Parallel Reality: Tandem Exploration of Real & Virtual Environments

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This thesis is submitted in partial fulfilment for the degree of PhD at the University of St Andrews

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Abstract

This thesis discusses the development of a 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

If you think you should be acknowledged here, write your name below.

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Introduction

> *"If the chaos of the nineties reflects a radical shift in the paradigms of visual literacy, the final shift away from the Lascaux/Gutenberg tradition of a pre-holographic society, what should we expect from this newer technology, with his promise of discrete encoding and subsequent reconstruction of the full range of sensory perception?"*
>
> *Burning Chrome, William Gibson*

Talk about history of alternate realities, talk about the disappointment of VR in the 90's & it's resurgence now thank to Oculus, etc.

2

Extended Example

"There's no there, there. They taught that to children, explaining cyberspace."

Mona Lisa Overdrive, William Gibson

*****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.**

"The implication of HR is that, wherever you are, you can always be somewhere else" - HyperReality p149

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 a platform that allows its user 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 real & virtual environments, combined with maintained user mobility, is not well encapsulated by any previously defined alternate reality terminology. It is therefore necessary to explore this terminology in order to correctly frame this new system in relation to them.

The closest existing label is the 'cross reality' paradigm; a cross reality system holds the distinction of two discrete environments, one real & one virtual, both 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.

The term 'parallel reality' is proposed to refer to systems such as that developed in this thesis, which combine complete real & virtual environments together in a manner that allows mobile exploration of them both in tandem, relating it & positioning it against previously explored alternate reality terminology.

3.1 Defining Alternate Realities

Alternate realities, any situations in which the environmental stimuli received by a subject have been somehow modified or mediated, have received substantial attention in recent decades. These themes have been explored for purposes as diverse as education [3] & new forms of data visualisation [4] to medical [5] & military training [6] in addition to entertainment [7]. Although terms such as *mixed reality* & *augmented reality* are now relatively common, both in the literature & in the mainstream, 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 classification framework.

The concept of *telepresence* is not included in this discussion, as it is not deemed representative of an *alternate* reality but rather the ability for a user to experience a sense of presence at a real location remote to them [8].

3.1.1 Milgram et al.'s Reality-Virtuality Continuum

Milgram et al. 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 [9, 10].

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 [11] 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.

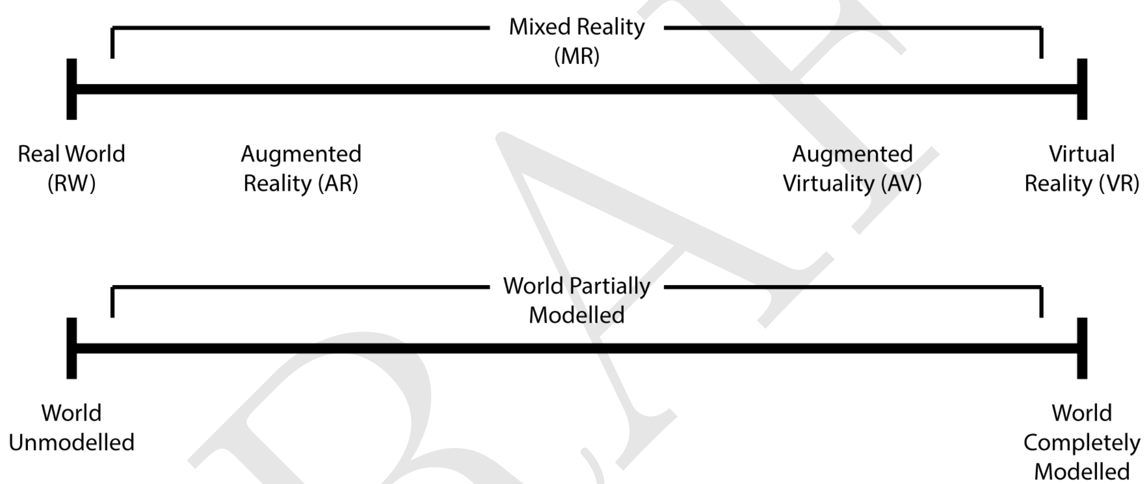


Figure 3.1: *Reality-Virtuality continuum* (top), parallel with *Extent of World Knowledge continuum* (bottom).

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 & 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, 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.

An 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 could not 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 [12]. 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.

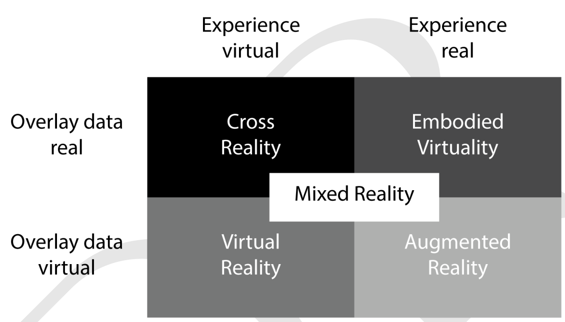


Figure 3.2: Want's original virtuality matrix.

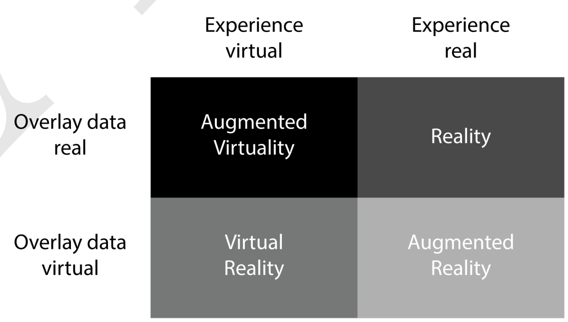


Figure 3.3: Modified Want matrix.

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 the user). 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 [13]. 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 the augmented virtuality and augmented reality regions.

3.1.3 Steve Mann's Venn Diagrams

Steve Mann, the *"father of wearable computing"* [14] & one of a group of researchers at MIT that became known as 'cyborgs' for their body-worn computers & always-on Internet connections [15], presented a Venn diagram to illustrate the relationships between the different categories of alternate realities when reviewing the problems that arise with existing taxonomies when discussing reality-modifying devices. Mann clarifies the use of the term '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"* [16]. Mediated reality thus encompasses all of mixed reality, but also the group of *modulated reality* which covers 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, as in Milgram et al.'s continuum).

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 covered in 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

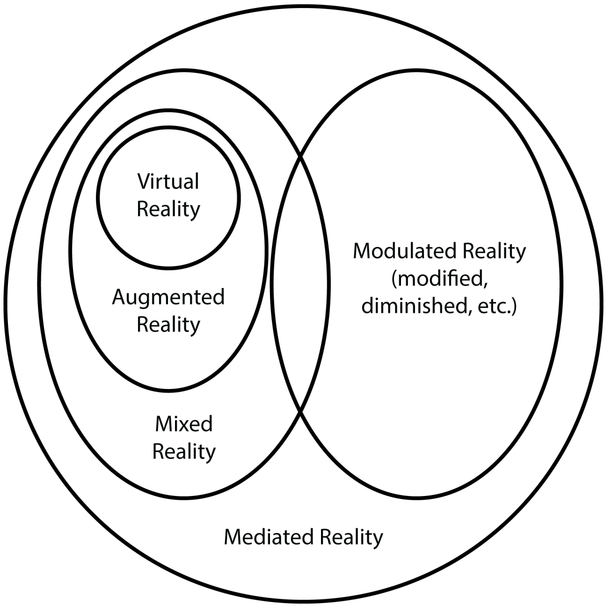


Figure 3.4: Original Mann Venn diagram.

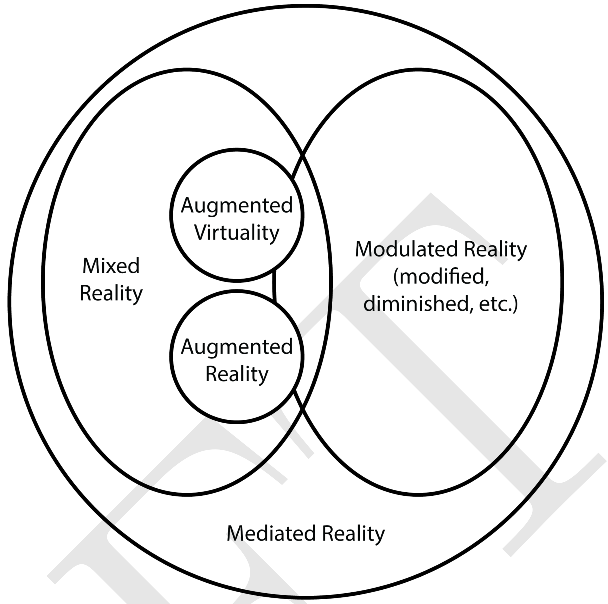


Figure 3.5: Modified Mann Venn diagram.

any modulation that could be performed by modulators external to the virtual environment software could almost certainly be better performed by the software itself.

3.2 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 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 [9, 10, 12]. 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 (such as by using Head Mounted Displays & body tracking techniques to remove logical anchors to the real world [17]) 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 after all completely modelled environments that exist entirely separate to the real world.
Distributed Virtual Reality (DVR)	Multi-user VR where telecommunications are employed to allow multiple (geographically distributed) users to occupy the same VR environment, allowing cooperation [18].
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, with real and virtual objects co-existing. 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 that has had virtual objects added to or overlain upon it. A common approach for achieving this addition/overlay is superimposing virtual objects over a direct or indirect view of the real environment using Head Mounted Displays &/or cameras [19].
Augmented Virtuality (AV)	A virtual environment upon which sampled real objects are overlain, perhaps through the use of cameras [20].
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"* [16]. 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.

3.3 Additional Alternate Reality Terms

In addition to the range of alternate realities covered in the previous section, there are several less commonly used terms that do not feature or fit well into the previously identified frameworks.

3.3.1 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

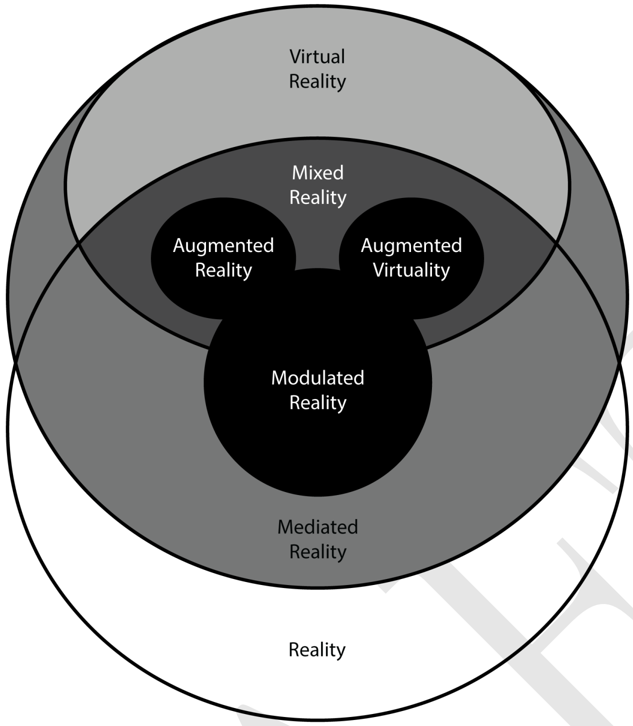


Figure 3.6: Further modified Mann Venn diagram.

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"* [18].

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 HR places emphasis on the integration of the virtual reality content into the real world in a seamless manner, 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 reality from a simulation of reality [21]).

3.3.2 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 [22]. It has been shown that *"effective interaction among participants is a contributing factor to presence"* [18], so it should not come as much surprise to observe people maintain PolySocial interactions between their real environment & a virtual one.

***** Mention place vs non-place?**

3.4 Cross Reality

*****Briefly mention standards, mainly ISO/IEC 23005 (MPEG-V)**

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 [23].

The principle features that distinguish XR from the other alternate realities covered so far are;

1. a shift from single- to bi-directional information flow between real and virtual environments [24];
2. that both environments are complete unto themselves (but are enriched by their ability to mutually reflect, influence and merge into one another). [25]

XR as an alternate reality paradigm has its roots in work undertaken by the IBM Virtual Universe Community [26–28], 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 ... 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[1] 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."*

It was the work of the Responsive Environments Group at MIT's Media Lab, centred around the research of Joshua Lifton in combining the Plug sensor/actuator platform [29] with a Second Life hosted virtual model of the physical Lab in the 'Shadow Lab' project, that truly launched XR as a research area. 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.

One of the driving motivations behind this work was what Lifton dubbed 'the vacancy problem';

> *"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."* [30]

Which the Shadow Lab addressed via the sensor/actuator infrastructure to more closely link the real & virtual environments, such that actions & events in one could manifest & be observed by users in the other even if they could not directly visually observe both environments in tandem. The vacancy problem was previously observed by HR researchers, touching on an observation of the PoSR situations observed among mobile phone users of the time as a manifestation of the problem before virtual environments were introduced to the picture;

[1] Second Life.

Figure 3.7: Side view of the virtual Shadow Lab.

Figure 3.8: A Ubiquitous Sensor Portal.

> *"One of the main problems with . . . virtual reality is what to do about the body that is left behind in physical reality . . . In HyperReality a person by definition is perceptually aware of the physical world around them, yet part of the attention normally given to the physical reality is given to interacting with virtual reality. It is difficult as yet to see how much this matters, but the increasing use of the mobile phone, which is a primitive form of HR, gives us some feel for the issues. People using a mobile phone can walk busy streets . . . while talking to someone who is not there."* [18]

3.4.1 Alternate Reality Definitions from Cross Reality

Lifton's use of alternate reality terminology does not conclude that MR is a broad term encompassing both AR & AV, but defines it as an environment ;

> *". . . which would be incomplete without both its real and virtual components. For example, the walls and windows of a mixed reality house might be real, but the view out the windows might be virtual, either generated by a projector or as a blue screen effect in a head-mounted display. Without both the real house and the virtual views out the windows, the illusion of a consistent reality is broken"* [30]

The diagram Lifton presents (figure 3.9) alludes to Milgram's continua but places MR, under the above definition, as a separate classification of alternate reality between AR & VR. Lifton does not mention AV, even though the XR systems he presents arguably cause it to manifest. Figure 3.10 is the result of modifying this diagram to match the definitions adopted by this chapter in section 3.2.

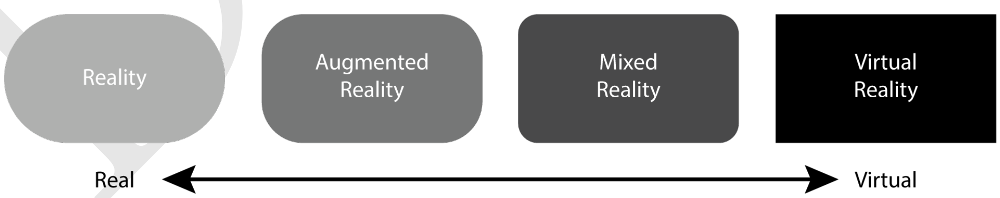


Figure 3.9: The *"virtual worlds taxonomy as viewed on the real-virtual axis"* presented by Lifton.

