Parallel Reality: Tandem Exploration of Real & Virtual Environments

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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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Abstract

This thesis discusses the design & implementation of a hardware & software system that allows its user to observe & move around their real world environment whilst wearing equipment that allows them to alternatively view an immersive virtual reality environment from the equivalent vantage point. This style of interaction with complete real & virtual environments is presented as a new category of alternate reality, called parallel reality. The position of parallel reality is established in relation to previously explored alternate realities & analysis & discussion of results from preliminary user studies of the system are presented.

Acknowledgements

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.

*****Second Earth parallel reality example, think about what that person at DEMOfest was saying about being able to walk around Paris & at any moment/location to transition into what it was like in the past.**

3

Background, Theory & Rationale

"Where are you?" Hiro says.

"In Reality or the Metaverse?"

"Both."

Snow Crash, Neal Stephenson

The subject of this thesis is the design, development & evaluation of platforms that allow their users to observe & move around their real environment whilst also being able to view an alternative virtual environment from the equivalent vantage point. This combination of 'parallel' real & virtual environments, combined with maintained mobility, is not well encapsulated by any previously defined alternate reality terminology, thus it is necessary to explore this alternate reality terminology & technologies in order to correctly frame these systems in relation to them.

The closest existing label is the cross reality paradigm, as a cross reality system holds the distinction of two discrete environments, one real & one virtual, complete-unto-themselves, however cross reality further focusses on a bidirectional exchange of information between the environments & not upon user mobility & tandem visual exploration of both environments.

Thus, we propose the new term parallel reality to refer to systems that combine complete & discrete real & virtual environments together in a manner that allows mobile exploration of them both in tandem, relating it & positioning it against existing alternate reality terminology previously explored by computer science & other disciplines.

3.1 Defining Alternate Realities

Alternate realities (any situation in which the environmental stimuli received by a subject have been somehow modified or mediated) have received substantial attention in recent decades, the themes explored for purposes as diverse as education [1] & new forms of data visualisation [2] to medical [3] & military training [4]. Although terms such as mixed reality & augmented reality are now relatively common in conversation & literature, definitions of such terms have often been used in vague & even conflicting manners.

This chapter investigates popular definitions, classifications & comparisons of alternate realities, combining & modifying these parameters to produce a canonical set of definitions for the remainder of this thesis, allowing 'parallel reality' to be introduced into a sound framework of classification.

3.1.1 Milgram & Kishino's Reality-Virtuality Continuum

Paul Milgram, Herman Colquhon and Fumio Kishino addressed the issue of alternate reality definitions in detail and can be accredited with introducing the terms augmented virtuality and mixed reality to the literature, prompted by their identification of the need for more encompassing terms to supplement the existing definitions of augmented reality [5, 6].

One of the overbearing concepts introduced by Milgram et al. 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 that stretches from an entirely real environment at one extreme to an ontologically parallel but entirely virtual environment [7] at the other − the Reality-Virtuality continuum (figure 3.1, top). The location of an environment along this continuum coincides with its location along a parallel Extent of World Knowledge continuum (figure 3.1, bottom) 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.

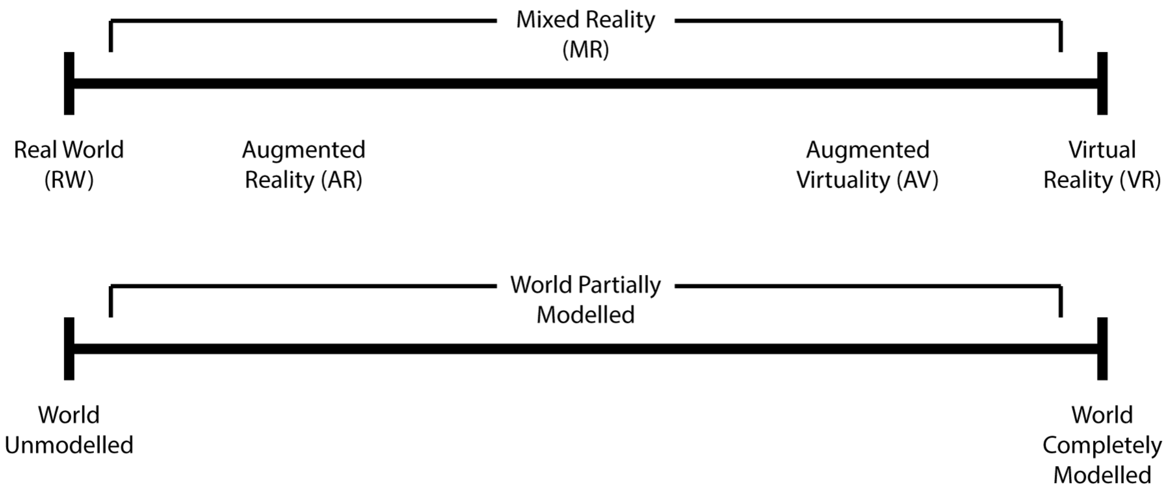


Figure 3.1: *Reality-Virtuality continuum* (top), parallel with *Extent of World Knowledge continuum* (bottom).

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 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 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 Roy Want's Virtuality Matrix

Another method of illustrating the relationships between 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 [8]. He presents a 2x2 matrix categorising the different terms according to whether the experience and overlay data are real or virtual (figure 3.2). Whilst this is a useful representation, some of the definitions & criteria depicted do not match with those of Milgram et al. or even with those of other authors in the same issue of Pervasive, let alone other publications concerning alternate realities. Figure 3.3 presents a modified version of this matrix that is in keeping with the framework laid out by Milgram et al. & the wider literature.

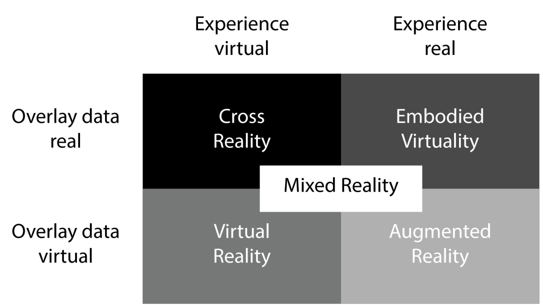


Figure 3.2: Want's original virtuality matrix.

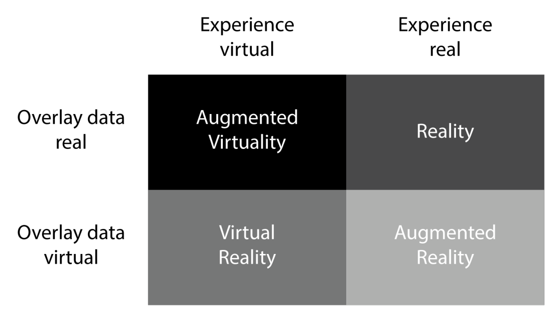


Figure 3.3: Modified Want matrix.

Where the original matrix positions cross reality in the upper left quadrant, at the congruence of 'experience virtual' and 'overlay data real', the modified matrix positions augmented virtuality. Referencing Milgram's continuum, 'experience virtual' relates to a position somewhere within the right half, while 'overlay data real' relates to presentation over this necessarily 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.

The original 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"*. The modified matrix adopts the position that the opposite of virtual reality is simply reality and that ubiquitous computing does not constitute an alternate reality but rather 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 [9]. However whether this real environment is augmented by virtual objects is not restricted by the concept.

Finally the modified matrix removes the central mixed reality section from the original matrix, as its position is 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, the reader could be led to believe that a purely virtual reality environment can be considered mixed reality, which is incorrect. If one wished 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.

3.1.3 Steve Mann's Venn Diagrams

Steve Mann, the *"father of wearable computing"* [**?**] & one of a group of researchers at MIT that became known as 'cyborgs' for their body-worn computers, digital displays clipped to spectacle frames & always-on Internet connections [**?**], presented a Venn diagram to illustrate the relationships between the different categories of alternate realities when discussing the problems that arise with existing taxonomies when discussing reality-modifying devices in general. Mann clarifies the use of mediated reality as *"a general framework for artificial modification of human perception by way of devices for augmenting, deliberately diminishing, and more generally, for otherwise altering sensory input"* [10]. Mediated reality thus encompasses all of mixed reality, but also the group of modulated reality which includes devices such as eyeglasses that use lenses/mirrors to invert the wearer's view, but do not apply computer mediation.

Mann's Venn diagram (figure 3.4) places augmented reality at a subset of mixed reality, but then further places virtual reality at a subset of augmented reality & in turn mixed reality. A modified version of this diagram (figure 3.5) removes virtual reality from this position, as although virtual reality is by definition mediated, it is not necessarily always presented as part of an augmented or mixed reality, as purely virtual environments can & do exist − Mann himself states that *"mixed reality exists in many forms along a continuum from augmented reality . . . to more recent efforts at augmented virtuality"*, which is contrary to the diagram's representation of virtual reality as necessarily a subset of augmented reality & in turn of mixed reality. Furthermore the modified diagram introduces augmented virtuality, mentioned by Mann in his prose but not included in the original diagram. An overlap is also introduced between those modulated reality environments that are also classified as mixed reality, as it is perplexing to think of a mixed reality environment that is neither augmented reality nor augmented virtuality (at least when considering a wholly real environment & a wholly virtual environment as the logically possible extremes).

Visualising the position of the basic classes of reality & virtual reality using this same method requires more drastic alteration to the Venn diagram, but is diagnostic in further revealing the relationships between the terms introduced within Mann's literature. The further modified Venn diagram (figure 3.6) shows that;

- mixed reality is the intersection of reality & virtual reality;
- mediated reality can be comprised from purely real or purely virtual content;
- all virtual reality is necessarily mediated;
- modulated reality can comprise only mediated real, or both real & virtual aspects in a mixed reality;
- augmented reality & augmented virtuality can feature in modulated reality systems.

This final iteration of the Venn diagram still contains ambiguity, however it is more diagnostic for categorising the majority of alternate reality systems than the previous two diagrams, whilst also avoiding over-complication. There are two ambiguities to recognise. First, this diagram maintains from the original diagram positions in which a system can exist that is both mixed & modulated, but which is neither augmented reality nor augmented virtuality. Second, this diagram does not accommodate a purely virtual environment that is then modulated: whether such a system would ever be created is arguable though, as any modulation that could be performed by modulators external to the virtual environment software could almost certainly be better performed by the software itself.

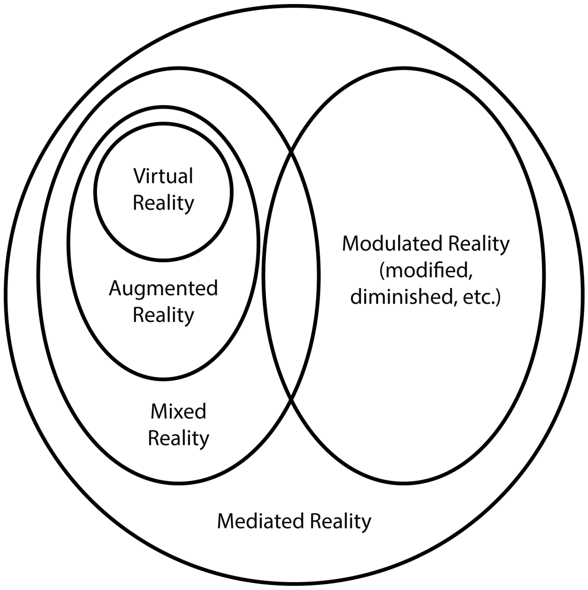


Figure 3.4: Original Mann Venn diagram.

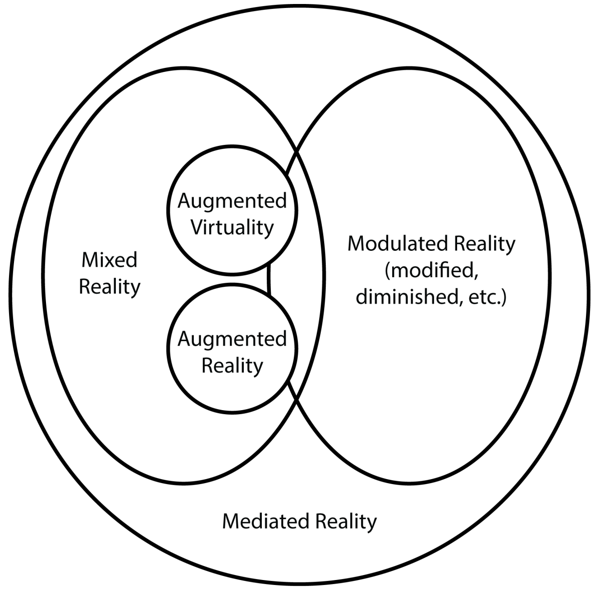


Figure 3.5: Modified Mann Venn diagram.

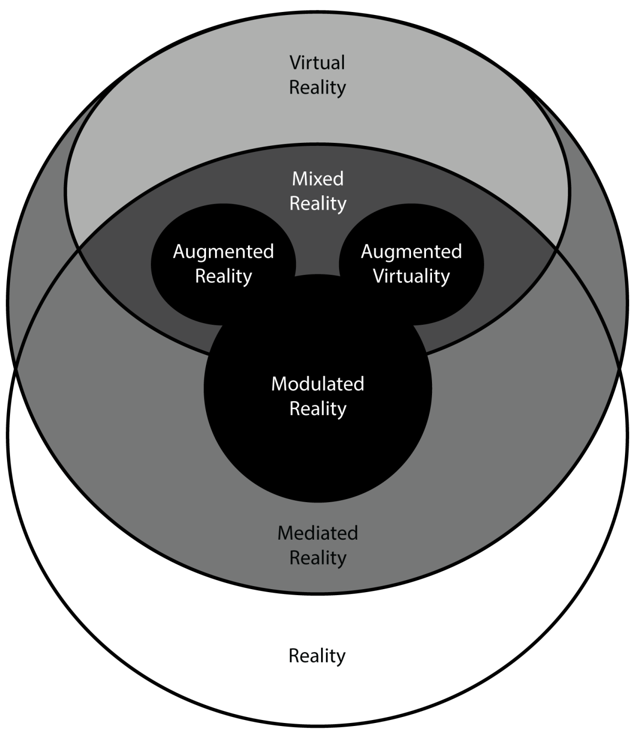


Figure 3.6: Further modified Mann Venn diagram.

3.1.4 Summary of Alternate Reality Definitions

Reality	An environment that is entirely unmodelled, with the viewport containing no virtual objects and with no computer-based quantitative information associated with any of the (necessarily real) objects.
Alternate Reality	Any environment in which the environmental stimuli received by a subject have been somehow mediated or modulated. That is, alternate reality is a term that encompasses everything that isn't purely 'reality'.
Virtual Reality (VR)	The polar opposite of *reality*, an environment that 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. [5, 6, 8] While traditional definitions of *virtual reality* require the environment to be completely immersive, such that when involved with the environment the user is completely unaware of the real environment that surrounds them (eg by using Head Mounted Displays & body tracking techniques to remove logical anchors to the real world [11]) the criteria adopted herein are less drastic, classifying the virtual environments presented by video games viewed via 2D monitors as rudimentary implementations of virtual reality; they are completely modelled environments that exist entirely separate to the real world.
Mixed Reality (MR)	The 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 virtual, where real and virtual objects co-exist. Both *augmented reality* and *augmented virtuality* are included under the broader classification of *mixed reality*.
Augmented Reality (AR)	A mixed reality environment comprising a real environment 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 [12].
Augmented Virtuality (AV)	A virtual environment upon which sampled real objects are overlain, perhaps through the use of cameras [13].
Mediated Reality	*"A general framework for artificial modification of human perception by way of devices for augmenting, deliberately diminishing, and more generally, for otherwise altering sensory input"* [10]. Encompasses all of mixed reality & modulated reality.
Modulated Reality	Platforms that aim to modify the user's view, by multiplicative, diminishing, rotational, etc. techniques, where the user's view can be wholly real, or a mix of real & virtual content.

3.2 Additional Alternate Reality Terms

In addition to the range of alternate realities covered in the previous section, there are several further less commonly used alternate reality terms that requiring understanding but which do not feature or fit well into the frameworks presented in sections 3.1.1 to 3.1.3.

3.2.1 HyperReality

HyperReality (HR) is the term given to a hypothetical communications infrastructure that allows the seamless commingling of reality & virtual reality, human intelligence & artificial intelligence. In terms of the previously explored alternate reality terms, a HR system is most accurately described as facilitating the creation of mixed reality environments that bring virtual reality content into real world locations – *"It seeks to make virtual reality something that is experienced as part of physical reality, so that virtual and real phenomena appear to interact with each other: HR is VR* as well as, not instead of, *PR"* [14] (emphasis original).

HR is an abstract, high level term that refers to a category of mixed reality environments that combine VR content with views of the real world in a manner that arguably falls under the moniker of augmented reality, however with HR there is an emphasis that the integration of the virtual reality content into the real world be performed seamlessly, such that HR enables hyperreality (this latter non-capitalised term referring to the postmodern usage of the word wherein an observer is unable to distinguish between objects that are real & objects that are virtual). *****this needs a citation, perhaps Simulation & Simulacra by Jean Baudrillard**

3.2.2 PolySocial Reality

PolySocial Reality (PoSR) describes situations in which people multiplex their physical reality, where they engage in face-to-face social interaction, with Web-based social networks & apps for Internet mediated social interaction. Instead of defining a new type of alternate reality in terms of the provenance of the audiovisual stimuli received by a subject, PoSR is concerned with the provenance of the multiple, simultaneous social interactions that are mediated through various telecommunications media [15].

3.3 Cross Reality

Cross Reality (XR) 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 bidirectional 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 [16].

The principle features that distinguish XR from the other alternate realities covered in section 3.1.4 are;

1. a shift from single- to bi-directional information flow between real and virtual environments [17]
2. that both environments are complete unto themselves (but are enriched by their ability to mutually reflect, influence and merge into one another). [18]

XR was realised & developed as a research area by the Responsive Environments Group at MIT's Media Lab, centred around the research of Joshua Lifton [19] in combining the Plug sensor/actuator platform [20] with a Second Life hosted virtual model of the physical Lab in the 'Shadow Lab' project. One of the driving motivations behind this work was what Lifton dubbed 'the vacancy problem'; *****See HyperReality p35*****

> *"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."*

These XR projects at the Media Lab furthered initial work by the IBM Virtual Universe Community [21–23], described in personal correspondence by Ian Hughes;

"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 . . . Equally the objects generated messages when they were physically switched on and off. As SL had an RPC interface it was possible . . . to subscribe to the same messages and send requests into SL to change states of object . . . So there were lights, blinds, proximity detectors and even the tilt sensors on the laptops that were instrumented with these messages."

Figure 3.7: Side view of the virtual Shadow Lab.

Figure 3.8: A Ubiquitous Sensor Portal.

The Shadow Lab project did not allow for tandem visual engagement with both constituent environments of the cross reality platform, focussing instead on the interplay of sensor data & actuator commands exchanged between the environments. The visual aspect was addressed in part by the subsequent Ubiquitous Sensor Portal project, which situated 45 I/O rich 'portals' (figure 3.8) throughout the Lab, each with a corresponding extension in Second Life. 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 reflecting intellectual affiliation as opposed to real-world location.

3.3.1 Alternate Reality Definitions from Cross Reality

Lifton's use of alternate reality terminology [19] does not conclude that MR is a broad term encompassing both AR & AV − in fact, AV is not mentioned at all, even though the XR systems presented arguably cause it to manifest. The diagram presented (figure 3.9) alludes to Milgram's continua but places MR as a separate classification of alternate reality between AR & VR, even though the discussion hints that it logically encompasses AR. Figure 3.10 is the result of modifying this diagram to match the definitions in section 3.1.4.

Lifton does however explain that while such a taxonomy can be successfully applied to most alternate reality efforts, it does not well address those that feature two complete realities, one real & one virtual, which is one of the defining & distinguishing characteristics of a XR system. *****is there a direct citation for this?*****

Figure 3.9: The *"virtual worlds taxonomy as viewed on the real-virtual axis"* presented by Lifton.

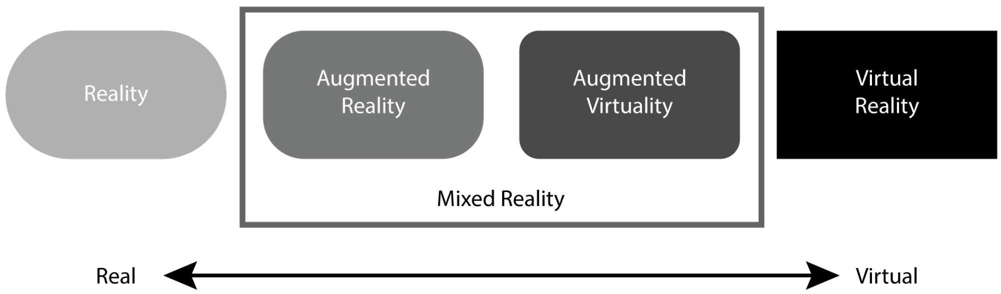


Figure 3.10: Lifton's taxonomy as modified by this review.

3.3.2 Position of Cross Reality

The position of XR in relation to other alternate realities can be visualised using Milgram & Kishino's virtuality continuum. As one of the defining characteristics of a XR system is that it features two environments, both complete unto themselves, the explanation herein distinguishes between environments themselves (depicted in figures 3.11 to 3.15 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 AR system[1], 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 3.11), a XR system instead features two discrete environments, one real & the other virtual, each complete unto itself (figure 3.12), with the user attending either to the stimuli originating from the real environment (figure 3.13) or to the stimuli originating from the virtual environment (figure 3.14).

Although a XR system as a whole should definitely be considered a case of MR, whether each of its constituent environments should be considered outwith or within the realm of MR (especially when visualised upon the continuum) is open to debate. Taking the real environment as an example, one could argue that the use of actuators to produce physically observable effects on behalf of controls from the virtual environment constitutes an AR environment. However in adhering to the definition of AR adopted earlier (see section 3.1.4) we would not label this an AR environment as we do not have *virtual* objects overlain upon our view of the real environment, but rather *real* objects controlled by the actions & events of a discrete virtual environment. So whilst an AR environment falls within the realms of MR, the constituent environments of a XR system when considered individually are considered as occupying the two extremes of the continuum, outwith the MR region & thus their depiction as such in figures 3.13 & 3.13.

[1]This discussion over the relationship between AR & XR also stands for the relationship between AV & XR, however as AV has received less attention in the literature & in commercially available implementations the discussion uses AR as its example.

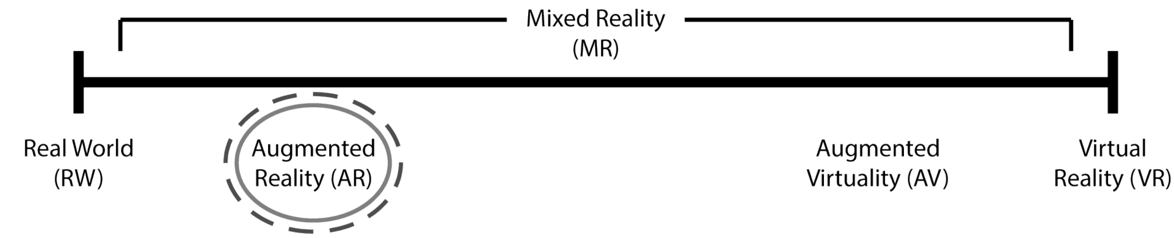


Figure 3.11: AR visualised using the virtuality continuum.

