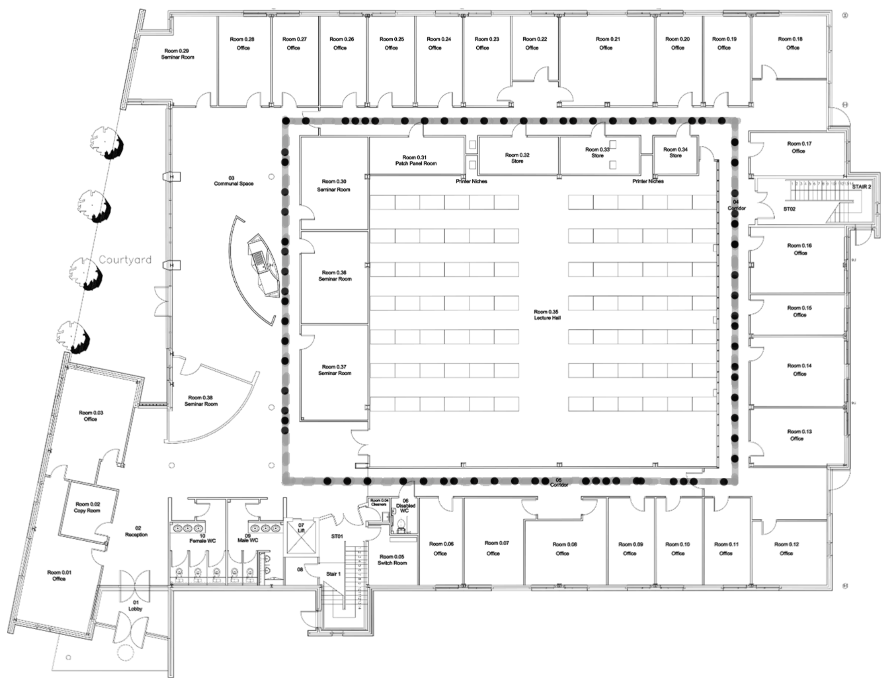

Figure 5.5: Positions (black circles) reported whilst walking a slow lap ($< 1\text{ms}^{-1}$, following gray path) of a departmental building. The building is approximately 40m wide by 30m tall.

Thus the HMD displays the feeds from the webcams as default & the user must trigger transitions to view the VR environment by pressing a button or pulling a trigger on the controller. Releasing the button/trigger causes the webcam feeds to be displayed again.

Hard switch

The user presses & holds the `[A]` button on the controller to switch the visual stimuli displayed by the HMD from RW to VR. When the `[A]` button is released, the visual stimuli displayed by the HMD switch back from VR to RW. This is a 'hard' or 'immediate' switch with no fading or transition effect. Figure 5.6 illustrates this scenario.

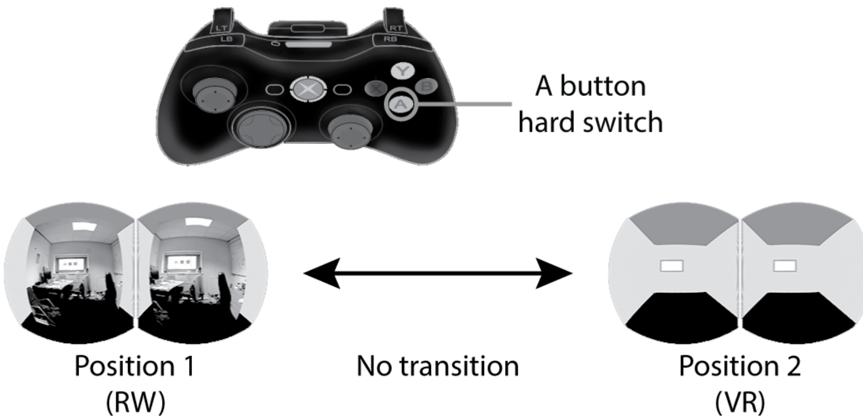

Figure 5.6: Hard switch.

Switch with linear interpolation

The user presses & holds the `[B]` button on the controller to switch the visual stimuli displayed by the HMD from RW to VR. When the `[B]` button is released, the visual stimuli displayed by the HMD switch back from VR to RW. This switch fades between RW & VR visual stimuli using linear interpolation on the opacity of the game objects that the webcam feeds are rendered upon. Figure 5.7 illustrates this scenario.

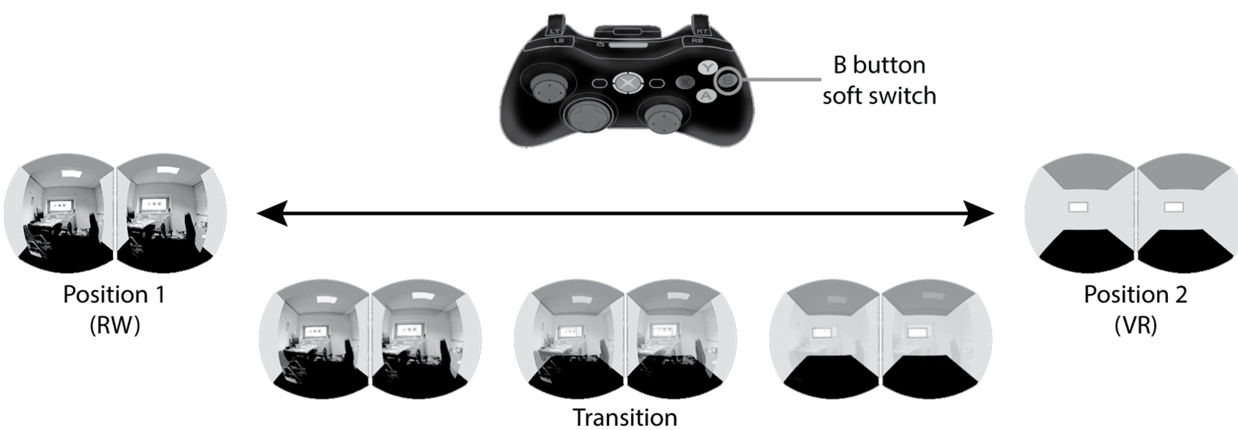

Figure 5.7: Switch with linear interpolation.

Analogue selectable opacity

The user pulls the right analogue trigger (`[RT]`) on the controller, where the position of the trigger maps directly to the opacity of the game objects that the webcam feeds are rendered upon. The user can choose to stop at any intermediary position that suits their needs, keeping the level of opacity of the webcam feeds at that position, as well as controlling the rate at which the visual stimuli from the RW environment fade (by changing how quickly they change their depression of the trigger). Pulling the trigger all the way in displays only visual stimuli from the VR environment, while releasing it completely displays only visual stimuli from the RW environment. The number of intermediary positions is limited only by the resolution of the trigger & the encoding of the value.

This method allows the user to superimpose VR visual stimuli upon RW visual stimuli. This is similar, but not identical, to AR, as instead of displaying a small number of virtual objects upon the user's view of their RW environment, a complete VR environment is superimposed upon the user's view of their RW environment. Figure 5.8 illustrates this scenario.

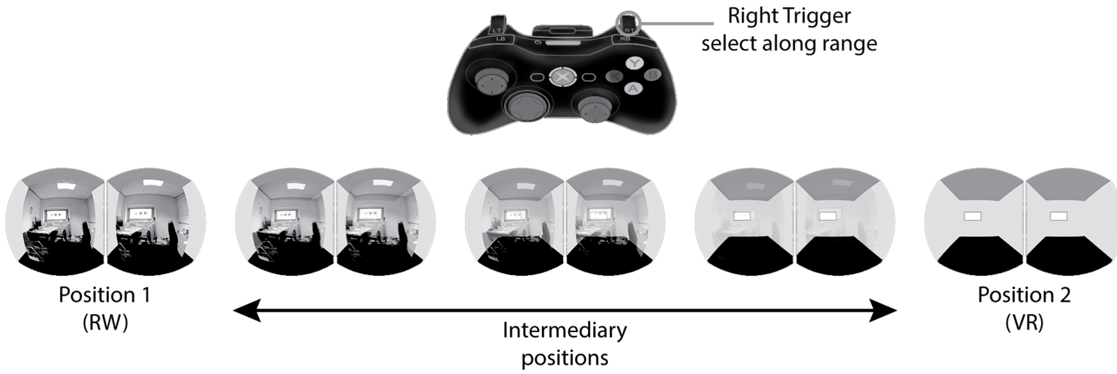

Figure 5.8: Analogue selectable opacity.

Periodic hard switches

Independent or in addition to any of the previous scenarios, the visual stimuli displayed by the HMD switch from RW to VR at a set interval & for a set amount of time. For example, every 3 seconds the stimuli switch from RW to VR for 0.2 of a second before switching back from VR to RW. Any user triggered transitions cause the interval timer to be reset, such that an 'automated' switch will never occur after less time from a user triggered switch than the set interval. Automated transitions are disabled whilst `[RT]` is at all depressed. Figure 5.9 illustrates this scenario, where `i` represents the interval between switches & `d` represents the duration of the switch from RW to VR.

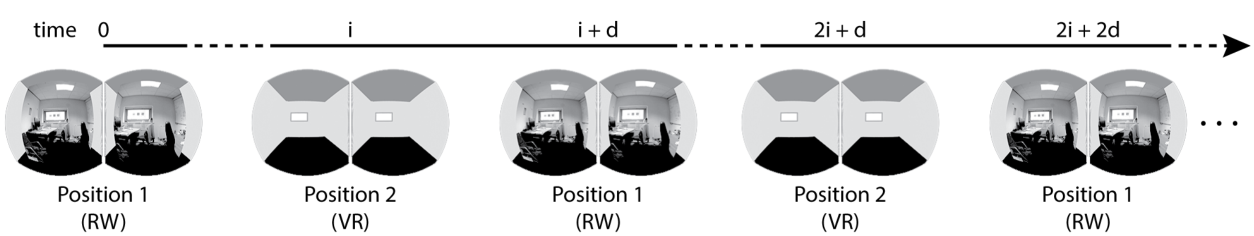

Figure 5.9: Periodic hard switches.

Reduced maximum opacity

Independent or in addition to any of the previous scenarios, the maximum opacity of the game objects that the webcam feeds are rendered upon is reduced, such that the 'default' position at which a transition has not been triggered (either by a button press, trigger movement or by a periodic switch) displays VR superimposed upon RW. Figure 5.10 illustrates this scenario in combination with a hard switch (from section 5.2.4) in which the user triggers hard switches between the default position of a superimposition of VR upon RW & a position where only VR stimuli are present.

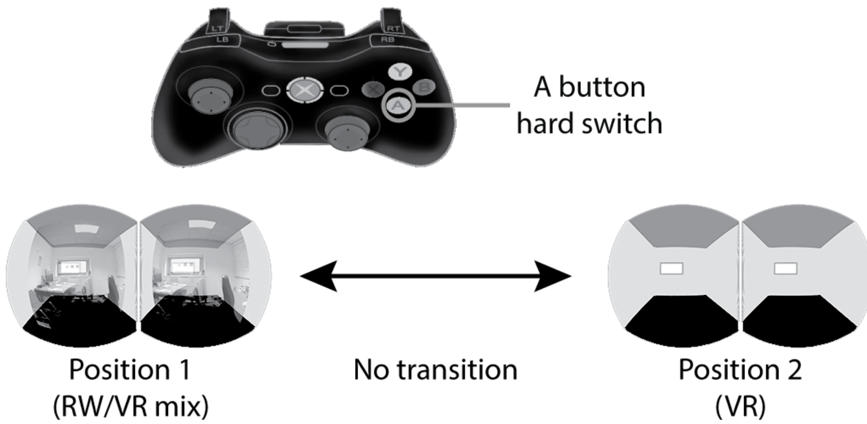

Figure 5.10: Hard switch from reduced maximum opacity.

5.2.5 Experimental Task & Setting

For these experiments, the HMD is worn upon the head of the participant & is connected to the laptop computer, battery pack & wireless receiver worn in a satchel. The smartphone is held in the left hand & the Xbox controller is held in the right hand (all of the buttons & triggers used for these experiments are on the right hand side of the controller, designed to be activated with only the right hand).

A task similar to that employed in the first investigation (see section 5.2 will be employed, encouraging participants to encounter multiple different scenarios of moving, remaining stationary, etc.

5.2.6 Evaluation

Evaluating users' preferences toward different methods of transitioning between visual stimuli in different situations pertains to studying their reactions & responses to ascertain the effect upon their focus of attention, concepts which are largely psychological in nature & highly subjective [63]. Thus, subjective measures will produce the bulk of the data for evaluation. However, objective data will also be collected & cross referenced with the subjective data in attempts to support or contradict any relationships that are identified.

It is hypothesized that a manner of transitioning between visual stimuli which results in a less severe BIP will be preferable to a manner of transitioning which results in a worse BIP. As focus in the Waterworth model is most closely related to presence in the VR literature [18], one of the subjective measures that will be used in this evaluation will be an established presence measure, to try to capture the behaviour of the user's position upon the focus axis.

Subjective Quantitative - Post-Task Questionnaire

After completing the task, participants will respond to the Igroup Presence Questionnaire (IPQ) [119] (see appendix **??** for the items of the IPQ) which will provide subjective quantitative insight into their experiences with the system, in particular in relation to their position upon the focus axis of the combined model. The IPQ represents a useful questionnaire for evaluation of users' subjective experiences of using the Mirrorshades platform because its terms, especially in the 'spatial involvement' scale, question about the RW environment in a manner that does not explicitly present it as a 'distraction' from the VR interaction as many other presence questionnaires do.

Whilst a traditional VR experience would hope to elicit high SP1 & SP4 results combined with low INV1 & INV3 results, Mirrorshades participants are expected to report high SP1 & SP4 combined with *high* INV1 & INV3. The results from participants in this investigation will be compared against those who partook in a 'traditional' VR experience wherein RW stimuli were considered a distraction.

Subjective Qualitative - Interview

A structured interview will be performed after the IPQ has been completed.

Objective Quantitative - Automatic Data Logging

The Unity app logs the following quantitative data each frame to a tab separated variable (`.tsv`) file;

- `<frame number>`
- `<timestamp>` - according to the laptop's internal clock
- `<original_position>` - the position as a Unity `Vector3` where the user begins the experiment
- `<position>` - the position as a Unity `Vector3` where the user is on this frame
- `<delta_x>` & `<delta_z>` - the difference in the `x` & `z` axes between `<original_position>` & `<position>` on this frame
- `<left_rotation>` & `<right_rotation>` - the orientations as Unity `Quaternion` of the two Unity camera game objects
- `<base_oapcity>` - the maximum opacity of the game objects upon which the webcam feeds are rendered (see section 5.2.4)
- `<left_opacity>` & `<right_opacity>` - the opacity on this frame of the game objects upon which the webcam feeds are rendered
- `<auto_tick>` - whether a periodic switch is in progress (see section 5.2.4)
- `<auto_duration>` & `<auto_spacing>` - the interval & duration values of the periodic hard switching
- `<framerate>` - an estimate of the current frame rate (frames per second)
- `<A_button>`, `<B_button>` & `<right_trigger>` - the current values of these inputs on the controller

An example line of this output;

```
420 08-05-2014 12-34-36-257 (3.4, 1.0, -8.3) (0.3, 1.0, -8.3) 3.153522 0.0001955032
(-0.1, -0.7, -0.1, 0.7) (-0.1, -0.7, -0.1, 0.7) 1 1 1 False 0 0 39.57977 False False 0
```

These data are expected to reveal relationships between various different metrics & the choice of transition methods. For example, it is expected that participants will perform short transitions to VR or transitions to a mix of RW & VR when moving & perform longer transitions to VR when stationary. This kind of relationship will support or contradict the subjective data collected through questionnaire & interview.

Objective Qualitative - Video Recording

During experiments, the video feed being displayed by the HMD will be recorded & the user will be recorded using a video camera (both video & audio). The video of the HMD graphics will be used in comparison with the quantitative data, while the video & audio recording of the user will provide objective insight into their behaviour.

6

Mirrorshades - Studies/Results

Studies are split into three parts; Phase 1, Phase 2.1 & Phase 2.2.

6.1 The Case for Mobile XR

This investigation compares two scenarios for interaction with a real location & a corresponding virtual location.

1. **Stationary scenario** - interacting with the virtual location from a fixed real location, then subsequently interacting with the real location.
2. **Mobile scenario** - using the Mirrorshades platform to interact with both the real location & the corresponding virtual location in tandem, whilst moving around both environments.

The locations in question are St Salvator's chapel & a virtual reconstruction of the chapel as it stood in 1450-1460. The stationary scenario is representative of how virtual reality technologies, including both CAVEs & HMDs, have previously been used for dissemination of virtual reality content in cultural heritage contexts [113] & thus this investigation serves to compare Mirrorshades with previous applications virtual reality content to these contexts.

6.2 Process

- Participants complete a pre-task questionnaire, which provides calibration for their subsequent responses by enquiring about age, gender identity, previous experience with VR hardware & previous interactions with either the real or virtual chapel. This questionnaire is included as Appendix **??**.
- Participants familiarise themselves with the experience of using the Oculus Rift DK1 HMD & the Xbox 360 controller by interacting with the 'Tuscany demo' prepared & maintained by the Oculus VR team. This is performed from a seated position.
- Participants complete the stationary scenario.
- After completing the stationary scenario, participants complete the System Usability Scale (SUS) [118] questionnaire, included as Appendix 6.2 & a 12-item questionnaire, included as Appendix **??**.
- Participants complete the mobile scenario.
- After completing the mobile scenario, participants complete the SUS questionnaire & the 12-item questionnaire again.

- Finally, the participant is engaged in a short structured interview. Interview prompts are included as Appendix **??**.

In addition to SUS, the 12-item questionnaire & the structured interview, quantitative data is logged by the Mirrorshades platform when a participant is interacting with virtual content in the first scenario & at all times during the second scenario.

6.3 The Scenarios

Both scenarios that participants complete for this investigation are designed to mimic the style of exploration & interaction that visitors to the chapel display, which was observed over several occasions. Visitors enter the chapel from the North/West corner then proceed to walk Eastwards along the nave, pausing to look around after passing through the rood screen, before continuing along the nave toward the altar. Visitors pause in front of the alter upon reaching the end of the pews & then walk North toward the tomb where they pause again to inspect it. Participants are instructed to imagine that they are performing a similar visit to the chapel & to follow a similar path, pausing after the rood screen, at the end of the pews & in front of the tomb. Participants are shown the map included as figure 6.1 to explain the scenario better.