Lifton does however explain that while such a taxonomy can be successfully applied to most alternate realities, with each falling into a different singular category, it does not well address those that feature two

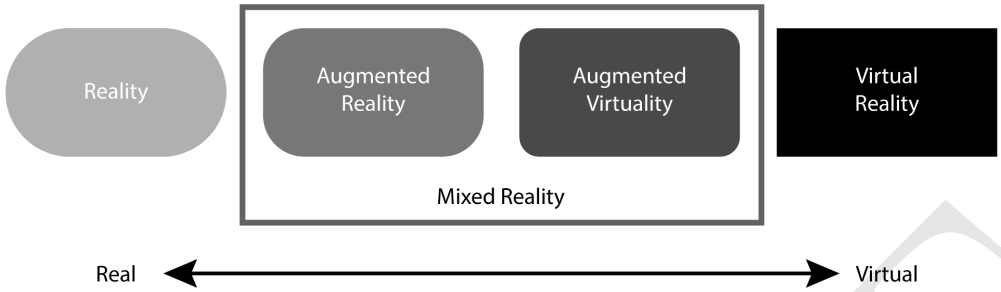


Figure 3.10: Lifton's taxonomy as modified by this review.

complete realities, one real & one virtual, which is one of the defining & distinguishing characteristics of a XR system & instead prefers figure 3.11 to show how sensor/actuator infrastructure can cause the real & a virtual environment to merge into a cross reality.

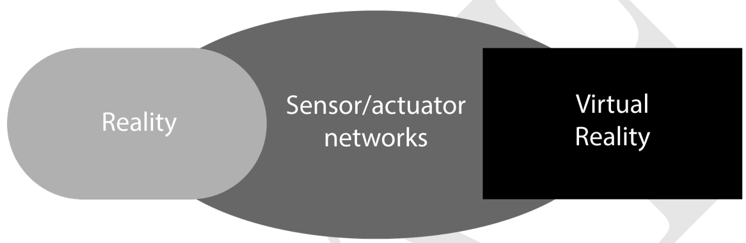


Figure 3.11: Sensor/actuator infrastructure merging a real & a virtual environment, creating XR.

3.4.2 Position of Cross Reality

The position of XR in relation to other alternate realities can be visualised using Milgram et al.'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 3.12 to 3.16 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[2], 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 3.12), a XR system instead features two discrete environments, one real & the other virtual, each complete unto itself (figure 3.13), with the user attending either to the stimuli originating from the real environment (figure 3.14) or to the stimuli originating from the virtual environment (figure 3.15).

A HR environment likewise constitutes a single physical environment, formed by the seamless introduction of VR content into the real world, rather than two complete environments;

> "*. . . virtual people, virtual objects & virtual settings can interact & thereby communicate with real people, real objects & real settings as though they were all part of the same world.*" [18]

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

[2]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.

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 3.2) 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 3.14 & 3.14.

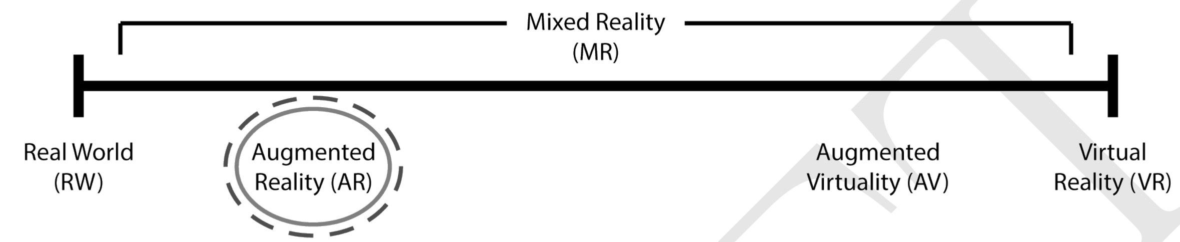


Figure 3.12: AR visualised using the virtuality continuum.

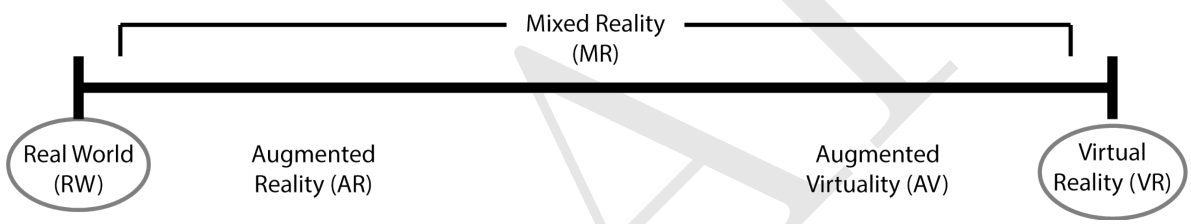


Figure 3.13: The two environments that comprise a XR system.

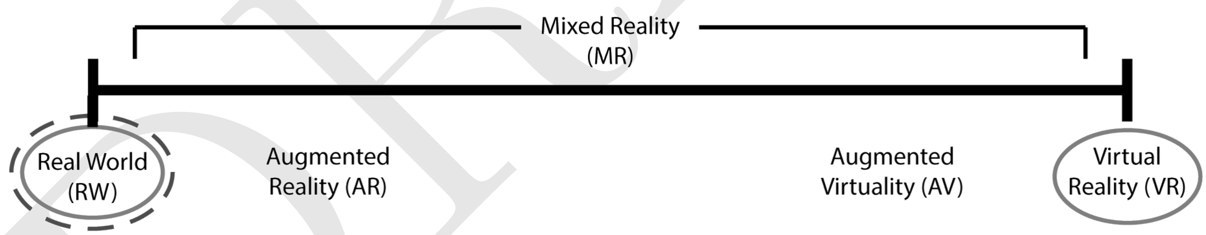


Figure 3.14: A XR system with the user attending to RW stimuli.

3.5 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 3.16, an integration of figure 3.11 with Milgram & Kishino's virtuality continuum).

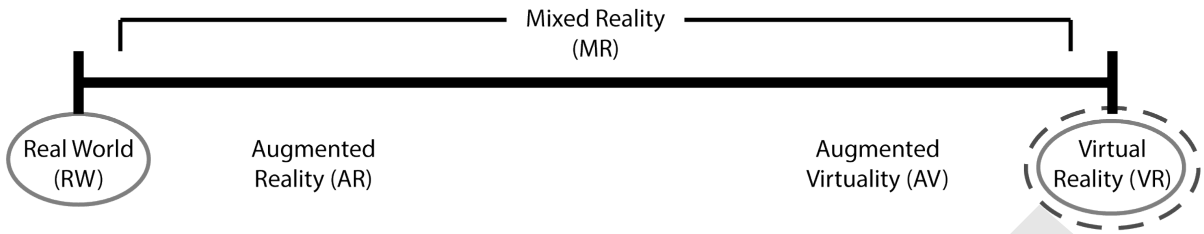


Figure 3.15: A XR system with the user attending to VR stimuli.

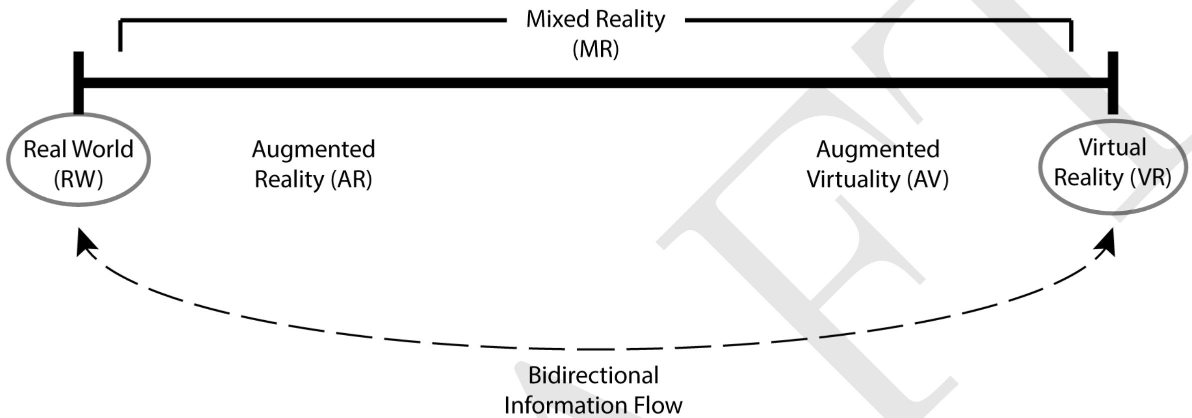


Figure 3.16: The two environments that comprise a XR system, plus the bidirectional information flow between them.

Whilst the system developed by this thesis features two discrete environments, one real & one virtual, that users can transition between visually observing (figures 3.14 & 3.15), it does 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 system developed in this thesis cannot be considered true a XR system as it does not meet both of the distinguishing criteria. The term **parallel reality** (PR[3]) is proposed to describe such a system. 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 PR system, or the ability to transition between receiving stimuli from either environment be introduced into a cross reality system, one would effect *parallel cross reality.*

3.5.1 Spatial Equivalence in Parallel Reality

When discussing a PR 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, to what extent) their layout, dimensions & content relate to each other − their *spatial equivalence.*

[3]Note that the use of 'PR' in the quotation in section 3.3.1 is a reference to 'physical reality' (that author's term for what this thesis simply calls 'reality') & is not a reference to parallel reality.

This distinction depends partly upon whether one adopts a dualistic concept of virtual space experience, wherein 'cyberspace' is a space in its own right with its own logic & metaphysics thus capable of playing host to any number of fantastical things & places, or whether one restricts the virtual environment by following a positivistic understanding of virtual space in which it serves only as a representation of real - using cyberspace for *"creating acceptable substitutes for real . . . environments"* instead of for *"constructing imaginary worlds that are indistinguishable from the real world"* [11].

One may also wish to consider this distinction in relation to the different stages identified by Baudrillard between simulacra & simulation, with complete spatial equivalence occupying the first stage of a faithful image or copy of a profound reality (the positivistic position), zero spatial equivalence occupying the fourth stage of pure simulation with no relation to anything in reality (the dualistic position) & partial equivalence perhaps occupying the second stage, a perversion of reality [21].

However one treats virtual space, a PR system would be unrewarding if the real & virtual environments were identical[4]. However a virtual environment that shares roughly the same fundamental dimensions & layout as the real environment (representing the same 'place') but presents an *alternative* representation has been proven to be a useful modality in previous XR research (see section 3.4) & it is this arrangement that the system developed in this thesis focuses 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. The combination 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 [32]. The system developed in this thesis focuses on a single small location, however it does not take a leap of imagination to understand the worth of such a system scaled to larger, even global, sizes.

Although the use cases for PR 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 system 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 '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 Samsumg Gear VR hint that we are not so far away from a time in which members of the general public will wish to multiplex their real environment with a virtual one while in public, in the same way that people commonly engage in computer-mediated communication (CMC) via their smartphones at the same time as walking through real environments & conversing with the people in them, in instantiations of PoSR. 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 [33], and with social roles and the community aspect constituting key aspects of these game's popularity [33, 34], informing the implementation of transitions between real & virtual in such systems with the findings of the experiments in this thesis into spatially equivalent PR systems promises to be beneficial to the further development of 3D social CMC.

[4] *"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."* [31]

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 reality & a simulation of reality.
PolySocial Reality (PoSR)	Describes multiple simultaneous social interactions mediated via various CMC technologies. [22].
Cross Reality (XR)	Systems that feature two environments, one real & one virtual, both complete unto themselves [25] but enriched by their ability to mutually reflect, influence & merge into one another thanks to bidirectional information flow between them [24].
Parallel Reality (PR)	Systems 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.

3.7 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 [35]. 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 senses of the user [36]. 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 virtual environment is, or the more similar the transformations in the virtual environment are to those in the real world, the higher the sense of presence [37].

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 experiencing a sense of presence [35].

3.7.1 Waterworth & Waterworth's three dimensions of virtual experience

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 [38]. 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 stimuli, virtual stimuli, or a mix) thus reducing presence[5] in that environment toward its antithesis − absence[6]; and the *sensus of attention* axis represents the level of conscious arousal (or 'wakefulness' [39]) of the user, whether directed toward percepts originating from real stimuli, virtual stimuli, or a mix, or not directed toward any percepts in the case of completely 'absent' conceptual reasoning.

[5]**Presence** in the context of this model is defined as a state of heightened perceptual processing of environmental stimuli (*"a psychological focus on direct perceptual processing"* [38]) 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.

[6]**Absence** is defined as *"a psychological focus on ... conceptual processing"* [38].

In this model, the notion of *involvement* relates 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 this model & Milgram et al.'s virtuality continuum, with the latter considered here to be analogous to the *locus of attention* axis; the combination of these models is shown by figure 3.17.

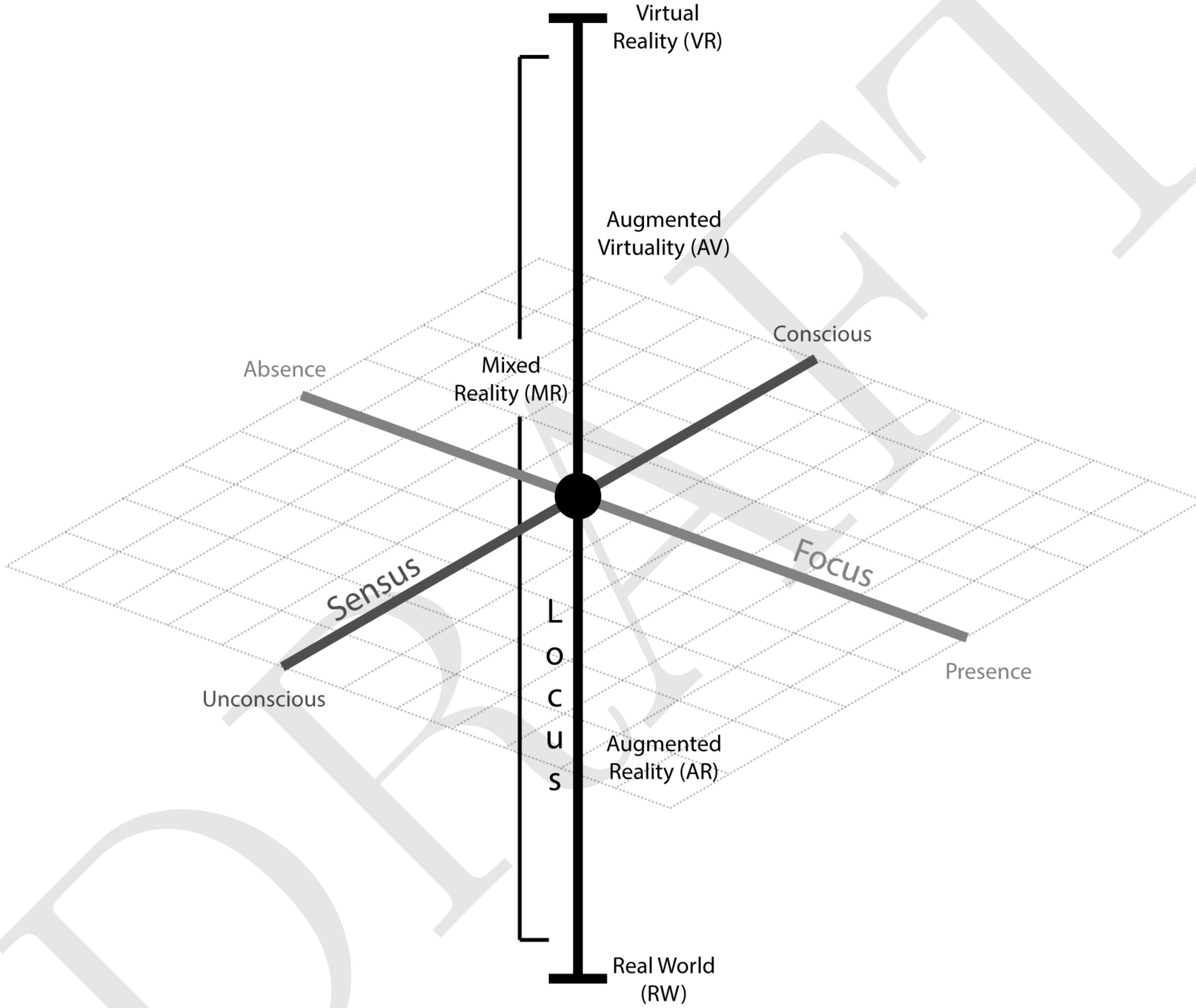


Figure 3.17: The combined virtuality continuum/three dimensions of virtual experience model.