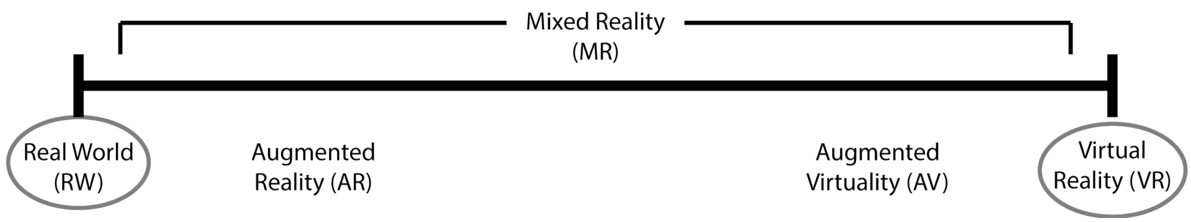


Figure 3.12: The two environments that comprise a XR system.

3.3.3 Parallel Reality

The discussion in the previous section highlighted that the first distinguishing factor of XR, that differentiates it from other alternate realities such as AR & AV, is that XR features two discrete environments, one real & one virtual. The second distinguishing factor is the presence of a bidirectional flow of information between these two environments (figure 3.15).

Whilst the systems developed & explored by this thesis feature two discrete environments, one real & one virtual, that users can transition between visually observing (figures 3.13 & 3.14), they do not feature this bidirectional information flow between the environments (other than using sensed real position information to maintain the user's vantage point into the virtual environment).

Thus, the systems developed & studied in this thesis cannot be considered true XR systems as they do not meet both of the distinguishing criteria. We propose the term *parallel reality* to describe such systems. Parallel reality is thus defined as;

> *A system comprising two environments, one real & the other virtual, each complete unto itself, wherein the user is granted the ability to transition between receiving stimuli from either.*

Should a bidirectional information flow be introduced to a parallel reality system, or the ability to transition between receiving stimuli from either environment into a cross reality system, one would effect *parallel cross reality.*

3.3.4 Spatial Equivalence in Parallel Reality Systems

When discussing a parallel reality system that allows a user to transition between two environments, one real & the other virtual, one must consider the relationship between the two environments, namely whether (& if so, how much) their layout, dimensions & content relate to each other − their *spatial equivalence.*

A parallel reality system would be unrewarding if the real & virtual environments were identical[2]. However a virtual environment that shares roughly the same fundamental dimensions & layout as the real

[2] *"For virtual reality to be interesting it has to emulate the real. But you have to be able to do something in the virtual that you couldn't in the real."* (Life on the Screen, p219)

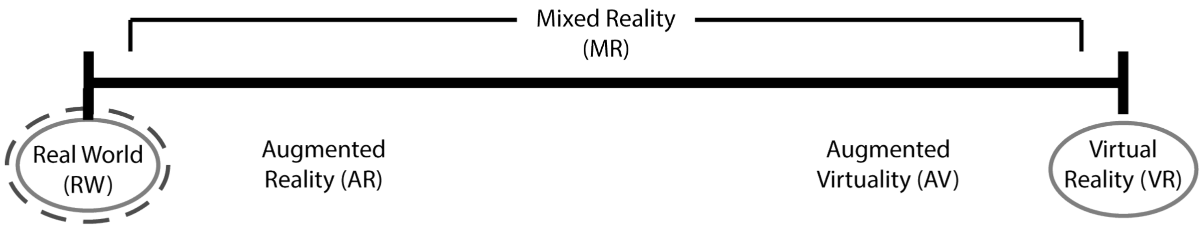


Figure 3.13: A XR system with the user attending to RW stimuli.

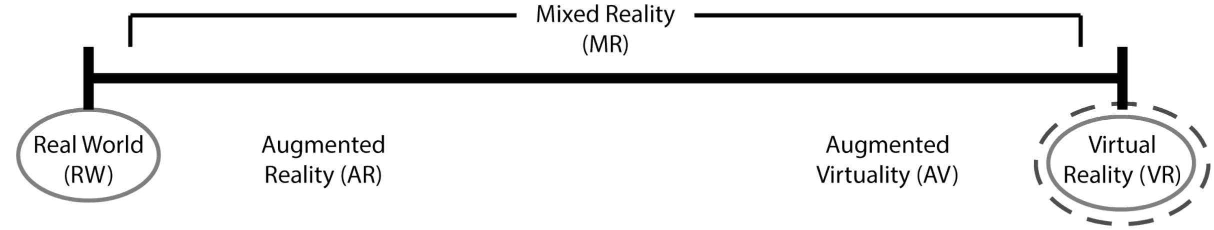


Figure 3.14: A XR system with the user attending to VR stimuli.

environment (it represents the same 'place') but presents an alternative representation has been proven to be a useful modality in previous XR research (see section 3.3) & it is this arrangement that the systems developed by this thesis focus on, in particular those where the virtual environment represents the same place as the real environment but at an earlier moment in time.

One might consider the 'Second Earth' concept to be the ultimate realisation of this scenario of spatially equivalent real and virtual environments. Discussed in detail in a 2007 Technology Review article [24], 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. The systems developed in this thesis focus on a single small location, however it does not take a great leap of imagination to understand the worth of such a system scaled to larger, even global, sizes.

Although the use cases for parallel reality systems that feature completely unrelated real & virtual environments (including where the virtual environment is entirely fictitious) may seem limited in terms of possible benefits to understanding or knowledge gain when comparing & contrasting the environments, an educated approach to implementing transitions between these environments, that takes similar considerations as the systems developed in this thesis, does conceivably have a purpose.

In the opening quote to this chapter, 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, the 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', however the protagonist still wishes to be able to experience both by transitioning between them, paying attention to one while travelling through the other. While this situation is currently science fiction, recent developments in mobile VR platforms such as Samsung Gear VR hint that we are not so far away from a time in which members of the general public will wish to multiplex

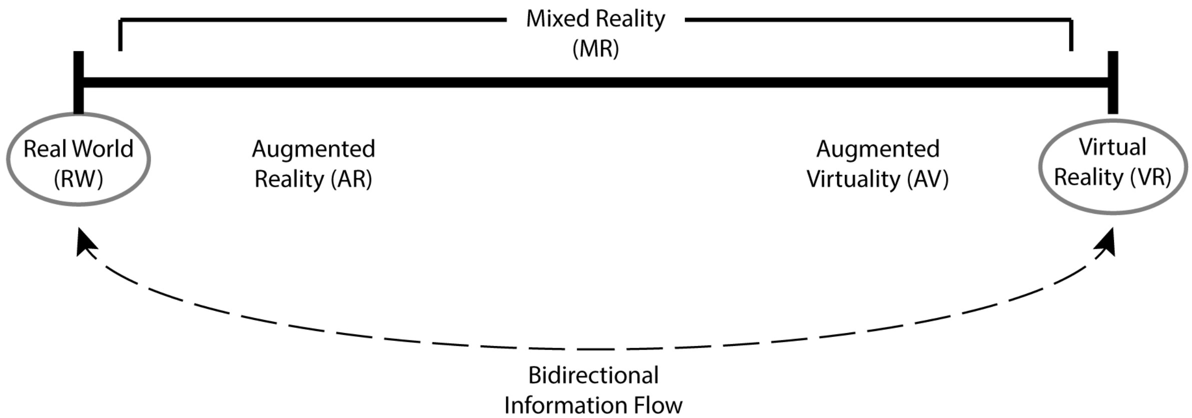


Figure 3.15: The two environments that comprise a XR system, plus the bidirectional information flow between them.

their real environment with a virtual one while in public, in the same way that people commonly engage in CMC via their smartphones at the same time as walking through real environments & conversing with the people in them, in instantiations of PoSR & informing the implementation of transitions in such systems with the findings of the experiments of this thesis into spatially equivalent parallel reality systems will be of benefit to them.

***** Ready Player One, bit where protagonist enters a net cafe & the clerk has a semi-transparent visor such that s/he can observe real world clients whilst also paying attention to a spatially inequivalent fictitious virtual environment.**

3.3.5 PolySocial Reality in Cross Reality Systems

Some references from HyperReality

3.3.6 Summary of Additional Alternate Reality Definitions

HyperReality (HR)	A hypothetical high level term referring to a category of mixed realities that combine VR content with views of the real world in a seamless manner such that the observer experiences *hyperreality*.
hyperreality	A postmodern term describing a situation wherein an observer is unable to distinguish between objects that are real & objects that are virtual.
PolySocial Reality (PoSR)	Describes multiple simultaneous social interactions mediated via various computer mediated communications (CMC) technologies. [15].
Cross Reality (XR)	Systems that feature two environments, one real & one virtual, both complete unto themselves [18] but enriched by their ability to mutually reflect, influence & merge into one another thanks to bidirectional information flow between them [17].
Parallel Reality (PR)	A system comprising two environments, one real & the other virtual, each complete unto itself, wherein the user is granted the ability to transition between receiving stimuli from either.

3.4 Presence

Any investigation into alternate realities, virtual reality in particular, is likely to involve discussion of *presence* - the subjective experience of being in one place or environment, even when one is physically situated in another [25]. Presence is distinguished from the concept of *immersion*, an objective description of a technology, describing the extent to which it is capable of delivering an illusion of reality to the sense of the user [26]. In current theoretical models, the sense of presence is seen as the outcome, or a direct function of, immersion; the more inclusive, extensive, surrounding & vivd the VE is, or the more similar the transformations in the VE are to those in the real world, the higher the presence [27].

Related is the concept of involvement, defined in this context as the psychological state experienced as a consequence of focusing one's energy & attention on a coherent set of stimuli & it is theorized that both involvement & immersion are necessary for experienced presence [25].

3.4.1 Waterworth & Waterworth three dimensions of virtual experience model

This notion of the sense of presence depending upon multiple factors is explored further by Waterworth & Waterworth who present the *three dimensions of virtual experience* model [28]. In this model, the *locus of attention* axis represents the environment where the stimuli that the user is perceiving originate from; the *focus of attention* axis 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[3] in that environment toward its antithesis − absence[4]; and the *sensus of attention* axis represents the level of conscious arousal (or 'wakefulness' [29]) 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.

In this model, the notion of *involvement* relates most closely to the *focus of attention* axis; heightened involvement pertains to concentrating on environmental stimuli or meaningfully related activities & events, while heightened focus pertains to increased perceptual/concrete processing; lessened involvement pertains to a preoccupation with personal problems or activities occurring outwith the environment of interest, while lessened focus pertains to increased conceptual/abstract reasoning.

Similarly, a relationship can be drawn between Milgram & Kishino's virtuality continuum & the three dimensions of virtual experience model, with the virtuality continuum here considered to be analogous to the *locus of attention* axis; the combination of these models is shown by figure 3.16.

3.5 Transitions in Parallel Reality

The novel aspect of a parallel reality system is the ability it imparts upon its user to switch their locus of attention between equivalent vantage points in RW & VR environments. In the systems developed by this thesis the users maintain mobility, such that they can move around the two environments in tandem, thus extending existing XR platforms that featured static locations at which a user in the real environment could see into the virtual & vice-versa. This combination of unhindered mobility with the ability to transition between real & virtual stimuli thus alleviates the vacancy problem.

In order to achieve the highest quality of experience with this style of interaction with a parallel reality system, it is vital to determine how best to implement the transitions; that is, to mitigate the increased cognitive load (manifesting as increased conceptual reasoning & reduced perceptual processing) required to comprehend each transition, as increased cognitive load will detract from engagement with the environments & reduce the user's willingness to perform subsequent transitions.

[3] **Presence** in this context is defined as a state of heightened perceptual processing of environmental stimuli (*"a psychological focus on direct perceptual processing"* [28]) 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.

[4] **Absence** is defined as *"a psychological focus on . . . conceptual processing"* [28].

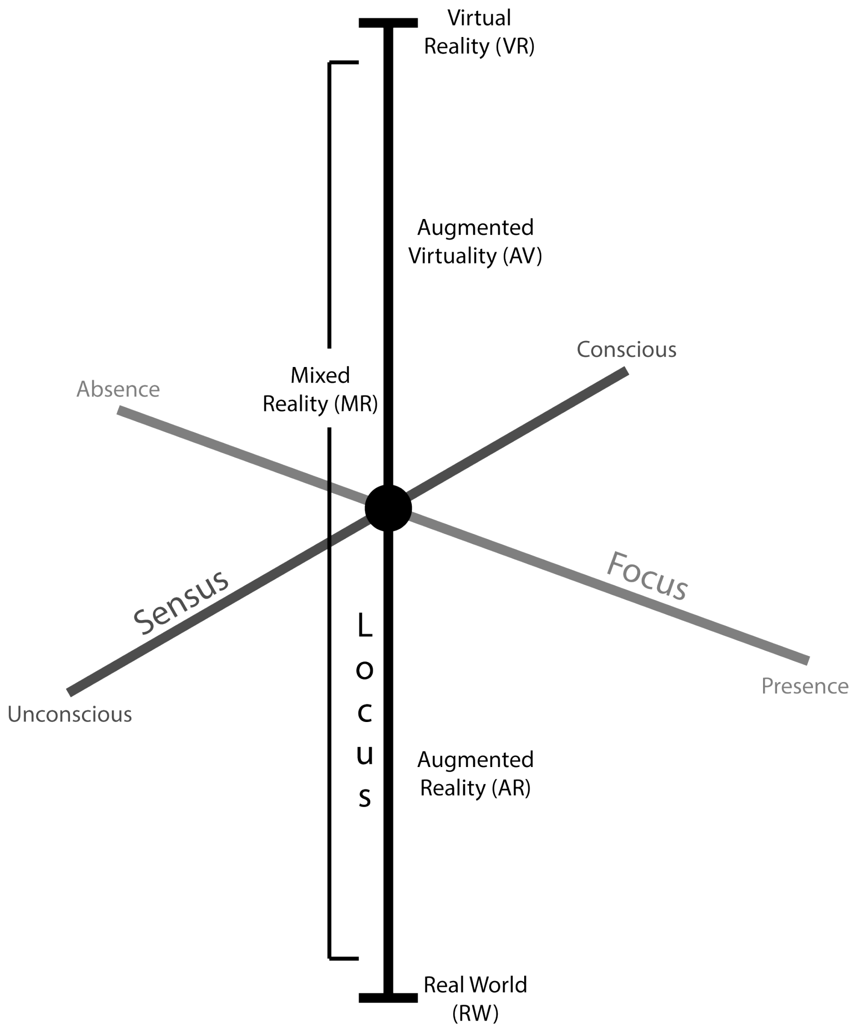


Figure 3.16: The combined virtuality continuum/three dimensions of virtual experience model.

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 [30], which would result in a substantial increase in cognitive load upon each transition, the systems in this thesis have 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) [31] & that when engaging with VR content a user's focus can even be said to typically be *shared* between VR & RW [28].

This latter position is particularly apt for situations wherein the RW & VR environments share the same fundamental layout & dimensions (spatial equivalence), as those in the parallel reality systems of this thesis do, as inherent familiarity between 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 [32, 33] 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 [34].

*****Updated Turkle quote on this from Alone Together, no?**

However, no matter how smooth the transition the process is expected to always result in some heightened cognitive load, a temporary *break in presence*[5] (BIP), as the user comes to terms with the new environment presented to them & comprehends its relation to the other environment that they were just perceiving.

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

To this end, several different implementations will be effected & 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 those developed by this thesis may be deployed. In particular, it is hypothesized that there will be a strong correlation between participant movement (or lack thereof) & choice of particular implementation.

3.5.1 Transitions using the Combined Model

Visualised using the combined model (figure 3.17) 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

3.6 The Case for Parallel Reality

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);

[5]The definition of **break in presence** adopted herein is the second from Waterworth & Waterworth [28] (p205): a movement along the focus axis away from presence in the real or a virtual environment & toward absence, which also relates to a reduction in *involvement*. This differs to Slater & Steed's original definition in [35] 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 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'.

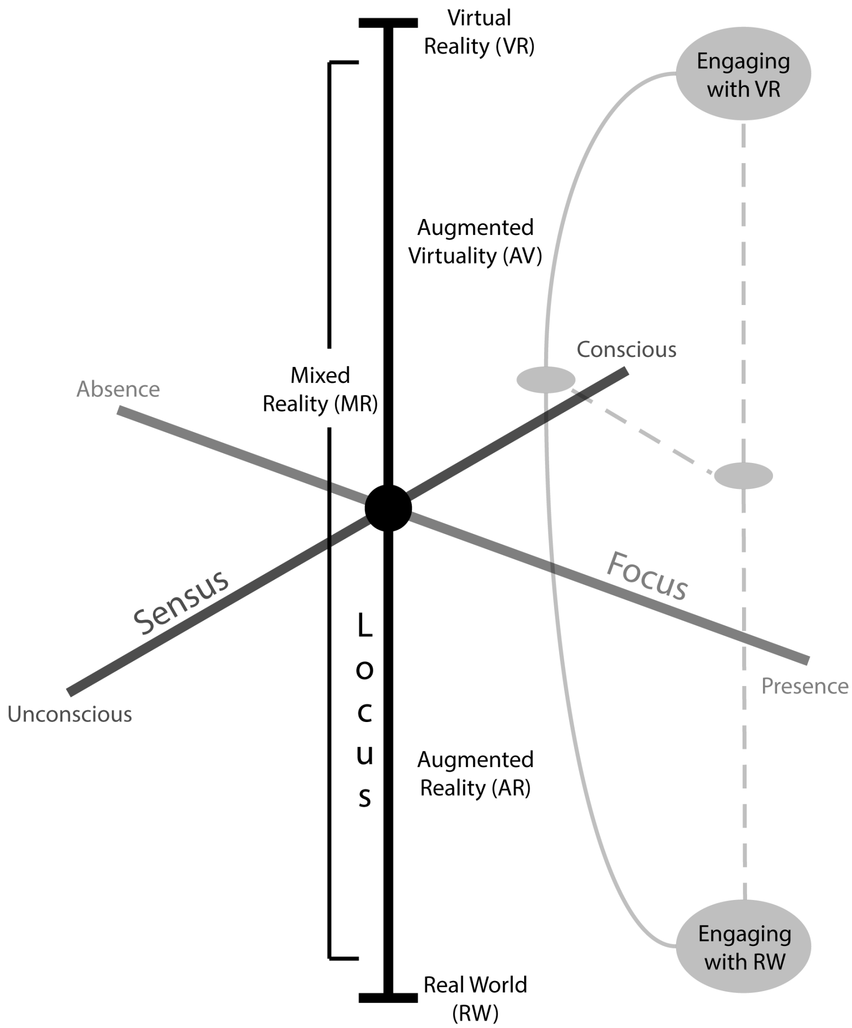


Figure 3.17: Operation of the Mirrorshades platform represented upon the combined model.

- 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 [37];
- 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 [38]) almost the whole RW view. While AR *"smears an informational coating over real space"* [39], 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.

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 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.

3.7 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 [40] 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 [41]. The term PolySocial Reality (PoSR) has been proposed to describe these multiplexed mixed realities [42], wherein individuals interact within multiple environments [15], and to identify the extent and impact of shared and unshared experience in such situations [43]. 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 [19], 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 [44], and with social roles and the community aspect constituting key aspects of these game's popularity [44, 45], 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 [46, 47]. 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 [16, 19] 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 [18] 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 [41]. The project described in this paper addressed these omissions with the Pangolin virtual world viewer [48] 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 [24, 49, 50]), 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’ [18] 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 [47, 51] (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 [52], 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 [53] 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) [54].

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 [55].

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 [56] GPS receiver; however poor API provision and meager documentation lead to use of a separate u-blox MAX-6 GPS receiver [57] outfitted with a Sarantel SL-1202 passive antenna [58]. 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" [59]. 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 [60] containing a gpsOne Gen 8A solution within its Qualcomm Snapdragon S4 processor [61] 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 [62, 63] and the PostGIS database extender's ST_HausdorffDistance algorithm [64] 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 [65] 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 [66]. The TinyGPS library [67] was used to abstract processing of NMEA messages from the MAX-6 to obtain the required latitude and longitude values.

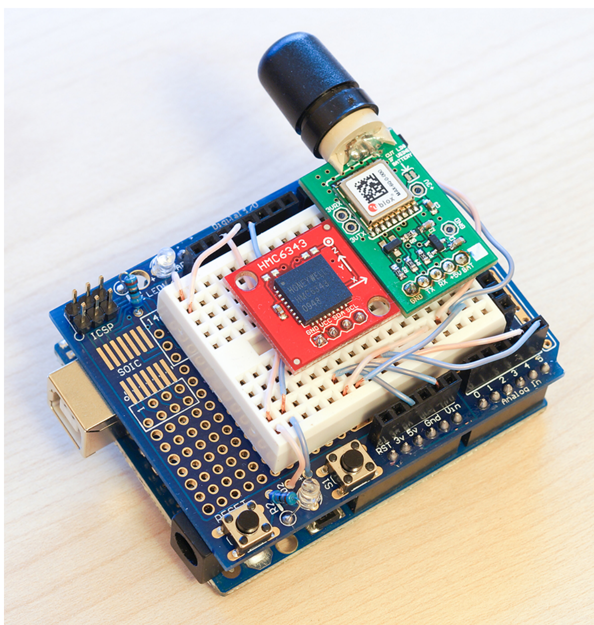


Figure 4.5: The HMC6343, MAX-6 and SL-1202 connected via a breadboard prototyping shield to the Arduino, in the setup and configuration that was then attached to the rear of the 110W for the experiments.

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.

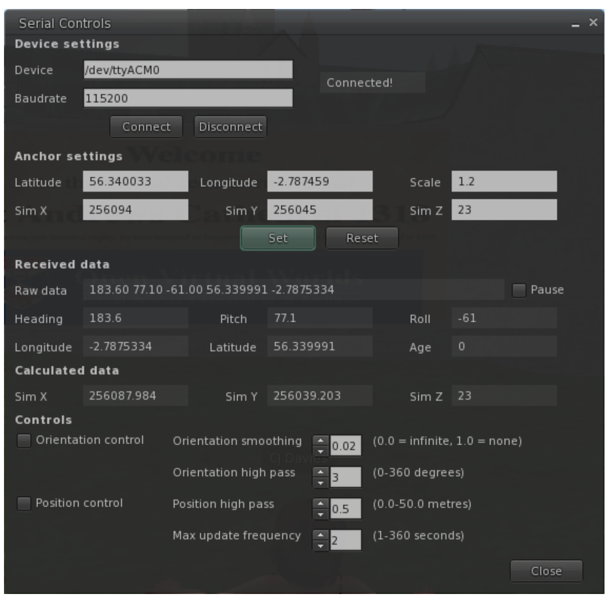


Figure 4.7: The GUI within the Pangolin viewer that allows administration of the position and orientation control of the avatar. In this screenshot Pangolin is connected to the Arduino and is receiving position and orientation data.