In the stationary scenario, participants interact with the virtual chapel using the Rift & Xbox controller, whilst in a sitting position. After completing the path, they remove the headset & then walk the same path in the real chapel. This scenario alludes to how virtual reality technologies have previously been applied to cultural heritage situations, allowing visitors to experience a virtual reality reconstruction or reimagination of the real environment from a fixed position & with their view of the real environment wholly occluded by their view of the virtual environment.

In the mobile scenario, participants wear the HMD, hold the Xbox controller in their right hand & the smartphone in their left, with the laptop & battery pack in a satchel worn over the right shoulder. They then walk the same path, but this time with the ability to transition at any time between viewing the real environment & the virtual environment from the same vantage point.

In this first investigation phase, only one transition is available to participants. Preliminary experiments involving the researchers' colleagues that allowed hard transitions, linear interpolated transitions & analogue selectable opacity, indicated that the linear interpolated transition was preferred to either the hard transition or the analogue selectable opacity & thus this is the transition available to participants in this first phase investigation.

6.4 Hypotheses

The aim of the mobile scenario is to improve participant engagement with & understanding of the relationships between the real & virtual environments, by addressing the problems of spatial & temporal separation inherent with the 'traditional' stationary scenario, by imparting upon the participant the ability to transition between equivalent vantage points within the real & virtual environments at will.

While we expect participants to report that the mobile scenario does indeed allow them to better compare & contrast the real & virtual environments, identify differences between the real & virtual environments & gain a better understanding of how the real & virtual environments relate to each other, we expect some participants to report that having to 'split' their attention between the two environments in the mobile scenario leads to lessened engagement & understanding & that the visual quality of the real view through the headset/cameras leads to some participants preferring to interact with the real environment without the headset.

We expect the cumbersome nature of the mobile scenario & the reduced quality of viewing the real environment via the headset/cameras to have a noticeable effect upon participants movement (both position & head orientation) in the mobile scenario.

Addressing these issues, such that participants don't find viewing the real through the headset to be such a reduction in quality compared to just seeing real, such that participants feel as though they can move &

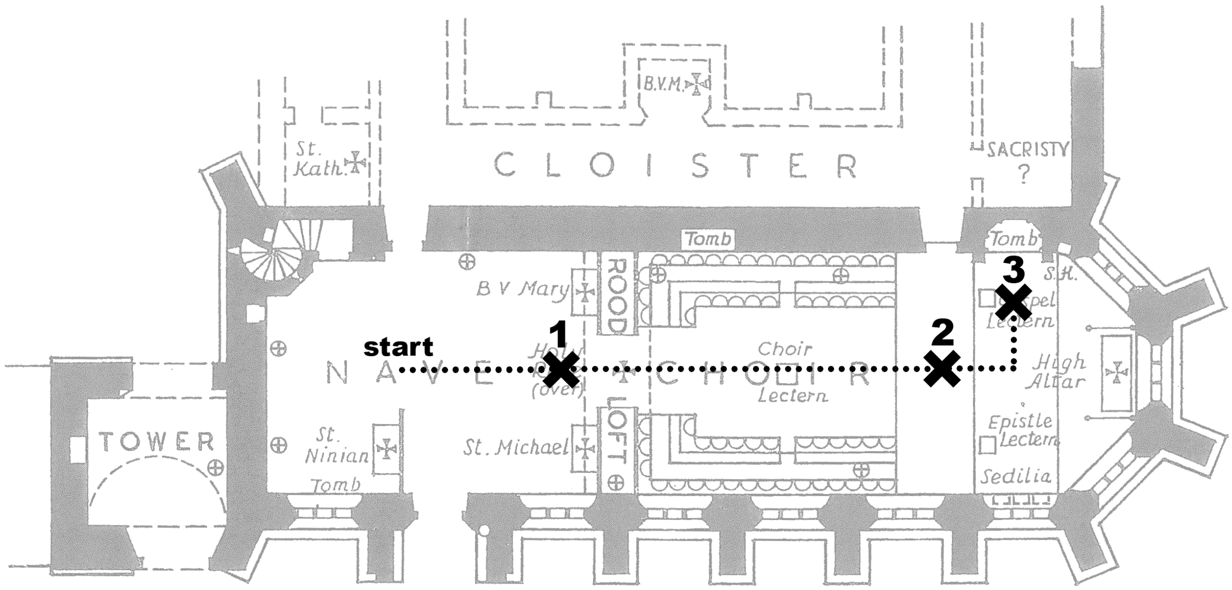

Figure 6.1: The path & positions within the chapel that participants are instructed to attend to.

look around themselves as much in the mobile scenario as in the stationary scenario & such that participants transition between real & virtual at any time instead of avoiding transitions in situations in which they think that they will be unpleasant/jarring, is key & what the next stage will focus on.

6.5 SUS

SUS scores for the mobile scenario are expected to average lower than those for the stationary scenario, due to the cumbersome nature of the platform when performing the mobile scenario; during the stationary scenario, participants are seated, whilst during the mobile scenario they are required to carry a satchel over one shoulder & hold a smartphone in their left hand. Participants who are able to overcome this cumbersomeness are expected to respond more favourably to the mobile scenario than those who cannot overcome it.

6.6 12-item Questionnaire

- Participants will find it easier to compare & contrast real & virtual environments in the mobile scenario than in the stationary scenario (q2)
- Participants will experience a greater sense of ‘being in’ the virtual environment in the mobile scenario than in the stationary scenario (q4, due to physical movement/embodiment)
- Participants will have a greater sense of ‘being in the past’ in the mobile scenario than in the stationary scenario (q7)
- Participants will maintain greater awareness of both real & virtual environments in the mobile scenario than in the stationary scenario (q5)

- Participants will gain a better understanding of what the chapel was like in the past in the mobile scenario than in the stationary scenario (q12)

6.7 Log data

- Head movement (pitch & yaw) will be more restricted in the mobile scenario compared to the stationary scenario
- Aversion to looking around (even at real) when moving in the mobile scenario
- Head movements will be larger discrete changes in the stationary scenario compared to the mobile scenario
- Tendency to only look at virtual when looking around

6.8 Interviews

- mobile scenario makes it easier to spot differences
- mobile scenario reveals differences that stationary didn't
- stationary does not reveal differences that mobile doesn't
- mobile scenario is preferred & is user-reported as 'more engaging'

6.9 Phase 1 Results

6.9.1 Pre-task Questionnaire

For n=5 ages ranged from 21-26, 3x female & 2x male, all reported previous experience using a games console controller, 1x reported previous use of a HMD, 2x reported having previously visited the chapel, none had previously interacted with the virtual chapel model.

6.9.2 SUS

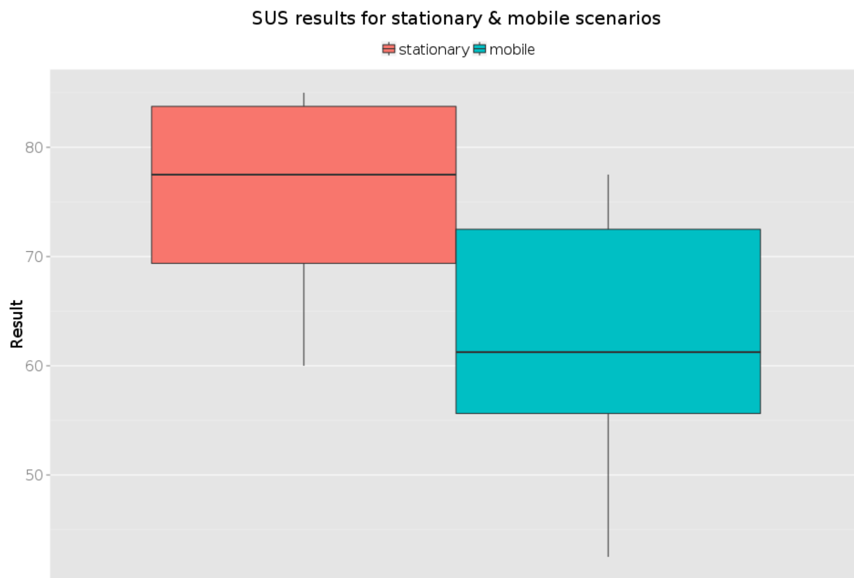

Figure 6.2: SUS results.

As expected, the SUS scores for the mobile scenario are lower than those of the stationary scenario, although not drastically so. Furthermore, although scoring lower on SUS, the mobile scenario came out above the stationary scenario when looking at the results of q8 in the 12-item questionnaire which asked participants if they thought they would have preferred a conventional computer monitor.

6.9.3 12-item Questionnaire

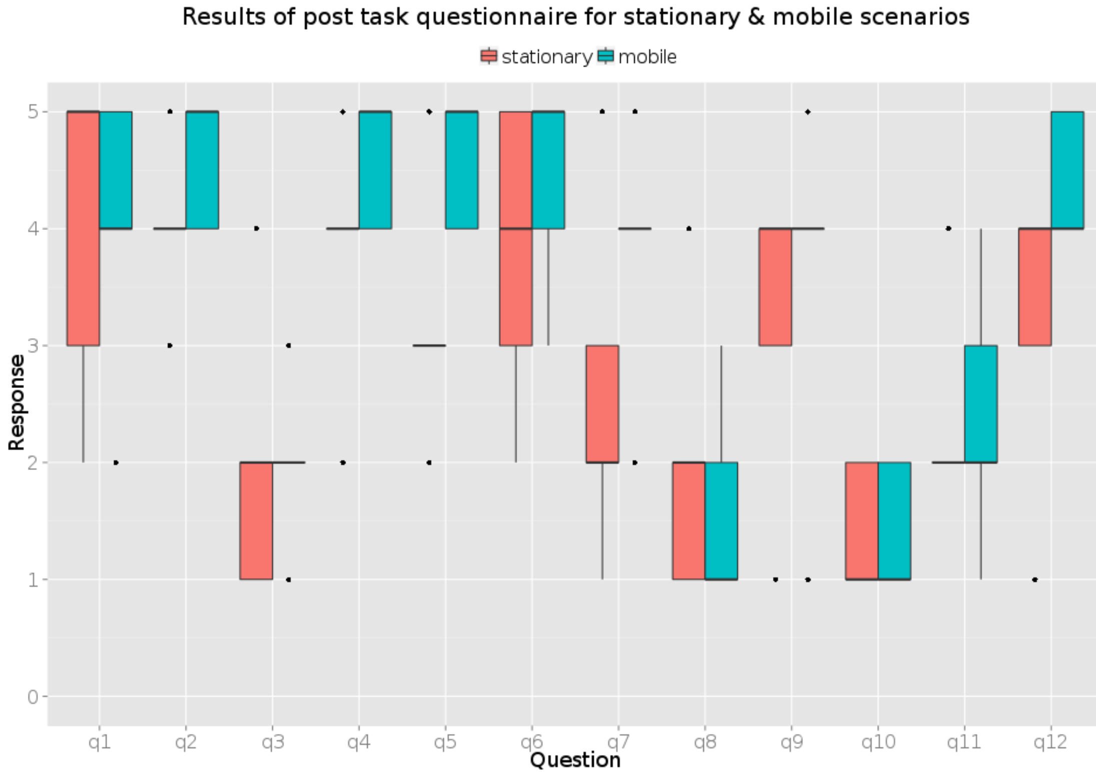

Figure 6.3: 12-item questionnaire results.

The hypotheses seem to hold, in particular;

- *Participants will maintain greater awareness of both real & virtual environments in the mobile scenario than in the stationary scenario* is supported by the responses to q5
- *Participants will have a greater sense of 'being in the past' in the mobile scenario than in the stationary scenario* is supported by q7 (thanks to embodiment?)
- *Participants will gain a better understanding of what the chapel was like in the past in the mobile scenario than in the stationary scenario* is supported by q12

It is worth highlighting the responses to q10 in relation to those to q2. Participants reported finding it easier to compare features from the past & present (q2) during the mobile scenario, however did not report a difference between not noticing differences between the real & virtual environments (q10).

6.9.4 Participant 1

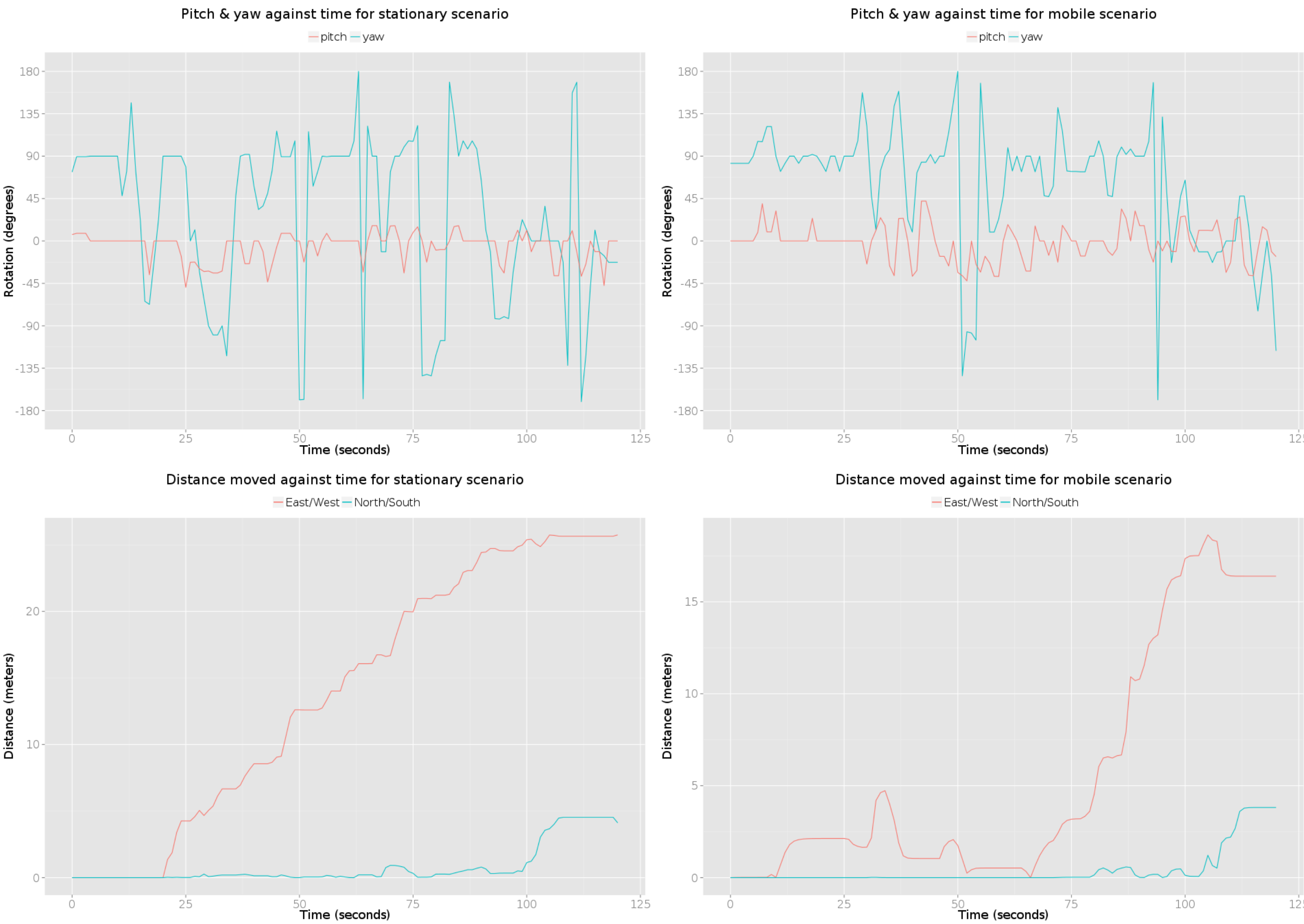

Figure 6.4: Some images, yah.

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetuer id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

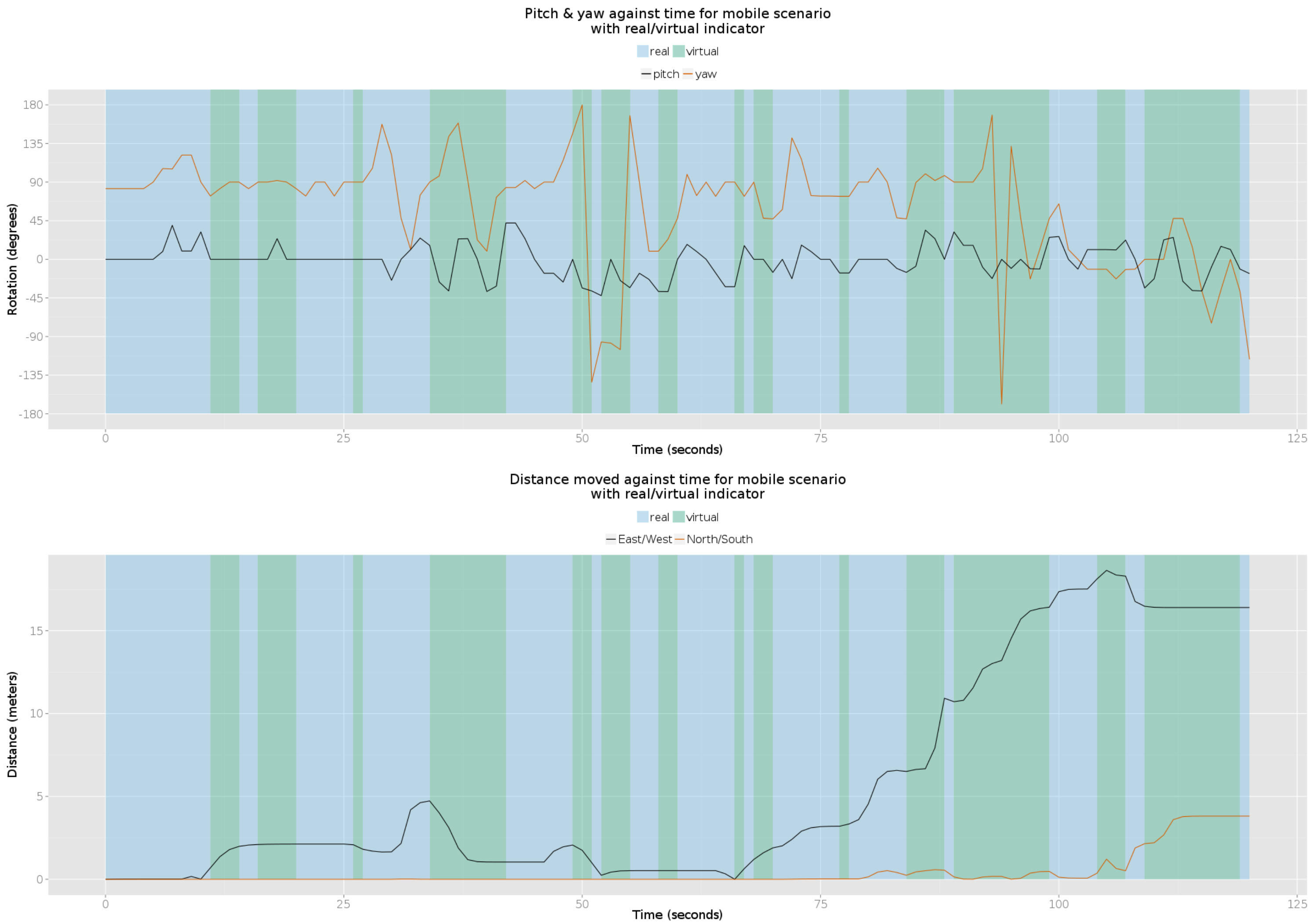

Figure 6.5: Some images, yah.