3.8 Transitions in Parallel Reality

The novel aspect of a PR system is the ability it imparts upon its user to switch their locus of attention between equivalent vantage points in RW & VR environments. In order to achieve the highest quality of experience with this style of interaction with a PR 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.

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 [40], which would result in a substantial increase in cognitive load upon each transition, the system developed in this thesis supports 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) [41] & that when engaging with VR content a user's focus can even be said to typically be *shared* between VR & RW [38], leading to a notion of 'distributed' presence, or simultaneously experiencing a sense of presence in multiple environments.

This latter position is particularly apt for situations wherein the RW & VR environments share the same fundamental layout & dimensions (spatial equivalence), as those of the PR system developed in this thesis does, as inherent familiarity between two environments intuitively reduces the cognitive load associated with transitioning between them.

Furthermore, the notion of experience of presence as changing continually from moment-to-moment [42, 43] 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 [44] & accelerated with mobile devices to the point where for many users today rapid cycling stabilizes them into a sense of 'continual copresence', where even just a mobile phone brings them into a world of continual partial attention to any particular subject or environment [15]. The advent of mobile phones has previously been credited with allowing a person to *"be in many places at once"* & to play multiple roles [18].

However, no matter how smooth the transitions, the process is expected to nonetheless result in some heightened cognitive load, a temporary *break in presence*[7] (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 expected that users will prefer different implementations in different situations, surroundings & scenarios (where 'preference' toward a particular implementation is expected to correlate with a less severe BIP being experienced upon its execution). To this end, several different implementations are effected & investigated 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 that developed in this thesis may be deployed (moving, stationary, etc.).

3.8.1 Transitions using the Combined Model

Visualised using the combined model (figure 3.18) these transitions are an oscillation along the locus axis, between a RW environment at one position & a VR environment at the other.

[7] The definition of **break in presence** adopted herein is the second from Waterworth & Waterworth [38] (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 [45] 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 system developed in this thesis, 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'.

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 (such as that used by the system developed in this thesis) 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

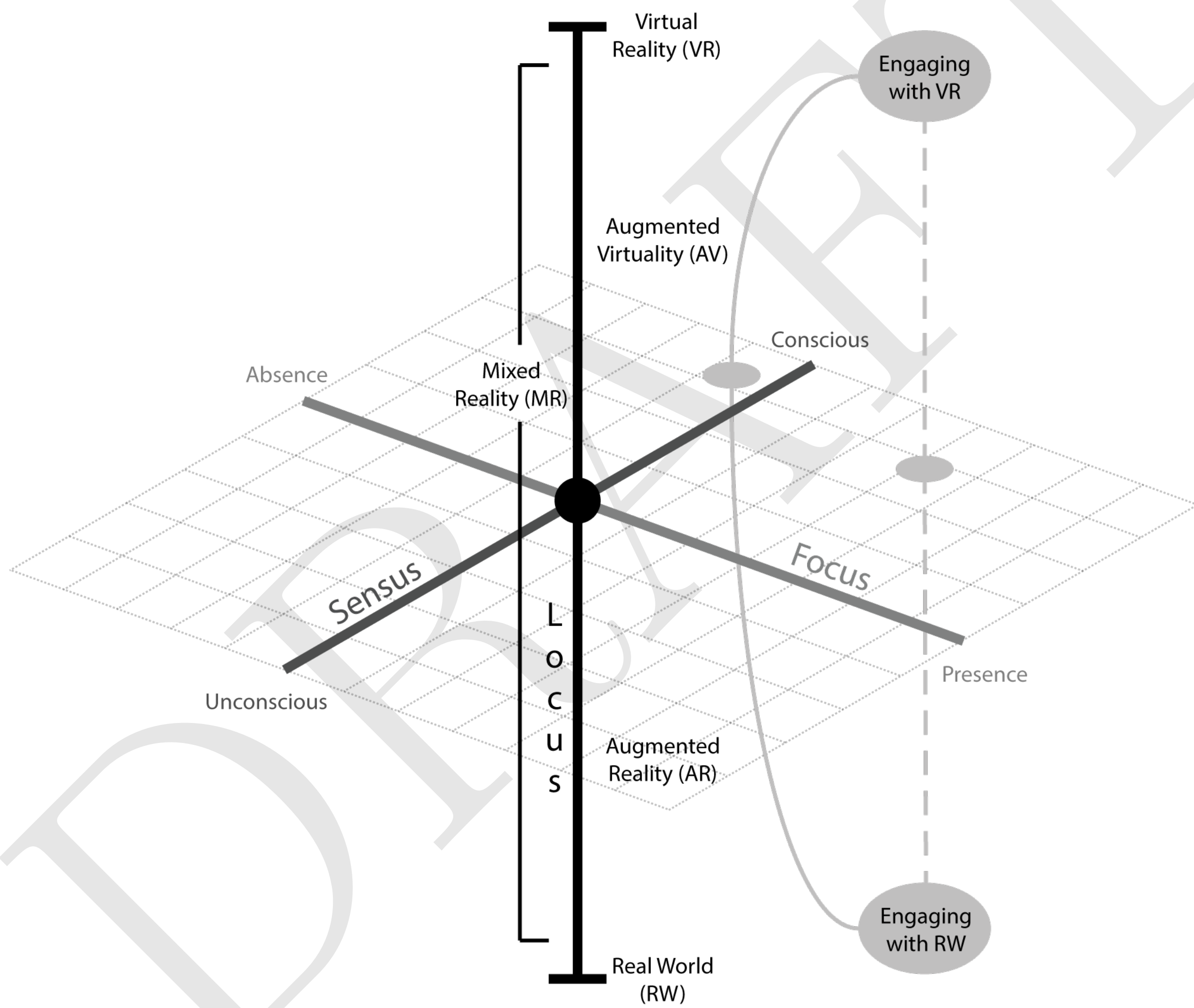


Figure 3.18: Operation of a PR system represented upon the combined model.

3.9 The Case for Parallel Reality

A PR system that presents the user with the choice between 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 previous alternate reality systems, including traditional AR implementations & XR systems;

- a PR system is less critical of registration (the accurate positioning/alignment) between real & virtual, as virtual objects are seen as part of a larger virtual environment instead of being rendered atop a view of the real environment;
- a PR system can make use of existing VR content without the overhead of decanting/extracting a subset of the virtual components into an AR framework (e.g. manually selecting which objects within the VR environment are to be displayed over the RW environment);
- the use of a complete VR environment allows 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.
- the vacancy problem is further addressed, but instead of doing so by linking real & virtual environments by sensor & actuator infrastructure, vacancy in either environment is alleviated by furnishing users with the ability to transition between visual stimuli from each environment.

Thus, a PR platform is well suited to situations in which interaction with the visual stimuli of both real & virtual environments 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 [46];
- 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 [47]) almost the whole RW view. While AR *"smears an informational coating over real space"* [48], PR presents a complete virtual environment. AR is beneficial where one wishes the juxtaposition of virtual objects upon what is already present in the RW environment, however PR is better suited to situations where one wishes to present a complete virtual alternative.

*****mention the redecorating/remodelling example, the 'real world as canvas for artistic expression' example, etc.**

3.10 Conclusions

Decades of research into alternate realities has furnished us with a rich continuum of approaches & technologies for creating, combining, augmenting & diminishing real & virtual environments. Many of the alternate reality labels that are now becoming commonplace are concerned with presenting a different environment to the user's real surroundings (as in telepresence & virtual reality) or mixing additional information into the user's view of their real or virtual surroundings (as in augmented/diminished reality & augmented virtuality).

Although less thoroughly investigated, the concept of creating an alternate reality system by combining two environments, one real & the other virtual & both complete unto themselves, into a cross reality system presents an interesting avenue for furthering alternate reality techniques & applications, in particular to addressing the vacancy problem that affects users when trying to distribute their attention between two environments.

Previous cross reality research focussed on alleviating this vacancy problem by integrating sensor & actuator infrastructure into the constituent real & virtual environments of a system, such that actions & events in one environment could manifest into the other. However directly visually engaging with both environments was not often possible in these systems & only from predetermined, static locations.

This thesis serves to extend alternate reality research by developing a system that allows its user to visually engage with both a real & a virtual environment, transitioning between them at any point, whilst maintaining mobility to walk through the environments in tandem. In trading the sensor/actuator infrastructure of a cross reality system for direct visual engagement with both environments, the parallel reality concept is born.

Simply put in the terms of Lifton's original definition of the vacancy problem, this thesis aims to allow people to be in more than one place (reality) at a time.

4

A Virtual Time Window

"The sinister thing about a simstim construct, really, was that it carried the suggestion that any environment might be unreal, that the windows of the shopfronts she passed now with Andrea might be figments."

Count Zero, William Gibson

This chapter presents the development of a preliminary PR system that combined a tablet computer, GPS, accelerometer & magnetometer, with an OpenSim based virtual environment to allow exploration of the real world ruins of a 14th century cathedral with a virtual reconstruction of it as it stood in its prime. Cultural heritage is introduced as an ideal area for which PR systems can be applied to beneficial effect, while the accuracy of GPS tracking emerged as a constraint on this style of implementation.

4.1 Virtual Heritage

Alternate reality technologies have been used for over two decades [49] to aid in the investigation, understanding & dissemination of information pertaining to our past in the fields of archaeology & cultural heritage. Whilst archaeology studies human activity through the recovery of remains, heritage is also concerned with intangible attributes of society; tradition, art, narratives & other cultural evidences [49]. *Virtual heritage* is the name given to the application of advanced imaging techniques, including alternate reality techniques, to the synthesis, conservation, reproduction, representation, reprocessing & display of this cultural evidence [50].

These techniques provide access to locations & artefacts scattered about the world, that may reside in private collections inaccessible to scholars (much less interested amateurs) & outwith of their original context of creation [51]. They allow recreations to be made of the numerous cultural heritage objects that are deteriorating or are at risk of being lost, both due to natural causes such as weather & natural disasters but also due to acts of man such as civil war [52].

Virtual heritage techniques offer substantial benefits to collaborative investigation of sites, where multiple users are provided the ability to collaborate via a multitude of different visualization modalities including video see-through head-tracked head mounted displays, projected table surfaces, large screen displays & tracked hand-held displays, including the ability for experts physically located at a particular site to collaborate with those remote to it [53]. This combination of different techniques not only benefits experts, but has been used in the creation of contiguous platforms for building & managing exhibitions of 3D models of artefacts accessed in museums, galleries & via the Web [54], focussed not only on the digitization & subsequent interaction with such content to aid in its preservation & protection, but also with making these resources as widely available as possible to any interested parties (scientists, archaeologists, curators, historians & interested amateurs) [55].

Even traditionally two-dimensional visual resources associated with cultural heritage can be integrated into such state-of-the-art systems, visualized via immersive CAVE techniques as part of ‘information landscapes’ [56]. Such techniques are of particular benefit to young people as cultural heritage sites often arouse little involvement in them, especially if the site’s present day appearance bears few traces of its original stature & makes it difficult to appreciate its original splendour & importance [57].

4.1.1 Alternate Reality Techniques in Virtual Heritage

Due to the number of combinations & diversity in approaches that have been used in the application of visualization techniques to the cultural heritage sector, attempting to comprehensively list them is impractical. Comparison via a taxonomical model that classifies approaches according to various characteristics is thus the approach adopted by Foni et al. [58] that produced the taxonomical space shown by figure 4.1.

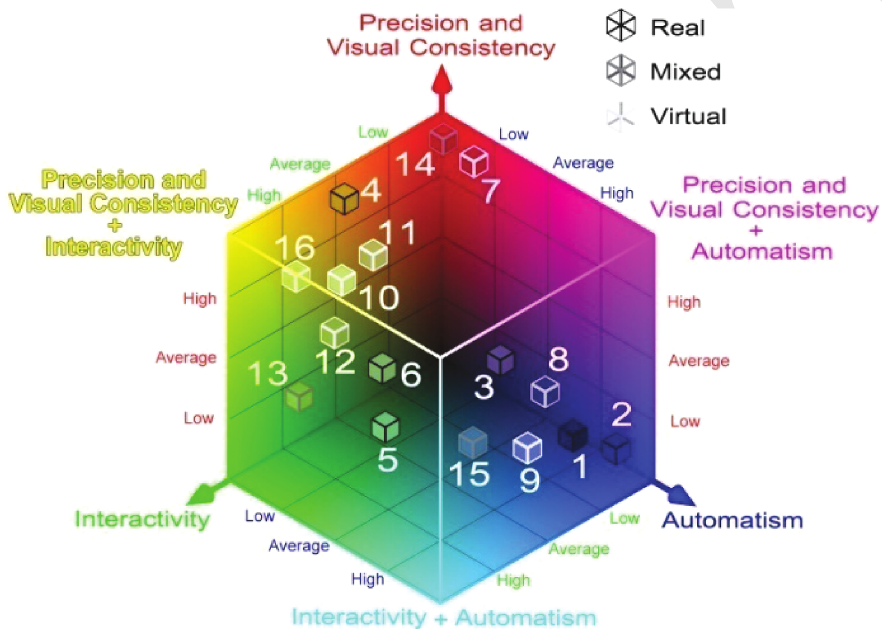


Figure 4.1: Taxonomical space of visualization strategies used in cultural heritage.

This model classifies visualization strategies according to four continua, represented by the three physical dimensions of the 3D cube & the degree of shading of each point within the cube. The x axis represents the level of automatism, which refers to the span of the development cycle required to produce the visualization; the y axis represents the level of precision, referring not only to the amount of geometrical detail but to all elements that can contribute to or enhance reliability; & the z axis represents the level of interactivity, defined in this context as;

> *“its capacity to contextually offer the possibility to subjectively experience an interactive behaviour in a synchronous way, thus enabling the user the opportunity to meaningfully contribute to a given experience or to affect in real time the visualized item”* [58].

The shading of each point within the cube represents its degree of virtuality, conceptually analogous to the reality-virtuality continuum of Milgram et al. (see section 3.1.1) with real world/world unmodelled represented as solid black, virtual reality/world completely modelled as completely white & positions in-between as various shades of grey. The position of 16 exemplar visualization techniques applied to cultural heritage are shown upon the cube & explained via the table figure 4.2, which includes both traditional techniques & state-of-the-art methodologies.

		Precision	Interactivity	Automatism	Virtuality
		R	G	B	V
1	Restitution drawings	0.1	0	0.7	0
2	Augmented pictures	0.1	0.1	0.8	0
3	Scale models	0.4	0.3	0.6	0
4	Physical reconstructions	0.8	0.6	0	0
5	Interactive scale models	0.4	0.8	0.5	0
6	Live experiments	0.5	0.7	0.4	0
7	Renderings	0.85	0	0.15	1
8	Digital catalogs	0.2	0.15	0.7	1
9	Digital panoramas	0.3	0.4	0.9	1
10	Real time VR simulations	0.8	0.9	0.4	1
11	Stereoscopic visualizations	0.7	0.7	0.3	1
12	Computer games	0.6	0.75	0.25	1
13	Real time AR simulations	0.5	0.85	0.25	0.5
14	Augmented movies	0.9	0	0.1	0.5
15	Semantically supplemented 2D	0.2	0.5	0.65	0.5
16	Semantically supplemented 3D	0.8	0.95	0.25	1

Figure 4.2: Coordinate sets for each approach within the taxonomical space (figure 4.1).