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 $1.33e^{-04\circ}$ (±14.8m N/S, ±8.2m E/W). The Hausdorff distance between the routes logged by the MAX-6 and the smartphone was $1.14e^{-04\circ}$ (±12.7m N/S, ±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 $7.23e^{-05\circ}$ (±8.05m N/S, ±4.47m E/W) throughout this sub-route, with the smartphone still behind with $8.99e^{-05\circ}$ (±10.01m N/S, ±5.56m E/W). Again the Hausforff distance between the receivers showed low correlation between the inaccuracies, at $6.43e^{-05\circ}$ (±7.12m N/S, ±3.98m E/W).

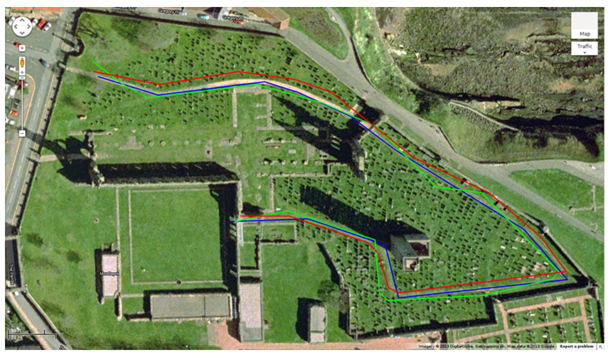


Figure 4.9: Aerial view oriented North upward of the St Andrews cathedral ruins; the blue line represents the first sub-route of the planned route, red the sub-route recorded by the MAX-6 and green the sub-route recorded by the smartphone whilst walking the first planned sub-route.

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).

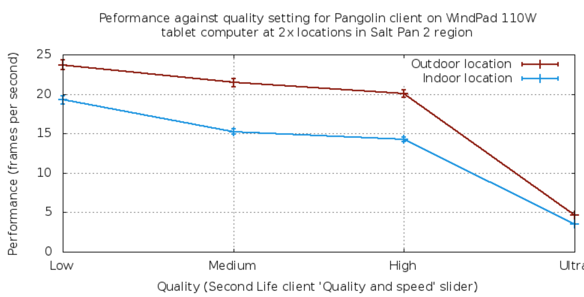


Figure 4.11: Plot of Pangolin's performance (measured in frames per second) against different graphical settings (selected via the 'Quality and speed' slider of the viewer) in two positions within the Salt Pan 2 region.

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 Example Application - Cultural Heritage

The field of cultural heritage has seen widespread applications of both AR [68–82] & VR [37, 83–88]. 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).

5.0.2 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).

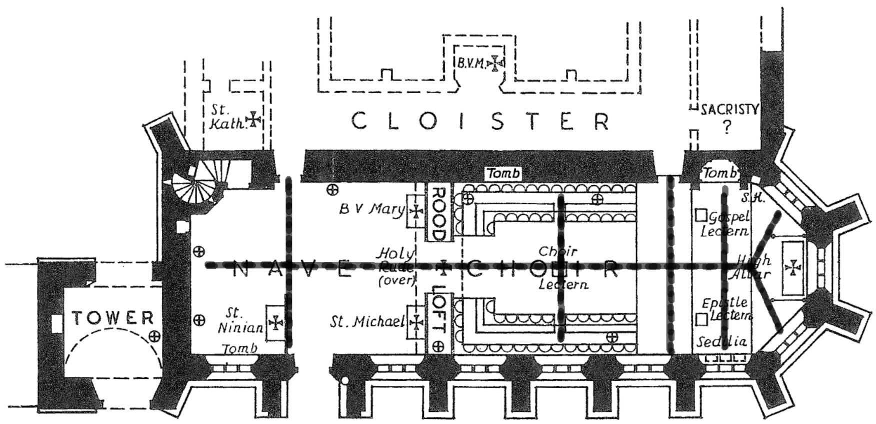


Figure 5.1: Floor plan of St Salvator's chapel, with IPS routes.

5.1 The Mirrorshades Platform

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

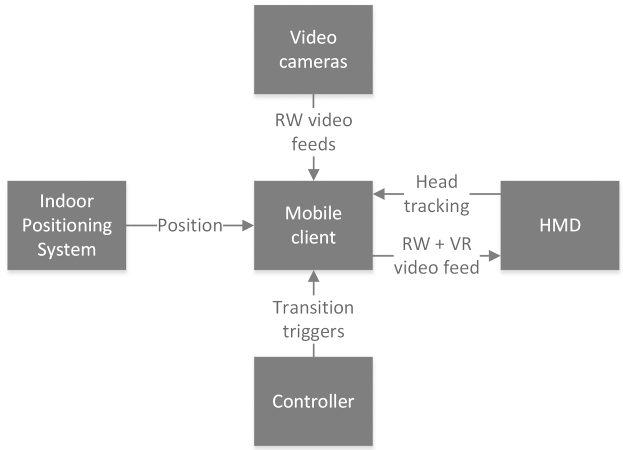


Figure 5.2: Overview of the Mirrorshades platform.

5.1.1 Implementation

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

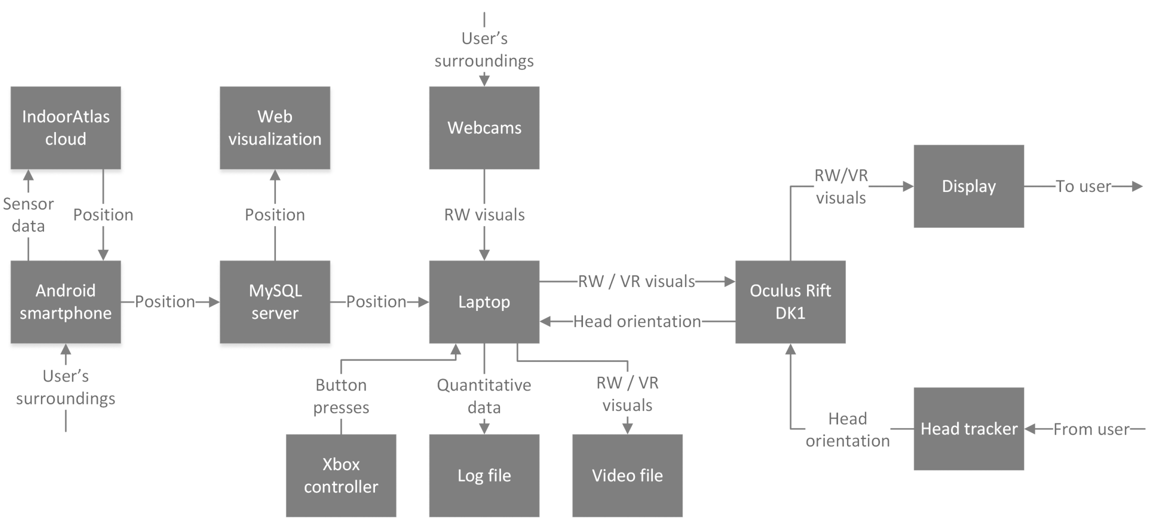


Figure 5.3: Implementation of Mirrorshades platform.

[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 [89] (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) [90].

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).

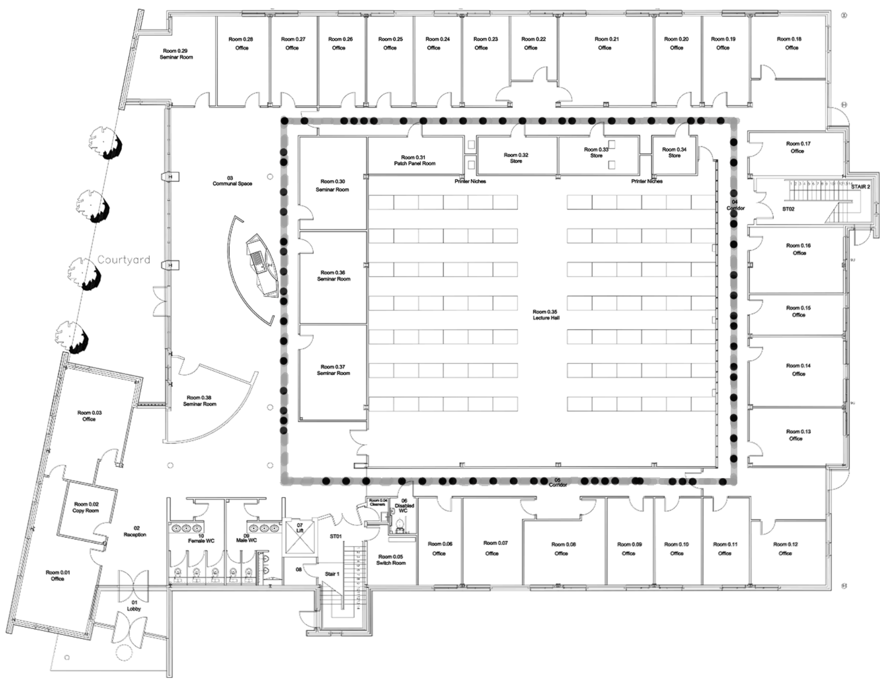


Figure 5.5: Positions (black circles) reported whilst walking a slow lap ($< 1\text{ms}^{-1}$, following gray path) of a departmental building. The building is approximately 40m wide by 30m tall.

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.

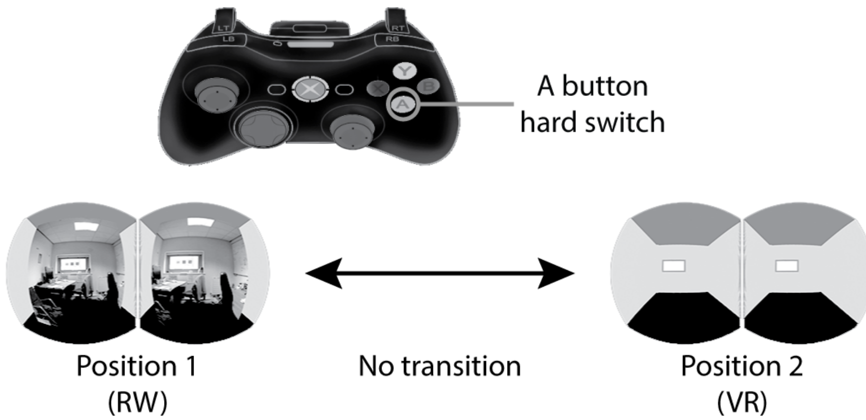


Figure 5.6: Hard switch.

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.

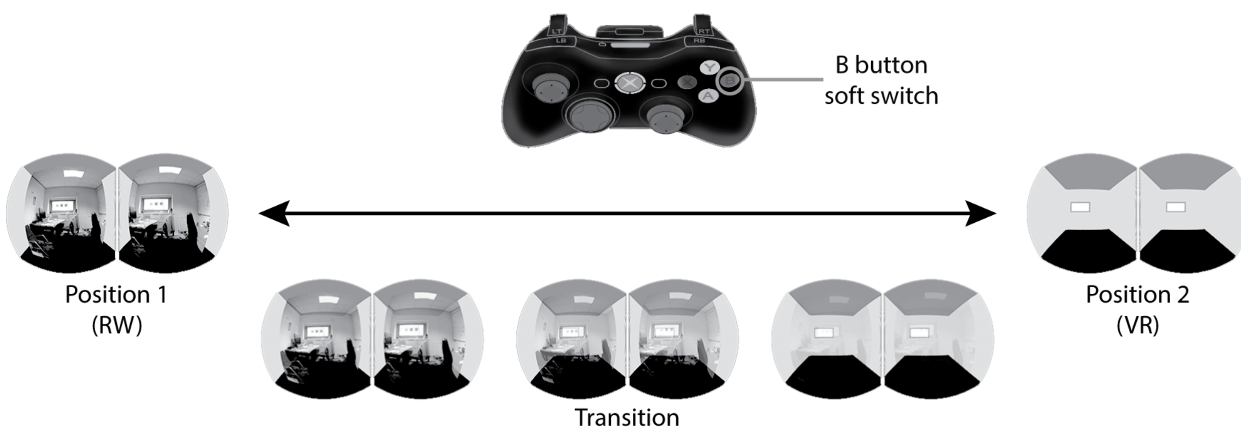


Figure 5.7: Switch with linear interpolation.

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.

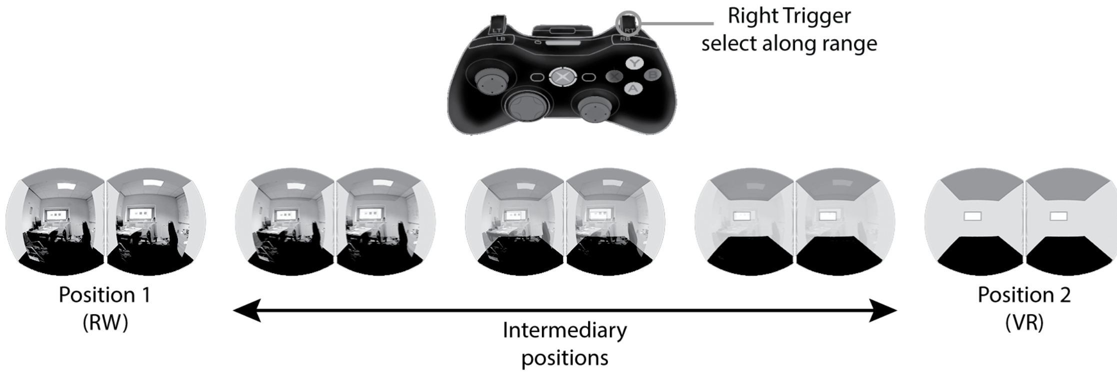


Figure 5.8: Analogue selectable opacity.

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.

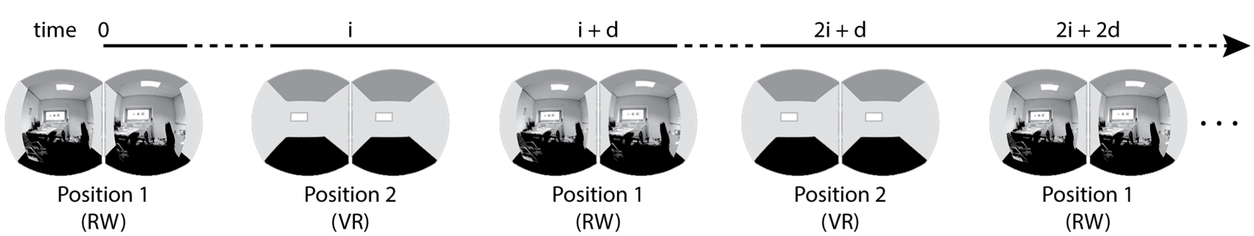


Figure 5.9: Periodic hard switches.

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.

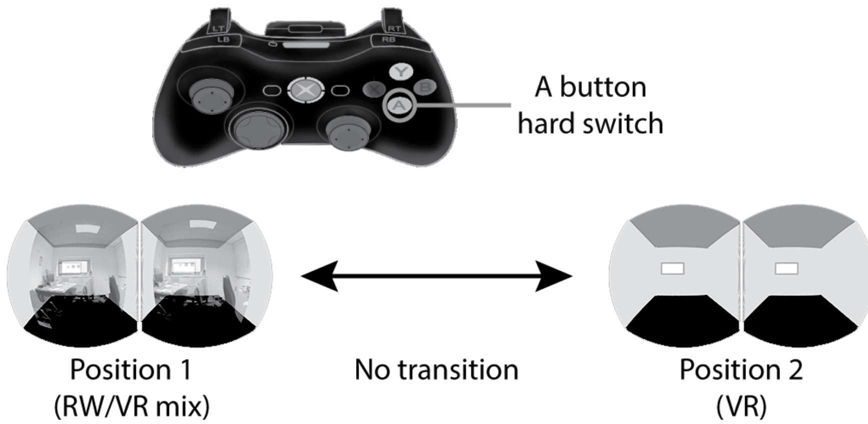


Figure 5.10: Hard switch from reduced maximum opacity.

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 [31]. 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 [28], 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) [91] (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 [85] & 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) [90] 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 &

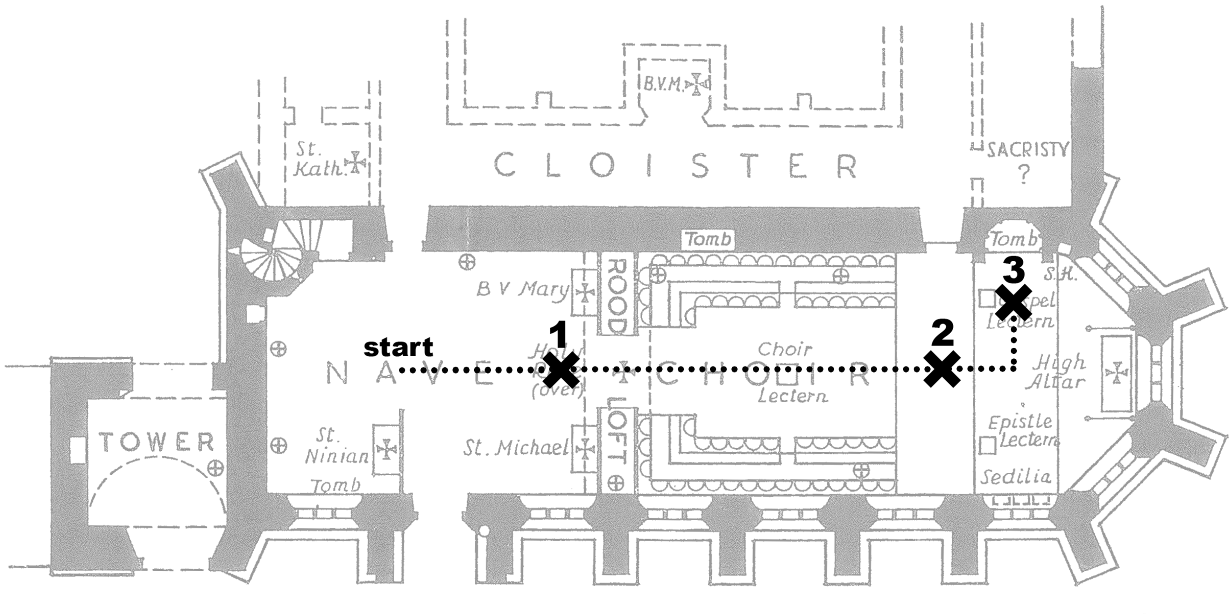


Figure 6.1: The path & positions within the chapel that participants are instructed to attend to.

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

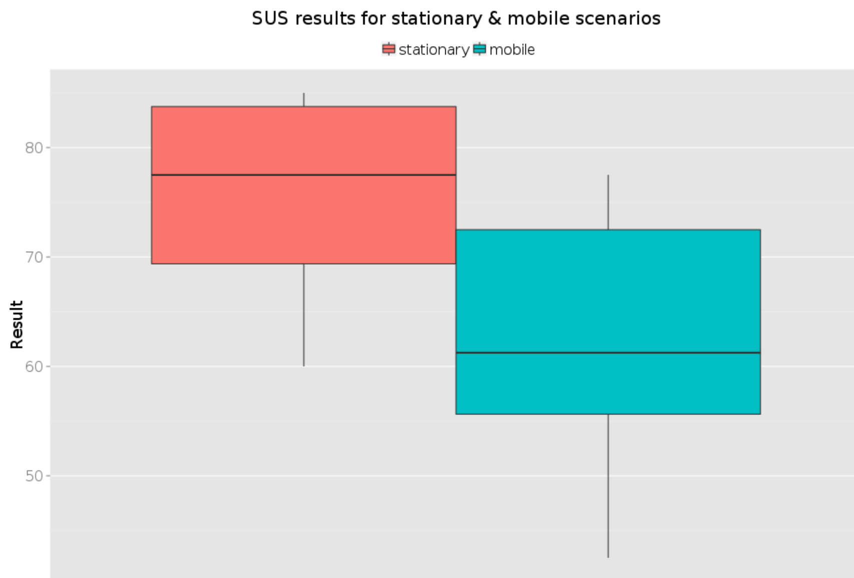


Figure 6.2: SUS results.