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6.9.5 Participant 3

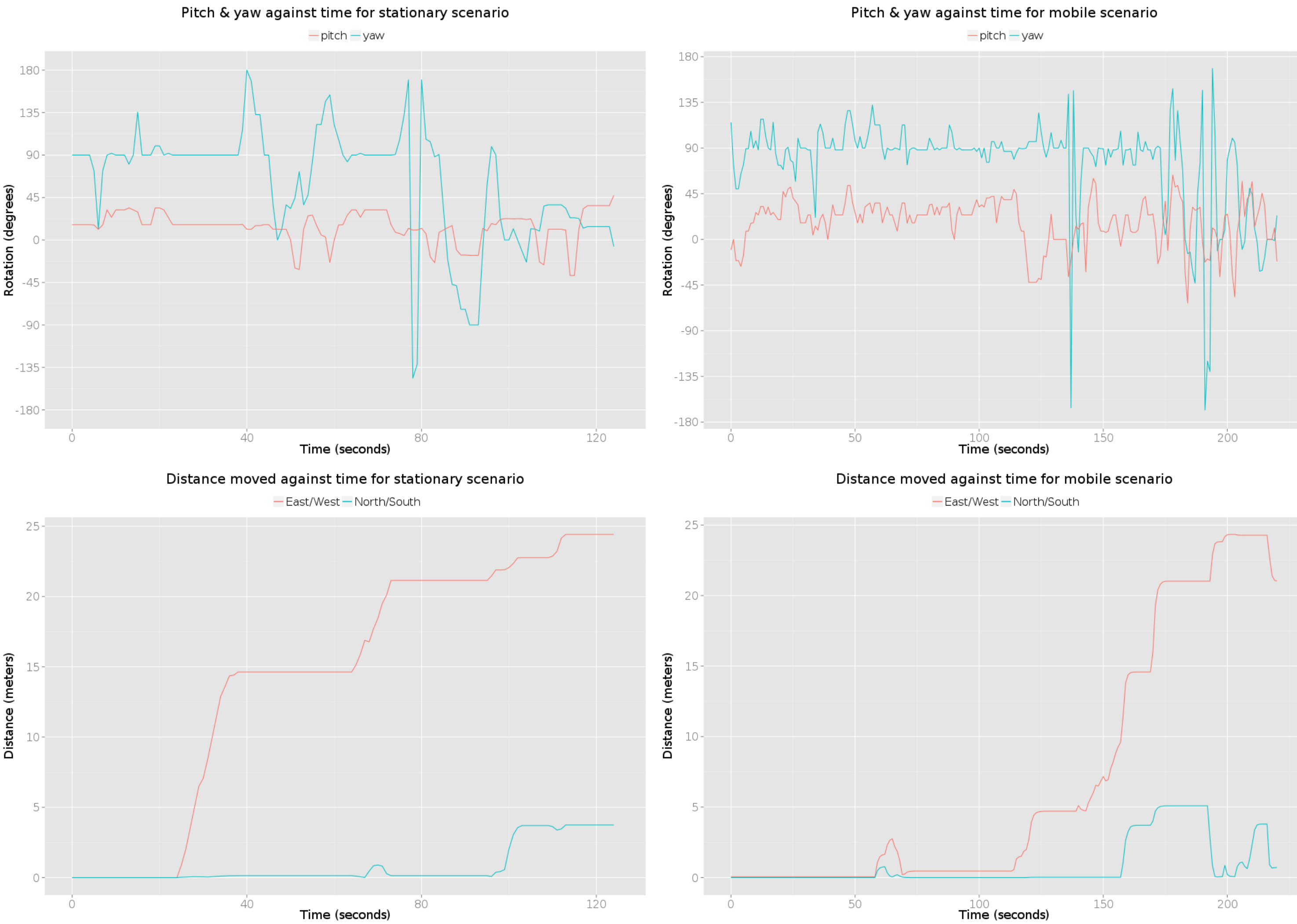

Figure 6.6: Some images, yah.

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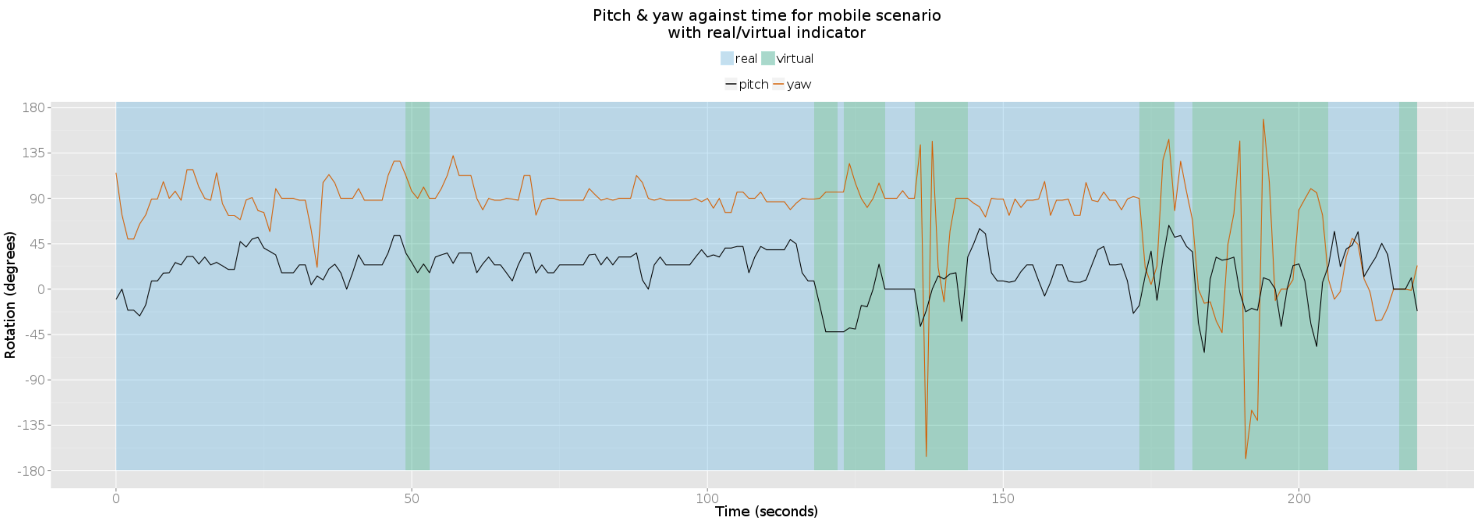

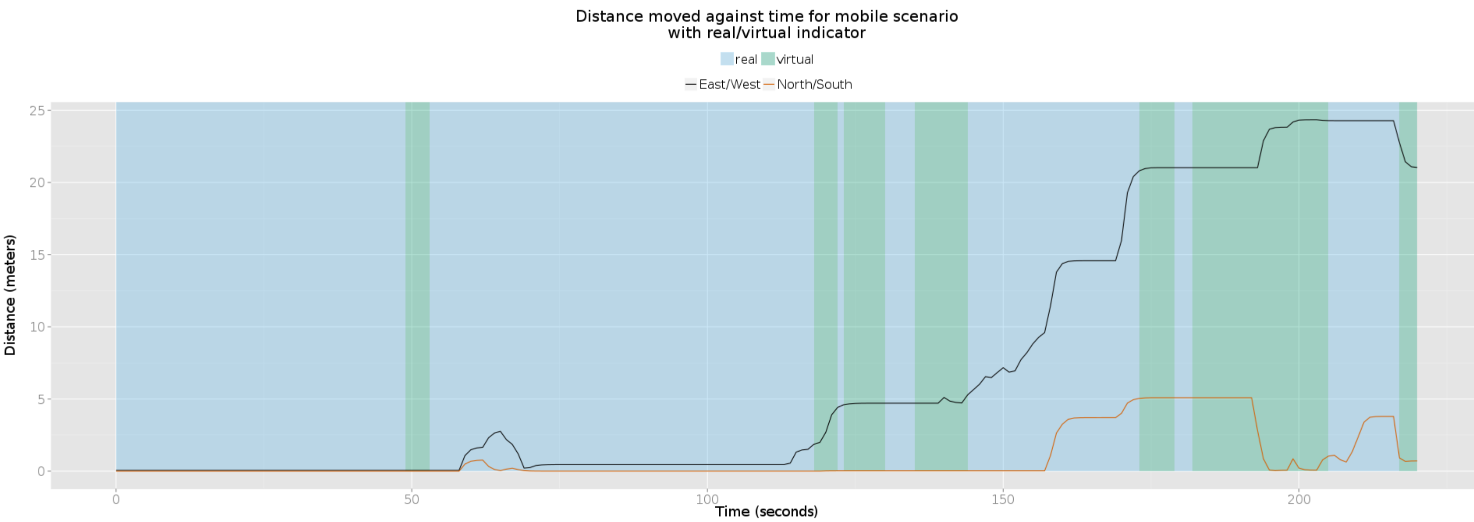

Figure 6.7: Some images, yah.

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6.9.6 Participant 4

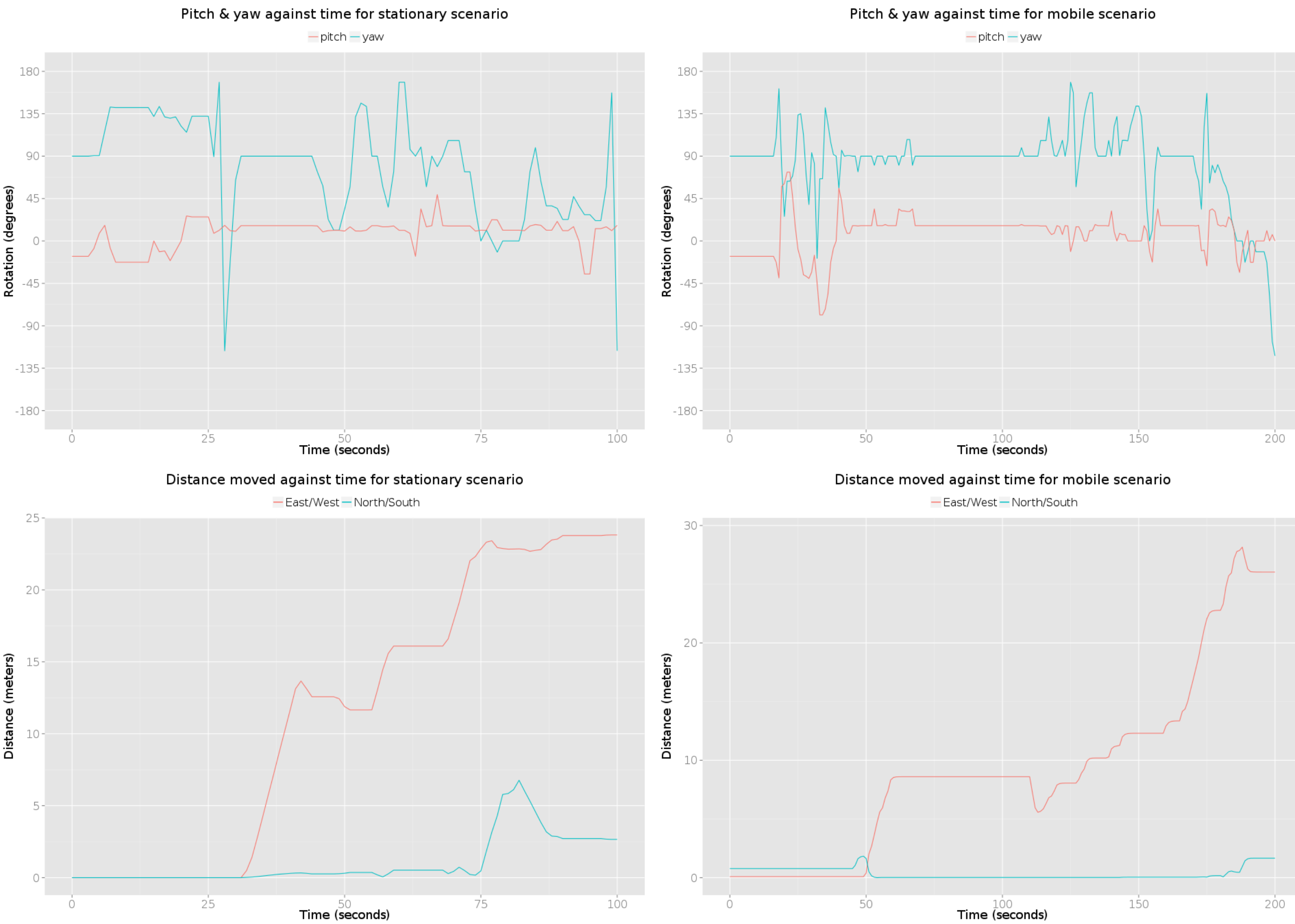

Figure 6.8: Some images, yah.

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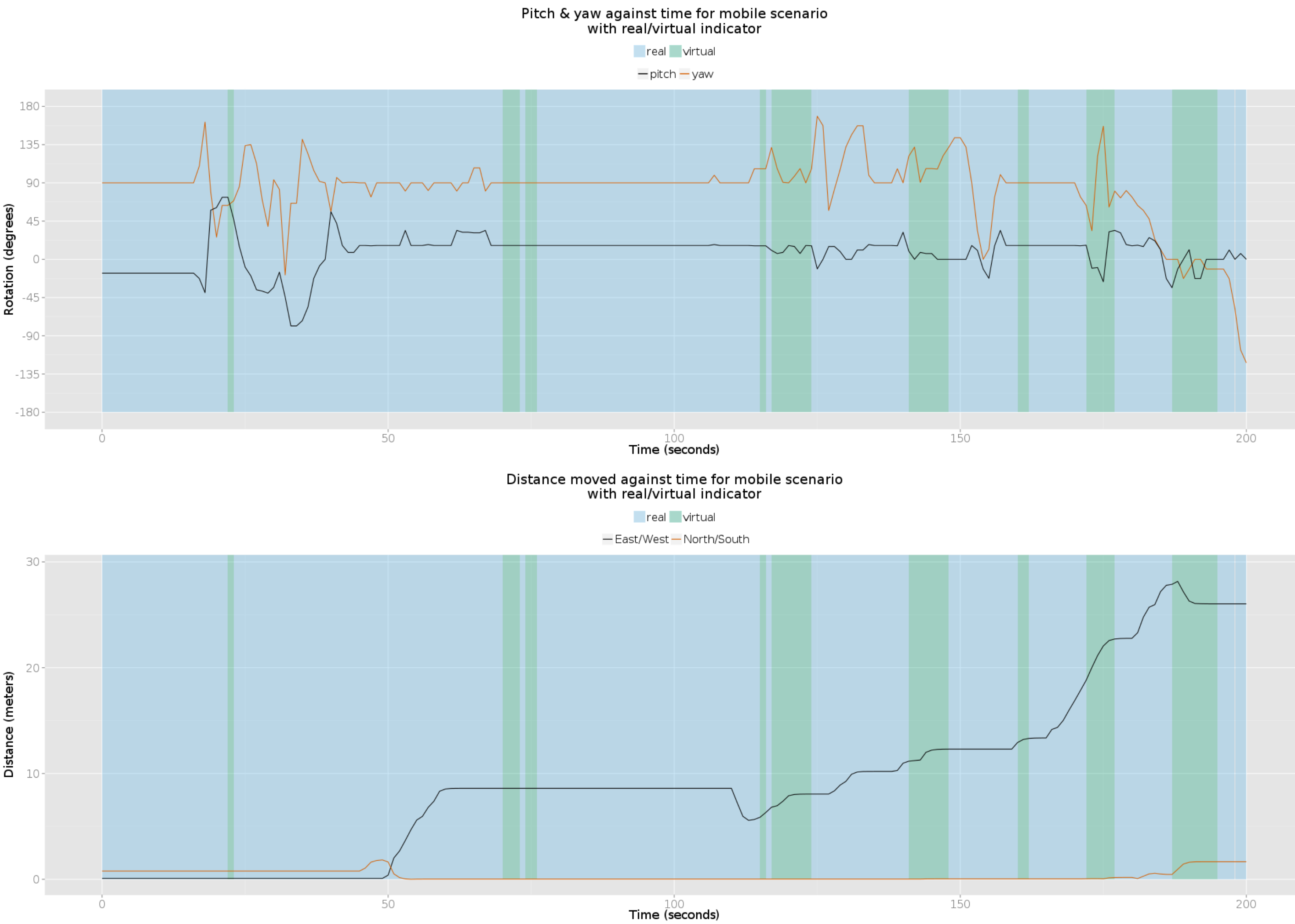

Figure 6.9: Some images, yah.