In terms of alternate reality techniques, real time AR simulations (category 13) have been used to add artefacts, actors & reconstructed architecture to views of present day sites that are still accessible & may bear traces of their original status, whilst real time VR simulations (category 10) have 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 its past status or is inaccessible due to latter development, change in landscape, etc..

The ARCHEOGUIDE project (Augmented Reality-based Cultural Heritage On-site GUIDE) [59] aimed to provide a 'personalized electronic guide & tour assistant' to cultural heritage site visitors. On-site help & augmented reality reconstructions of on-site ruins were presented via a laptop, a tablet computer & a PDA, using GPS for location tracking & magnetometer to ascertain direction such that augmentations could be placed accordingly. The applications claimed to be supported by the platform range from archaeological research to education, multimedia publishing & cultural tourism. The platform was prototyped at the archaeological site of Olympia, Greece.

As well as being used for walking tours, AR has been combined with the concept of telepresence to create 'augmented telepresence', allowing participants to experience a 'fly-through' of the ancient Nara Heijo-kyo capital of Japan, by combining aerially captured omnidirectional video augmented with related information using AR techniques [60, 61].

Augmenting views of the real world with real-time animated virtual humans has been explored by several projects, including the LIFEPLUS EU IST project, which aimed to produce *''an innovative 3D reconstruction of ancient frescos-paintings through the real-time revival of their fauna and flora, featuring groups of virtual animated characters with artificial life dramaturgical behaviors, in an immersive AR environment"*. This project pushed established augmented reality applications to the field by exploring narrative design in fictional spaces, with the aim of increasing immersion via realistic interaction, making use of captured/real-time video of a real scene [62], presenting the visitor with *"an immersive and innovative multi-sensory interactive trip to the past"* [63]. These realistic simulations of animated virtual human actors were employed in a mobile & wearable setup, in abandonment of traditional concepts of static cultural artefacts or rigid augmentations of real world features, making use of a markerless camera tracker & mixed reality illumination model for more consistent real-virtual & virtual-real rendering. This platform was demonstrated in a case study on the real site of ancient Pompeii & whilst initially targeted at the cultural heritage sector, the author(s) clarifies that as a platform it is not limited to such subjects [64]. This concept of extending rigid & static AR with character-based event representations hopes to recreate not just discrete artefacts but the entirety of 'daily life' at the scene [65].

Although many applications of AR to cultural heritage sites are mobile in nature, using a variety of tracking techniques to localise the user & determine their orientation, including GPS [59], visual tracking of robust features of the environment [66] & omnidirectional range sensing of a landmark database [67], there are also those that present a static interface similar to coin-operated telescopes situated at popular tourist attractions [68].

VR is not only useful where the real site is no longer accessible, too remote or does not bear any similarity to its original status, but also allows for more effective control over the atmospheric qualities of the environment being recreated; effects such as fog, sky, water & particles, exploiting the latest graphical hardware by making use of shaders to deliver high quality graphics [46]. The use of a head mounted display or CAVE [69, 70] that completely blocks stimuli from the user's real world surroundings allows for this complete level of control. Unless an AR system employs various environmental monitoring techniques, the augmentations that it overlays upon the user's view of the real world will often have differing illumination than their real surroundings which has an effect upon their perceived realism [71].

Whereas many heritage representations, architectural walkthroughs & simulations of artefacts & places have defined a practice where photorealism is considered an important measure of the representation's success, there is an argument that whilst such an emphasis on realism & historical accuracy & authenticity is important, such photorealistic methods can limit the flexibility of the reconstructions with regards to how much they can be modified & altered to explore different reconstruction hypotheses [50]. Emphasis on photorealistic graphical quality also has considerations when it comes to real time performance & many intelligent techniques must be employed to maintain acceptable performance as complexity of reconstructions increases [72]. Particularly for dissemination to the public in museums & visitor centres, acceptable performance is often more important than extreme historical accuracy.

4.1.2 Virtual Heritage at the University of St Andrews

*****Include references to Kris Getchell's thesis? Experiential learning, etc?**

The Open Virtual Worlds (OVW) research group at the School of Computer Science at the University of St Andrews has been employed in virtual heritage projects since 2007 [73], producing a number of reconstructions of cultural heritage sites in Scotland & further afield. These reconstructions have been produced through collaborations with academics from the university's Art History, History & Archaeology departments, as well as with domain experts from heritage organisations including Historic Scotland & the National Trust for Scotland. These projects range from small reconstructions of a church, to much larger reconstructions such as that of the cathedral at St Andrews which represents several years of work [74]. Whilst the cathedral reconstruction was completed as a research project, other reconstructions were produced specifically for use in schools in Scotland (such as Linlithgow palace, figure 4.3, 4.4), others for outreach purposes (Mosfell Viking farmstead, figure 4.5, 4.6) & still others were built specifically for installation into museums (Caen Township, figure 4.7, 4.8). Some of these reconstructions are inhabited with virtual humans that are scripted to perform certain actions specific to the role they depict at the site (figure 4.9, 4.10).

These reconstructions were made using OpenSim, an open source implementation & extension of the Second Life server which is compatible with the numerous forks of the Second Life client program. This architecture allows straightforward construction & dissemination of the models, thanks to accessible modelling tools provided by the Second Life client itself & the client/server model that allows the models to

Figure 4.3: Linlithgow Palace today.

Figure 4.4: Linlithgow Palace reconstruction.

Figure 4.5: Mosfell Viking Longhouse.

Figure 4.6: Longhouse interior.

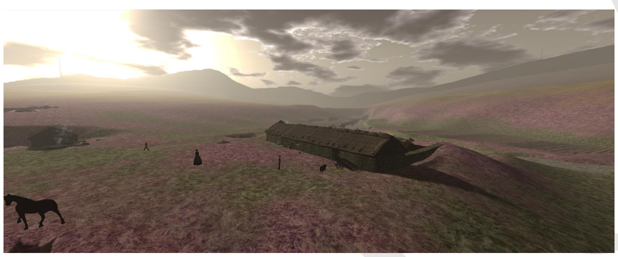


Figure 4.7: Caen Township.

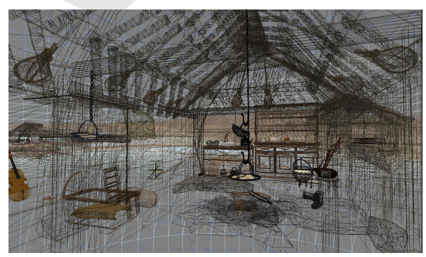


Figure 4.8: Caen Township wireframe detail.

be accessed in various deployment scenarios including temporary deployments within controlled network & client conditions as well as remotely via the Internet.

The reconstruction process involves the use of Geographic Information System (GIS) data from Ordnance Survey (OS) to accurately model the basic elevation of the ground. Where there is higher resolution elevation data, such as from Lidar laser surveying often employed on archaeological surveys, this is used to increase the accuracy of the resultant reconstruction. Where access to the site is possible & depending upon development surrounding the site prior to the date being reconstructed, 360° panoramic photographs are captured & then used to create a backdrop for the reconstruction, allowing identifiable aspects of the surrounding environment to improve the experience of the reconstruction. Buildings/structures are then reconstructed upon the ground layer, using numerous sources as input; satellite views, archaeological surveys, contemporary accounts, views of the site itself if relics still exist, photographic evidence, etc. Domain experts are then brought in to iteratively improve the model, commenting on aspects of the reconstruction to be altered in order to visualise a different reconstructive hypothesis.

Figure 4.9: Virtual humans in cathedral reconstruction.

Figure 4.10: Conversing with virtual humans.

These reconstructions have been used to host workshops at 10 schools throughout Scotland, at both primary & secondary institutions, where all requisite computing infrastructure was taken, assembled at the school, then disassembled & removed at the end of the day. Students are split into groups of 4-5, sharing a computer with screen, keyboard, mouse & Xbox controller (a control modality instantly recognised by most school students). Worksheets with tasks are used to structure their interaction with the reconstructions & guide the experiential learning experience over 20-40 minute sessions (figure 4.11). Similar workshops have also been performed in museums, using the same approach of temporary setups of computing hardware (figure 4.14). In addition to traditional computer screens, larger LCD television screens & still larger projection screens, Oculus Rift VR headsets have been used with this same content 4.13.

In addition to these temporary workshops, the reconstructions have also been used in permanently installed exhibits in museums & visitor centres, including the Virtual Time Travel Project (VTTP), which combines multi-head projection with Natural User Interaction (NUI) via Microsoft Kinect, which has been installed at the Timespan Museum & Arts Centre in Helmsdale, allowing visitors to explore the reconstruction of the Caen Township by using simple gestures, instead of relying upon a keyboard, game controller or other traditional interface (figure 4.12).

Figure 4.11: School students learning via a reconstruction.

Figure 4.12: VTTP installation at Timespan.

Figure 4.13: OVW via Oculus Rift.

Figure 4.14: Museum workshop.

4.1.3 Parallel Reality in Virtual Heritage

Applications of alternate reality techniques within virtual heritage have thus far broadly fallen into the categories of AR, experienced at the site, or VR, experienced away from the site (in terms of space, time, or both). The dissemination of the OVW group's content has been no exception to this observation, falling into categories 10-12 of figure 4.2, with complete virtual environments that are experienced with both spatial & temporal separation from the real site that they represent.

Applying the concept of parallel reality to virtual heritage represents an opportunity to explore an exciting new modality of interaction that combines the complete virtual environments of categories 10-12 with the real time juxtaposition between real & virtual environments of AR systems from category 13. In terms of the four categories of the taxonomic space, such a PR system would combine the high precision & interactivity of a VR system (category 10) with two values of viruality, as the user is provided the ability to observe either the complete virtual environment (virtuality = 1) or the unmodified real environment (virtuality = 0). The automatism of such a system would occupy a position between that of VR & AR; whilst the system will require a more involved development cycle than a purely VR one, the slackened requirements on registrational accuracy of a PR system compared to an AR system promise higher automatism than a purely AR system.

4.2 The Virtual Time Window

The Virtual Time Window (VTW) is an application of parallel reality to virtual heritage, leveraging the OVW group's existing OpenSim virtual reconstructions of cultural heritage sites in a handheld package that allows tandem exploration of both the real cultural heritage sites & their spatially equivalent virtual reconstructions.

VTW manifests as a tablet computer which is capable of tracking its position via GPS, its compass heading via magnetometer ('electronic compass') & its pitch via accelerometer. Existing AR projects have proven through application the suitability of smartphones & tablets for mobile, position & orientation aware applications that present virtual content within a cultural heritage context. These devices are also entering ubiquity today & thus present a platform that can be quickly assimilated by most users. The tablet runs a modified version of the Second Life client in order to access, via wifi, a virtual reconstruction of a cultural heritage site hosted by an OpenSim server. The Second Life client is controlled entirely by the tablet's position & orientation - the user does not manually control any aspect. The modality of interaction offered is similar to that of using a smartphone to take a photograph, but whereas the screen of the smartphone shows the real environment as it is, the screen of the VTW tablet shows the environment as it was in the past - a window to the past, or *Virtual Time Window*. The user is free to explore the real cultural heritage site, observing it in its current state, whilst at any moment 'looking through' VTW to see what a particular vantage looked like in the past. See figure 4.15 for a representation of the components of the platform at the conceptual level.

In terms of the combined Milgram/Waterworth model, the displacement along the locus axis when the user switches their attention between their real environment & the virtual environment upon the tablet will displace less toward the VR extremum than shown in figure 3.18 which represents transitions between real & virtual environments when using a HMD that effectively blocks all stimuli from the real world when observing the virtual. When considering the environmental provision, VTW features two complete environments, one real & the other virtual. From the perspective of transitioning between receiving stimuli from each environment, there is an obvious difference between VTW's tablet based approach compared to a HMD approach, as the latter effectively forces all percepts to emanate from one environment whilst the former allows percepts emanating from both environments to be perceived simultaneously.

Whilst this will intuitively make transitions easier to perform & create less risk of a jarring Gestalt switch, it will also intuitively limit the intensity of the sense of presence attainable in the virtual environment as the sense of 'looking in to' the virtual environment will always leave the user readily aware of the real environment surrounding them. Whilst VTW is a PR system, one might liken the experience of interacting

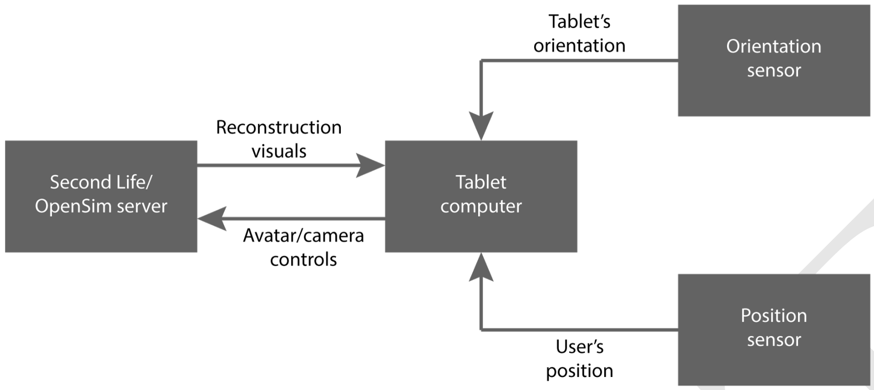


Figure 4.15: High level architecture of VTW.

with it to be similar to that of an AR system.

4.2.1 Second Life & Mobility

At the time of the VTW project (Summer 2012) the only fully-featured Second Life clients available were for x86 platforms. Whilst the Android client Lumiya[1] was available, it was in its earliest stages & very limited in its features & usability. This limited the choice of tablet to those few x86 models that had reached market, with the MSI WindPad 110W[2] presenting the most promising solution: a 10" tablet sporting an AMD Brazos Z01 APU (combining a dual-core x86 CPU with a Radeon HD6250 GPU).

The Second Life client, intended for use on a desktop or laptop computer, provides provision for controlling the avatar's position & the camera orientation by keyboard, mouse & joystick. For the purposes of VTW, this position & orientation control must be tied to the physical position & orientation of the tablet itself. To this end, it is necessary to make use of various sensors connected to the tablet (either internally, or externally) & to interface these with the Second Life client in such a way that it can make use of their collected data to appropriately control the avatar's position & camera orientation.

4.3 Orientation Control

In order to control Second Life's camera in the fashion required of VTW, sensor data are required for the orientation in which the user is holding the tablet. Specifically, the tablet's yaw & pitch are needed; roll is less important as it is conceived that the user will generally hold the tablet roughly level with the horizon when looking 'through' it.

VTW considers yaw in terms of magnetic compass bearing, as this provides a value that can be used to directly control the yaw of the virtual camera while the virtual reconstruction within OpenSim is correctly oriented to OpenSim's own compass. Magnetic compass bearings are sensed electronically via a 3-axis micro-electromechanical (MEMS) magnetometer, which measures the strength of magnetic field being experienced along each of its 3 axes. By comparing the values of each axis to the known direction of the field lines of Earth's magnetic field, a compass bearing relative to the magnetometer's orientation can be calculated. Pitch is sensed using a 3-axis MEMS accelerometer, which measures force of acceleration along each of its 3 axes. In the case of static or slow moving applications, this acceleration is predominantly that caused by the Earth's gravitational pull & by comparing the values of each axis the direction of this acceleration (down toward the centre of the Earth) can be determined in relation to the orientation of the accelerometer itself & thus the accelerometer's own orientation can be deduced.