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

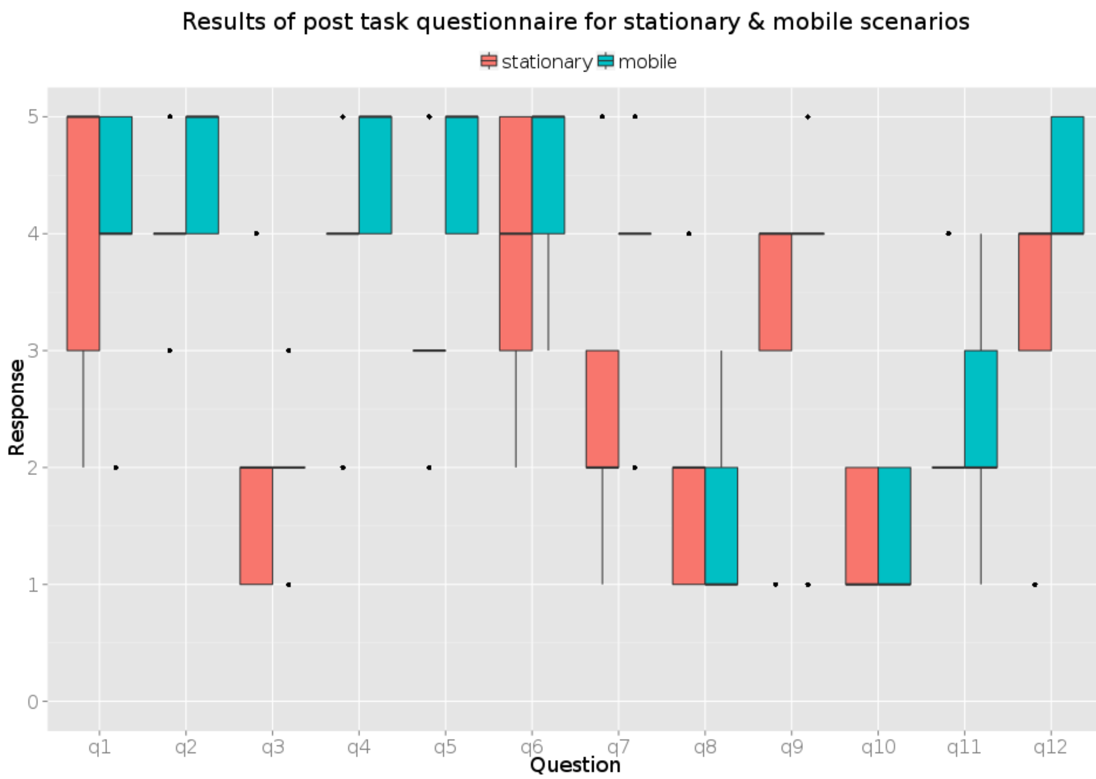


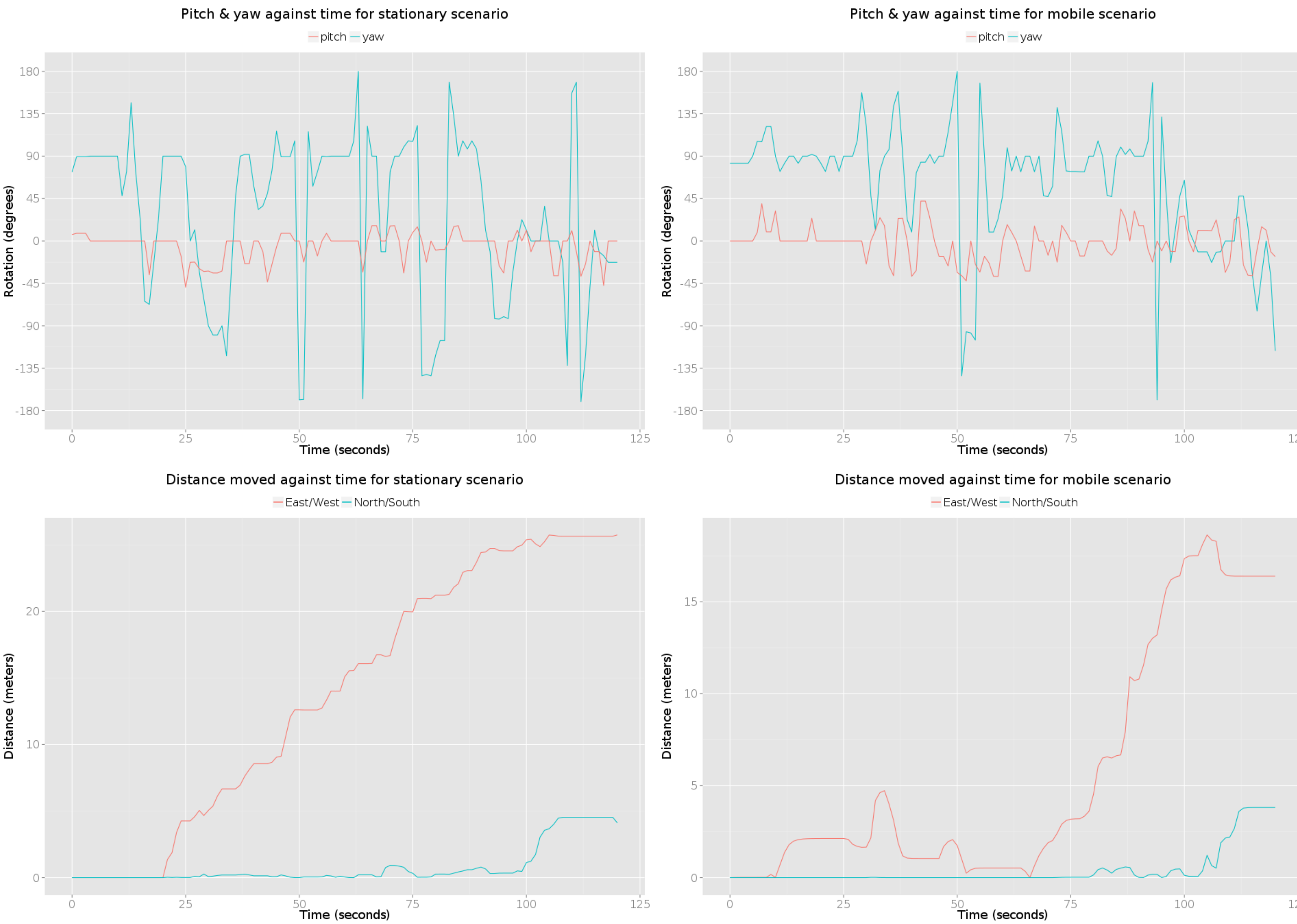
Figure 6.3: 12-item questionnaire results.

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



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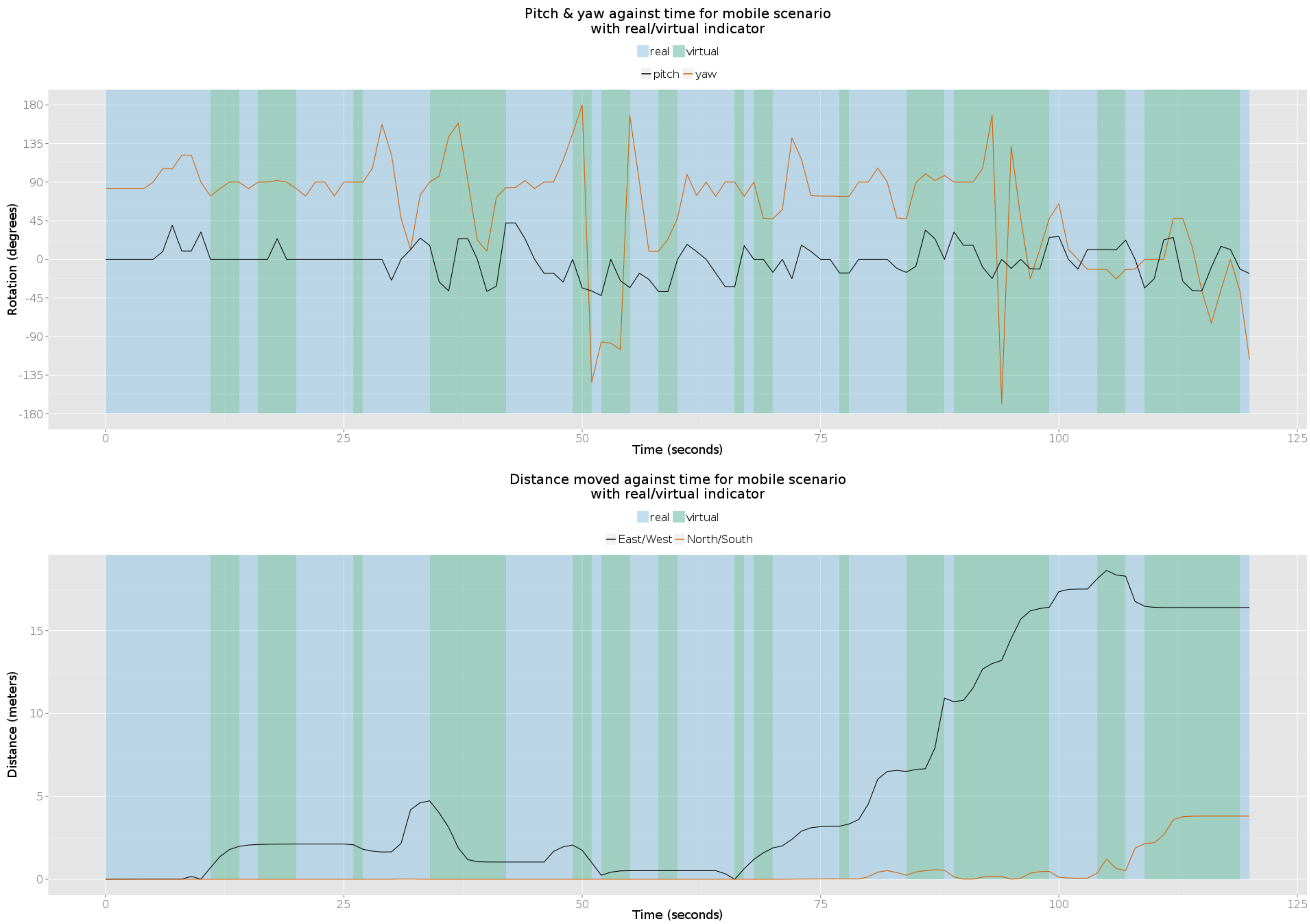

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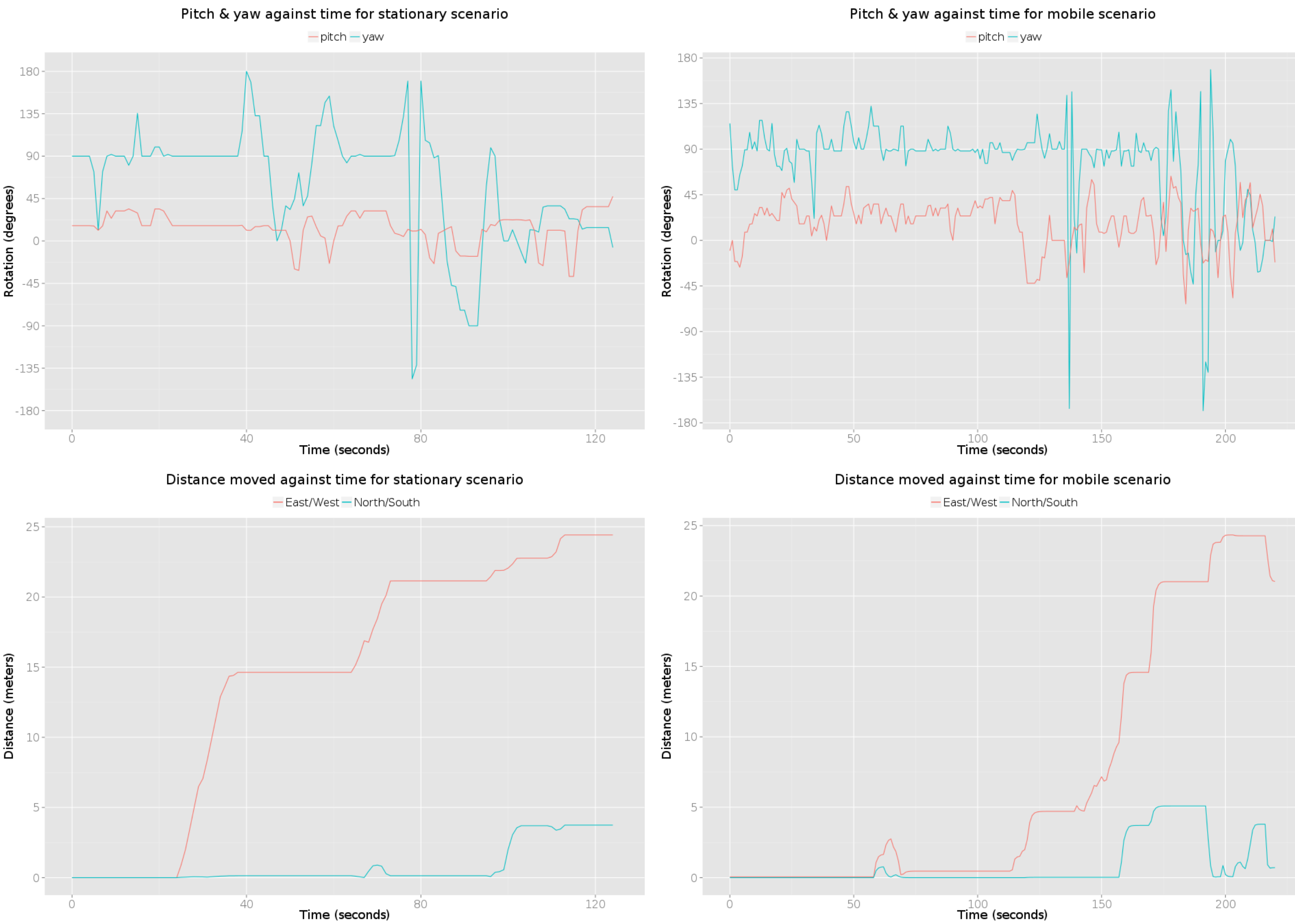
6.9.5 Participant 3



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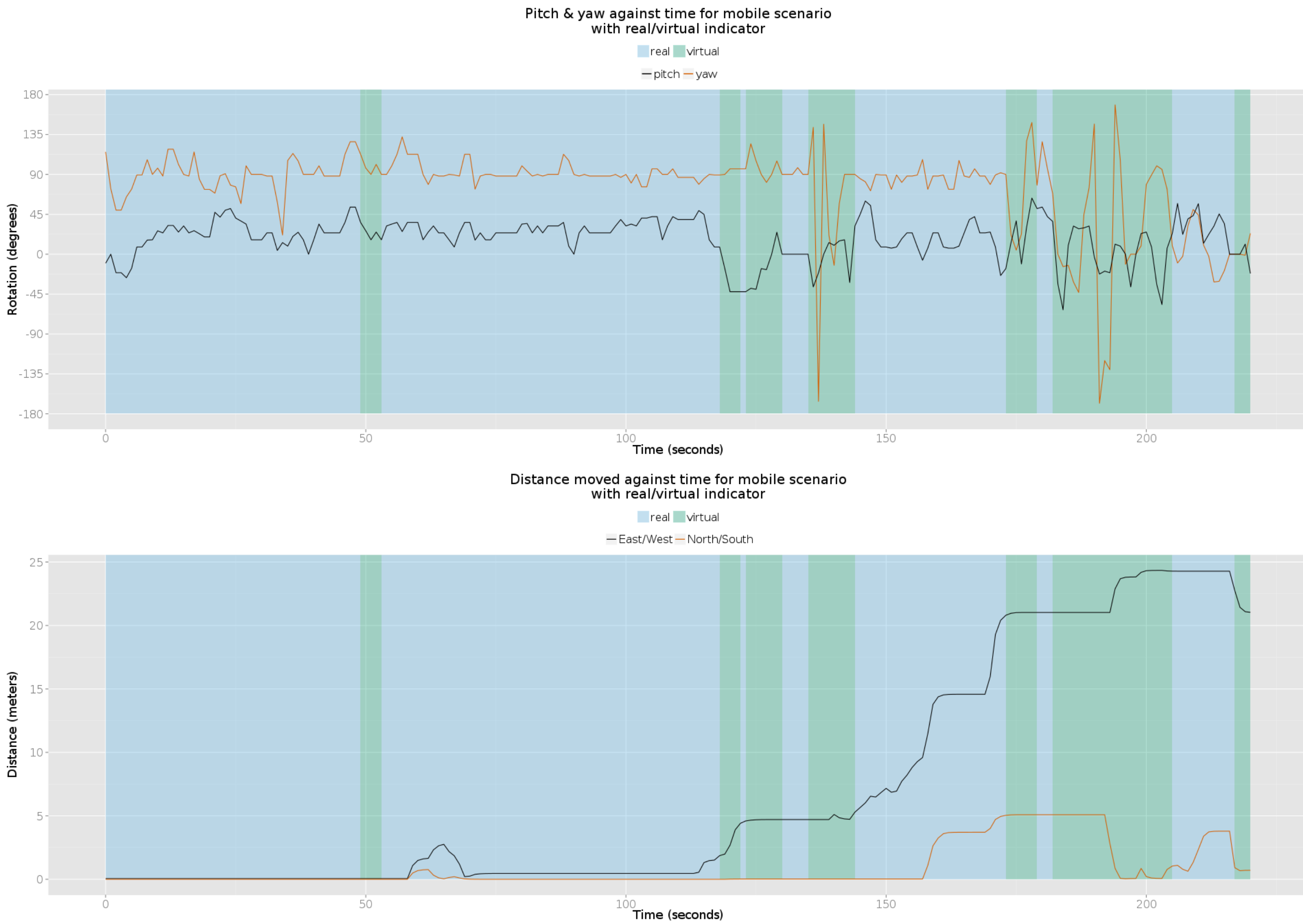

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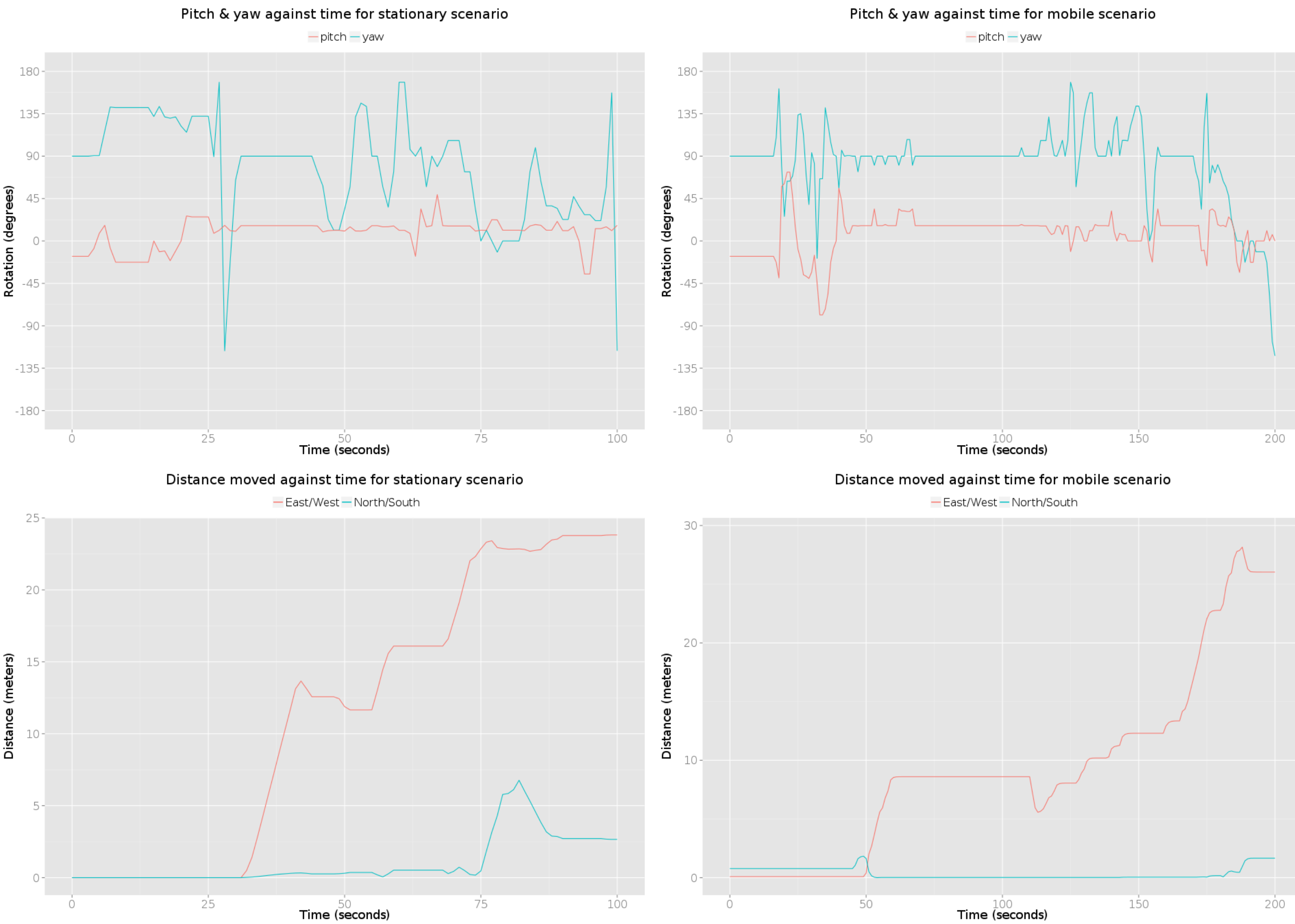
6.9.6 Participant 4



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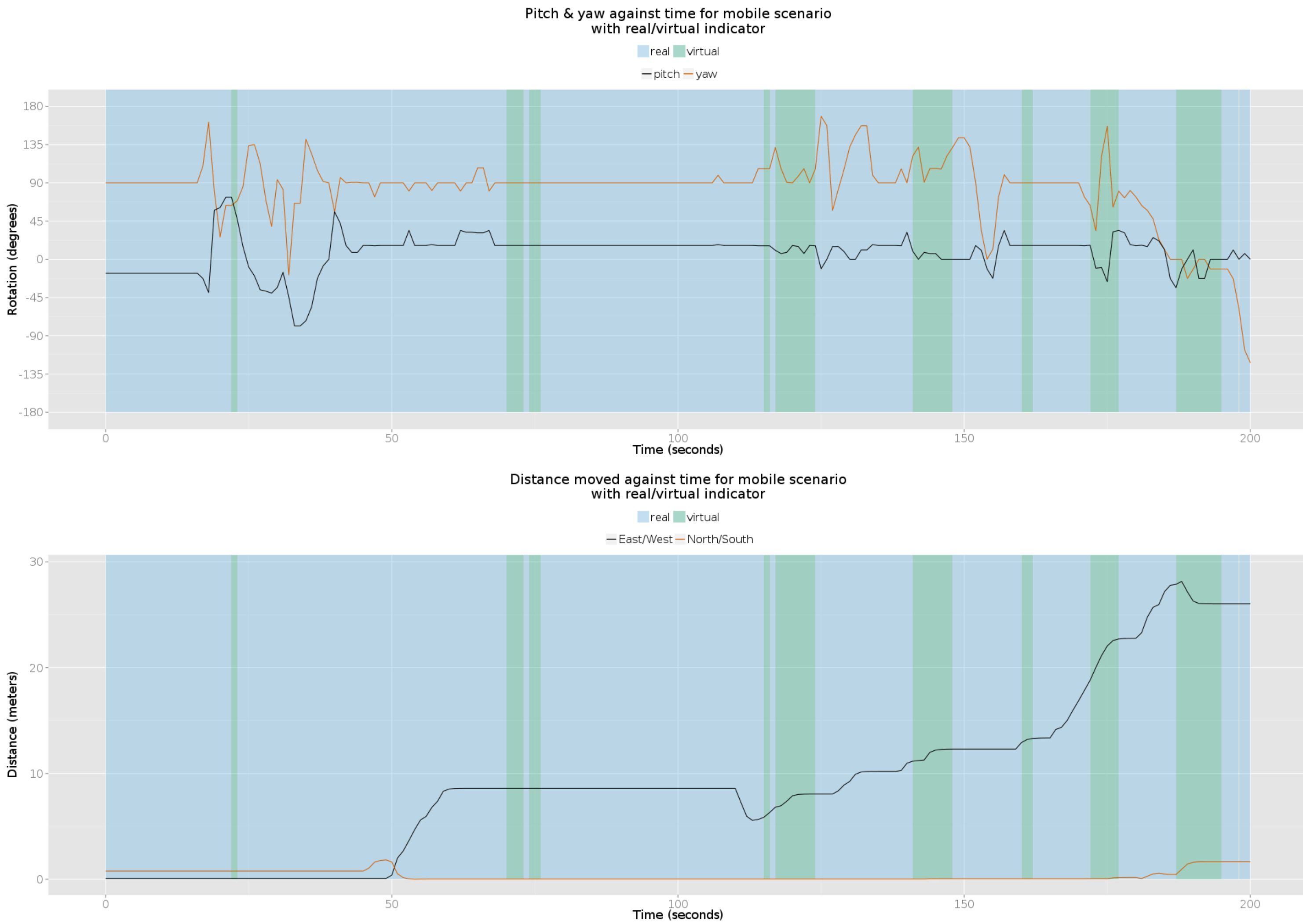