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6.9.7 Participant 5

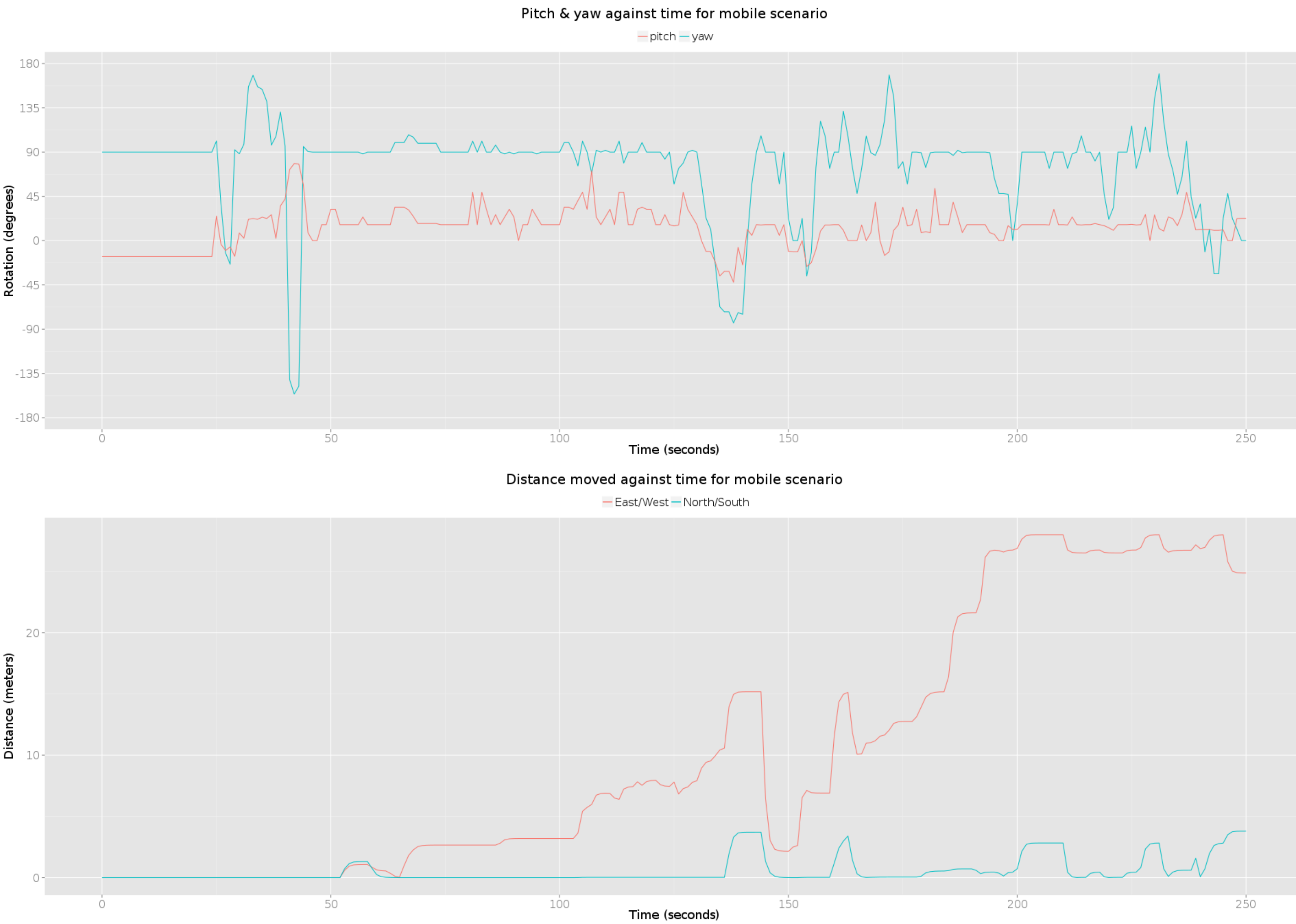

Figure 6.10: Some images, yah.

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Figure 6.11: Some images, yah.

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6.9.8 Participant 6

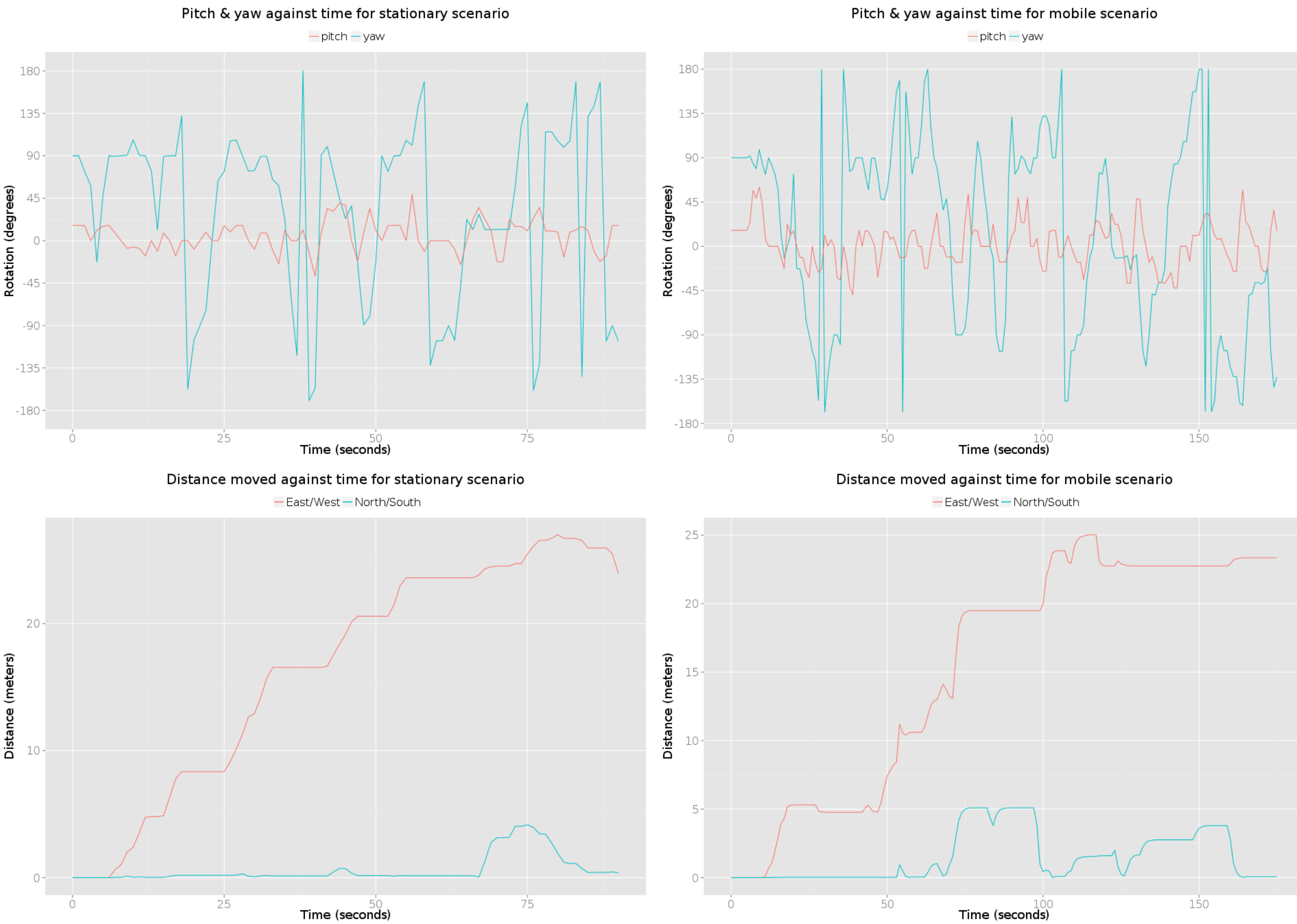

Figure 6.12: Some images, yah.

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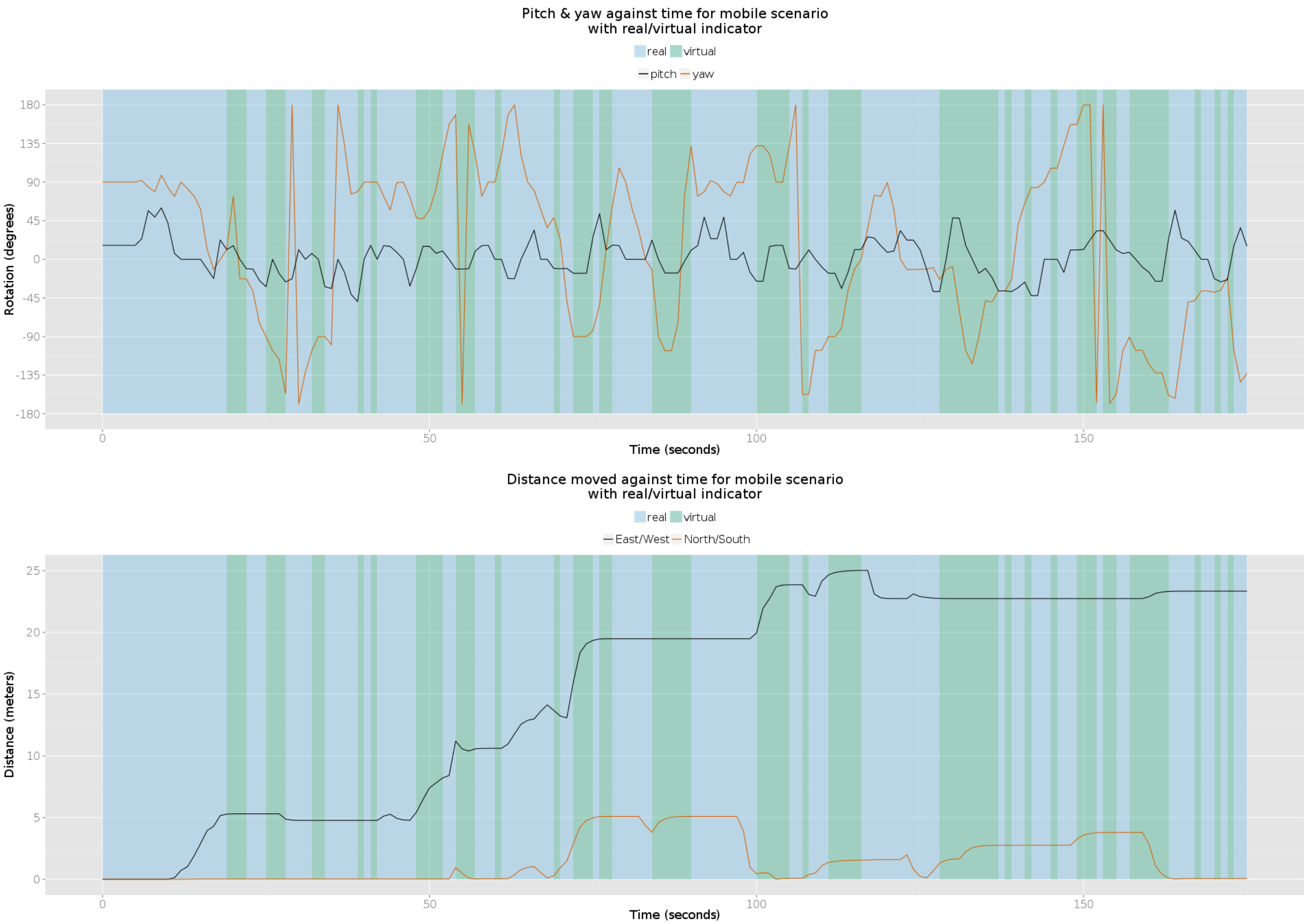

Figure 6.13: Some images, yah.

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6.10 Phase 2.1 Results

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6.10.1 Participant 7

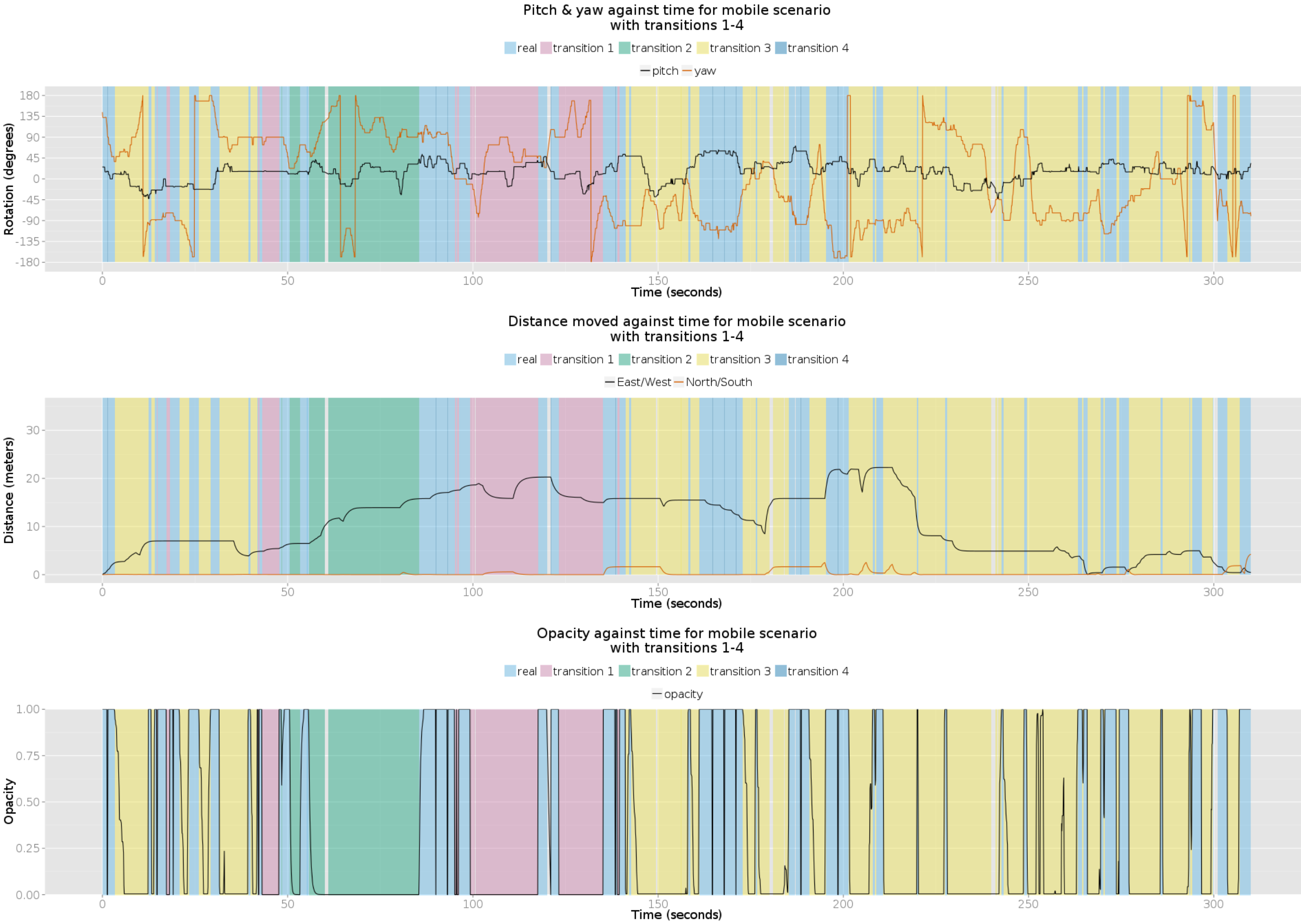

Figure 6.14: Some images, yah.

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6.10.2 Participant 8

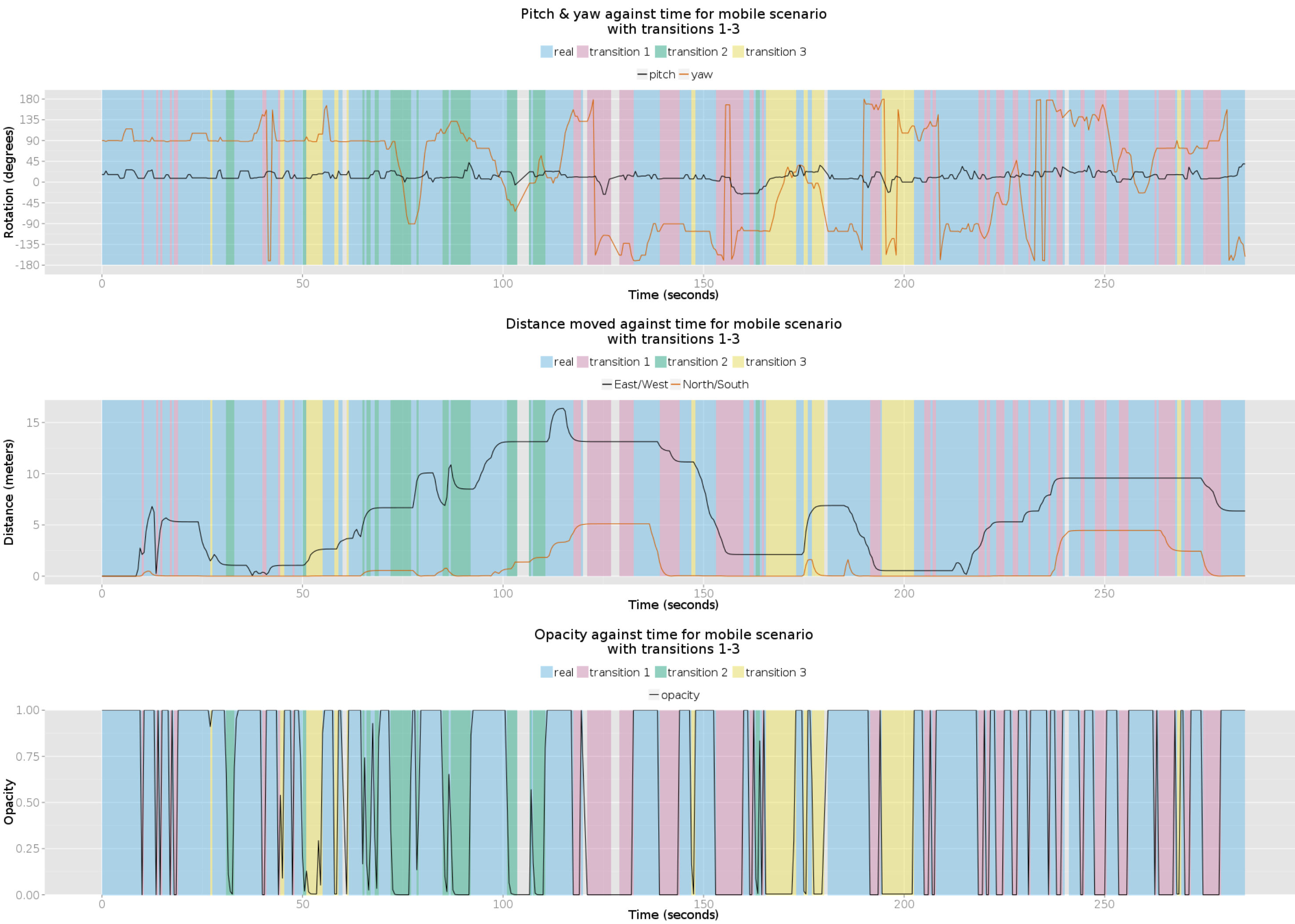

Figure 6.15: Some images, yah.