[1] https://play.google.com/store/apps/details?id=com.lumiyaviewer.lumiya&hl=en_GB
[2] http://www.msi.com/product/windpad/WindPad-110W.html

Due to the fact that the WindPad tablet does not feature a built-in magnetometer & its built-in accelerometer is little more than a rudimentary tilt sensor for differentiating between discrete cases of landscape and portrait orientation for screen rotation, it was necessary to interface external magnetometer & accelerometer sensors. The popular Arduino[3] microcontroller platform was used for prototyping with several different sensor packages, including the MMA8452[4], the ADXL335[5] & the HMC5883L[6]. The package adopted for use with VTW from this prototyping stage was the HMC6343[7], which combines a 3-axis MEMS magnetometer & 3-axis MEMs accelerometer into a single package sporting an I2C interface, along with algorithms to internally apply the accelerometer's readings to 'tilt compensate' the magnetometer's readings. Figure 4.16 provides a wiring diagram for connectivity of a HMC6343 to an Arduino Uno R3, with the pinout values provided by table 4.1 & Figure 4.17 shows an assembled unit.

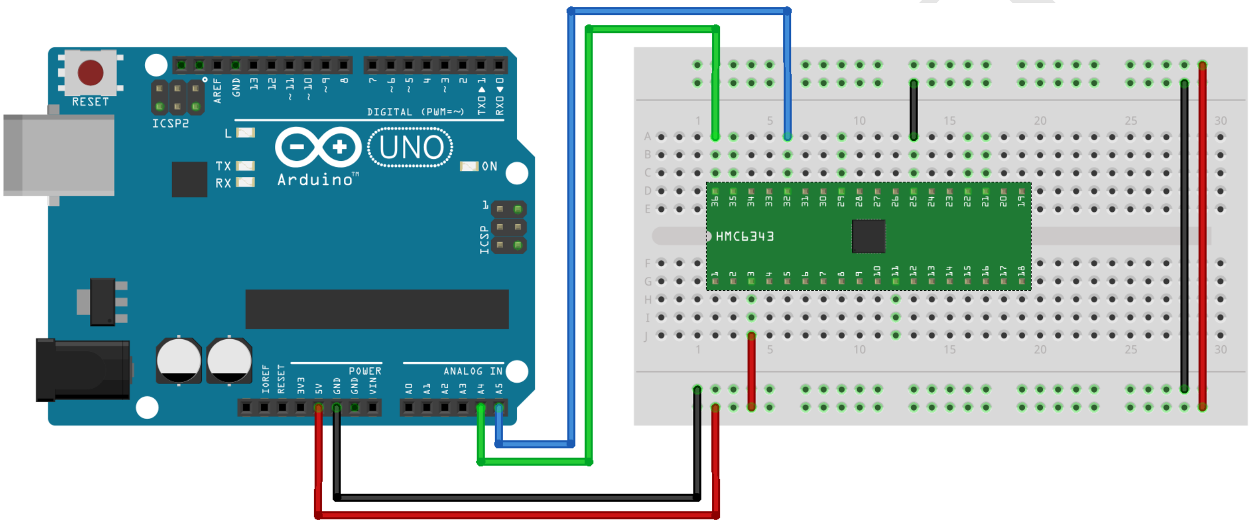


Figure 4.16: Example wiring for Arduino with HMC6343 for joystick operation.

A magnetometer used alone is only capable of providing a meaningful compass bearing when held level. In the case of applications where a compass bearing is required of a device that is not maintained level, such as in the case of VTW, the non-level orientation of the device must be taken into account to offset the readings of the magnetometer & provide a correct compass bearing. The HMC6343's combination of magnetometer, accelerometer & algorithms provides a single package that internally performs this process, using the readings from its accelerometer to compensate the readings from its magnetometer & provide a meaningful compass bearing in non-level orientations.

Further requirements for obtaining accurate compass bearings from a MEMS magnetometer are to account for distortions to the magnetic field it senses & to compensate the bearings it reports for the amount of magnetic declination for the location & date wherein it is being used. Various materials that influence magnetic fields or produce their own magnetic field will distort the Earth's magnetic field & thus impact the readings that a MEMS magnetometer collects. In the case of VTW, the sources of primary consideration are the electronics of the Arduino, tablet & associated wiring. Due to the nature of these sources & the fact that they are permanently situated & attached to the same frame of reference as the magnetometer, moving as

[3] http://www.arduino.cc/

[4] http://cache.freescale.com/files/sensors/doc/data_sheet/MMA8452Q.pdf

[5] http://www.analog.com/static/imported-files/data_sheets/ADXL335.pdf

[6] http://www51.honeywell.com/aero/common/documents/myaerospacecatalog-documents/Defense_Brochures-documents/HMC5883L_3-Axis_Digital_Compass_IC.pdf

[7] http://www51.honeywell.com/aero/common/documents/myaerospacecatalog-documents/Missiles-Munitions/HMC6343.pdf

HMC6343 pin	Arduino Uno R3 pin
VCC	5V[a]
GND	GND
SDA	A4[b]
SCL	A5

[a]The HMC6343 requires 2.7 to 3.6V input on VCC/VDD, this table showing connection to 5V assumes a HMC6343 breakout with appropriate step down.

[b]The HMC6343's I2C lines must be pulled up to 3.3V, this table shows connection to an Arduino Uno R3's I2C lines which are pulled up to 5V assuming a HMC6343 breakout with appropriate level shifters.

Table 4.1: Pin designation for figure 4.16.

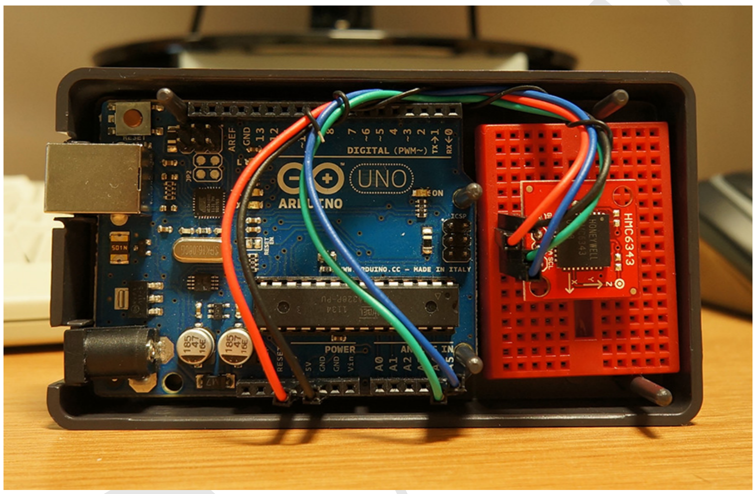


Figure 4.17: Assembled Arduino Uno R3 + HMC6343.

it moves, the distortions can be mitigated using a hard iron offset approach. Magnetic declination refers to the difference between 'magnetic north' & geographic 'true north'. This value varies depending upon world location & changes over time, so must be updated when the magnetometer is deployed to a different location or used at a subsequent date.

4.3.1 Exploiting Second Life's Joystick Support

As highlighted in section 4.2.1 the Second Life client can be controlled only via mouse, keyboard & joystick. Using the HMC6343's compass bearing & yaw values therefore requires one of two approaches;

1. Encapsulating the compass bearing & yaw values into mouse, keyboard &/or joystick commands;
2. Modification to the Second Life client to allow the compass bearing & yaw values to be used directly at a lower level of abstraction.

Method 1 has the advantage of having no reliance upon any particular Second Life client, as all available clients are forks of the official client from Linden Lab & maintain the same keyboard, mouse & joystick interfaces. However if the level of control attainable by re-purposing these interfaces for control from magnetometer & accelerometer data is not enough, method 2 will be the only option.

Conceptually, all Arduino boards are programmed over an RS-232 serial connection. When the platform was first launched, the Arduino boards themselves had a physical DE-9 serial connector with which to connect to a host computer's serial connector. But as serial connectors all but disappeared from modern computers, the Arduino's serial connector was replaced in later revisions with a USB connector, as USB is now all but ubiquitous on today's computers. The move from a physical RS-232 connector to a USB connector requires additional hardware upon the Arduino board to convert between RS-232 & USB, as the ATMega328[8] microcontroller at the heart of the Arduino Uno R3 does not have a USB interface itself. For this reason the current revision, the Arduino Uno R3, sports an ATMega16U2[9] microcontroller that serves to convert communications between the two standards, RS-232 & USB.

With its stock firmware, the Arduino's ATMega16U2 presents itself to the host computer as a USB-to-serial bridge. However the ATMega16U2 can have this stock firmware replaced in order to change its behaviour. One of these new behaviours is to act as a USB Human Interface Device (HID) class controller, identifying itself to the host computer as one of a myriad input devices - including joysticks. Using a USB HID class joystick firmware for the ATMega16U2[10], based upon the Lightweight USB Framework for AVRs (LUFA)[11], the Arduino can imitate a standard USB joystick, sending joystick commands to the host computer using the protocol in the USB specification.

In this manner, the Arduino can marshal the values obtained from the HMC6343 into standard USB HID joystick commands, allowing the Second Life client's stock joystick interface (see figure 4.18) to be used to control the camera orientation (& avatar movement) according to the physical orientation of the HMC6343, as can be seen in[12].

Figure 4.18: Configuration in Second Life client for Arduino + HMC6343 'joystick'.

Unfortunately, the precision attainable through this approach is not sufficient for the style of control & interaction required for VTW. Specifically, the Second Life client's joystick interface applies smoothing/-damping to the joystick inputs, preventing reliable rotations or movements of specific values - sending a joystick command to rotate the camera by x° followed by a second command to rotate the camera by $-x^\circ$

[8] http://www.atmel.com/devices/atmega328.aspx
[9] http://www.atmel.com/devices/ATMEGA16U2.aspx
[10] http://hunt.net.nz/users/darran/weblog/a3599/
[11] http://www.fourwalledcubicle.com/LUFA.php
[12] https://www.youtube.com/watch?v=-ddtmqoGNmg

does not reliably return the camera to its original orientation before the application of the first rotation. As the interaction required is to map the *absolute* orientation of the tablet to the Second Life camera, this discrepancy (which cannot be disabled from the Second Life client's joystick configuration) renders the approach unworkable.

4.4 Position Control

In order to control the position of the Second Life avatar, sensor data are required for the position of the user in the real world. As the cultural heritage sites that VTW was intended for use upon are outdoor sites, namely those where there are traces of ruins & clear views of the sky, GPS is the logical choice for tracking user position. GPS has been widely used as a localization technique within virtual heritage, particularly for AR applications.

In order for readings from a GPS receiver to be used to control the position of the Second Life avatar within a reconstruction, a translation must be performed between the coordinate system of GPS (latitude & longitude) & the coordinate system of Second Life (simple X,Y coordinates within 256 metre square 'regions'). This is achieved by use of a single 'anchor point', for which both the real world latitude & longitude & the corresponding virtual world X,Y coordinates are known. Calculating Second Life displacement from these X,Y coordinates is achieved by applying the scale of the reconstruction to the displacement between the anchor point's latitude & longitude & the user's current position reported as latitude & longitude by a GPS receiver. This real world displacement is calculated using the haversine formula [75], which is used to calculate the 'great circle' (orthodromic) distance between two points on the surface of a sphere (such as the Earth, when simplified from its oblate spheroid shape). The central angle $\left(\frac{d}{r}\right)$ between the two points is given by;

$$\text{haversin}\left(\frac{d}{r}\right) = \text{haversin}(\phi_2 - \phi_1) + \cos(\phi_1)\cos(\phi_2)\text{haversin}(\lambda_2 - \lambda_1) \tag{4.1}$$

where;

- haversin is the haversine function
$$\text{haversin}(\theta) = \sin^2\left(\frac{\theta}{2}\right) = \frac{1-\cos(\theta)}{2} \tag{4.2}$$
- d is the distance between the two points along a great circle of the sphere,
- r is the radius of the sphere,
- ϕ_1, ϕ_2 are the latitudes of point 1 & point 2,
- λ_1, λ_2 are the longitudes of point 1 & point 2.

The equation can be solved for the distance d by applying the inverse haversine function or through application of arcsine;

$$d = r\ \text{haversin}^{-1}(h) = 2r\arcsin\left(\sqrt{h}\right) \tag{4.3}$$

where h is haversin $\left(\frac{d}{r}\right)$;

$$\begin{aligned} d &= 2r\arcsin\left(\sqrt{\text{haversin}(\phi_2-\phi_1) + \cos(\phi_1)\cos(\phi_2)\,\text{haversin}(\lambda_2-\lambda_1)}\right) \\ &= 2r\arcsin\left(\sqrt{\sin^2\left(\frac{\phi_2-\phi_1}{2}\right) + \cos(\phi_1)\cos(\phi_2)\sin^2\left(\frac{\lambda_2-\lambda_1}{2}\right)}\right) \end{aligned} \tag{4.4}$$

The prerequisites for this approach are that the Second Life model is aligned correctly to the Second Life compass as the real location is aligned to real bearings (also required for orientation control from the previous section), a single anchor point for which both the real world latitude & longitude & the corresponding virtual world X & Y coordinates are known & that the reconstruction adheres to a known, consistent scale.

Figure 4.19 illustrates this arrangement. In the real world, on the left, we know the latitude & longitude of the anchor point, as well as the latitude & longitude of the user's current position as reported by the GPS receiver. In the virtual world, on the right, we know the X,Y coordinates that are equivalent to the latitude & longitude of the anchor point & we must calculate the X,Y coordinates that are equivalent to the user's current position as reported by the GPS receiver.

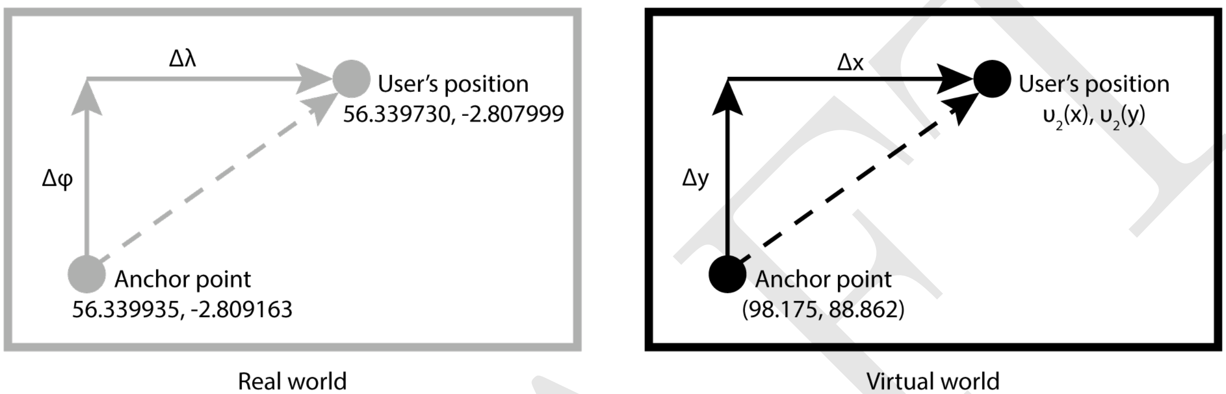


Figure 4.19: Using haversine to mimic real world movement in a virtual world.

The difference in longitude between the anchor point & the user's position, $\Delta\lambda$, is given by;

$$2r \arcsin\left(\sqrt{\sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right)}\right) \tag{4.5}$$

While the difference in latitude between the anchor point & the user's position, $\Delta\phi$, is given by;

$$2r \arcsin\left(\sqrt{\sin^2\left(\frac{\phi_2 - \phi_1}{2}\right)}\right) \tag{4.6}$$

Applying the scale of the reconstruction to these values gives Δx & Δy, which can then be added or subtracted from the X,Y coordinates of the anchor point to give the coordinates of the user's position, $\upsilon_2(x), \upsilon_2(y)$.