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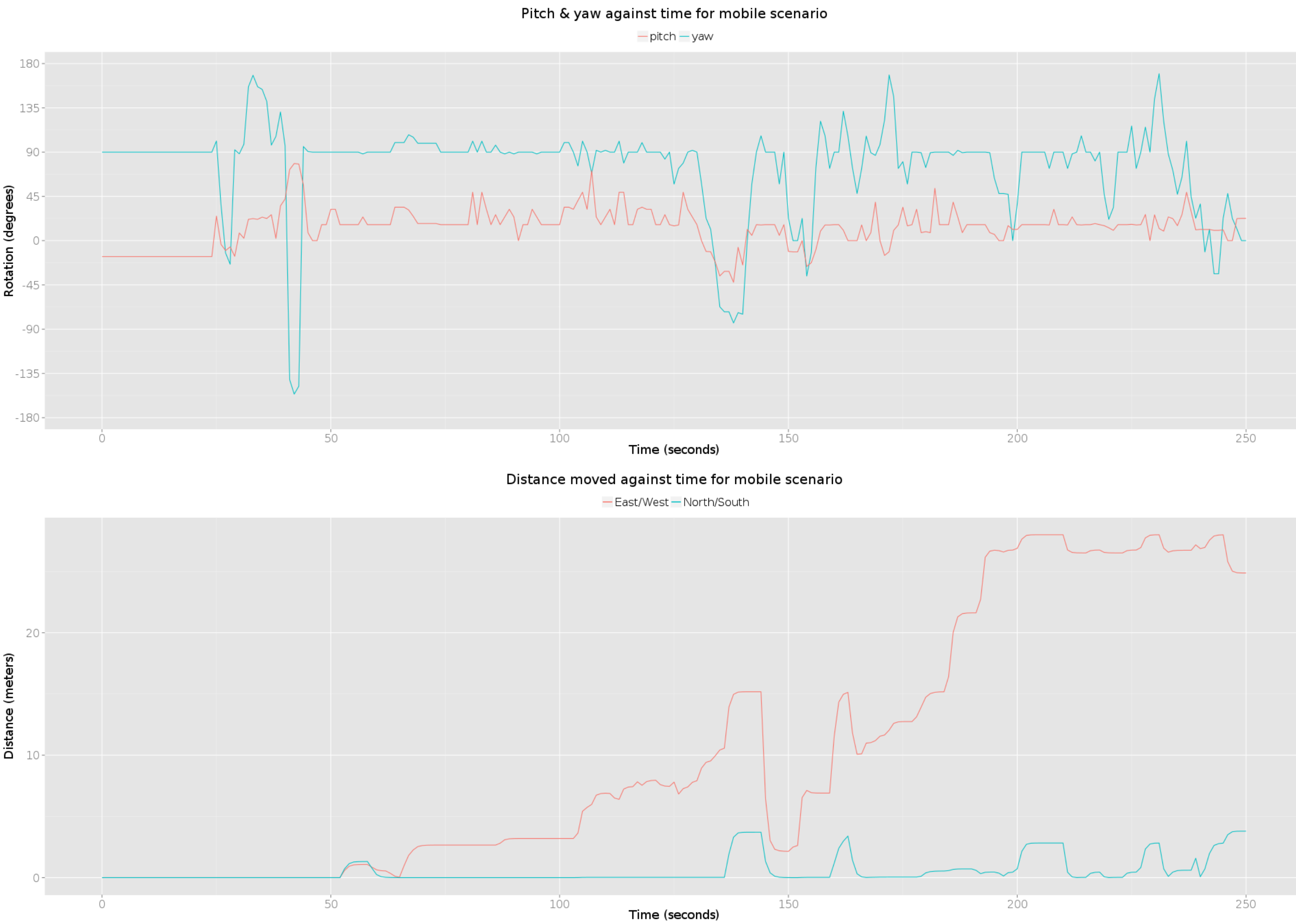
6.9.7 Participant 5



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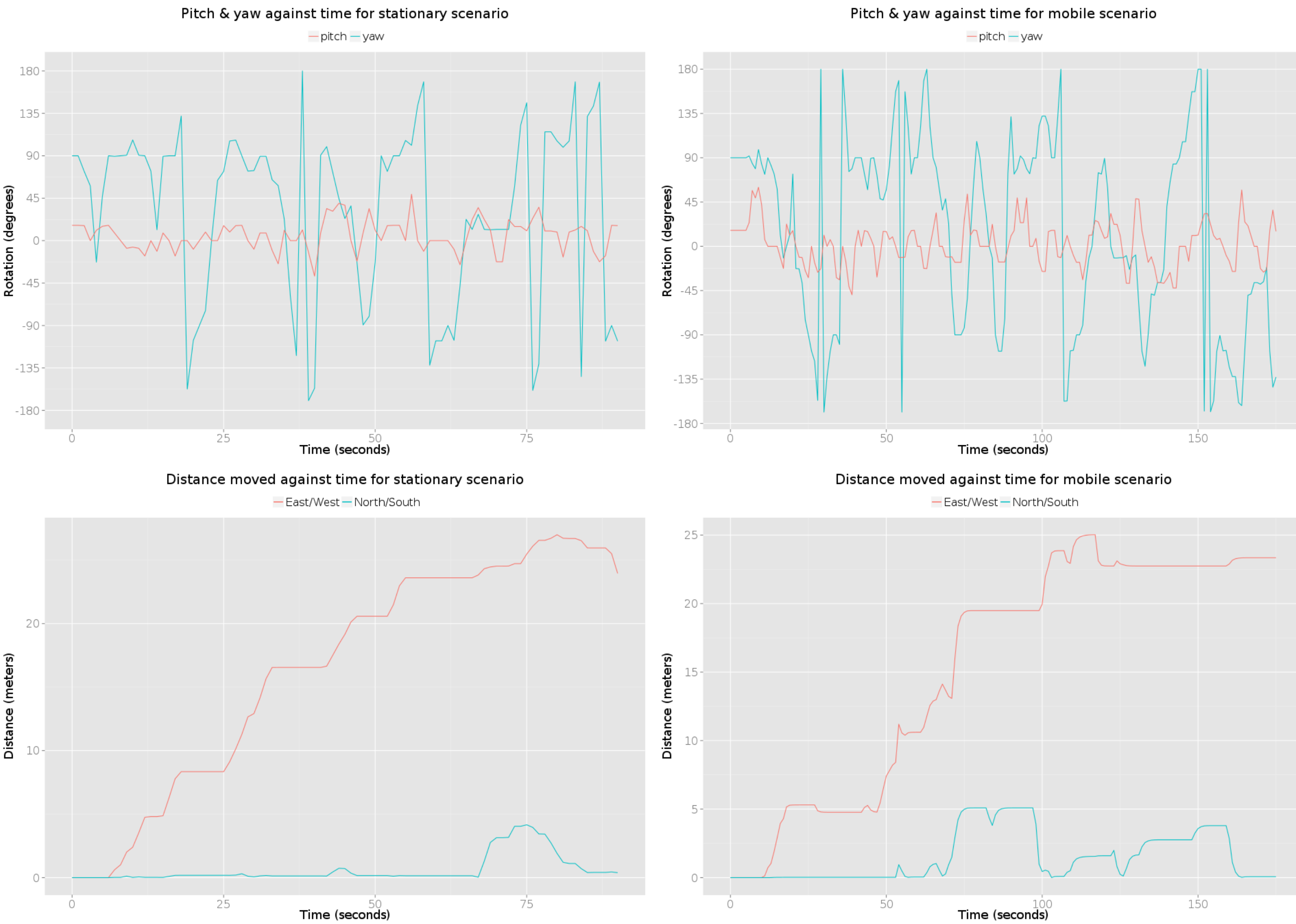
6.9.8 Participant 6



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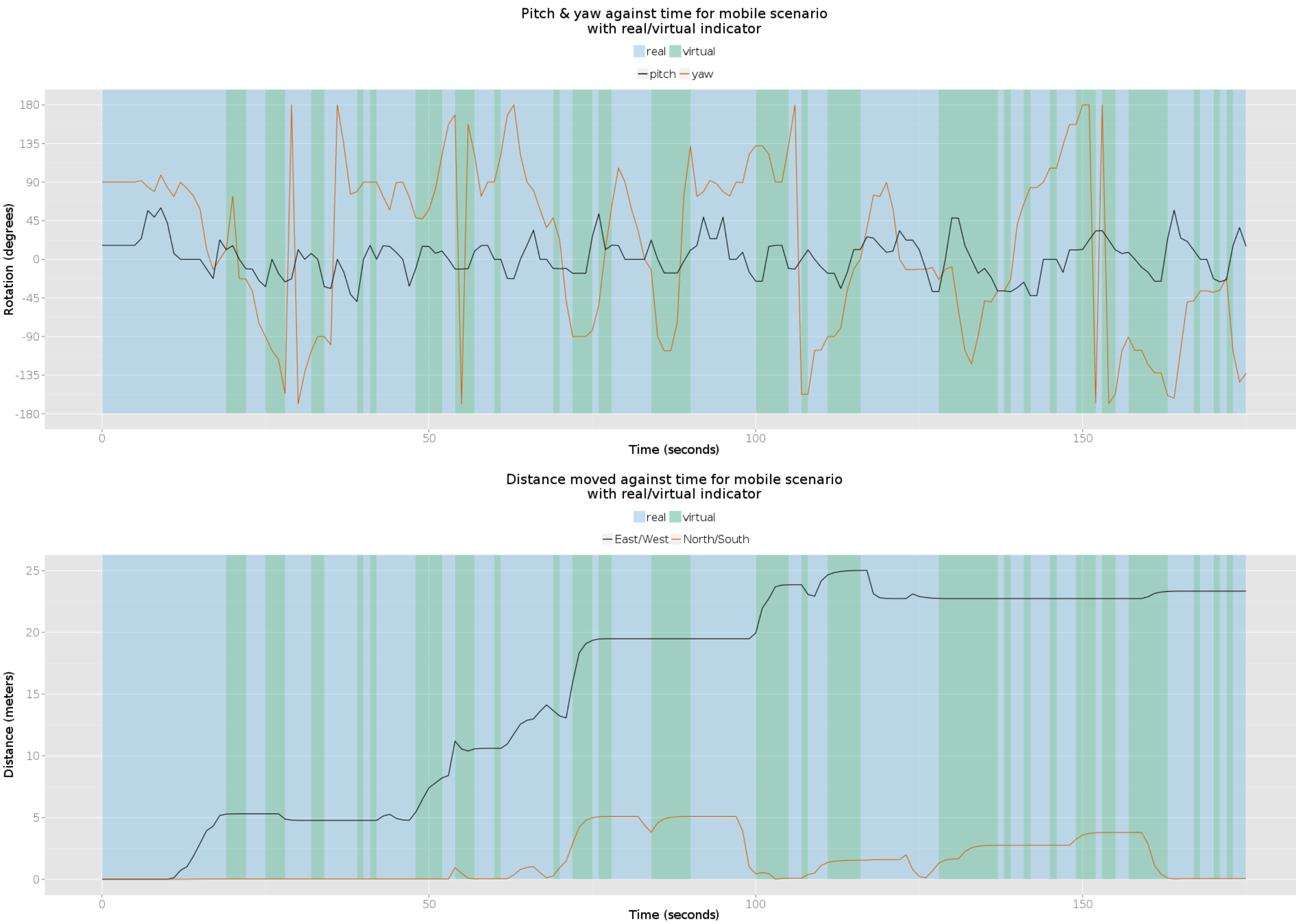

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6.10 Phase 2.1 Results

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6.10.1 Participant 7

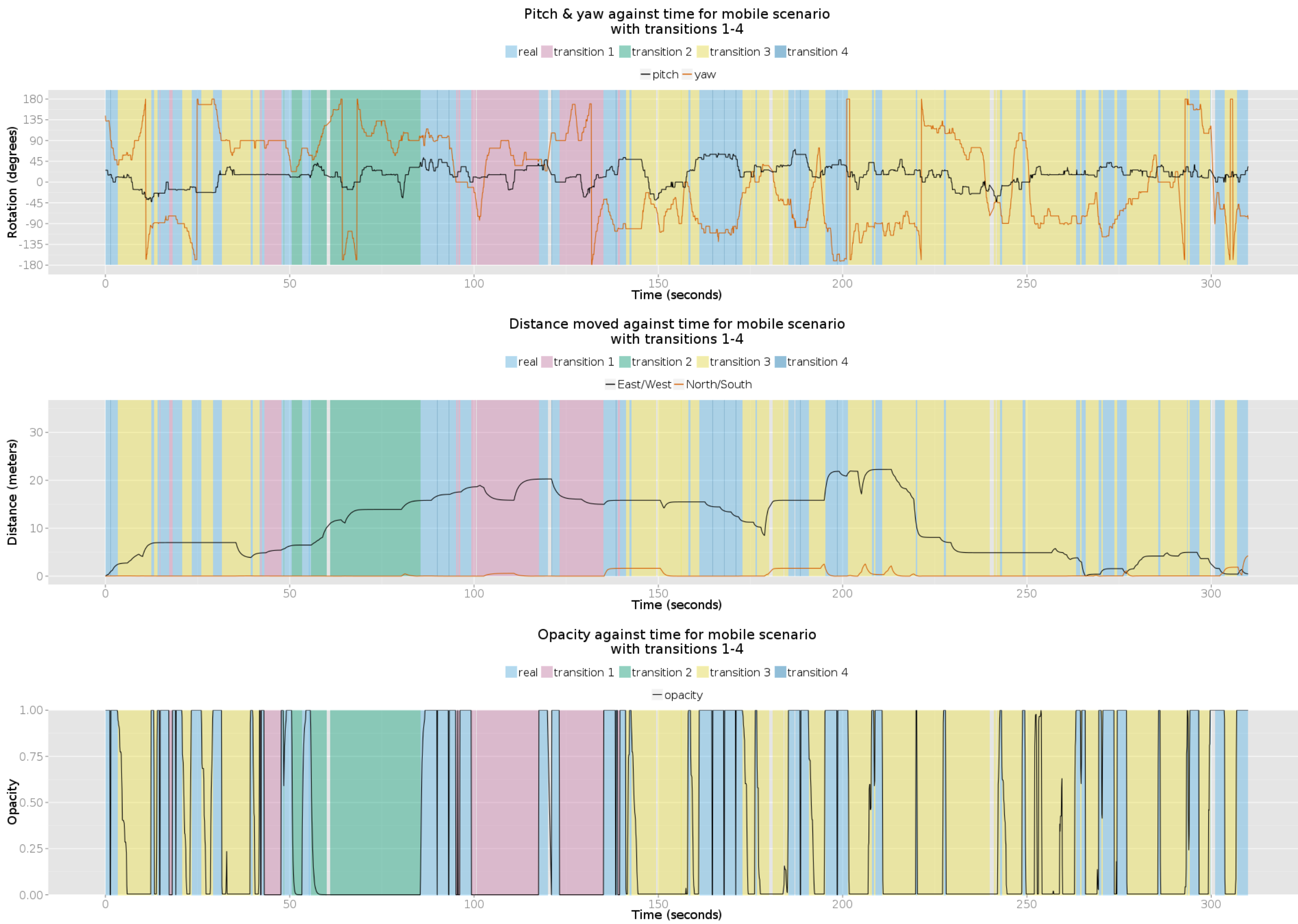

Figure 6.14: Some images, yah.

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6.10.2 Participant 8

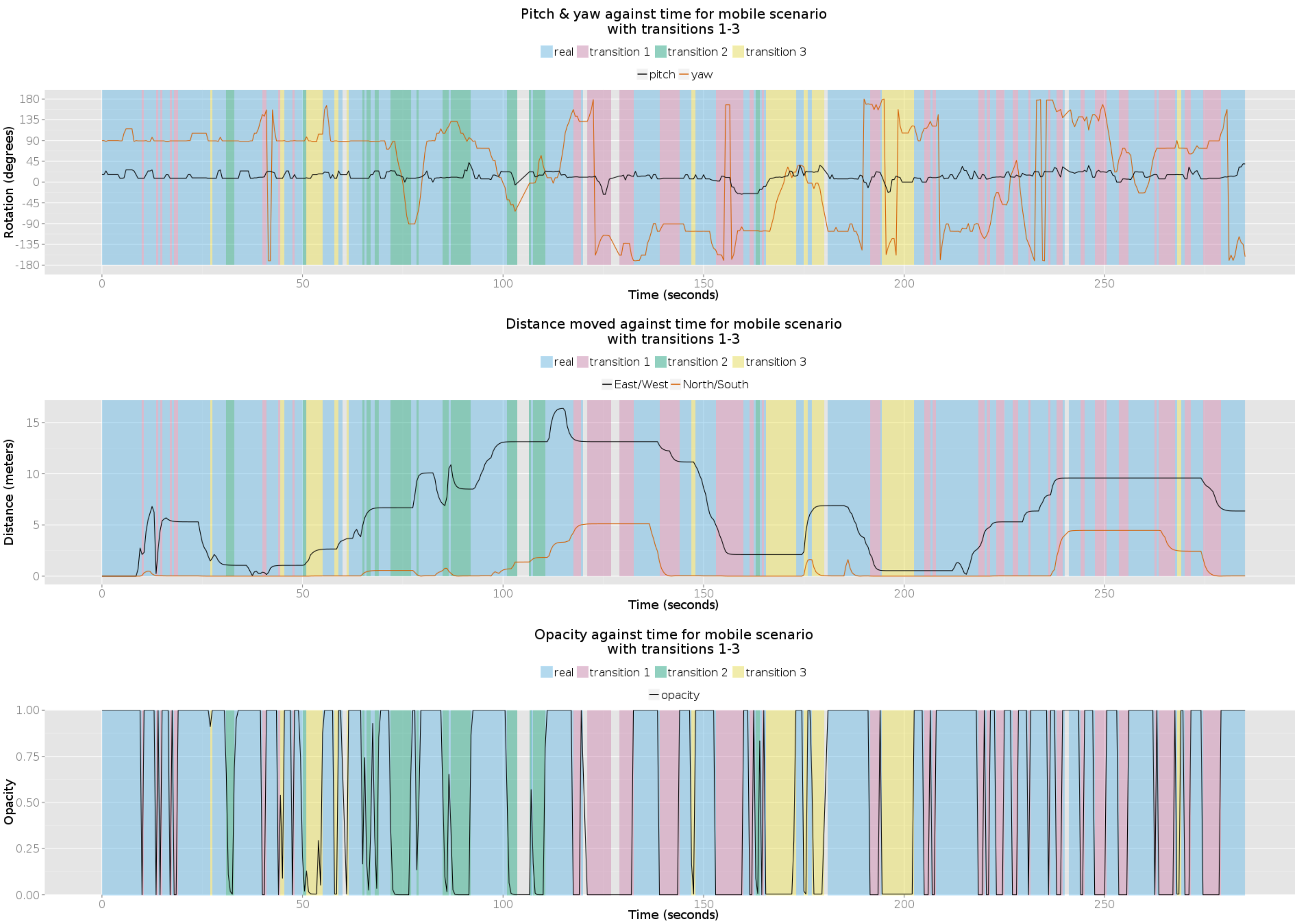

Figure 6.15: Some images, yah.

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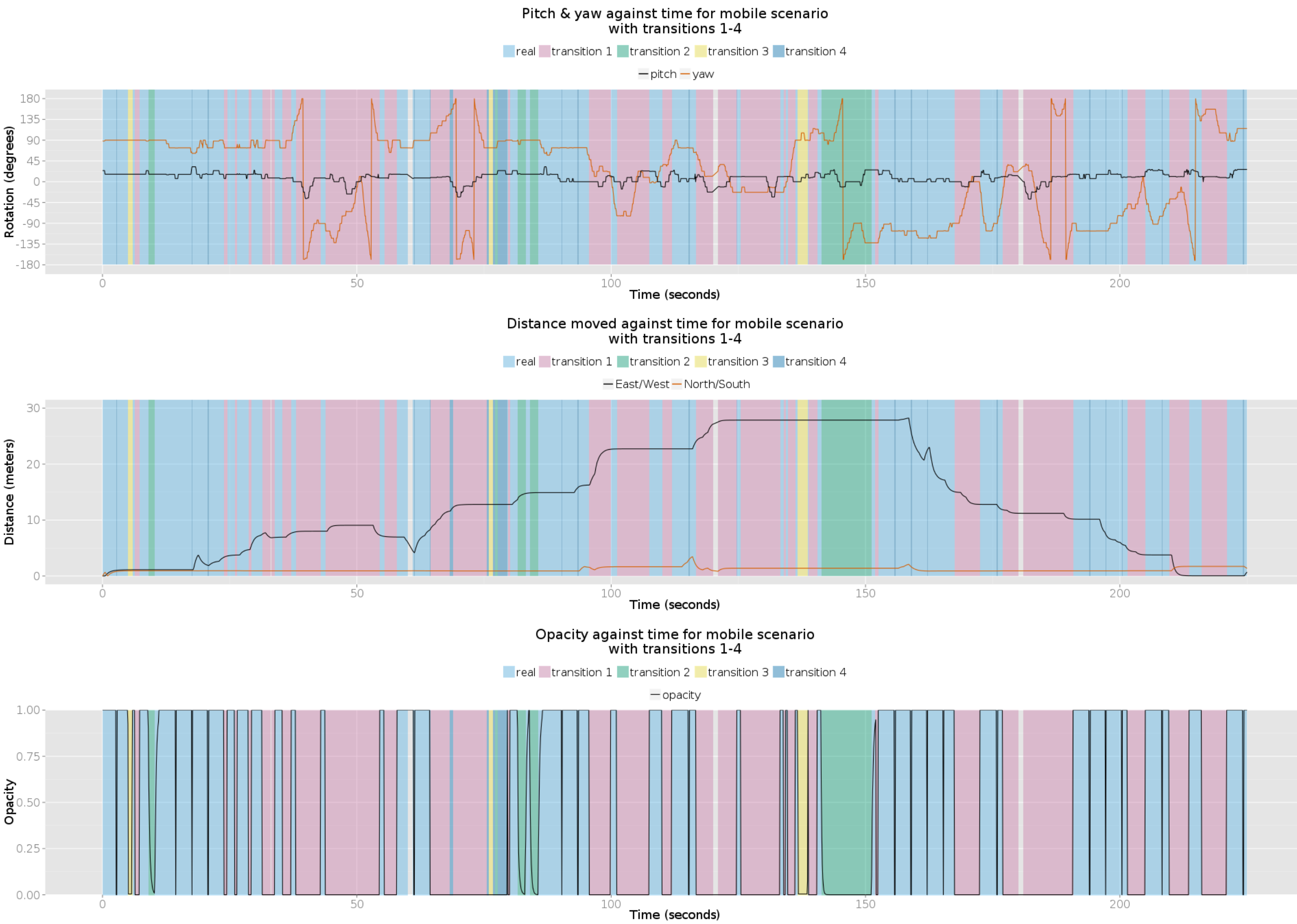

Figure 6.16: Some images, yah.