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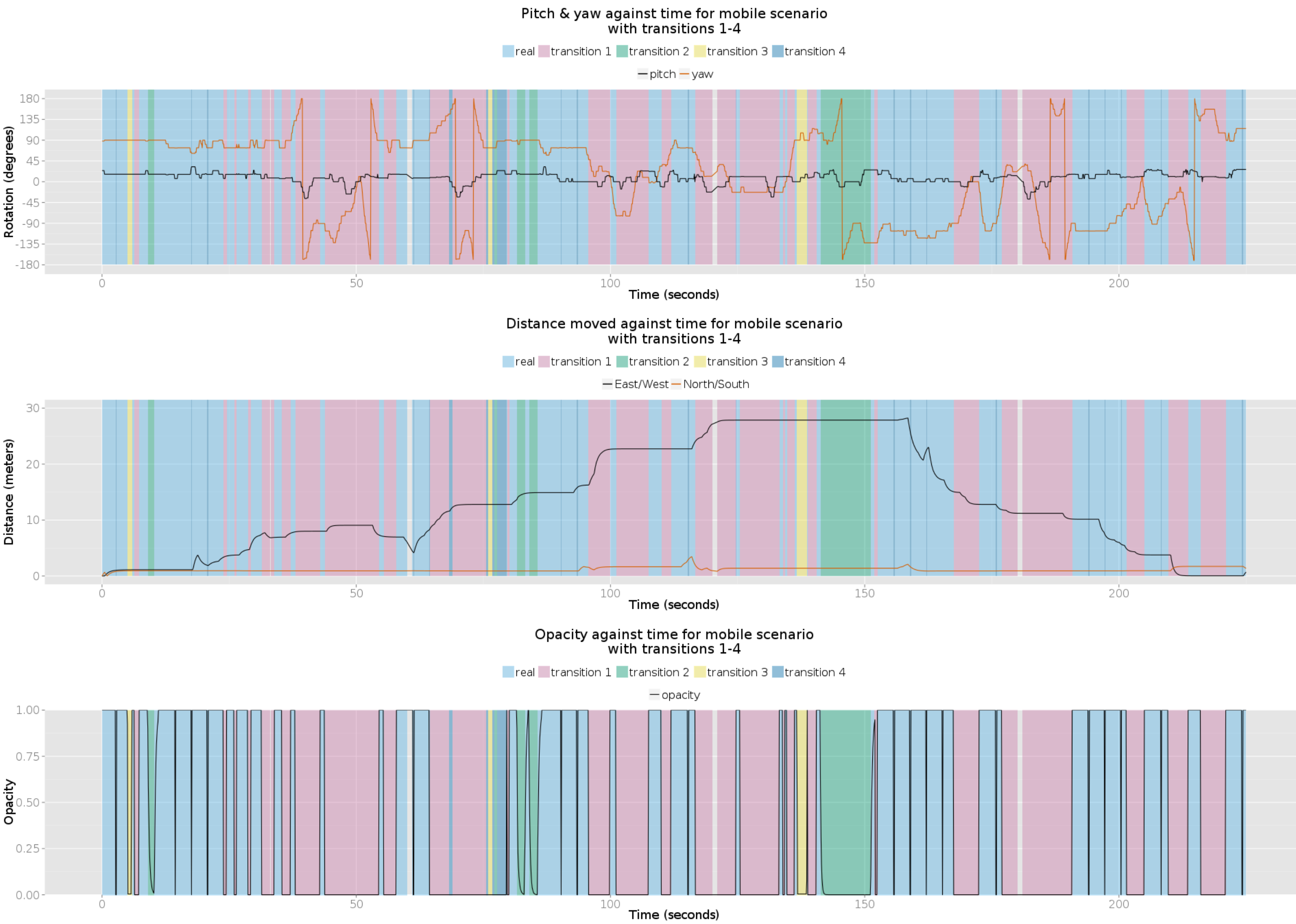

Figure 6.16: Some images, yah.

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6.10.3 Participant 9

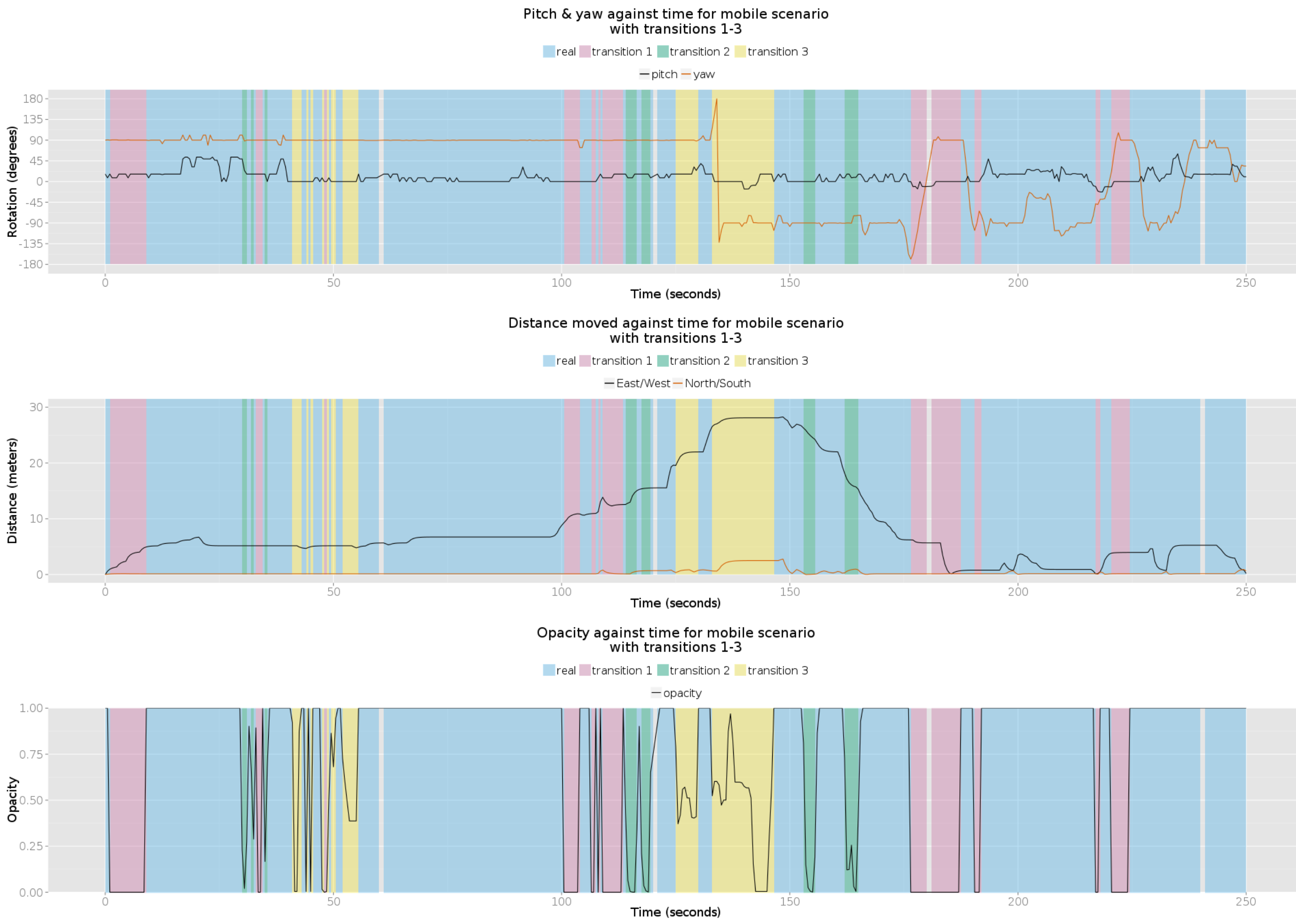

Figure 6.17: Some images, yah.

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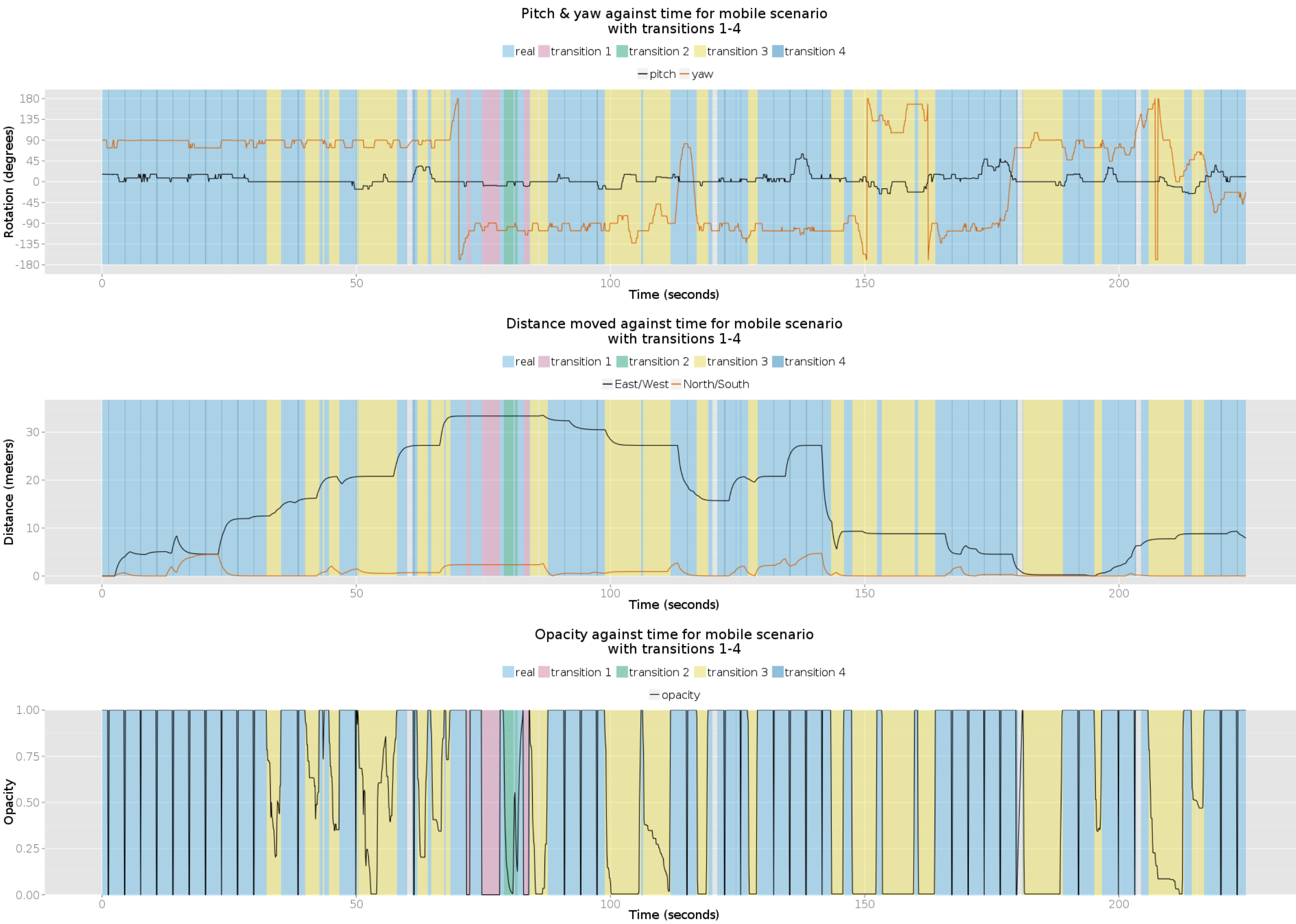

Figure 6.18: Some images, yah.

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6.10.4 Participant 10

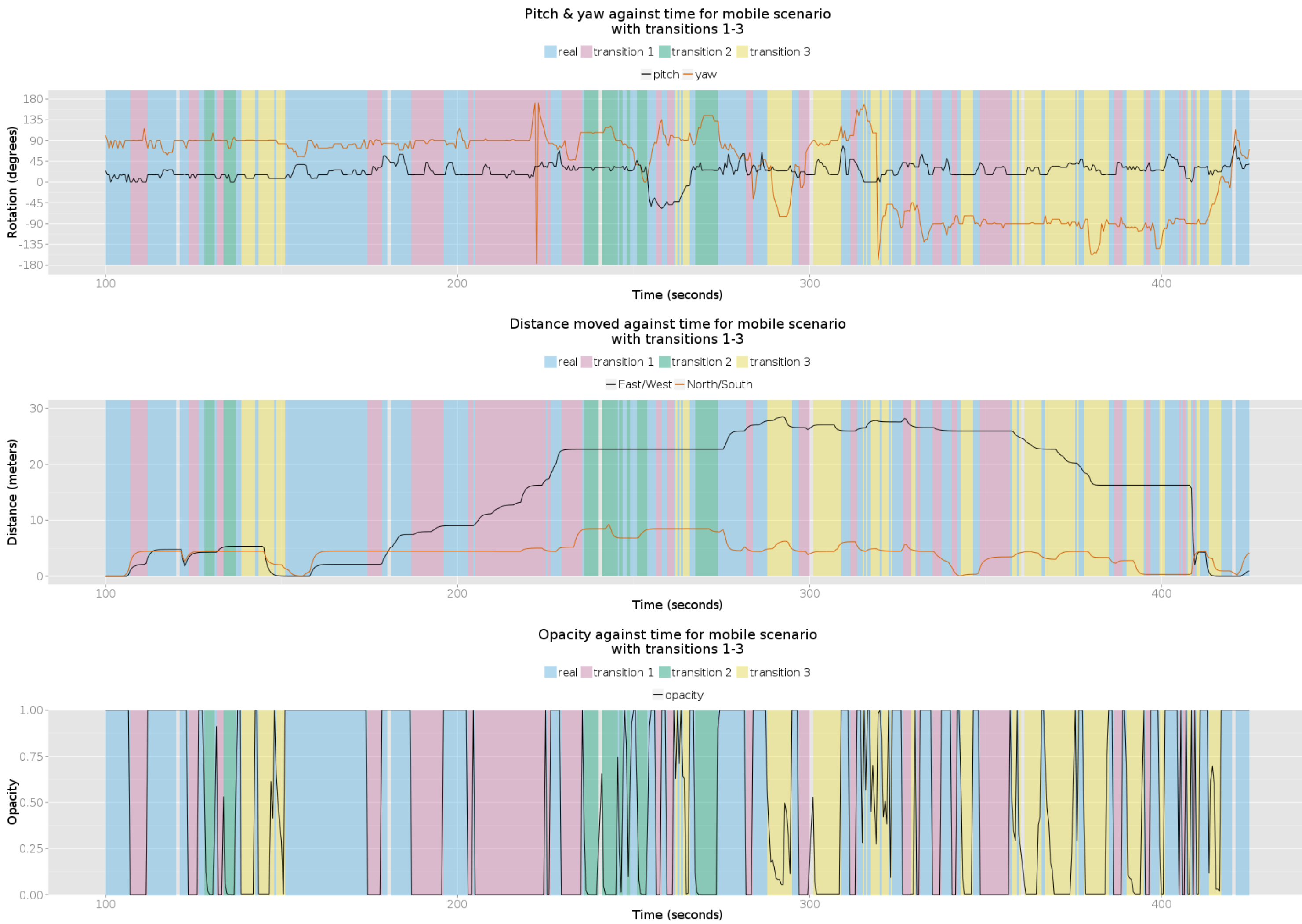

Figure 6.19: Some images, yah.

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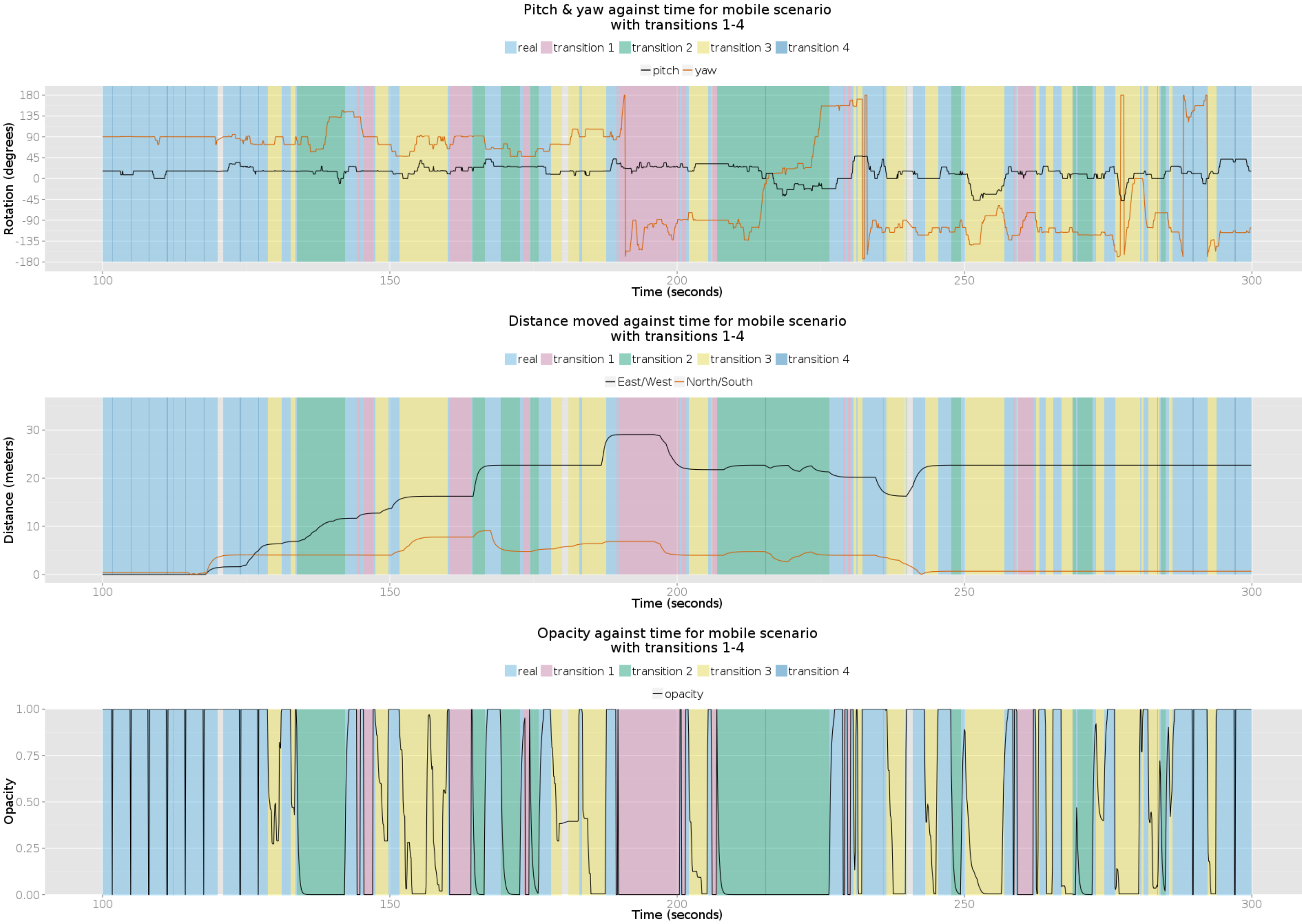

Figure 6.20: Some images, yah.