4.4.1 GPS Receivers

The WindPad features an internal AzureWave GPS-M16 GPS receiver[13], however poor API provision and meagre documentation required the adoption of an alternative receiver. As an Arduino was already being used to provide orientation data from accelerometer & magnetometer, integrating the GPS receiver into this package such that all orientation & position data came from a single source seemed prudent. After receiving input & advice from the UK High Altitude Society[14], *"a loose collection of people who are interested in launching unmanned high altitude balloons into near space"* who make extensive use of GPS receivers

[13] `http://www.azurewave.com/product_GPS-M19_1.asp`
[14] `http://ukhas.org.uk/`

HMC6343 pin	Arduino Uno R3 pin
VCC	5V[a]
GND	GND
SDA	A4[b]
SCL	A5

Table 4.2: Pin designation for figure HMC6343.

[a]The HMC6343 requires 2.7 to 3.6V input on VCC/VDD, this table showing connection to 5V assumes a HMC6343 breakout with appropriate step down.

[b]The HMC6343's I2C lines must be pulled up to 3.3V, this table shows connection to an Arduino Uno R3's I2C lines which are pulled up to 5V assuming a HMC6343 breakout with appropriate level shifters.

MAX-6 pin	Arduino Uno R3 pin
VCC	5V[a]
GND	GND
RXD	D4 [b]
TXD	D5

Table 4.3: Pin designation for figure MAX-6.

[a]The MAX-6 requires 2.5 to 3.6V input on VCC, this table showing connection to 5V assumes a MAX-6 breakout with appropriate step down.

[b]The data pins of the MAX-6 need to be pulled up to between 0.7 to 1.0 of the supply to VCC, so a breakout with appropriate level shifters is required for connection directly to an Ardunio Uno R3's 5V digital pins.

for tracking their launches, the u-blox MAX-6[15] GPS receiver outfitted with a Sarantel SL-1202[16] passive antenna was chosen to provide position data for the VTW platform. 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.

Figure 4.20 provides a wiring diagram for connectivity of a u-blox MAX-6 to an Arduino Uno R3, along with the HMC6343 from section 4.3, with the pinout values provided by tables 4.2 & 4.3. The LED & 220Ω resistor on digital pin 12 is used for diagnostic output. The wiring shown here for a MAX-6 breakout without I2C connectivity, instead using Arduino's SoftwareSerial[17] library.

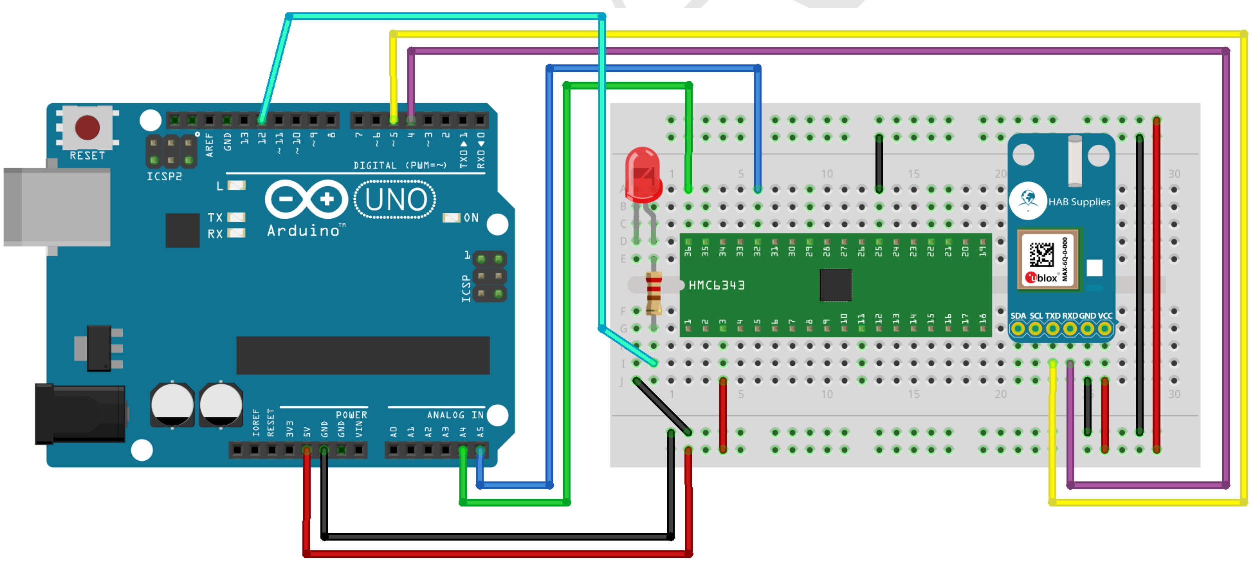


Figure 4.20: Example wiring for Arduino with HMC6343 + u-blox MAX-6.

[15]https://u-blox.com/en/gps-modules/pvt-modules/previous-generations/max-6.html
[16]http://www.sarantel.com/sl1200_(33).html
[17]http://arduino.cc/en/Reference/SoftwareSerial

Figure 4.21 shows an the assembled unit, comprising an Arduino Uno R3, prototyping shield, HMC6343 & MAX-6, while figure 4.22 shows the packaged unit attached to the back of the WindPad.

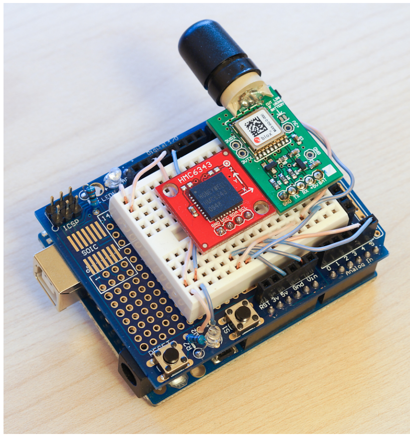


Figure 4.21: Assembled Arduino/sensors.

Figure 4.22: Arduino/sensors attached to tabet.

The MAX-6 is configured as follows;

1. Dynamic Platform Model set to Pedestrian.
2. SBAS via EGNOS is enabled,
3. GPGLL/GPGSA/GPGSV/GPVTG messages are disabled,
4. GPRMC/GPGGA messages are enabled.

The Dynamic Platform Models adjust how the navigation engine processes the readings that the receiver produces & by choosing the correct model for the receiver's application accuracy of position output is increased. As VTW is an application in which the user walks about an outdoor cultural heritage site, the pedestrian model is most suitable. Satellite Based Augmentation System (SBAS) is enabled for the European Geostationary Navigation Overlay Service (EGNOS), which is available at the cultural heritage sites in Scotland that VTW will be used at, to improve the accuracy of the position output.

The output of the receiver is in the form of messages in the NMEA 0183 protocol from the National Marine Electronics Association. By default, the MAX-6 sends many more message types than are required for VTW & as the Arduino's processing power is limited the superfluous messages are disabled. The GPRMC message format contains the recommended minimum amount of information for transit applications, including time, latitude & longitude.

These configurations are effected by sending the MAX-6 commands encoded in the UBX protocol as arrays of hex values. For example, setting the Dynamic Platform Model to Pedestrian is performed with the code in figure 4.23, where `sendUBX` is a function that writes out using SoftwareSerial;

These hex arrays can be generated by hand from the UBX protocol specification[18], or the MAX-6 can be configured by connecting it directly to a host computer (such as by using an Arduino as an UART by connecting the MAX-6 to digital pins 0 & 1), configuring the MAX-6 using the u-blox u-center software & then copying the resultant config as hex messages from the relevant console window.

NMEA messages from the MAX-6 are processed on the Arduino using the TinyGPS library[19], extracting the latitude & longitude values before combining them with magnetic compass bearing (yaw) & pitch values from the HMC6343 & sending these to the host computer via the Arduino's USB connective.

[18] `https://u-blox.com/images/downloads/Product_Docs/u-blox6_ReceiverDescriptionProtocolSpec_(GPS.G6-SW-10018).pdf`

[19] `http://arduiniana.org/libraries/tinygps/`

```
uint8_t CFG_NAV5[] = {0xB5, 0x62, 0x06, 0x24, 0x24, 0x00, 0xFF, 0xFF,
                      0x03, 0x03, 0x00, 0x00, 0x00, 0x00, 0x10, 0x27,
                      0x00, 0x00, 0x05, 0x00, 0xFA, 0x00, 0xFA, 0x00,
                      0x64, 0x00, 0x2C, 0x01, 0x32, 0x3C, 0x00, 0x00,
                      0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00,
                      0x00, 0x00, 0x00, 0x00};
calculateUBXChecksum(CFG_NAV5, (sizeof(CFG_NAV5)/sizeof(uint8_t)));

while (!success)
{
  sendUBX(CFG_NAV5, (sizeof(CFG_NAV5)/sizeof(uint8_t)));
  success = getUBX_ACK(CFG_NAV5);
}
success = 0;
```

Figure 4.23: Setting MAX-6 Dynamic Platform Model to Pedestrian in an Arduino sketch.

4.4.2 OpenSim Region Module

One of the extensions that the OpenSim server provides over the Second Life server that it emulates, is extensibility via Region Modules.

> *"Region modules are .net/mono DLLs. During initialization of the simulator, the OpenSimulator bin directory (bin/) and the scriptengines (bin/ScriptEngines) directory are scanned for DLLs, in an attempt to load region modules stored there. Region modules execute within the heart of the simulator and have access to all its facilities. Typically, region modules register for a number of events, e.g. chat messages, user logins, texture transfers, and take what ever steps are appropriate for the purposes of the module."*[20]

Region modules allow for more complex & powerful extensions, written in C#, to be developed external to the OpenSim platform than would otherwise be possible via Second Life's internal Linden Scripting Language (LSL). Similar to how the Second Life client's joystick interface represented an opportunity to implement the orientation control of VTW without relying upon a bespoke, modified client, an OpenSim Region Module represents the possibility to implement the position control required by VTW without relying upon a similarly bespoke client.

An excerpt from the implementation of the position control required by VTW is included as 4.24 (full Region Module code available online[21]). This shows the use of haversine, implemented using the `atan2()` function, calculating the displacement in real world latitude between the anchor point & the new GPS reading (lines 5-8), applying the scale of the reconstruction to this displacement (lines 10-14) & then applying this scaled displacement to the virtual world Y coordinate of the anchor (lines 16-24). This process is then repeated for the longitude/X coordinate & the avatar can then be moved to the position within the OpenSim reconstruction that is equivalent to the user's new real world position.

4.5 Modifying Second Life for Orientation & Position Control

Due to the Second Life client's existing control interfaces not allowing enough control over camera orientation for VTW's requirements (section 4.3.1), it was necessary to modify the client's codebase to produce a bespoke client allowing complete control over orientation by magnetometer & accelerometer input. Although sufficient

[20] http://opensimulator.org/wiki/IRegionModule
[21] https://bitbucket.org/cj_davies/sharedregionmodulegpsavatar

```
private Vector3 LatitudeLongitudeToRegionCoordinate(double newLat, double
    newLong, double anchorLat, double anchorLong, Vector3 anchorVector, double
     scale) {

    double d, a, c, X, Y;

    //calculate the difference in y (latitude) between the anchor & the new
        reading
    d = Math.Abs(ToRadians(newLat - anchorLat));
    a = Math.Sin(d / 2) * Math.Sin(d / 2);
    c = 2 * Math.Atan2(Math.Sqrt(a), Math.Sqrt(1 - a));

    //mean radius of the Earth is 6371km (6371000m)
    d = 6371000 * c;

    //apply scale
    d *= scale;

    //sum appropriately from the anchor
    if (newLat > anchorLat) {
        mlog.DebugFormat("[GPSAvatarModule]:
            LatitudeLongitudeToRegionCoordinate() - (Y) newLat > anchorLat.");
        Y = (anchorVector.Y + d);
    }
    else {
        mlog.DebugFormat("[GPSAvatarModule]:
            LatitudeLongitudeToRegionCoordinate() - (Y) newLat < anchorLat.");
        Y = (anchorVector.Y - d);
    }
```

Figure 4.24: Excerpt of OpenSim Region Module for avatar movement via GPS.

position control could be achieved via an OpenSim region module (section 4.4.2) it was prudent to also encapsulate position control through the modified client; not only does this allow for finer grain control, it also removes the dependency upon the virtual reconstruction being hosted upon an OpenSim server (Second Life's own servers do not support extension via Region Modules). Thus, the Second Life client was modified with the addition of the ability to;

- connect to a serial device for I/O,
- control movement of the avatar according to input from this serial device,
- control the camera according to input from this serial device.

4.5.1 Overview of Second Life Client Modifications

The Second Life client is written predominantly in C++ so the Asio library[22] from the popular Boost project[23] is used to imbue it with serial connectivity, allowing it to receive messages from the Arduino in an asynchronous non-blocking fashion. The fundamental buffered asynchronous serial handling is implemented

[22] http://www.boost.org/doc/libs/1_57_0/doc/html/boost_asio.html
[23] http://www.boost.org/

using Terraneo Federico's `AsyncSerial` class[24] which is included in the client codebase as `/indra/newview/AsyncSerial`. The majority of the functionality added to the client is then contained within `/indra/newview/LLViewerSerialMovement`. The core executable of the viewer, `/indra/newview/LLAppViewer` obtains an instance of `LLViewerSerialMovement` & then calls `LLViewerSerialMovement::update()` upon each iteration of the client's main update loop, `LLAppViewer::mainLoop()`. These modifications are visualised by figure 4.25.

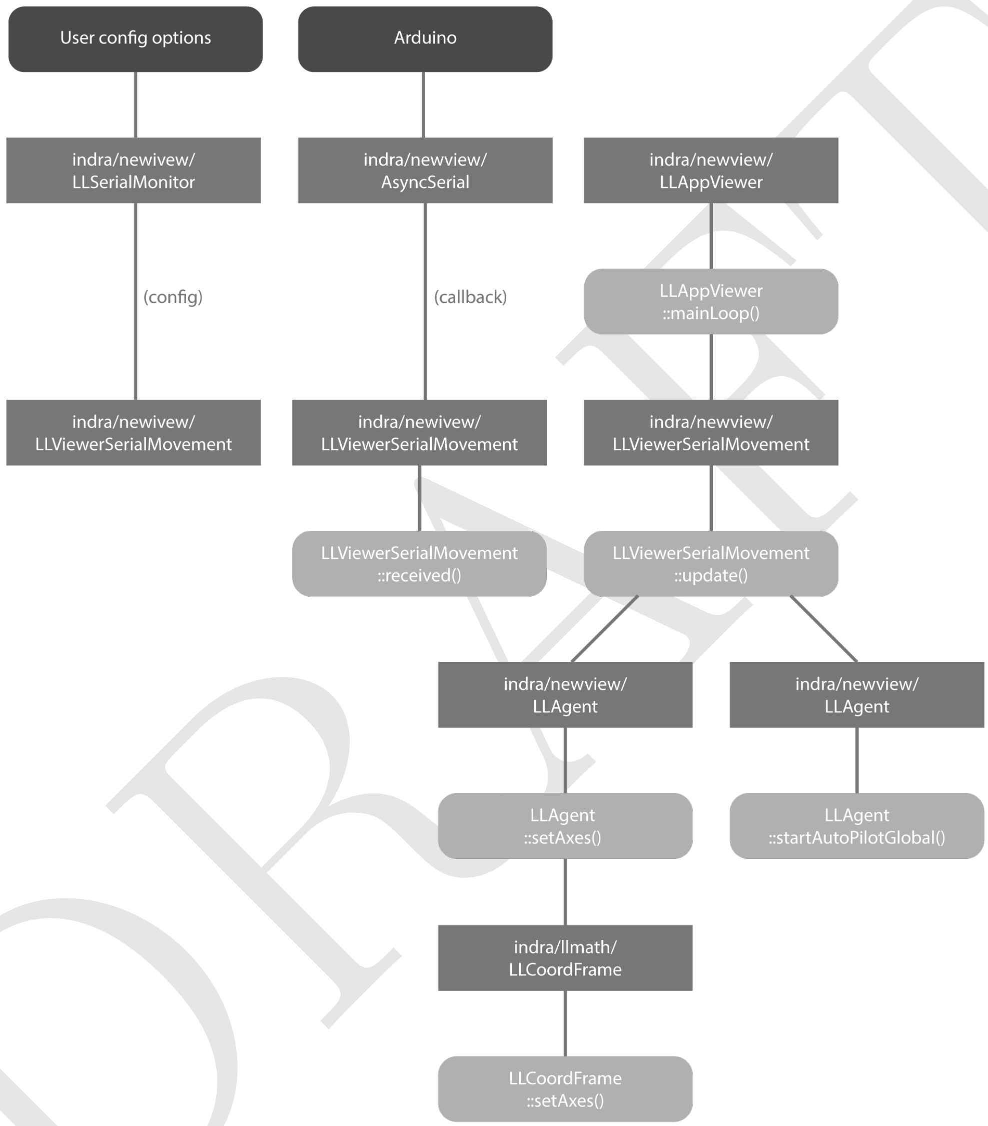


Figure 4.25: Overview of modifications to Second Life client.