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6.10.3 Participant 9

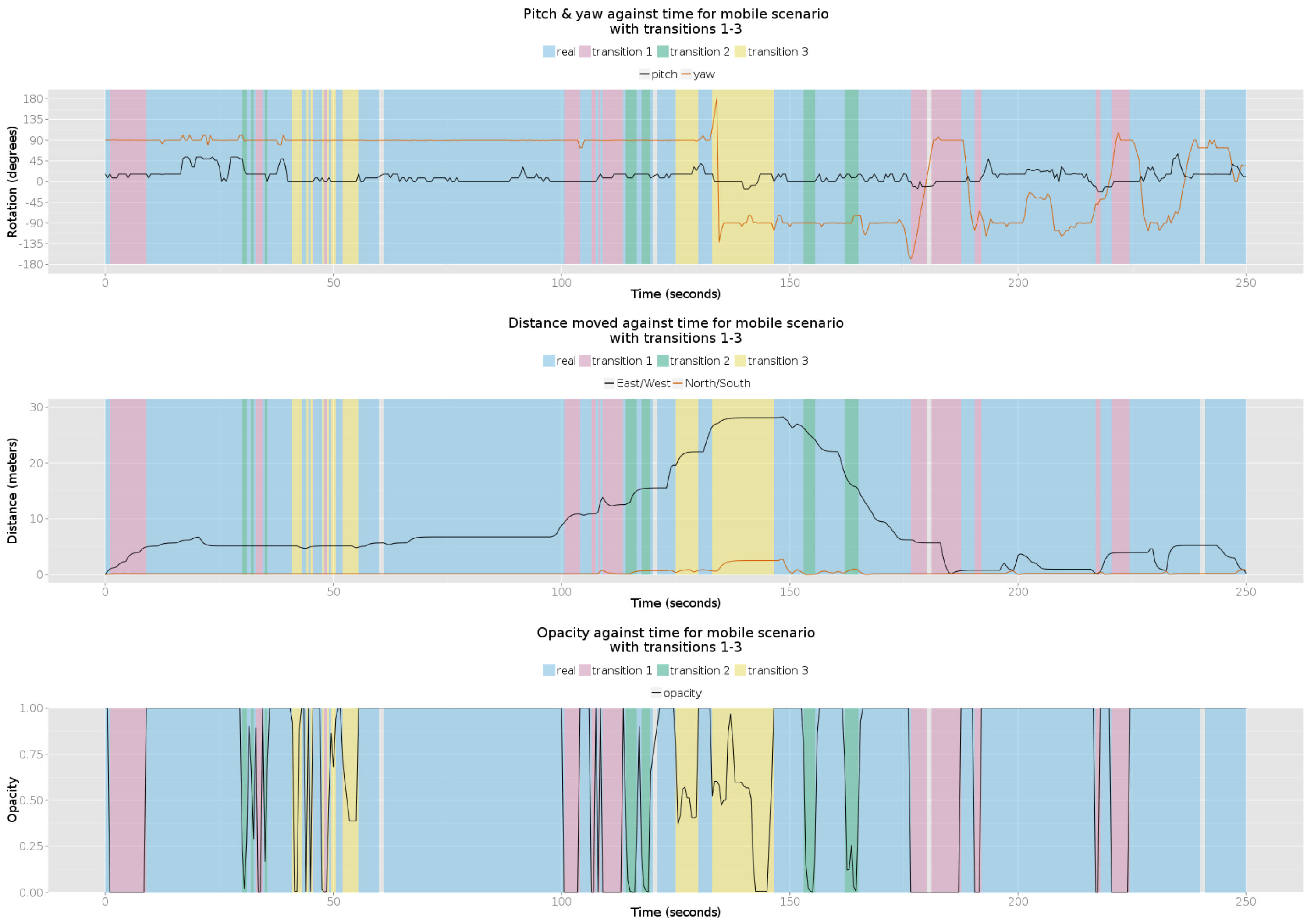

Figure 6.17: Some images, yah.

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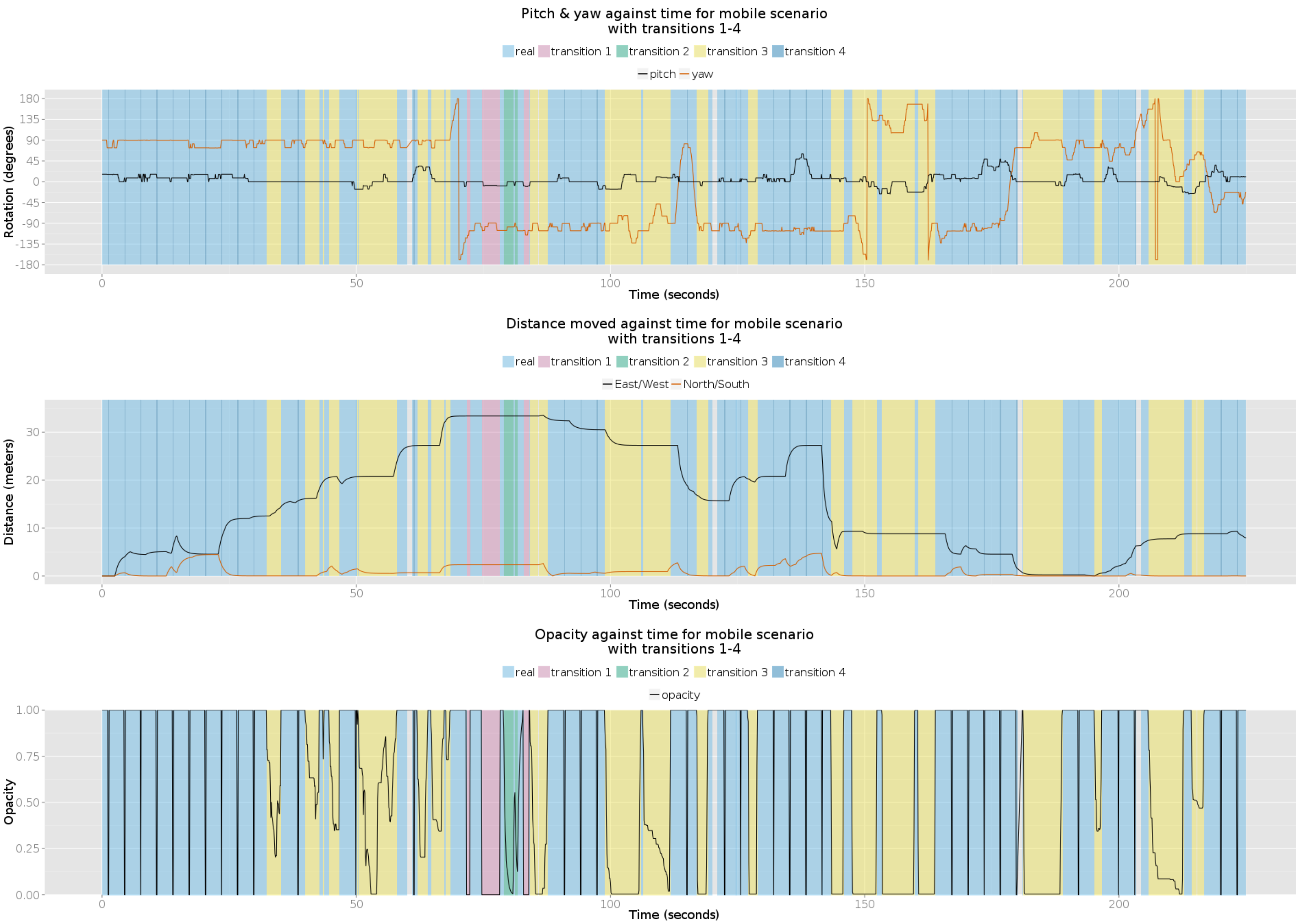

Figure 6.18: Some images, yah.

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6.10.4 Participant 10

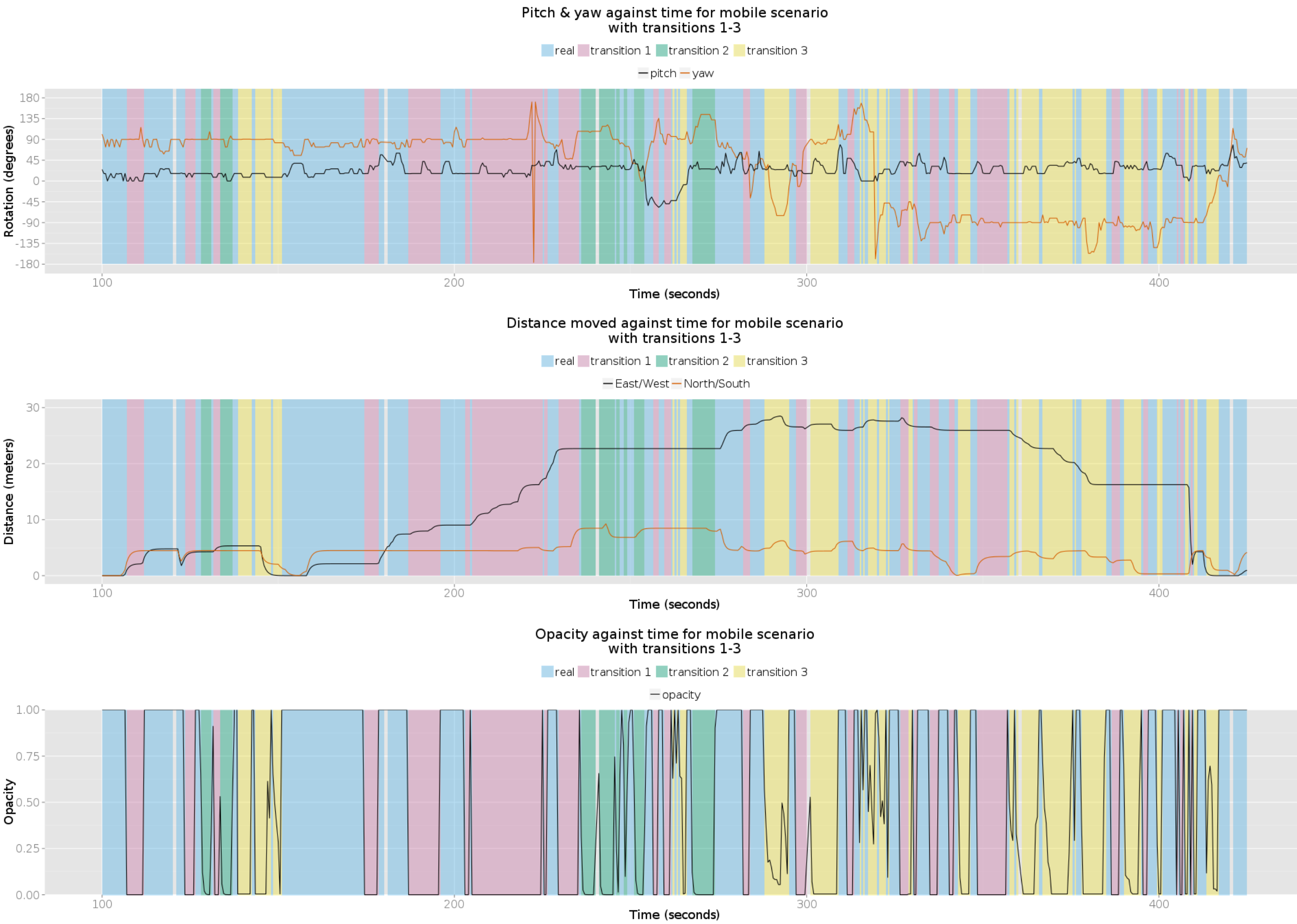

Figure 6.19: Some images, yah.

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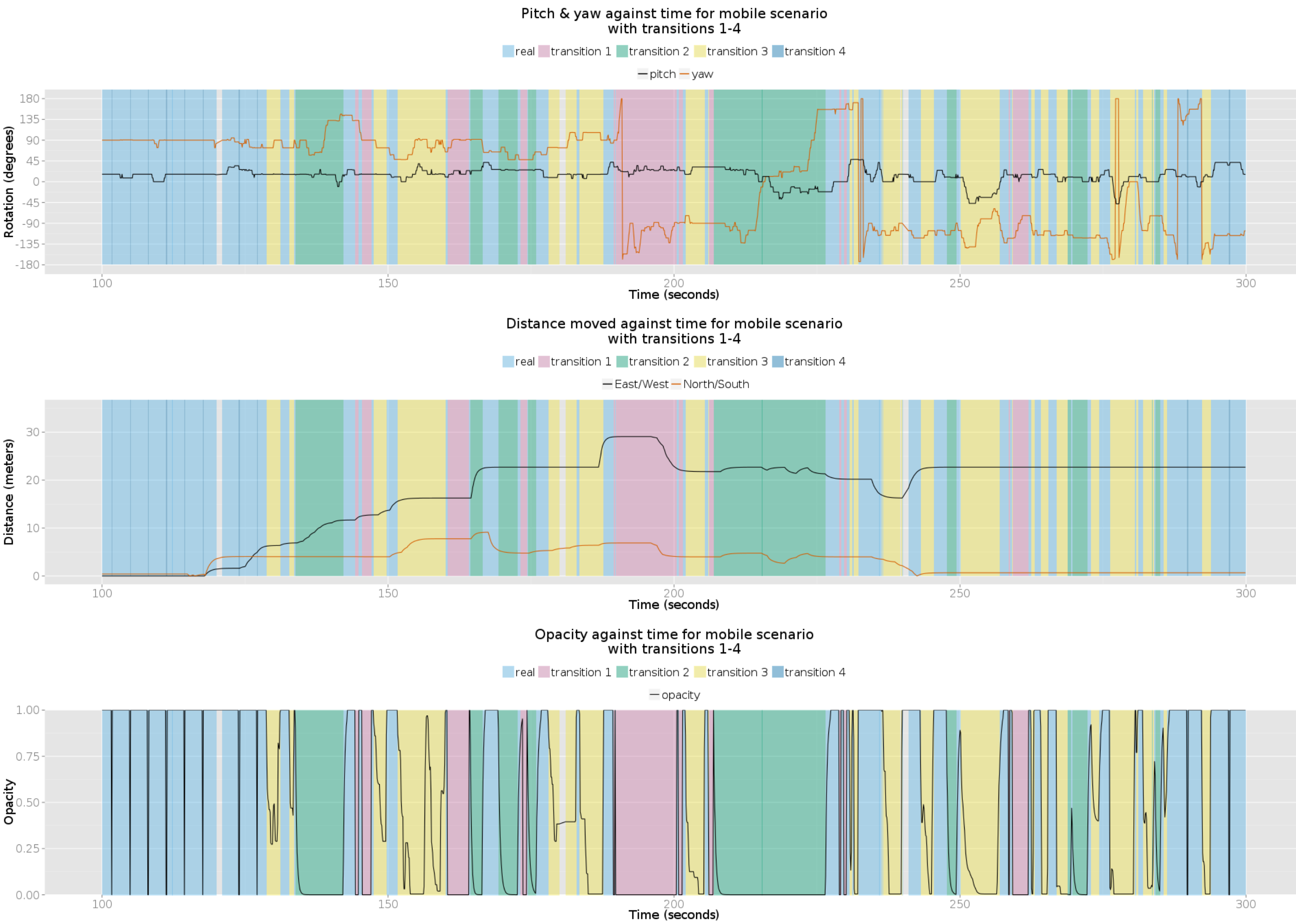

Figure 6.20: Some images, yah.

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6.10.5 Participant 11

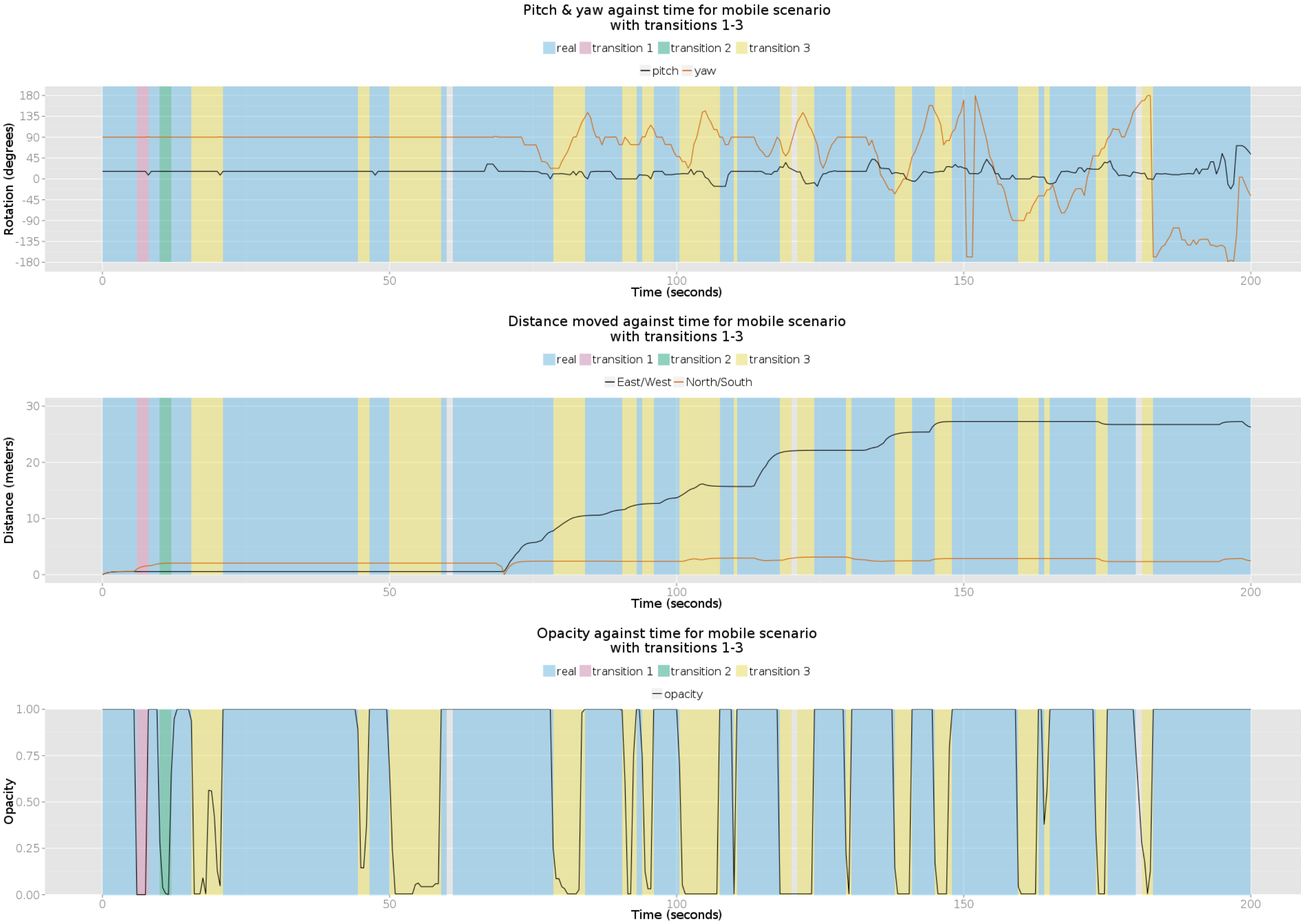

Figure 6.21: Some images, yah.

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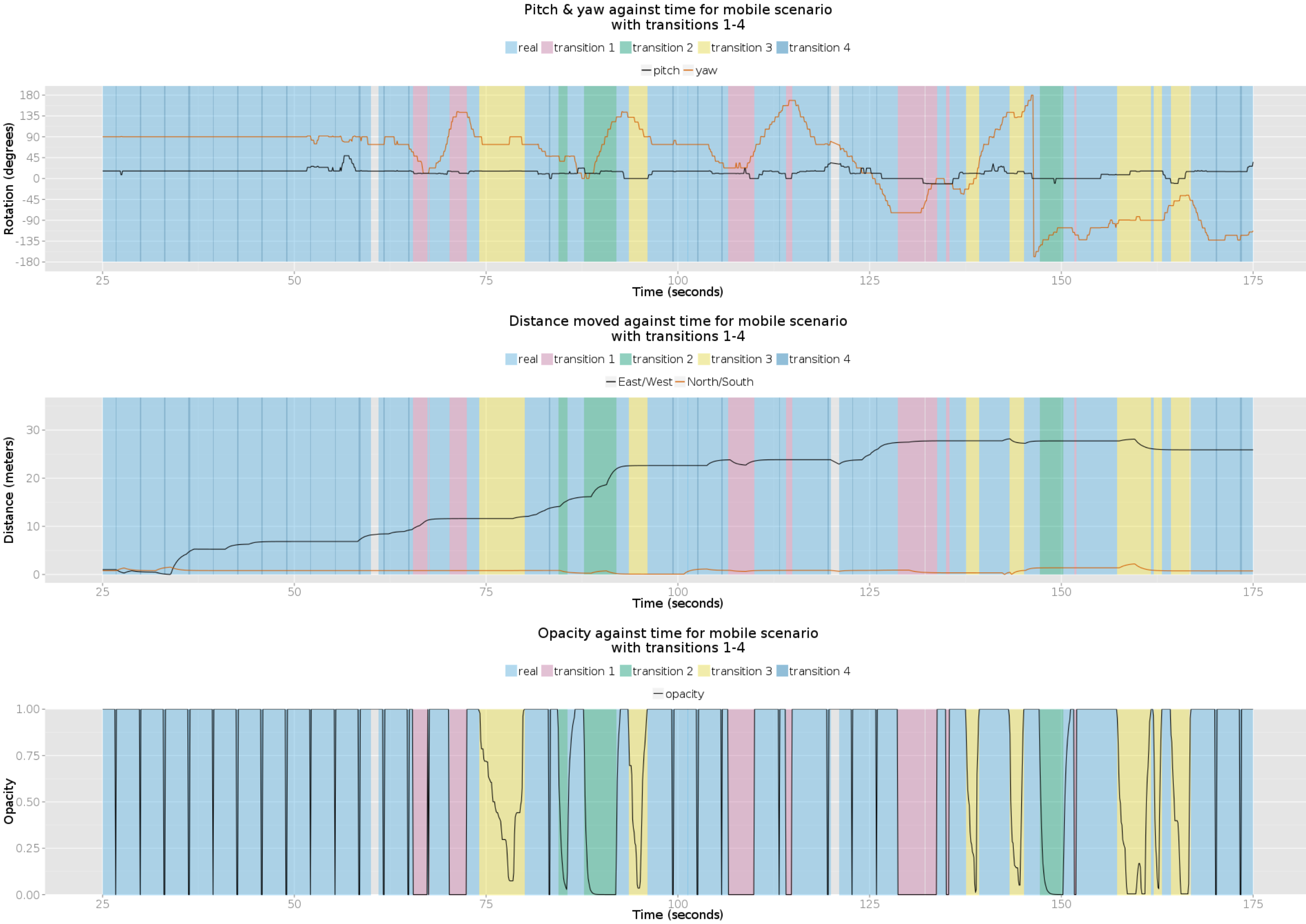

Figure 6.22: Some images, yah.