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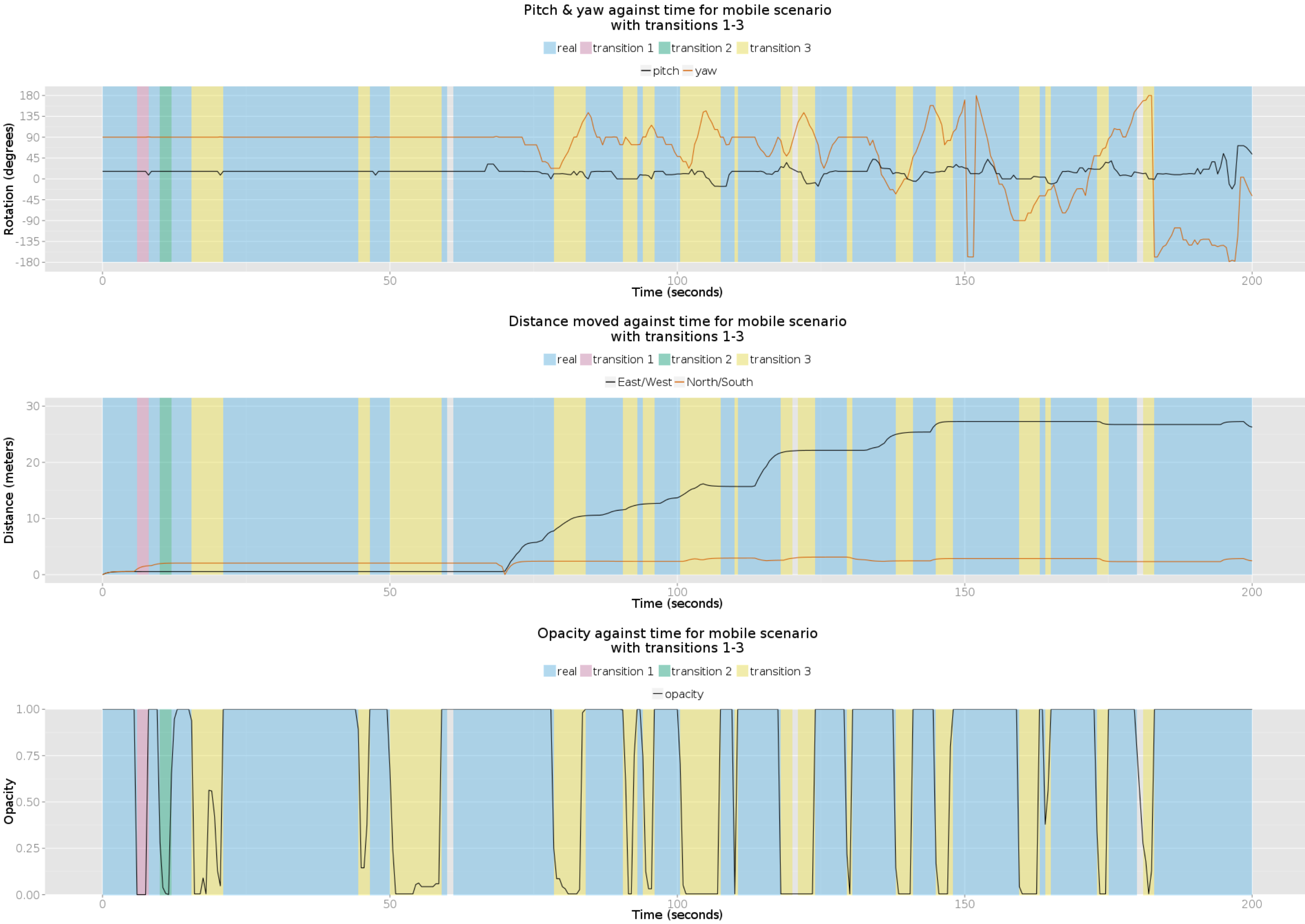
6.10.5 Participant 11



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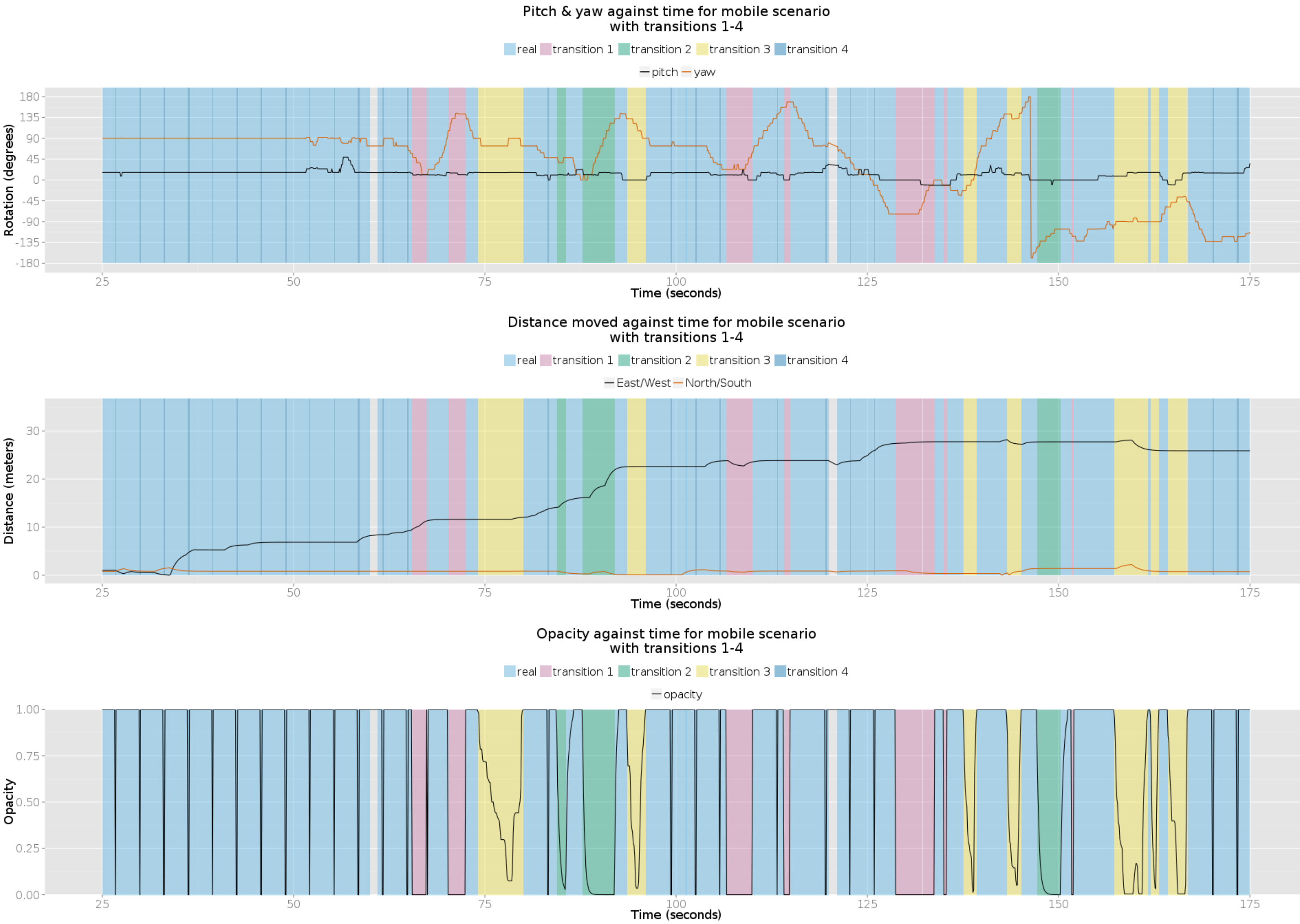

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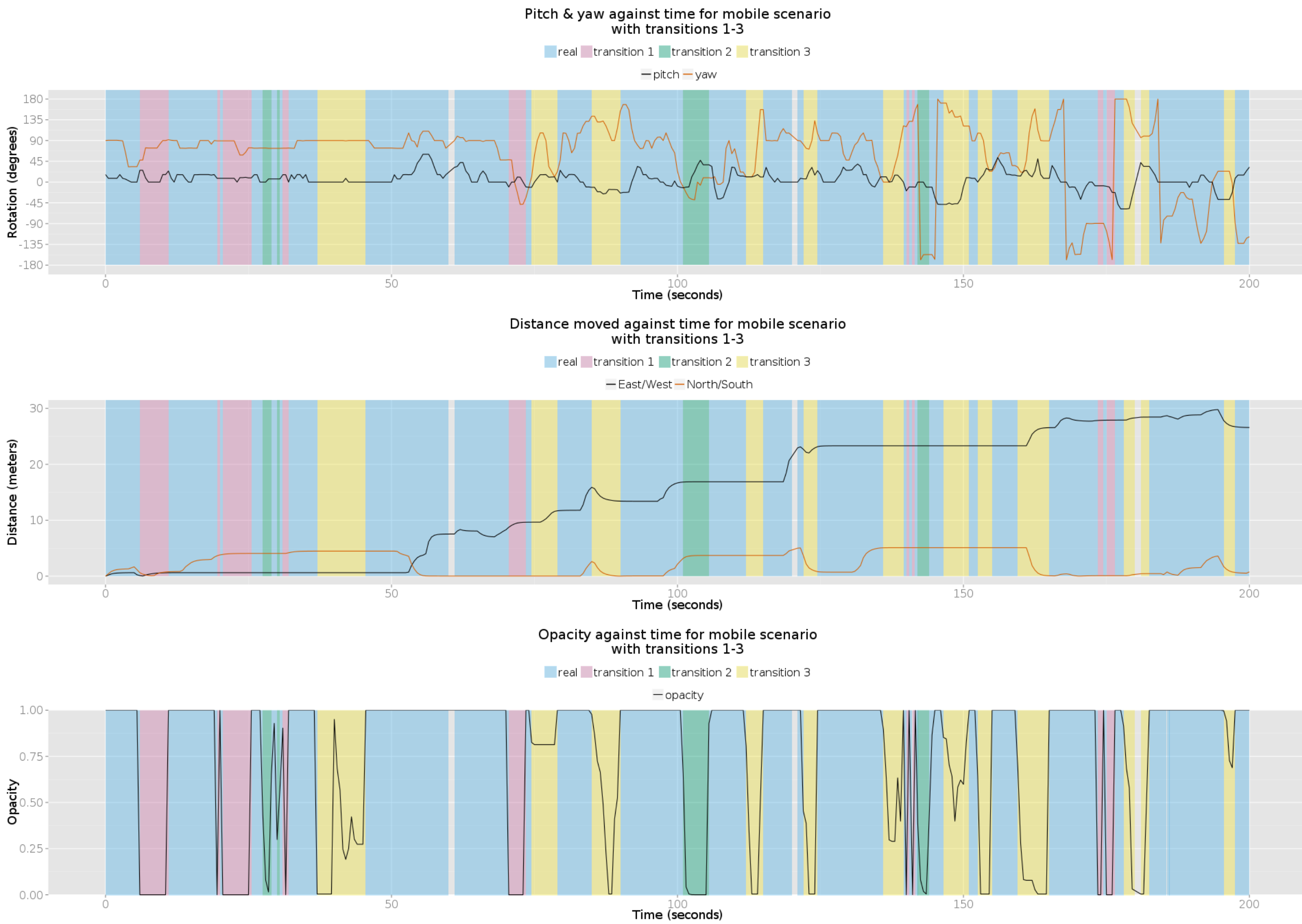
6.10.6 Participant 12



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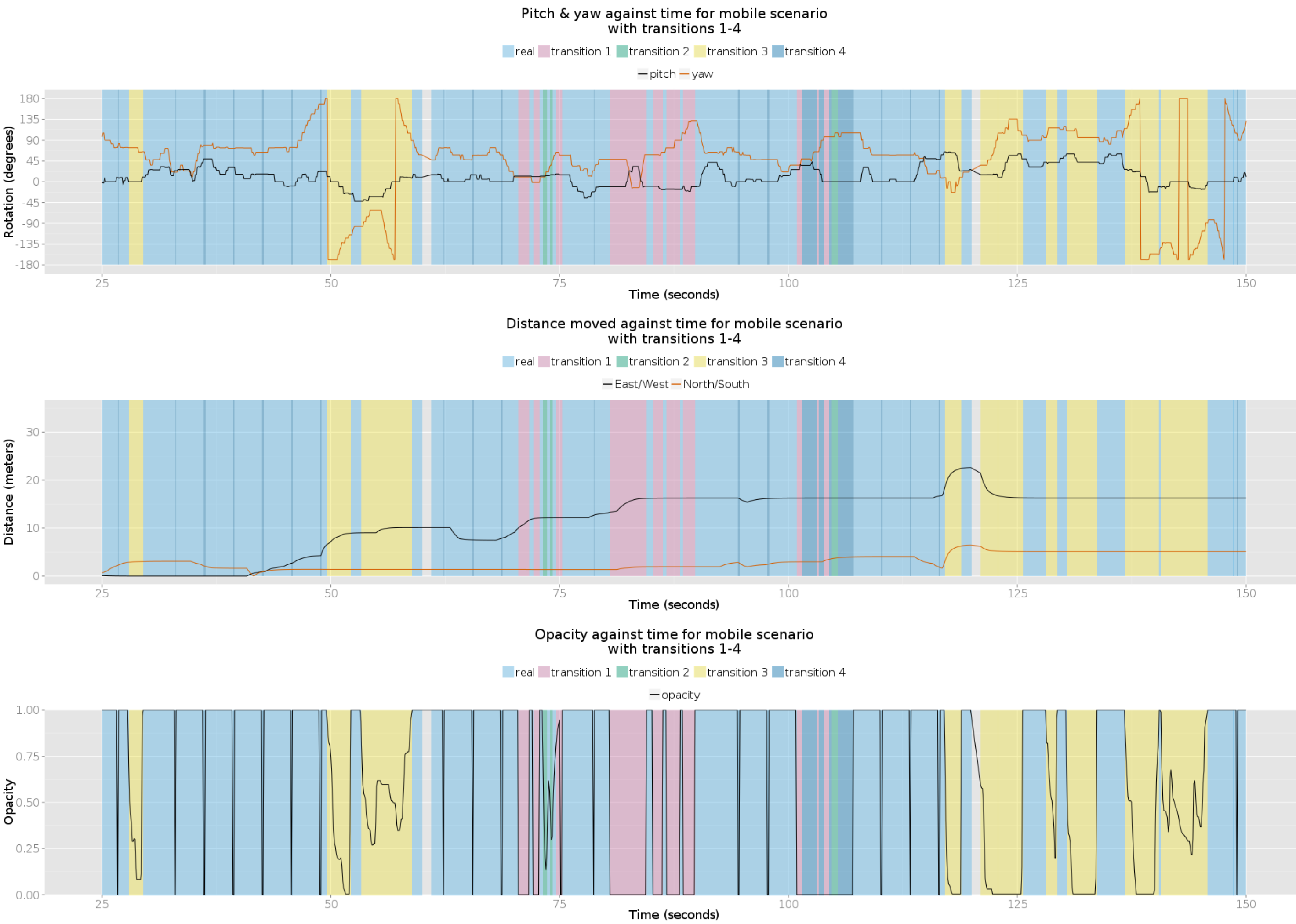