4.5.2 `LLViewerSerialMovement` reference

Brief documentation of the functions in `/indra/newview/LLViewerSerialMovement` follows.

[24] `http://www.webalice.it/fede.tft/serial_port/serial_port.html`

`::connect`	Safely connects to a serial device (if not already connected).
`::disconnect`	Safely disconnects from a serial device (if already connected).
`::received`	A callback method registered to the `CallbackAsyncSerial` class in `/indra/newview/AsyncSerial`. This function parses the data (`const char *data`) from the serial device, extracting complete messages to the variable `mostRecentMessage`. Because of the nature of the serial I/O, `*data` is not guaranteed to contain a discrete message from the Arduino containing both orientation & position data, thus this function must parse the array & assemble discrete messages from possibly multiple subsequent callbacks.
`::update`	Called upon each iteration of `LLAppViwer::mainLoop()` & further calls `::updateFromMostRecentMessage()`, `::updateOrientation()` & `::updatePosition()`.
`::updateFromMostRecent-Message`	Processes a complete message from the Arduino which has been assembled by `::received()` & extracts the constituent orientation & position values.
`::updateOrientation`	Applies the orientation values extracted from an Arduino message to the avatar's camera. This is achieved by a call to `LLAgent::setAxes()` which calls `LLCoordFrame::setAxes()` in `/indra/llmath/LLCoordFrame`. The orientation values are passed as a quaternion, converting the bearing, pitch & roll values extracted from the Arduino message as degrees using `::quaternionFromDegrees()`.
`::updatePosition`	Applies the position data extracted from an Arduino message to the avatar, using `LLAgent::startAutoPilotGlobal()` to perform smooth movement between the avatar's current position (obtained with `LLAgent::getPositionGlobal()`) & the new position from the Arduino (converted from latitude & longitude to Second Life region coordinates in `::latitudeLongitudeToRegionCoordinates()`).
`::quaternionFromDegrees`	A helper method to convert bearing, pitch & roll expressed in degrees, into a single quaternion. Quaternions are frequently used to represent rotations in 3D applications, as they do not suffer from gimbal lock - Second Life is no exception to this & internally uses quaternions for all rotation data, providing `/indra/llmath/LLQuaternion` for this purpose.
`::latitudeLongitudeTo-RegionCoordinate`	Converts a real world position, expressed as a longitude & latitude pair, to the equivalent Second Life coordinates, applying the haversine formula using knowledge of the real world & corresponding Second Life position of the anchor point & the scale of the Second Life reconstruction compared to the real world.
`::degreesToRadians`	A helper method to convert values expressed in degrees to the equivalent value expressed in radians (implementations of the haversine formula usually make use of radians).

Controlling the avatar's position according to latitude & longitude readings from the GPS receiver is once again implemented using the haversine formula. This implementation, included as figure 4.27 can be compared to the OpenSim region module version included previously as figure 4.24. One important difference between the Second Life client implementation & the OpenSim region module implementation is that the former uses global coordinates, rather than local coordinates[25]. This means that the Second Life client implementation allows positional control of an avatar across region boundaries, crucial for use with a cultural heritage reconstruction that spans multiple regions in an OpenSim 'megaregion'[26] such as that used for testing of VTW.

These modifications to the Second Life client are configured/controlled via a window added to the client & accessed via a menu entry (see figure 4.26). The implementation of this resides in `/indra/newview/LLViewerSerialMonitor`. This allows for specification of the path to the serial device, along with its baudrate, as well as the specification of the anchor point - the latitude & longitude of the point in the real world & the equivalent X/Y coordinates in the Second Life reconstruction. The window then provides diagnostic output showing the messages coming in from the serial device, along with controls to individually enable/disable orientation & position control & alter the high-pass & smoothing applied to both controls.

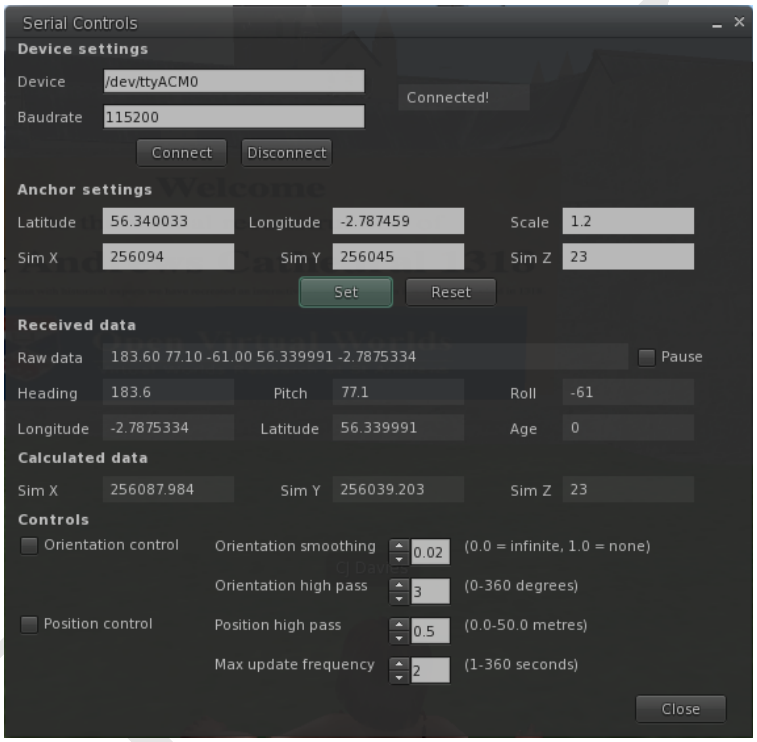


Figure 4.26: Config pane in modified Second Life client for HMC6343 + MAX-6.

[25] This is not due to any limitation on the part of OpenSim, but simply due to the Second Life client modifications being pursued further than the OpenSim module.

[26] `http://opensimulator.org/wiki/Setting_Up_Mega-Regions`

```
boost::tuple<float, float, float> LLViewerSerialMovement::latitudeLongitudeToRegionCoordinate(double newLat, double newLong, float anchorLat, float anchorLong, float scale, boost::tuple<float, float, float> anchorCoordinates) {

    double d, a, c, X, Y;

    // calculate difference in y (latitude) between anchor & new reading
    d = fabs(degreesToRadians(newLat - anchorLat));
    a = sin(d / 2) * sin(d / 2);
    c = 2 * atan2(sqrt(a), sqrt(1 - a));

    // mean radius of the Earth is 6371km (6371000m)
    d = 6371000 * c;

    // apply scale
    d *= scale;

    // sum appropriately from the anchor
    if (newLat > anchorLat) {
        Y = (anchorCoordinates.get<1>() + d);
    }
    else {
        Y = (anchorCoordinates.get<1>() - d);
    }

    // calculate difference in x (longitude) between anchor & new reading
    d = fabs(degreesToRadians((newLong - anchorLong)));
    a = sin(d / 2) * sin(d / 2) * cos(degreesToRadians(newLat)) * cos(degreesToRadians(anchorLat));
    c = 2 * atan2(sqrt(a), sqrt(1 - a));

    d = 6371000 * c;

    // apply scale
    d *= scale;

    // sum appropriately from anchor
    if (newLong > anchorLong) {
        X = (anchorCoordinates.get<0>() + d);
    }
    else {
        X = (anchorCoordinates.get<0>() - d);
    }

    return boost::make_tuple(X, Y, anchorCoordinates.get<2>());
}
```

Figure 4.27: Converting longitude & latitude to Second Life coordinates using haversine.

4.6 VTW in Use

The backdrop for real world experimentation with the VTW platform was the impressive ruins of St Andrews cathedral.

Figure 4.28: St Andrews Cathedral recreation set on the sunny St Andrews day afternoon 1318, showing the West Gate in the foreground & ships in the background.

St Andrews Cathedral occupies a site used for worship since the 8th Century AD. Work on the Cathedral began around 1160 and was completed nearly 150 years later (the west façade and parts of the nave collapsed in a storm around 1270). It was finally consecrated in 1318 four years after the battle of Bannockburn and in the presence of King Robert I of Scotland. St Andrews Cathedral was in its prime, the centre of Scotlands religious life, its largest and most magnificent church. In 1378 the Cathedral suffered a significant fire prompting a reworking of many of its features including the West and East End windows. Its presence was the catalyst for the foundation of a university at St Andrews in the early fifteenth century [76], which remains an important seat of learning to this day. In 1561 following the Scottish reformation the Cathedral was abandoned by the Bishops and replaced by the parish church as the chief place of worship. The former headquarters of the Scottish Church was left to fall into ruin, with much of its stone being used in the construction of town dwellings.

During its time the Cathedral was central to Scottish personalities and history. St Andrews was the highest ranking Scottish see. The establishment of Augustinian Cannons followed by the initiation of building work by Bishop Ernald reflected integration with the European church, economic dynamism and decline of the Celtic Church. The diocese funded Robert Bruce during the Wars of Independence. Its Bishop William de Lamberton contributed to the formulation of the Declaration of Arbroath, a central document in the formation of Scottish Nationhood. Isabella, sister of Donnchadh IV, last Pictish Earl of Fife, crowned Bruce King. John Knox personally lead his congregation against the Cathedrals finery and following the murder of Cardinal Beaton the first Scottish protestant congregation was established in the Bishops palace.

Important fragments of the remain. The east gable of the presbytery, where the relics of St Andrew were purported to be kept, along with the south wall of the nave, and the majestic West Entrance all point to the Cathedrals former majesty. The cloister retains its ruined chapter house and stone-vaulted under crofts. Consequently, much evidence of the Cathedrals form exists. A view from the nave looking towards the choir in figure 4.29.

The OVW Group's reconstruction of St Andrews cathedral, as shown in figures 4.28 & 4.30, represents the site as it stood in 1318, the year of its consecration. This virtual reconstruction, presenting a historically accurate model of the cathedral as it stood at the peak of its former glory, is very large at over 400m by 600m & spanning multiple storeys, featuring the cloisters as well as the Cannons' living quarters.

Figure 4.29: St Andrews cathedral today.

Figure 4.30: St Andrews cathedral reconstruction.

4.6.1 Experimental Implementation

*****Go through Arduino sketch & talk about things like magnetic declination, etc.**

For the purposes of testing VTW at the cathedral, a temporary server & network setup was effected using a Lenovo ThinkPad X61s[27] laptop computer to host the OpenSim server with a Linksys WRT54G[28] wireless router powered from a 12V sealed lead-acid battery to provide wireless communication between the OpenSim server & the WindPad over a much larger range than the laptop's internal wireless interface could provide. This setup is shown in use at the cathedral by figure 4.31, the architecture of this experimental implementation is shown by figure 4.33 & figure 4.32 shows VTW in use at the cathedral.

Figure 4.31: OpenSim Server & wireless AP.

Figure 4.32: VTW at the cathedral.

4.6.2 Real World Performance of VTW

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"*[29]. 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

[27] `http://support.lenovo.com/us/en/documents/pd012148`

[28] `http://support.linksys.com/en-eu/support/routers/WRT54G`

[29] `https://u-blox.com/images/downloads/Product_Docs/MAX-6_ProductSummary_(GPS.G6-HW-10089).pdf`

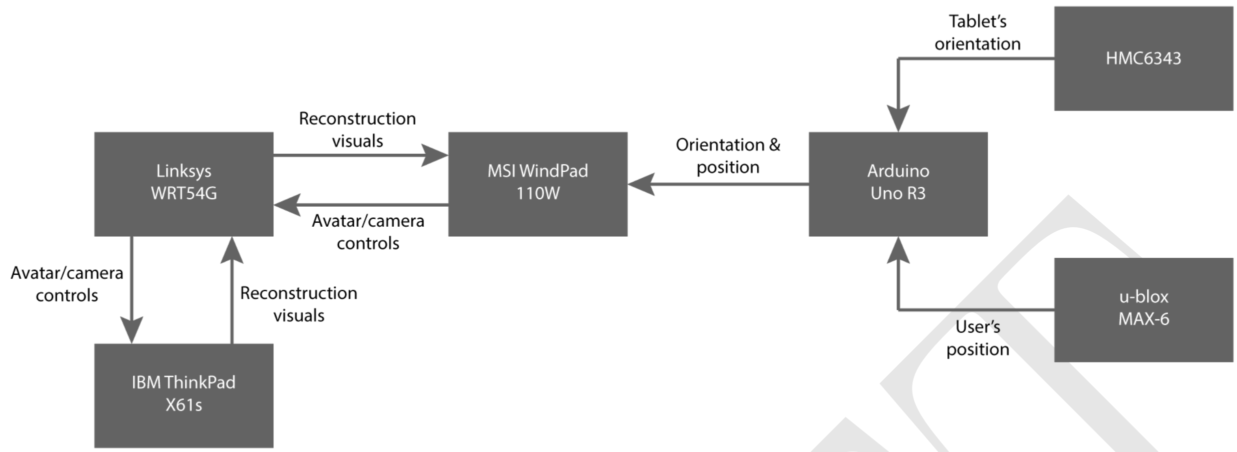


Figure 4.33: Implementation of VTW.

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.

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 NMEA messages into the u-center[30] 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[31] containing a gpsOne Gen 8A solution within its Qualcomm Snapdragon S4 processor[32] and using Google's My Tracks[33] 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 and the PostGIS database extender's `ST_HausdorffDistance` algorithm[34] 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.

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 4.34 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.

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

[30] `https://u-blox.com/en/evaluation-tools-a-software/u-center/u-center.html`
[31] `http://www.htc.com/uk/smartphones/htc-one-s/`
[32] `https://www.qualcomm.com/products/snapdragon/processors/s4-s1`
[33] `https://play.google.com/store/apps/details?id=com.google.android.maps.mytracks&hl=en`
[34] `http://postgis.net/docs/ST_HausdorffDistance.html`

Figure 4.34: 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.

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 (as can be seen in figure 4.29) 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 4.35, 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).