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6.10.6 Participant 12

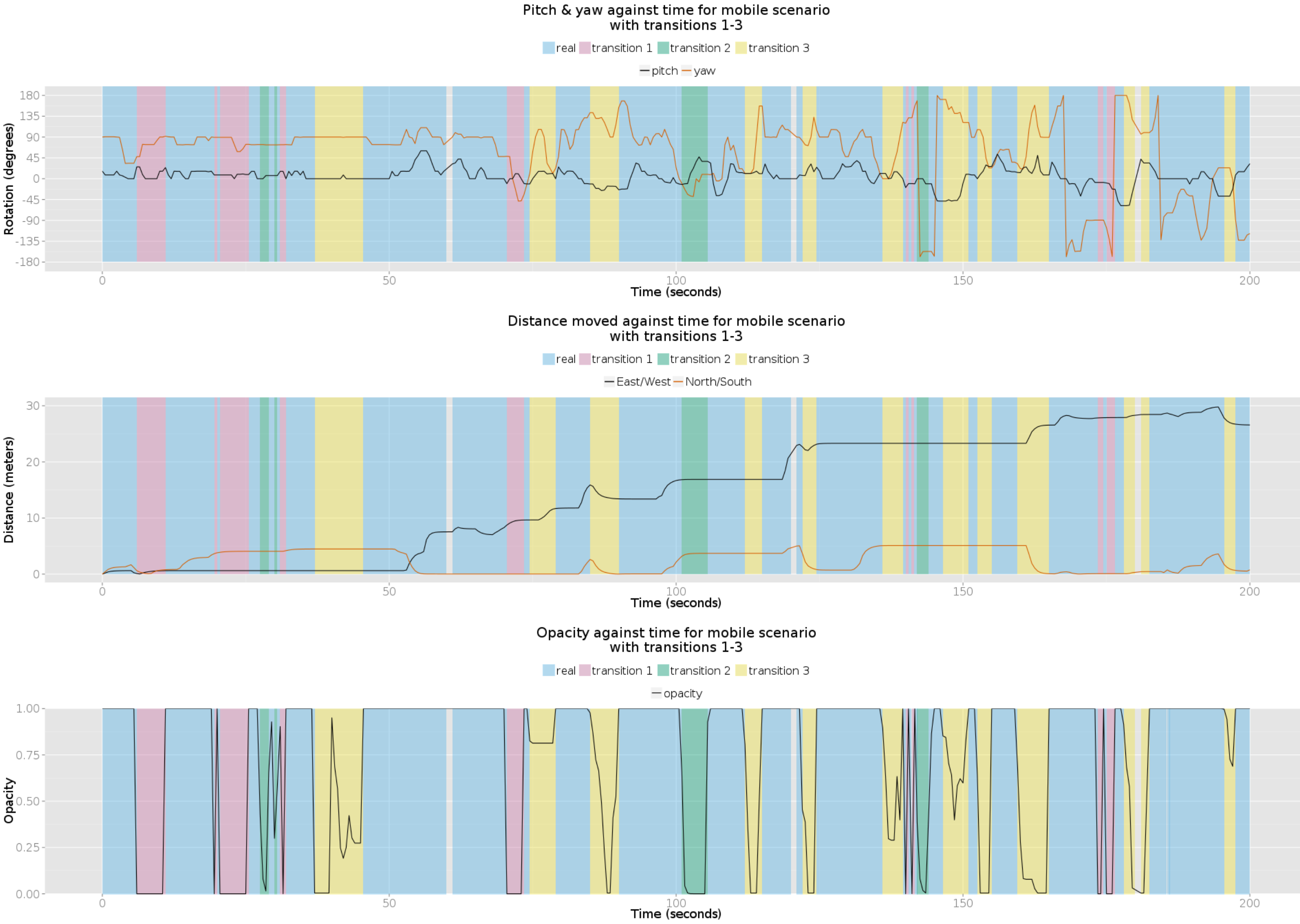

Figure 6.23: Some images, yah.

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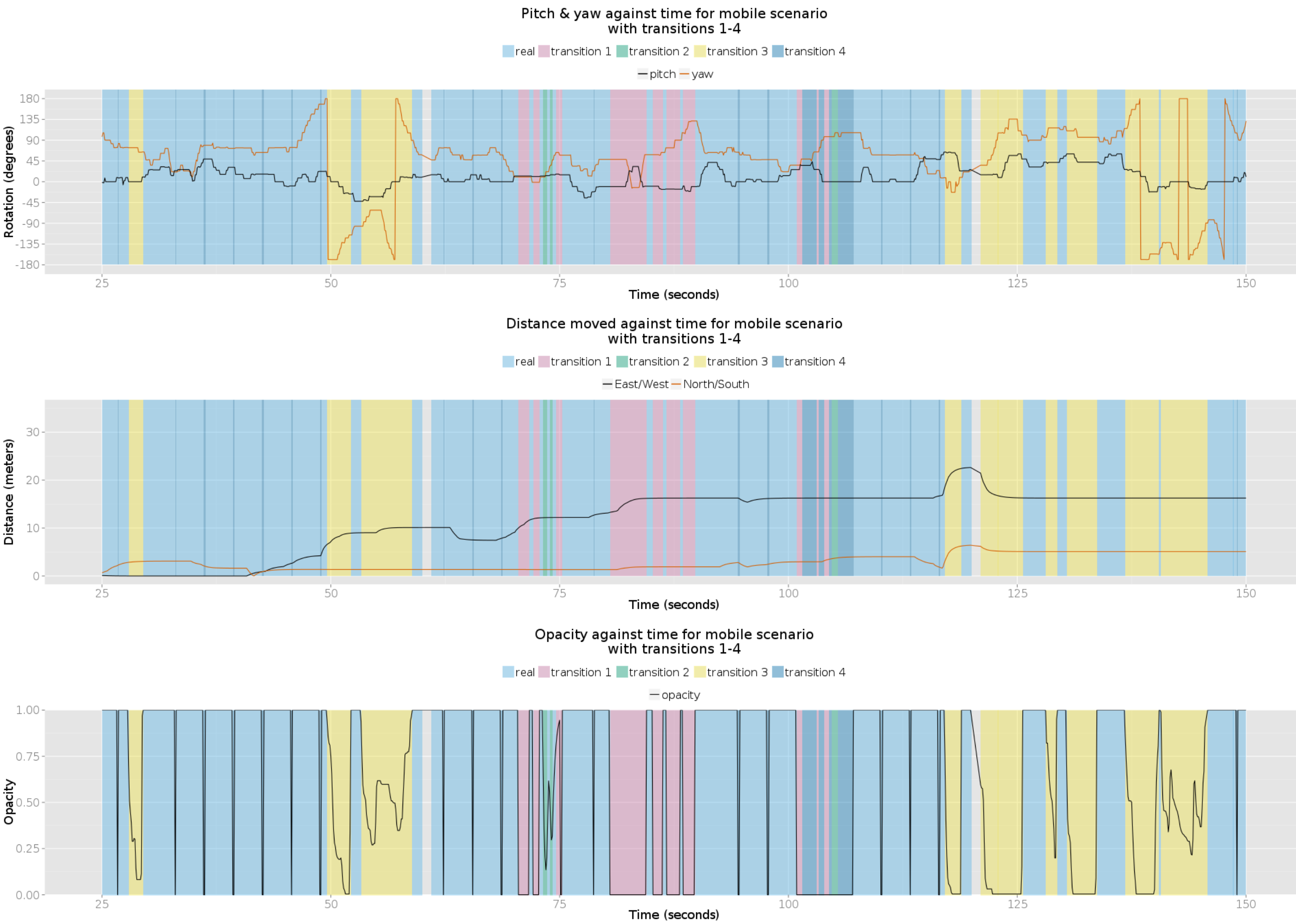

Figure 6.24: Some images, yah.

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6.10.7 Participant 13

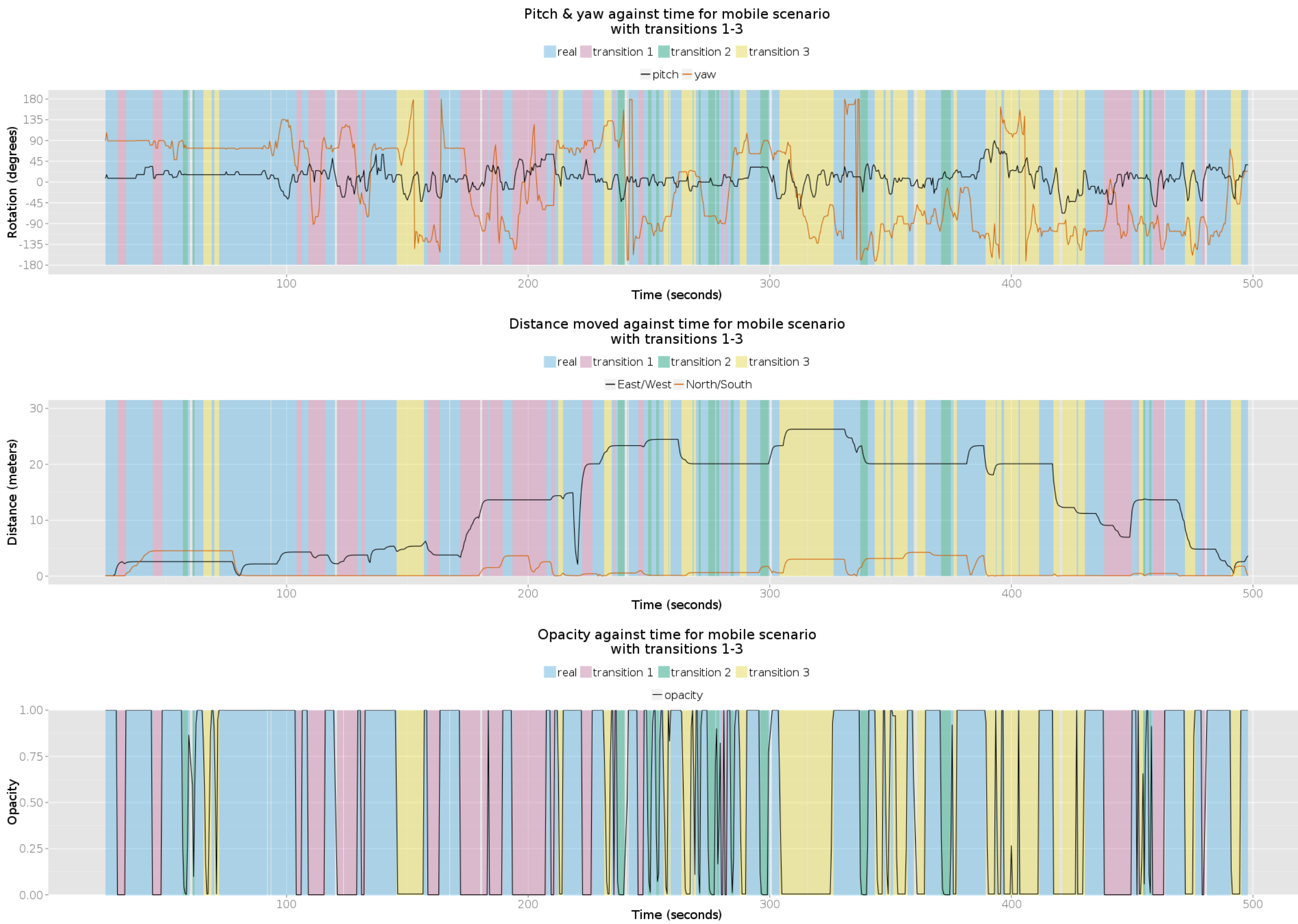

Figure 6.25: Some images, yah.

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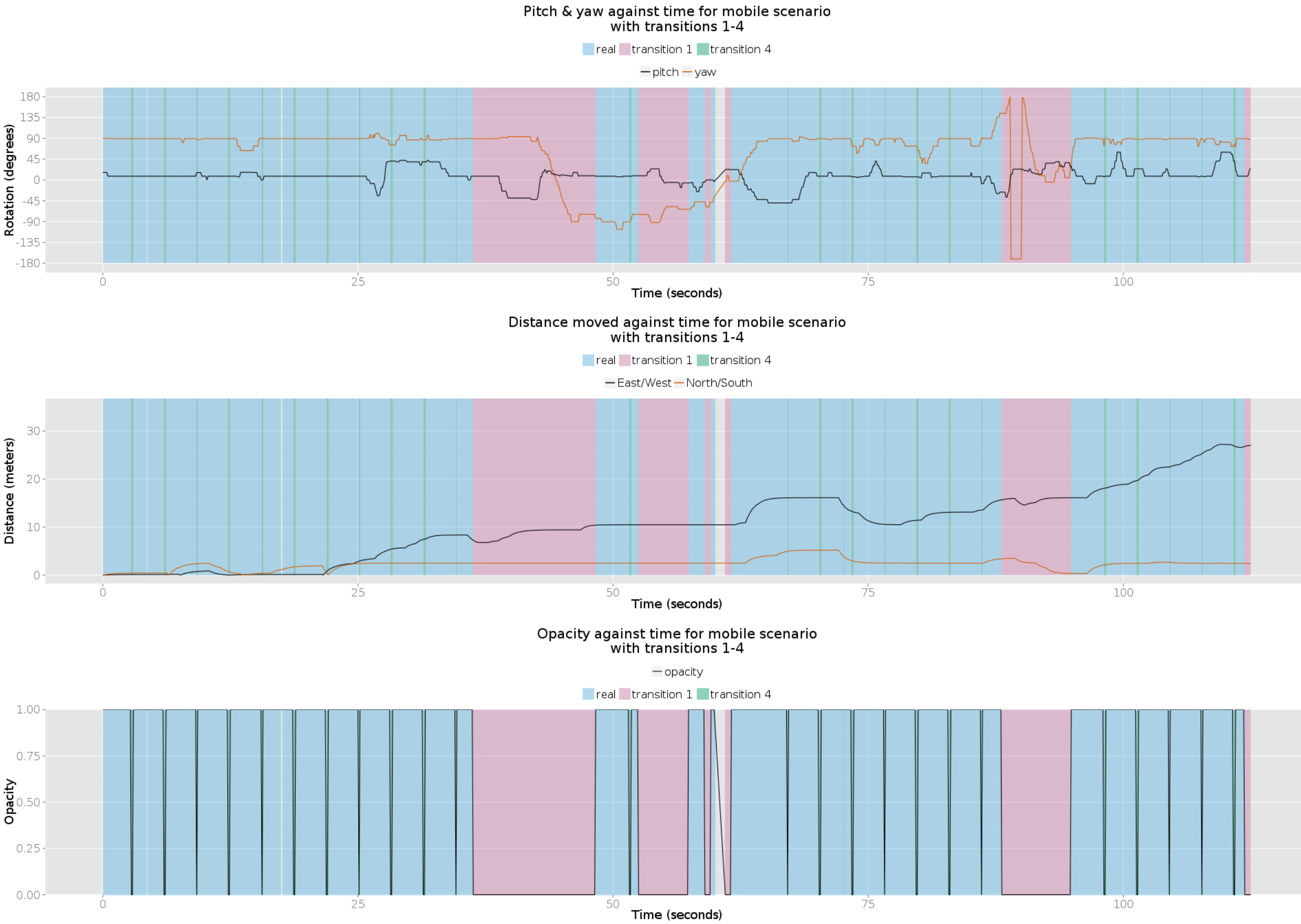

Figure 6.26: Some images, yah.

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6.11 Phase 2.2 Results

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6.11.1 Participant 14

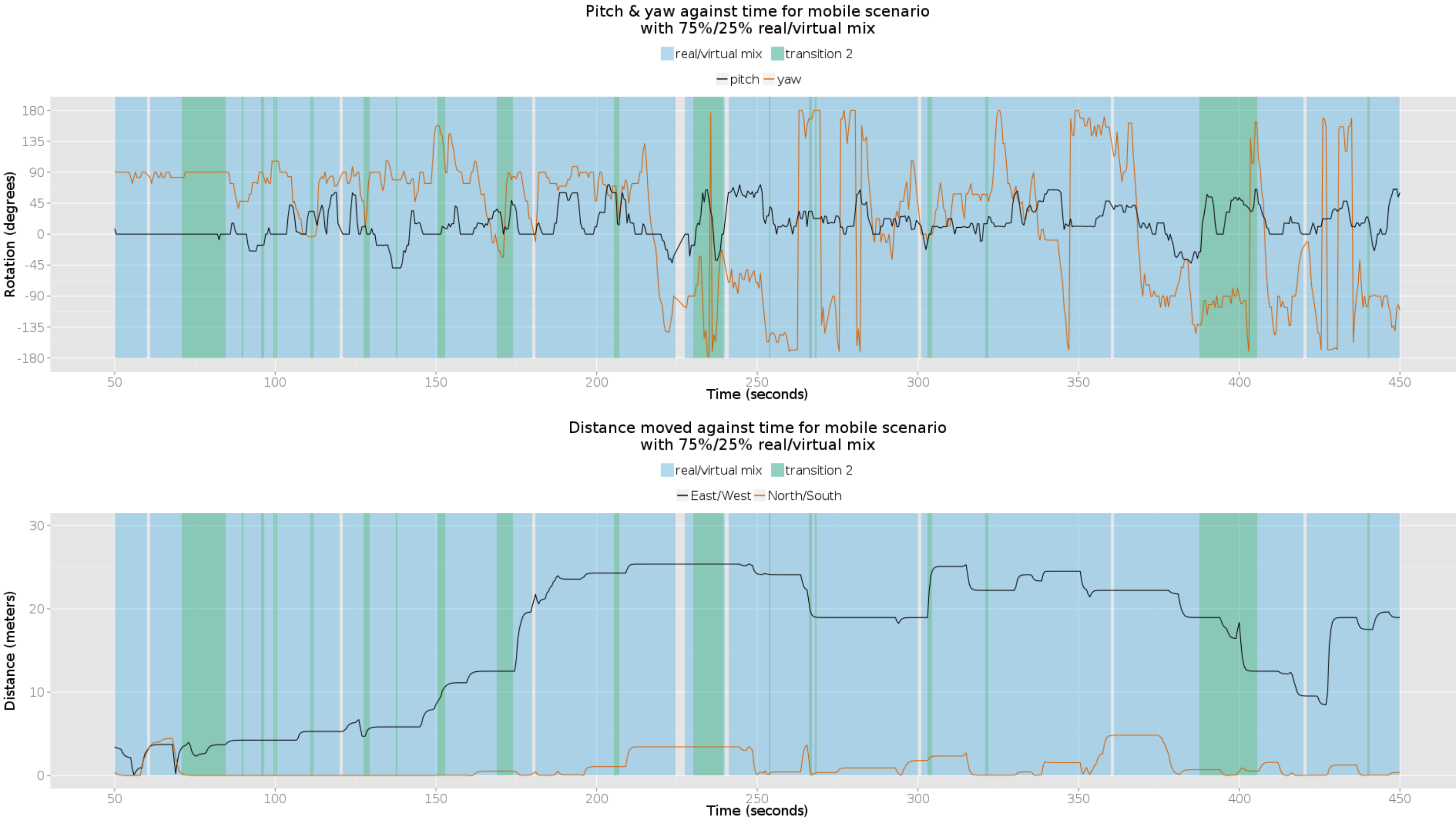

Figure 6.27: Some images, yah.

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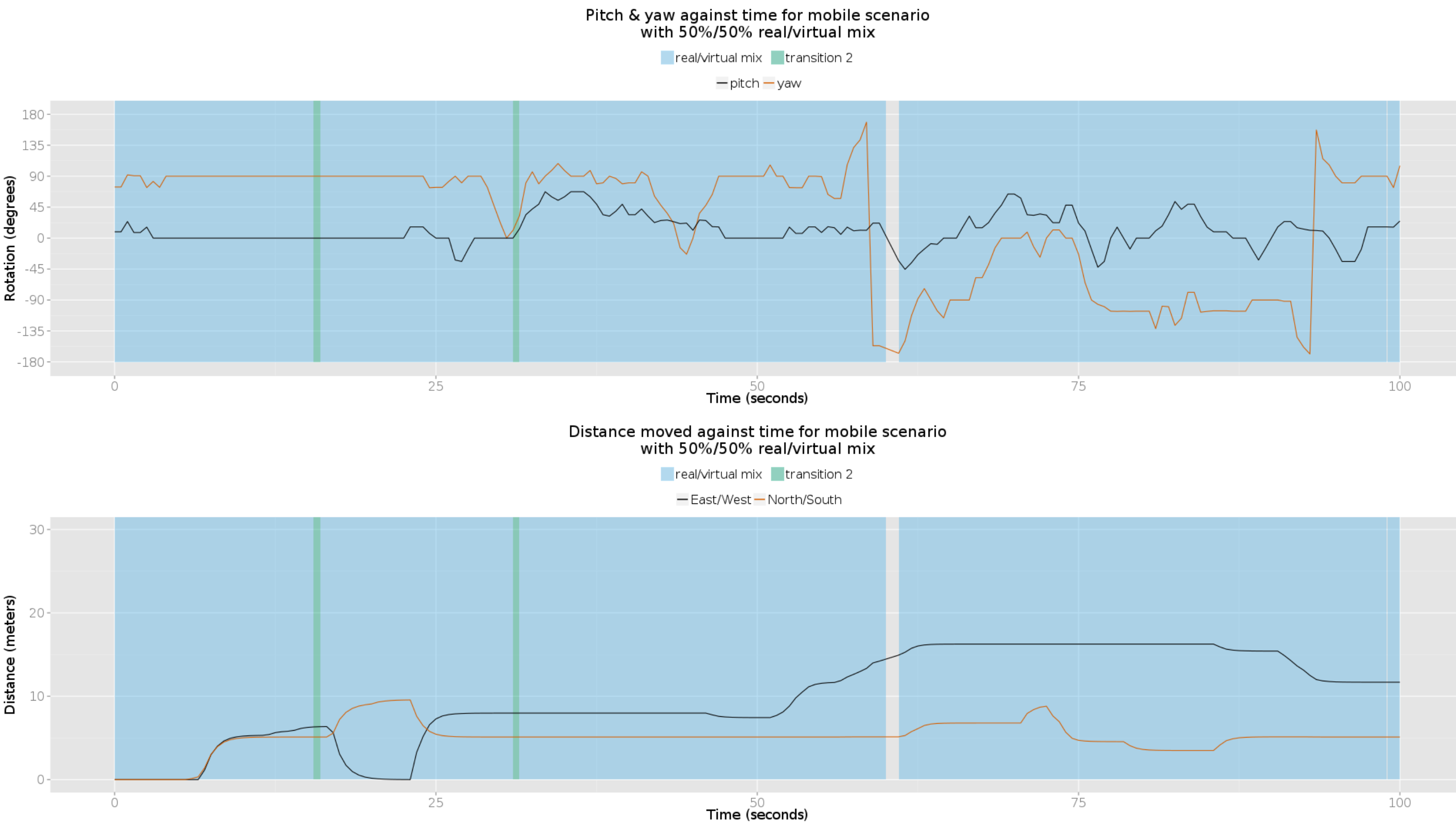

Figure 6.28: Some images, yah.