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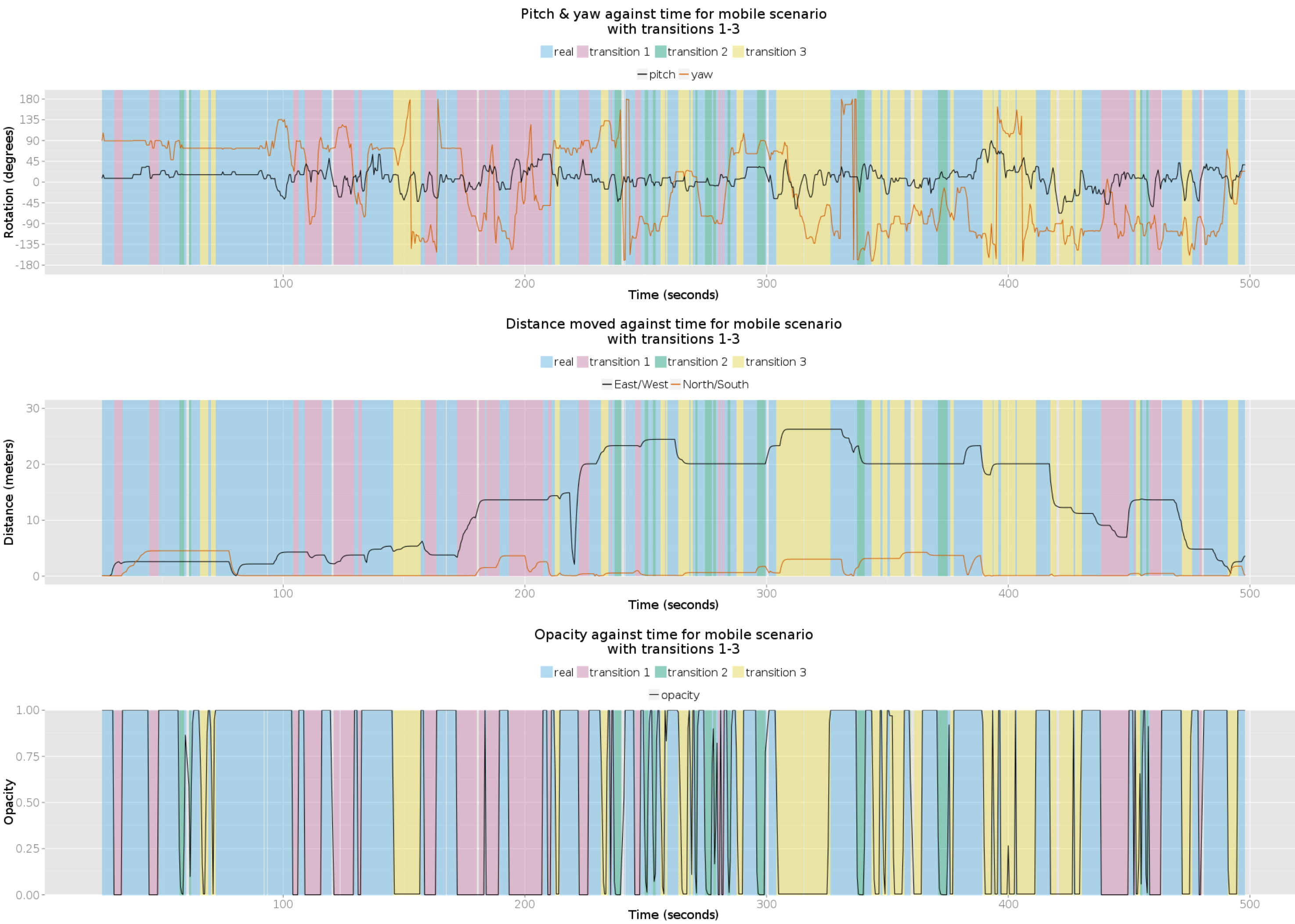
6.10.7 Participant 13



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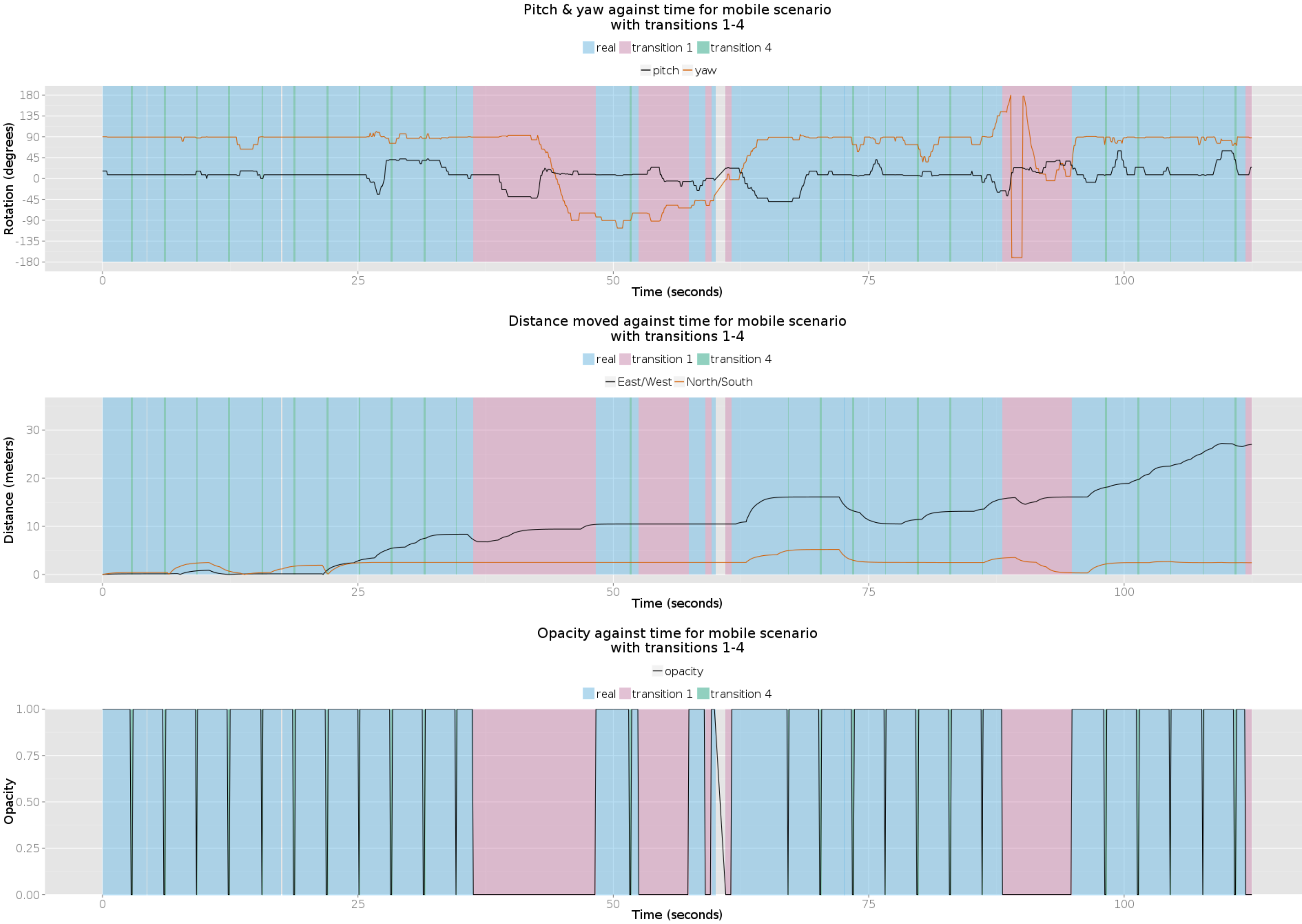

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6.11 Phase 2.2 Results

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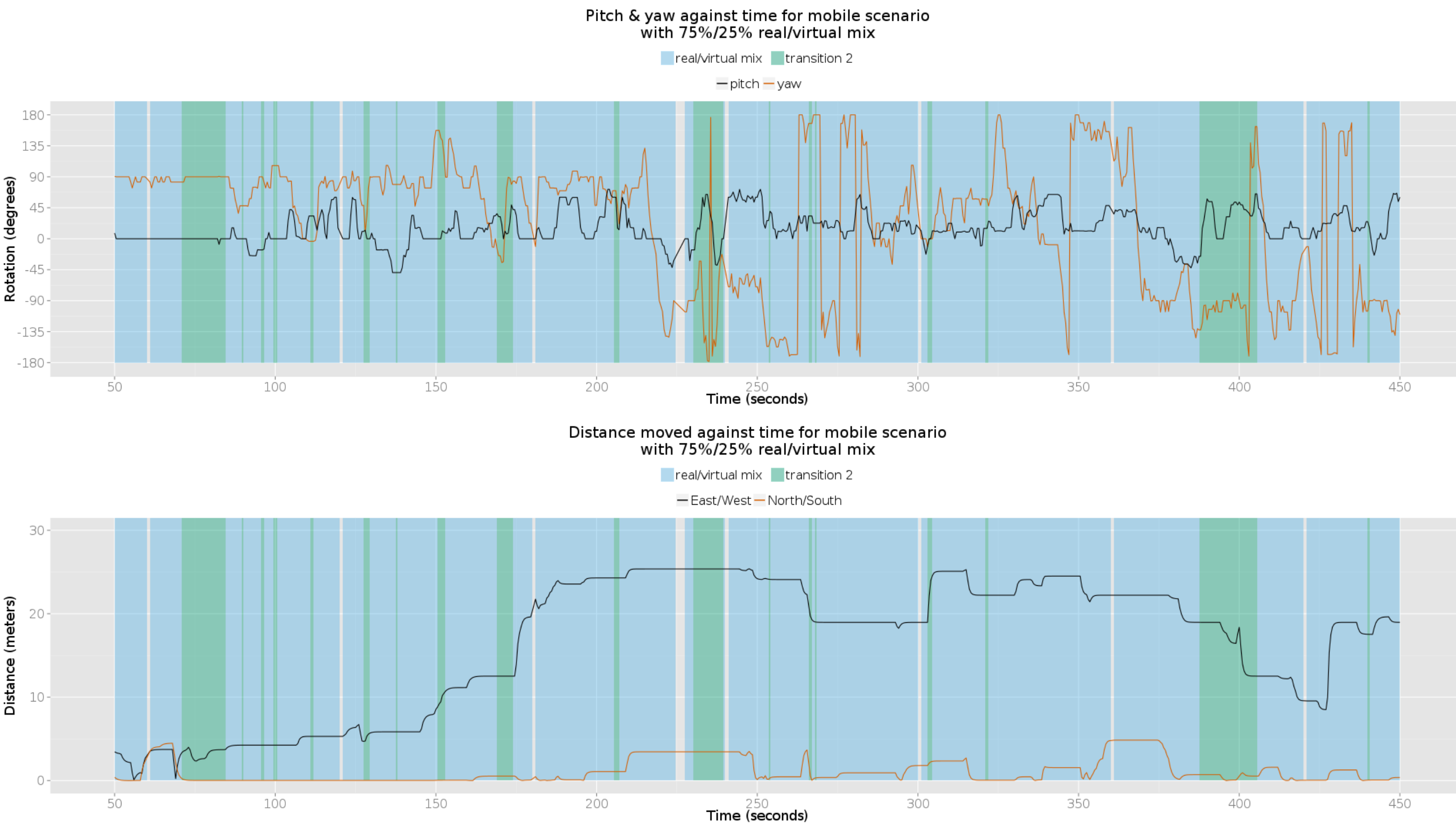
6.11.1 Participant 14



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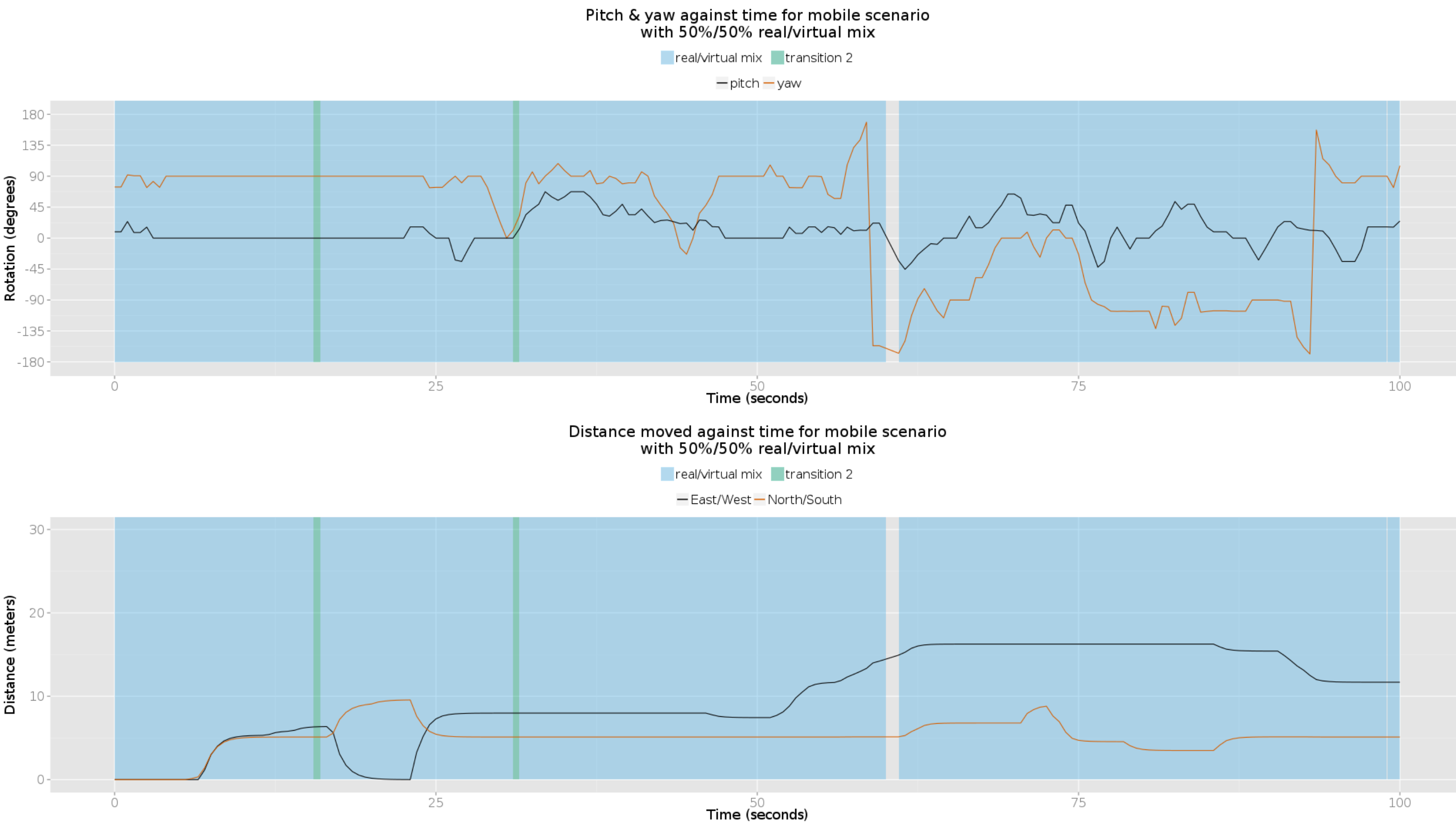

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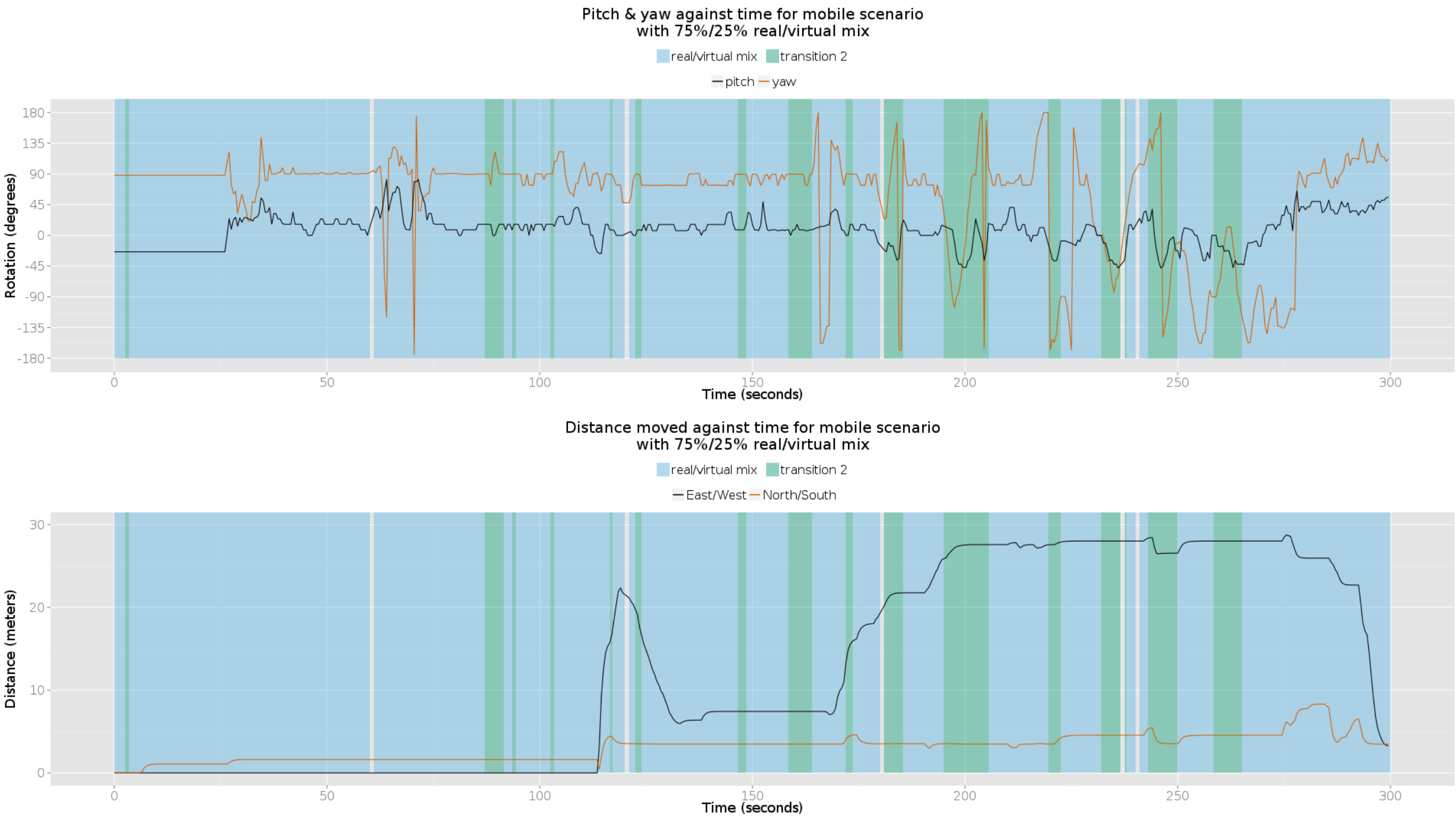
6.11.2 Participant 15



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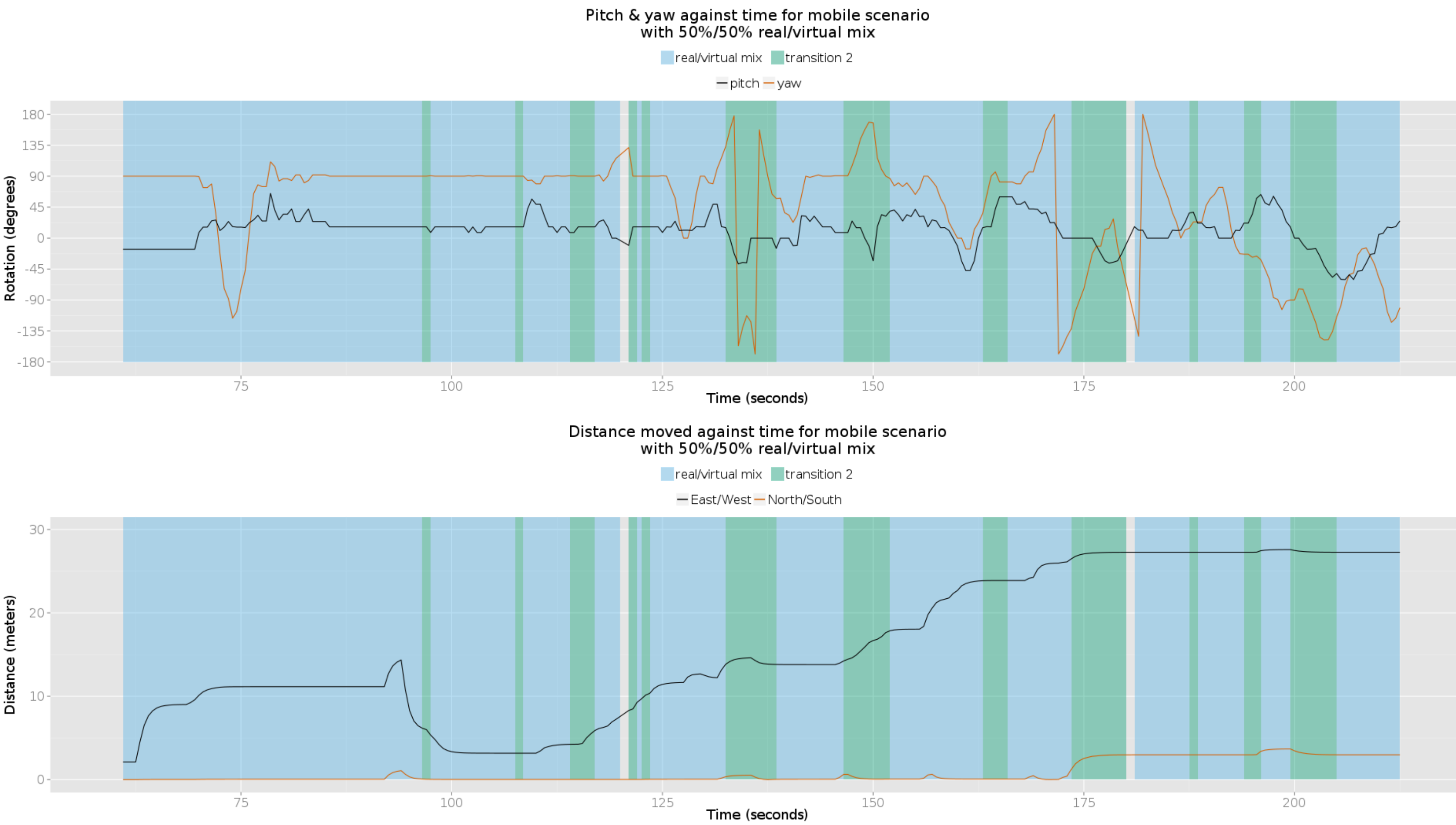

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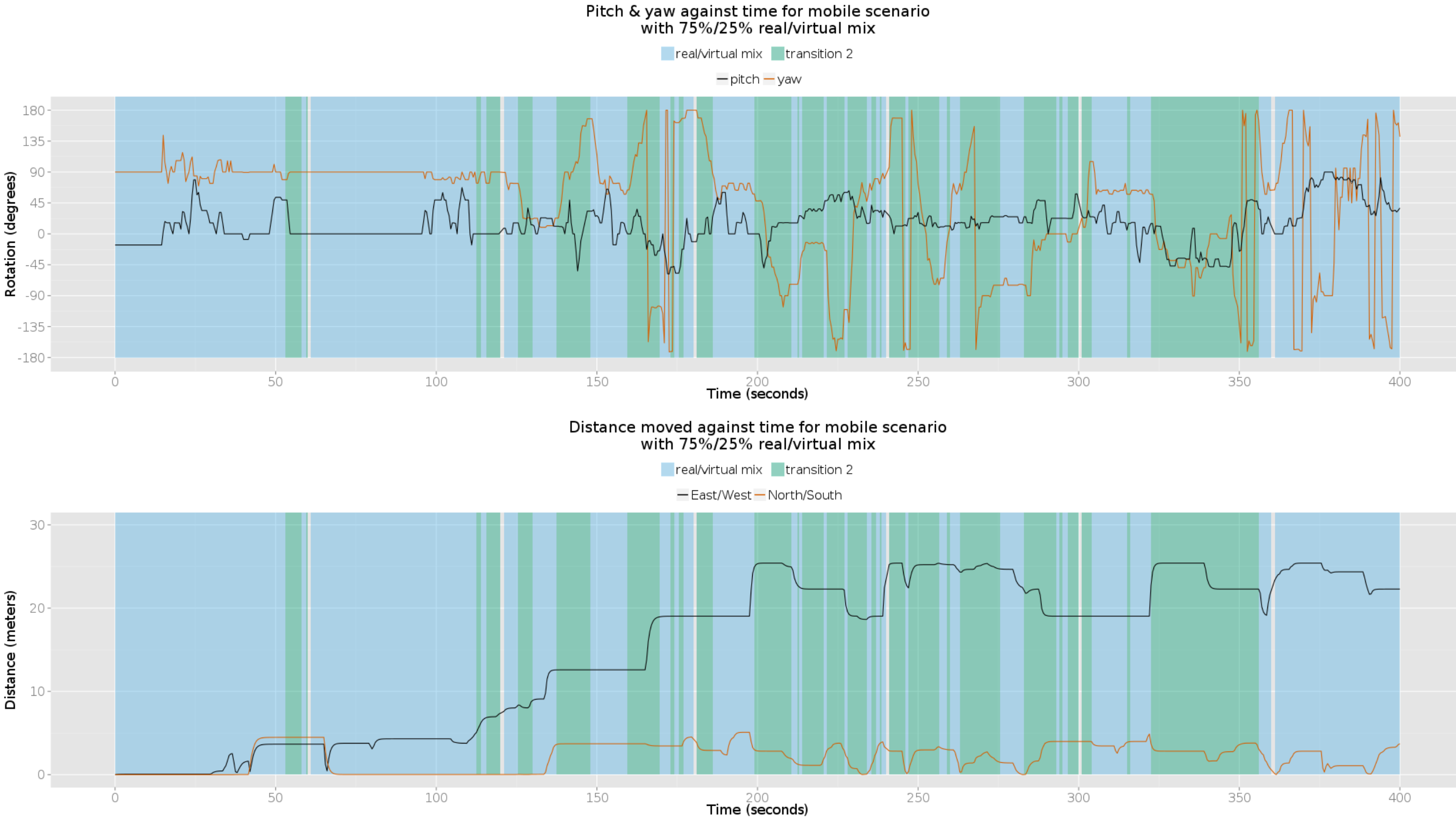
6.11.3 Participant 16



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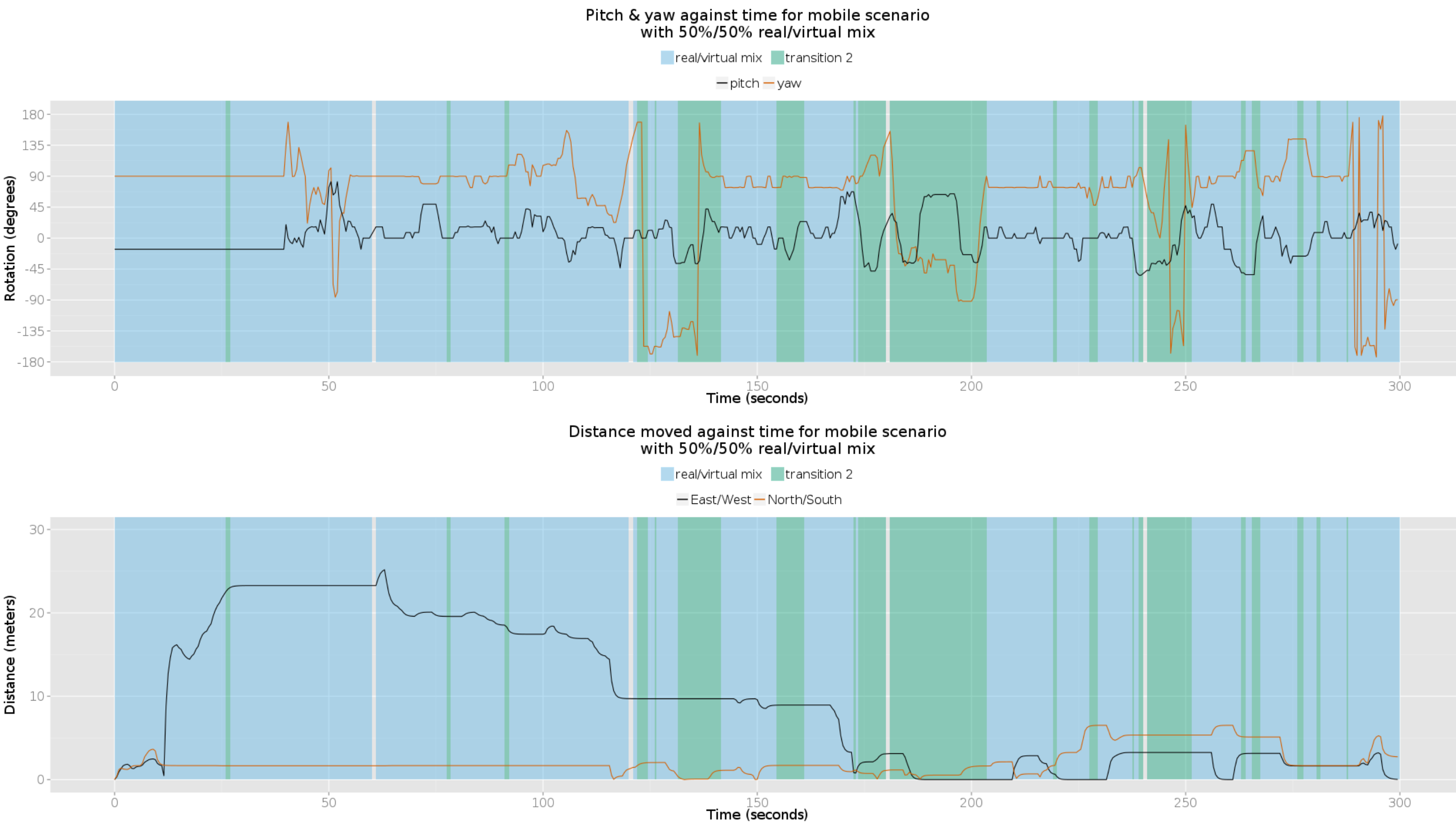

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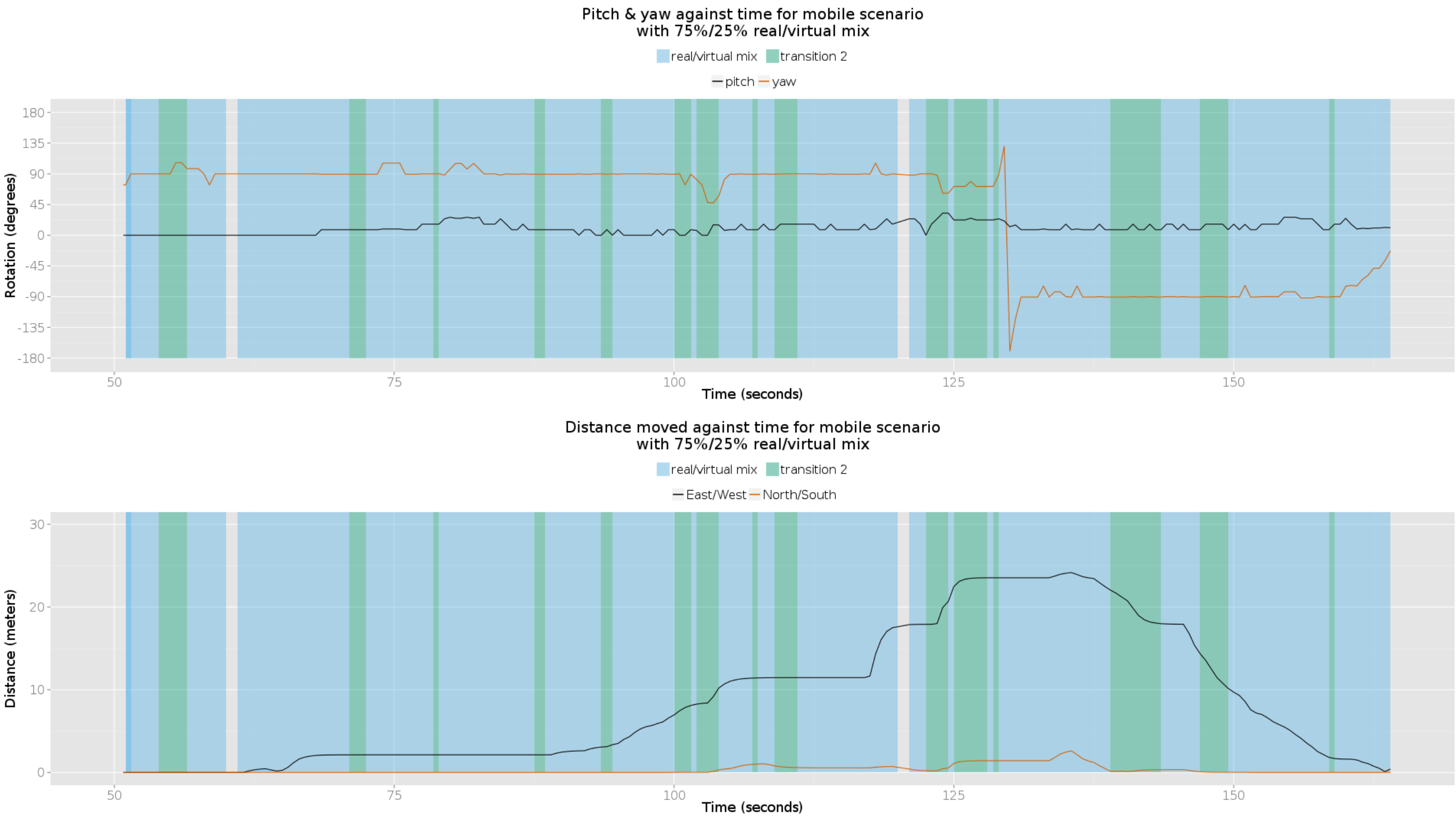
6.11.4 Participant 17



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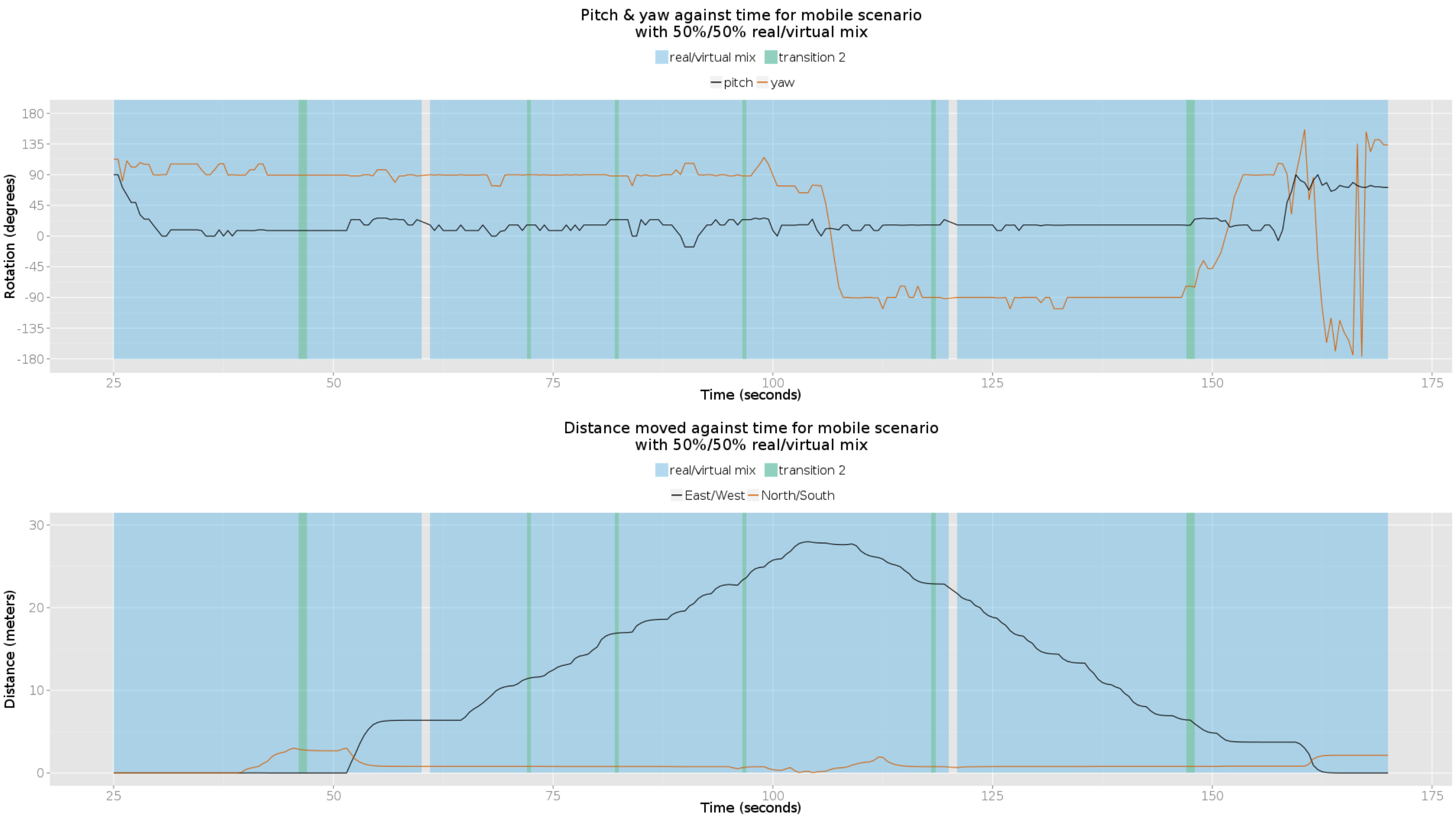

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7

Conclusions & Discussion

- **Content -** More in-depth explanation of contributions, identify future work (but don't dwindle).
- **What has been done -** Nothing.
- **What is left to do/how long should it take -** Should probably be written towards the end, after all design & implementation, evaluation & discussion has been completed. Should be a short section, 10 pages is probably far too long, shouldn't take long to write if the evaluation & discussion section is done properly.

Appendices

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