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6.11.2 Participant 15

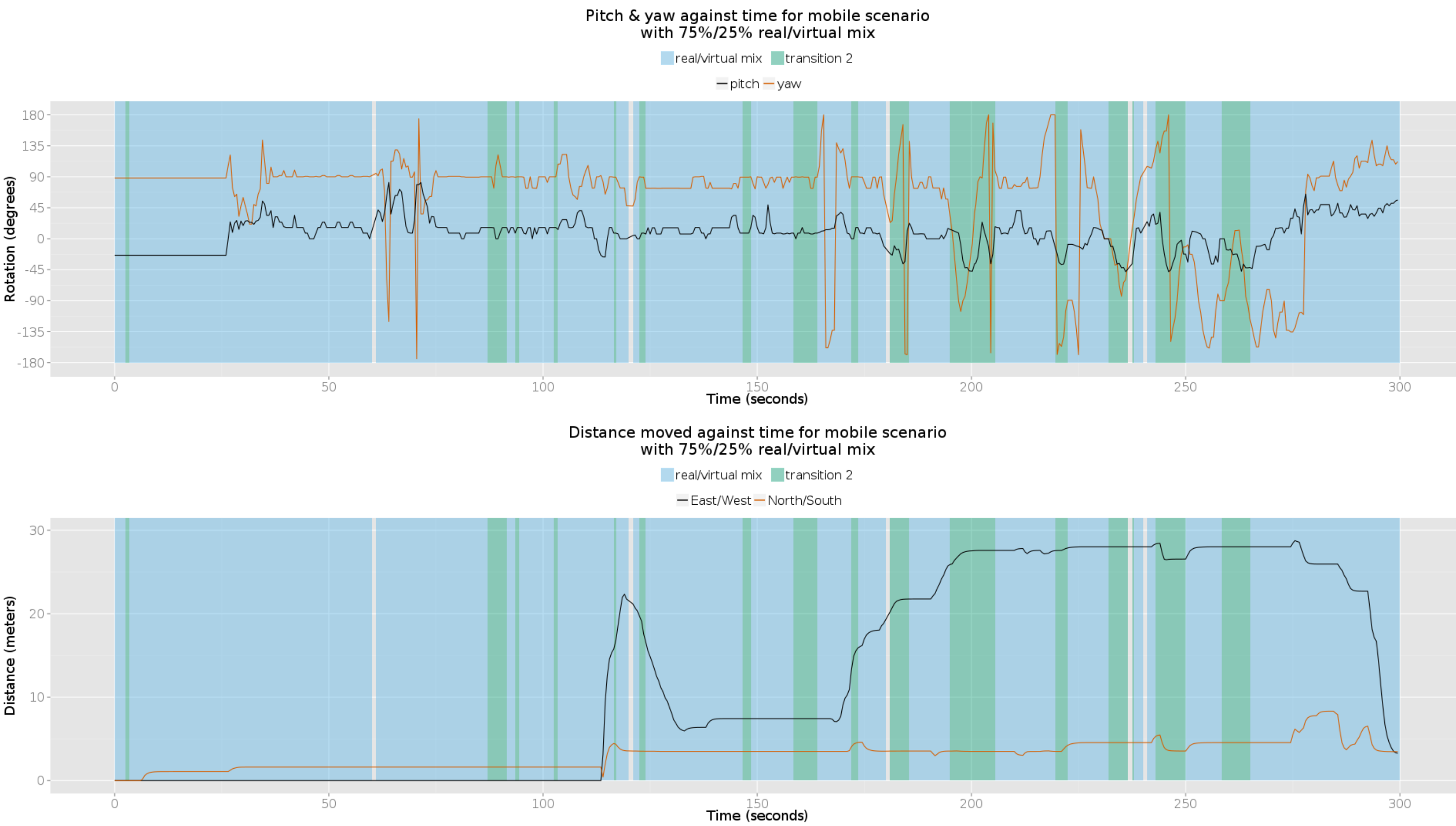

Figure 6.29: Some images, yah.

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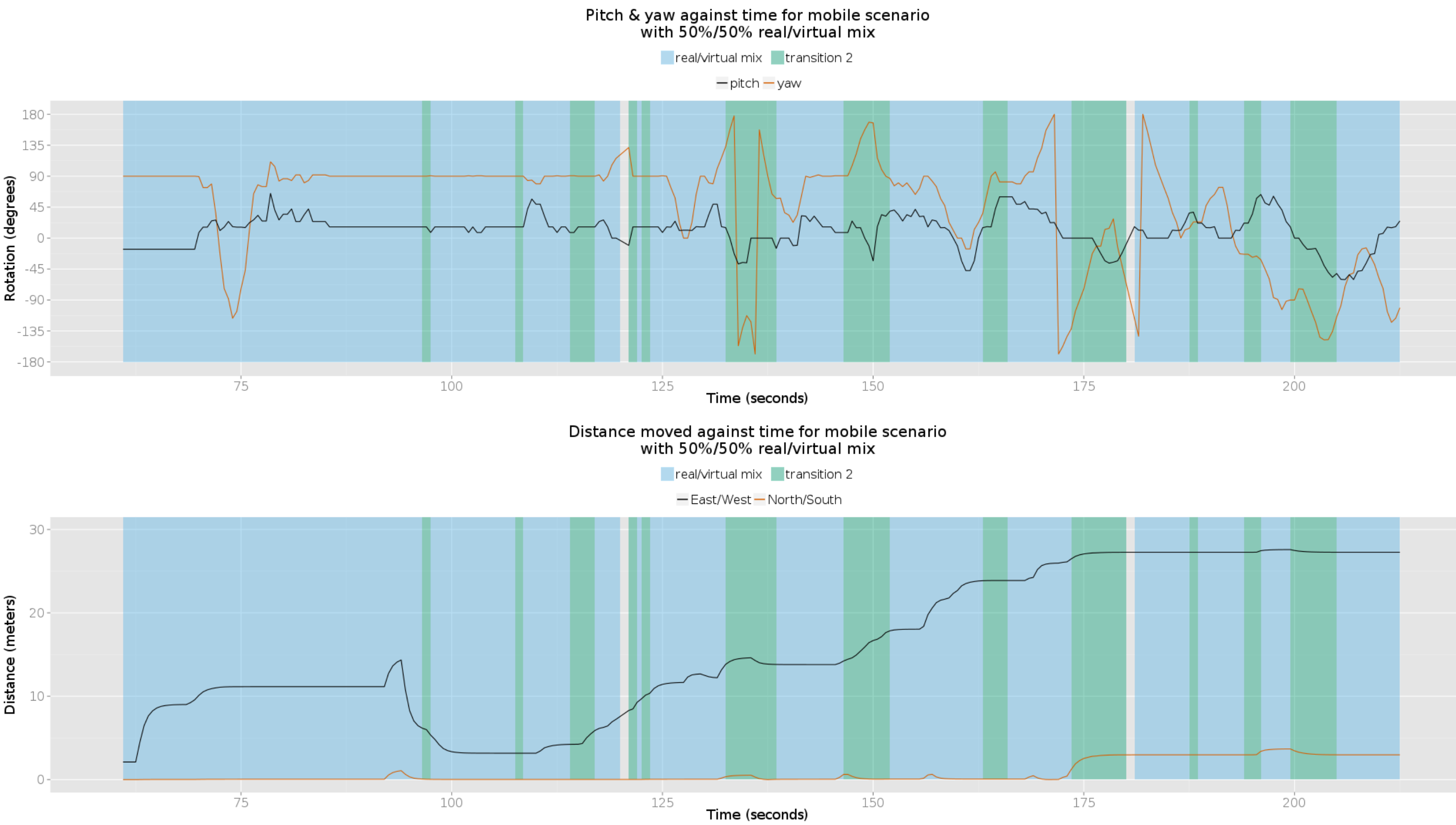

Figure 6.30: Some images, yah.

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6.11.3 Participant 16

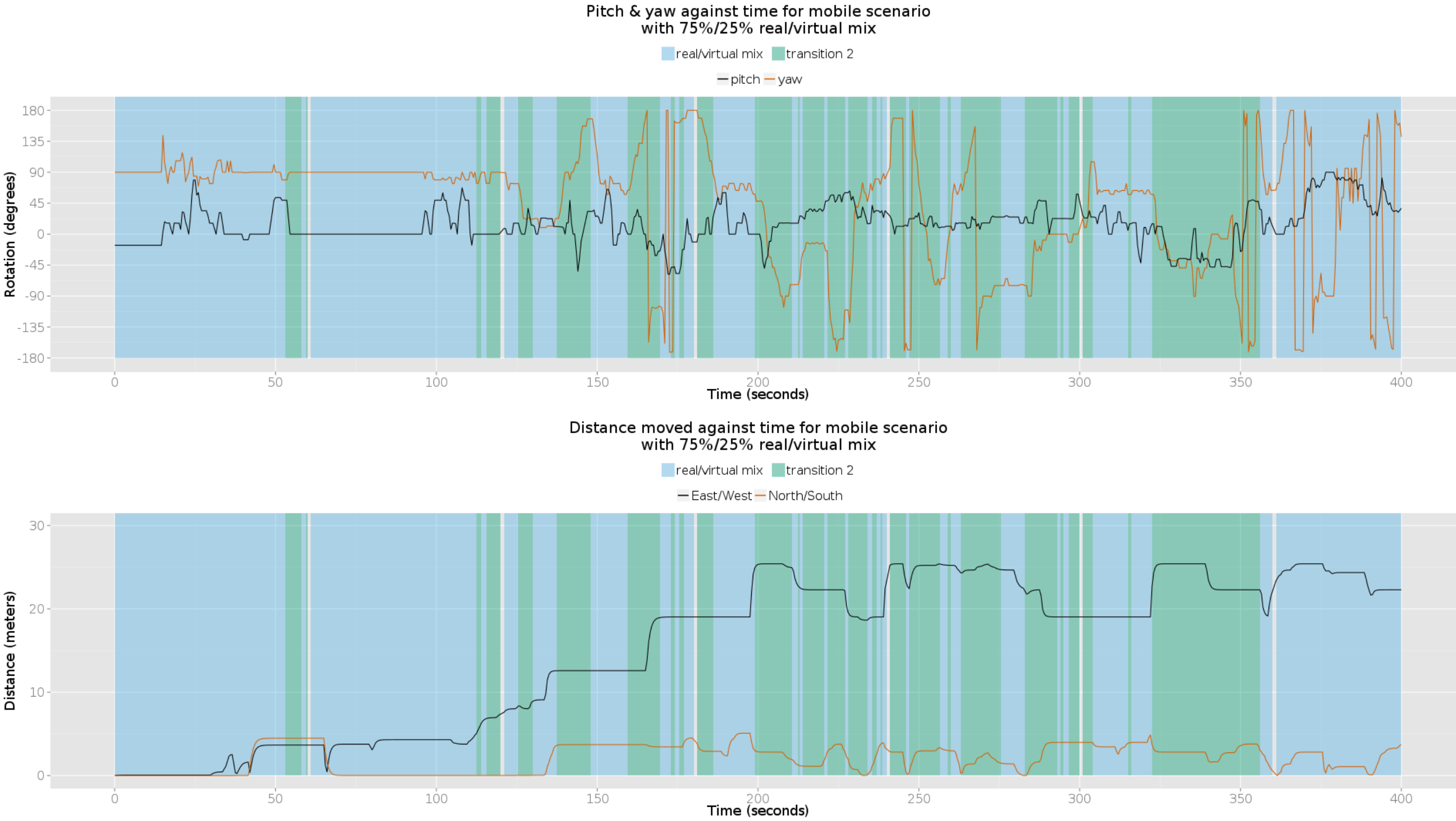

Figure 6.31: Some images, yah.

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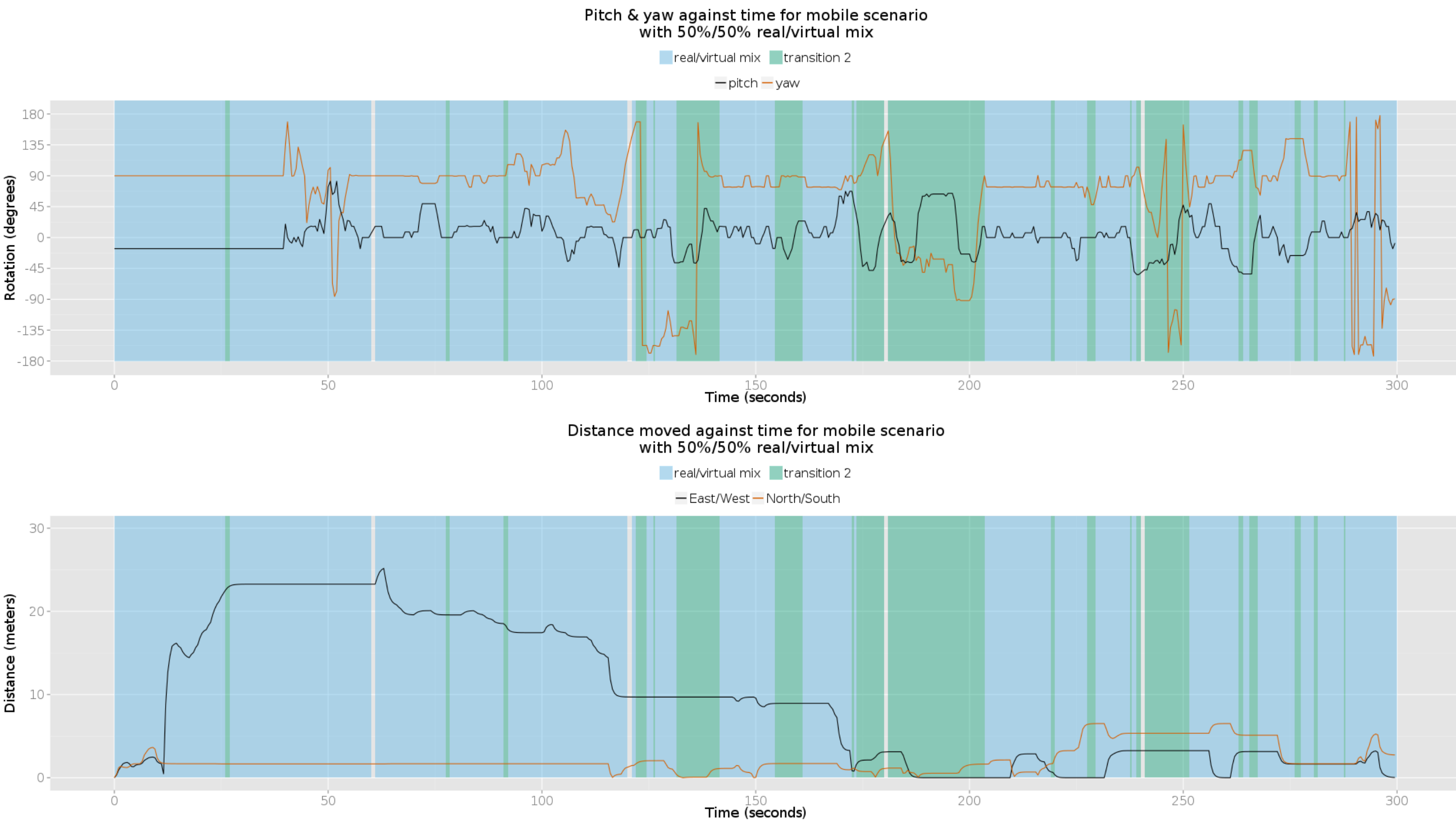

Figure 6.32: Some images, yah.

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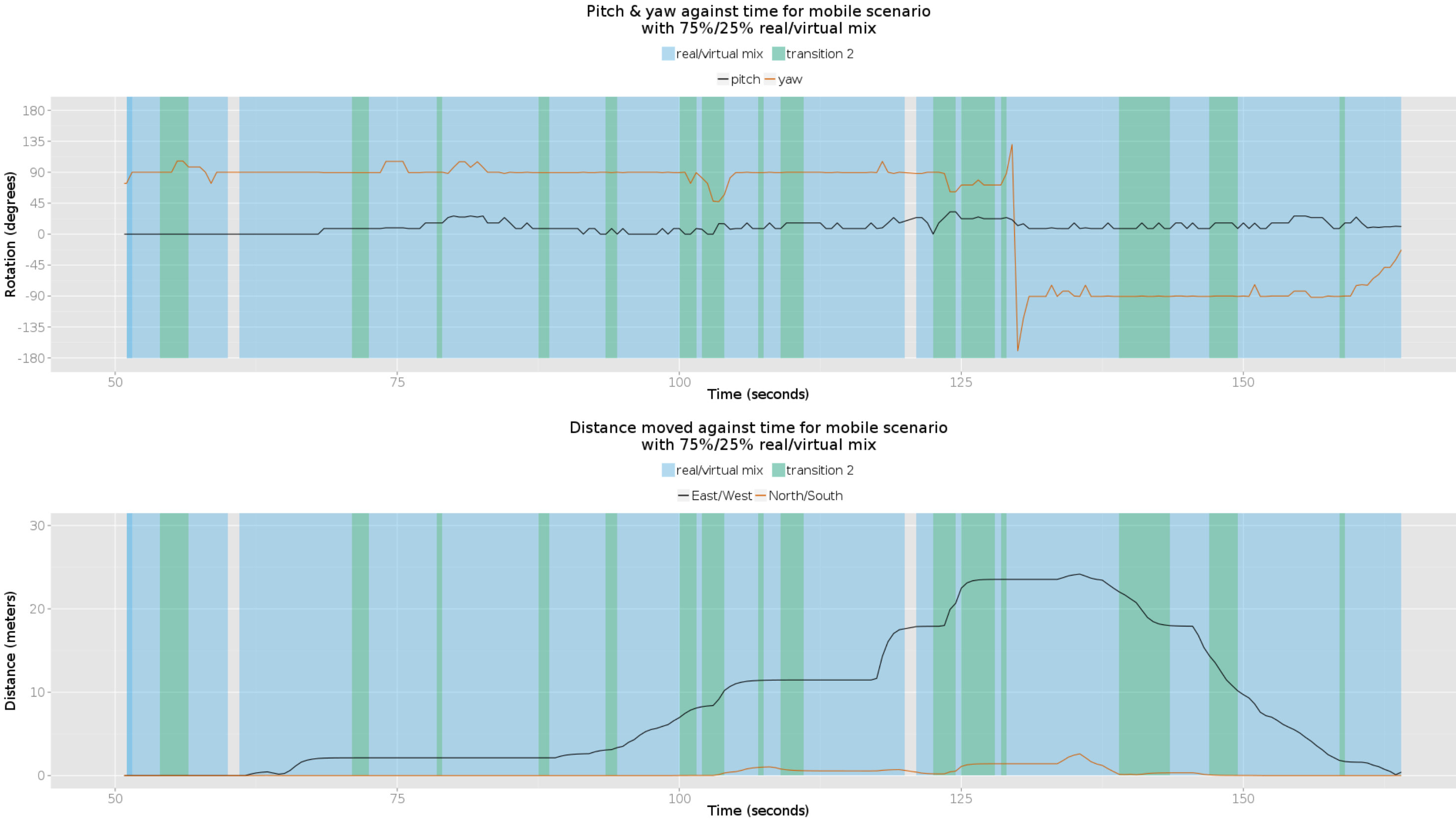
6.11.4 Participant 17



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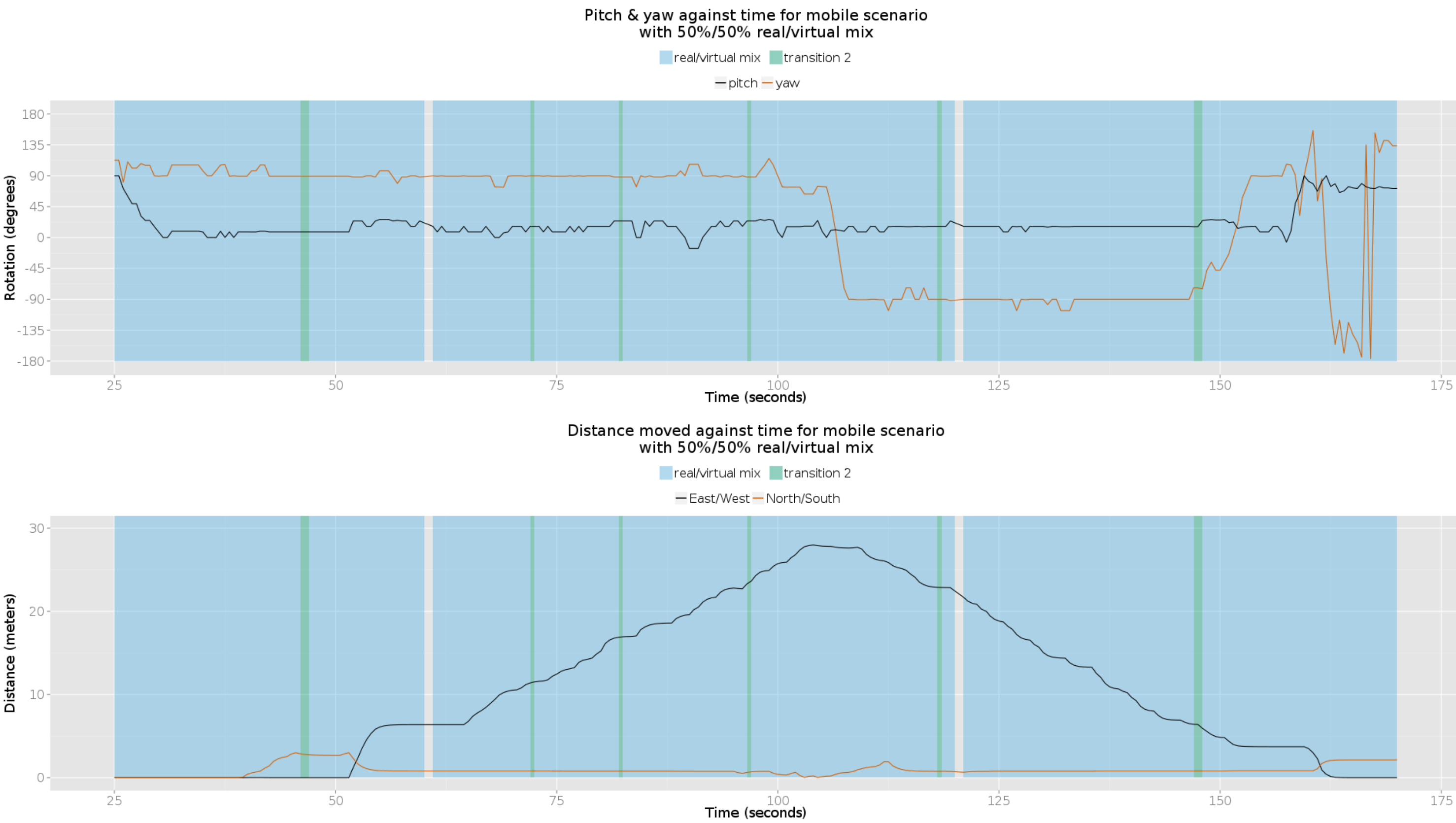

Figure 6.34: Some images, yah.

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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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