When analyzing the tracks in the vicinity of the nave (see figure 4.36) 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.

VTW's camera control from orientation data does not have as stringent performance criteria as the movement control from position data. Unlike AR applications 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

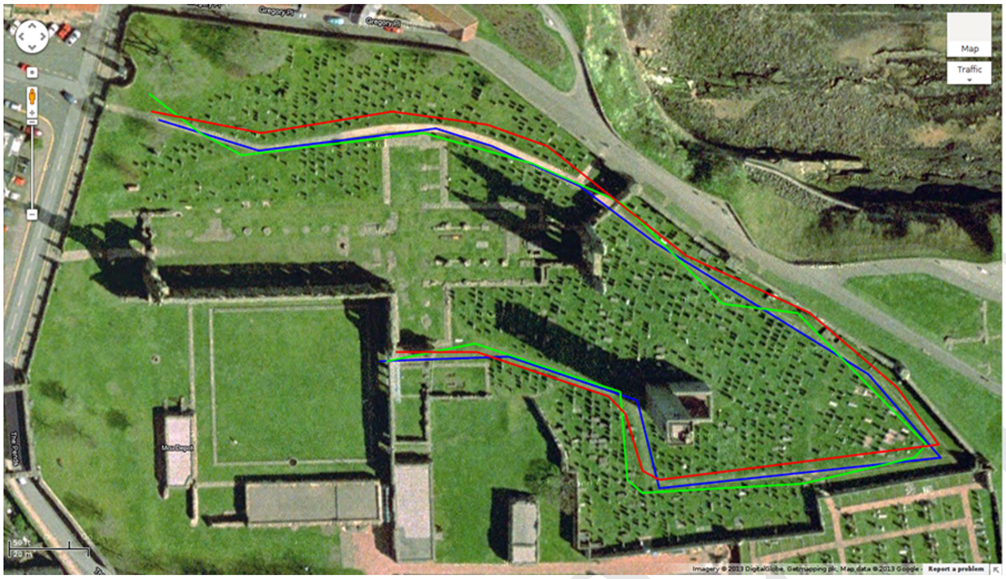


Figure 4.35: Aerial view oriented North upward of the St Andrews cathedral ruins; the blue line represents the first sub-route of the planned route, red the sub-route recorded by the MAX-6 and green the sub-route recorded by the smartphone whilst walking the first planned sub-route.

to work well, PR 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 VTW whilst navigating the route averaged between 15 and 20 frames per second with the Second Life client'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 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 VTW. Performance of VTW on a less graphically complex OpenSim region 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'.

4.6.3 Performance Implications

*****Talk about static modality being too similar to existing XR projects (& mobile modality needs better positional tracking). Also mention how tablet isn't immersive enough & HMD (with better trackig) is the next plausible step (eg next chapter!)?**

The positional accuracy of $1.02e^{-04\circ}$ attained by the MAX-6 is not sufficient for the style of interaction that VTW envisaged. This value, analogous to a combination of $\pm$11.3m of North/South inaccuracy or $\pm$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

Figure 4.36: 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.

value is too large to differentiate between, for example, two sides of a wall & is likely to situate a user's virtual presence on the opposite side of a wall to their real presence, especially when that wall still exists in the real world to interfere with GPS reception, ruining the effect of being able to switch between real & virtual stimuli. After experiencing VTW with, at times, theoretically as low as 2m CEP, an accuracy of around 1m CEP (analogous to $8.98e^{-06\circ}$ latitude or $1.62e^{-05\circ}$ longitude around the location of the St Andrews cathedral) is envisaged as the minimum for successful implementation of the VTW concept.

The accuracy of orientation tracking does not change with different positional accuracy and the accuracy attained in the experiments was sufficient for an acceptable user experience, however the experience would benefit greatly from better graphical quality and higher responsiveness to changes in user orientation. The immersiveness of a hand held tablet is also rather poor, which does not fit well with one of the major proposed benefits of the PR concept - the ability to produce immersive, atmospheric virtual visuals (especially when compared to paradigms such as AR which have established hand held implementations).

4.7 Conclusions

This chapter has introduced virtual heritage as a field in which the successful application of alternate reality techniques has a proven history & to which the application of PR promises to be of further benefit. The Virtual Time Window project was introduced as an initial foray into the realm of applying PR to virtual heritage, making use of an x86 tablet computer imbued with position & orientation sensing via GPS & combined accelerometer/magnetometer, for PR exploration of outdoor cultural heritage sites & their virtual reconstructions hosted upon an OpenSim framework. An implementation of this platform is presented, however real world experimentation revealed that the accuracy of positional tracking obtainable, even by discrete GPS receivers that outperform those mainstream receivers found in smartphones, is not sufficient for the envisaged style of interaction. Furthermore, the ability of a complete virtual environment presented on a small hand held display to provide a greater sense of immersion in a complete, atmospheric virtual environment was found to be lacking & thus the pursuit of this modality of PR interaction was not continued.

5

Mirrorshades - Development

> *"A vacant-eyed clerk glanced up at me ... He was wearing a bifocal visor, which gave him a semitransparent view of the OASIS while also allowing him to see his real-world surroundings."*
>
> *Ready Player One, Ernest Cline*

This chapter discusses the design & development of a hardware & software platform which allows its user to observe & move around their Real World (RW) environment whilst wearing a wide field of view (FOV), stereoscopic 3D, Head Mounted Display (HMD) which allows them to alternatively view an immersive Virtual Reality (VR) environment from the equivalent vantage point. This is achieved by combining a head-tracked HMD, webcams, an indoor positioning system (IPS) & a 3D game engine, into a mobile PR interface. This project addresses the shortcomings identified in the VTW platform, by using more accurate position tracking, faster & more responsive orientation tracking & a more immersive virtual display.

5.1 Learning from VTW

The development of the VTW platform as a first foray into applying the concept of PR to the field of virtual heritage was met with concerns, in terms of both quantitative performance & qualitative experience. Firstly & most critically, the accuracy of position tracking attainable by using a GPS receiver, even one of higher specification & real world performance than those commonly found in smartphones, was not sufficient for the envisaged style of interaction. Secondly, the ability of a hand held display (the tablet) to provide immersive 3D graphics of a complete, atmospheric reconstruction was limited. Moving forward from VTW, a new project was embarked upon to address these concerns with aims to greatly improve the experience of PR in a virtual heritage scenario.

In contrast to VTW, which was intended for outdoor use upon cultural heritage sites where either no remnants or only parts of original structures still stand, the successive platform is intended for use indoors. This not only allows the investigation of the application of PR to cultural heritage to be expanded to indoor scenarios, for sites where more of a historic structure still stands, but also allows for the use of an indoor positioning system, many of which offer substantially more accurate proven real world accuracy than GPS does for outdoor positioning.

Furthermore, in place of a hand held display such as the tablet used by VTW, the successive platform makes use of a head mounted display offering stereoscopic 3D graphics over a wide field of view, that promises much greater immersion, with a head tracking solution that substantially outperforms the orientation tracking employed by VTW both in terms of accuracy & responsiveness.

5.1.1 The Mirrorshades Platform

Figure 5.1 presents a high level architectural overview of the successive PR platform, dubbed Mirrorshades[1]. This is a hardware & software platform which allows its user to observe & move around their Real World (RW) environment whilst wearing a wide field of view (FOV), stereoscopic 3D, Head Mounted Display (HMD) which allows them to alternatively view an immersive Virtual Reality (VR) environment from the equivalent vantage point.

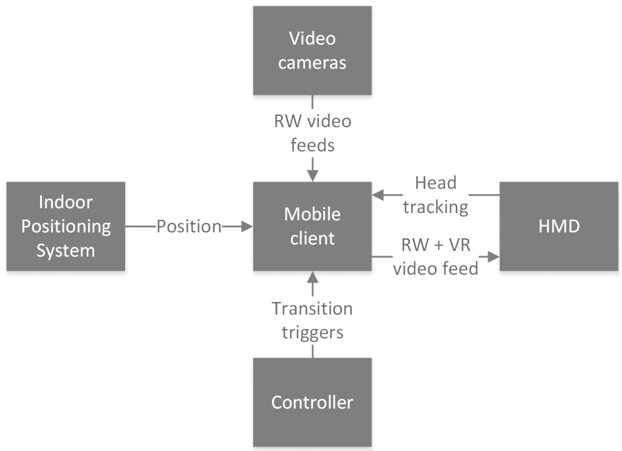


Figure 5.1: Overview of the Mirrorshades platform.

The HMD is imbued with video see-through functionality by the addition of cameras, to allow the user to see their RW environment. A controller held by the user allows them to trigger their view to switch between RW & VR. The users' location within the cultural heritage site is tracked using an Indoor Positioning System (IPS). The mobile client that produces the graphical content delivered to the HMD can either be carried about the person (perhaps as a belt pack, or worn in a bag/satchel) or possibly be streamed from a powerful static computer to a lightweight mobile receiver carried about the person.

*****I think there needs to be some more explanation/diagram/picture of the system here before I start talking about the specifics of the implementation?**

5.1.2 St Salvator's Chapel

The stage upon which the Mirrorshades platform was designed & developed to perform upon was St Salvator's chapel in St Andrews. Founded in 1450 but internally stripped of its medieval fittings during the Protestant Reformation (1517 - 1648), the chapel 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 the Mirrorshades PR system to be deployed.

This reconstruction project has virtually recreated St Salvators chapel as it was built and furnished for Bishop James Kennedy between 1450 & 1460. The chapel was of the greatest significance for the new architectural ideas that it introduced into Scotland, at a time when Scotland was particularly open to external artistic influences. However, although the shell of the chapel survives and remains in use, it has lost its vault,

[1]**Mirrorshades: The Cyberpunk Anthology** (1986) is a defining cyberpunk short story collection, edited by Bruce Sterling. Mirrored sunglasses are a symbol considered synonymous of cyberpunk, a genre whose fiction has frequently involved immersive multi-user virtual environments & head mounted displays.

Figure 5.2: St Salvator's chapel, present day.

Figure 5.3: St Salvator's chapel, reconstruction.

its window tracery and its liturgical furnishings, and it now requires specialist skills to appreciate the quality of its original state. As with other reconstructions from the OVW group, the virtual St Salvator's chapel is a product of a collaboration between architectural & art history & computer science scholarship. On the combined evidence of a highly detailed late medieval inventory and of the architecture itself, it has been possible to show how the chapel was furnished internally with altars, choir stalls, lecterns, screens, stained glass and wall paintings. The virtual chapel is enhanced with lighting, sound and movement may be explored from a variety of physical and temporal locations through an avatar. The architectural, liturgical and spatial analysis allows our understanding of the history of the Chapel as a living building to be enormously enhanced by experiencing the building in its original context.

Figure 5.4: Looking towards the altar, present day.

Figure 5.5: Looking towards the altar, reconstruction.

St Salvator's college was founded on 27 August 1450 by Bishop James Kennedy, who played a leading role in Scottish & international politics. St Salvators was to be open to students who were prepared to live within the college. In this, St Salvators was the first college in Scotland to place the education of students so firmly at the heart of its role. It was dedicated for worship in 1460. The chapel is an aisle-less rectangle with a three-sided east apse. Deeply projecting three-stage buttresses define the bays, which are now capped by pinnacles of 18612. The windows which occupy the full space available between the buttresses, no longer reflect their original forms. The main entrance to the chapel was through a doorway in the second bay from the west of the south flank, which is covered by a vaulted porch between the buttresses. Two doorways on the north side presumably opened into a lost sacristy and treasury range.

The interior of the chapel is known to have been covered by a stone vault, which is assumed to have been of pointed barrel form with a decorative pattern of ribs, like the small vault over the south porch. The interior is now covered by an inappropriate timber roof.

St Salvators chapel is considered the first Scottish example of a church planned with an aisle-less rect-

Figure 5.6: Looking from the altar, present day.

Figure 5.7: Looking from the altar, reconstruction.

angular main body terminating in a polygonal eastern apse, a type that was to have a long future for a range of Scottish church types. Such chapels were common in university colleges in France & since Bishop Kennedy had a highly placed kinsman in the university of Paris and drew many ideas for the organisation of his college from that universitys constitution, it is reasonable to assume that he also drew some of his ideas for the architecture of his chapel from there. On this basis, St Salvators must be seen as an outstandingly important channel for the introduction into Scotland of new architectural ideas from France. The new architecture made a significant statement in its Scottish context.

The reconstruction of the chapel involved both the mental reconstruction of modified and lost features, and the establishment of the range of ways in which buildings that represent a spirituality alien to modern students were intended to function. As such it offers an invaluable academic discipline for those involved in the reconstruction, providing eminently practical ways of testing theories and assumptions. It is then of the greatest value for conveying more widely the understanding that has been gained. The development of a PR system which enables comparison between the real and virtual chapel in the same time and place aims to further enhance the value of the reconstruction.

5.2 Virtual Reality Head Mounted Displays

The concept of virtual reality & the associated head mounted displays that provide wide field of view, stereoscopic 3D graphics coupled with head tracking is currently experiencing a resurgence of interest & investment, thanks largely to the advent of Oculus & their Rift platform. Whilst the first head mounted computer display was created in the late 1960s by Ivan Sutherland [1], it was not until the late 1980s & early 1990s that VR began to be pushed to the consumer. Unfortunately, both the hardware & software was not ready for consumer adoption at this time & these systems failed to live up to the substantial hype of being a *"revolutionary technology"* which *"promises to transform society"* (see figure 5.8), resulting in the VR bubble bursting.

Decades after this initial disappointment with consumer VR, Oculus now looks set to finally begin realising a successful consumer VR platform, thanks largely to the substantial advances in display technologies made during the past decade driven by the explosive popularity of smartphones & tablets. Pre-Oculus HMDs predominantly made use of two separate microdisplays, one for each eye; Sutherland's original 'Sword of Damocles' made use of two tiny CRT screens, whilst later HMDs made use of two OLED microdisplays. As the number of market applications for microdisplay technology was (& continues to be) relatively small, there are limited models to chose from & they command high prices when considering integration into a consumer device.

Oculus have taken a different approach for their Rift HMD. Instead of using two small displays, one for each eye, it uses a single larger display upon which two separate images are rendered, side-by-side. This approach has two distinct advantages compared to prior dual display techniques. Firstly, the complexity of the device is reduced, which effects both price, integration & content development. Secondly, the cost

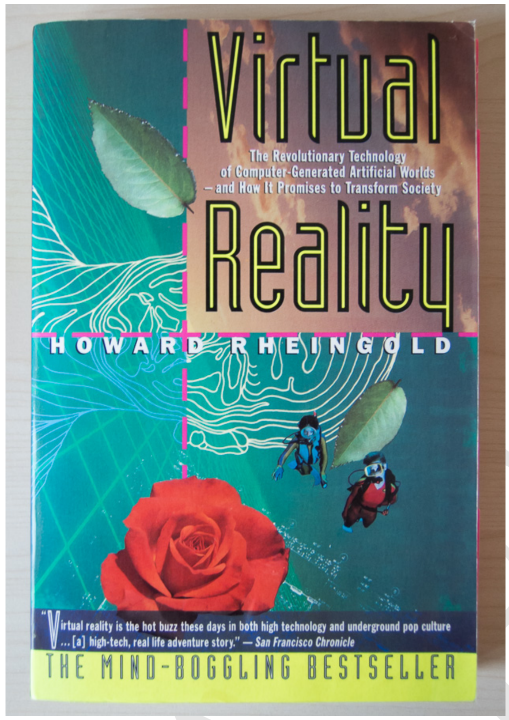


Figure 5.8: Howard Rheingold's 1992 bestseller *Virtual Reality* [1].

of a single display in the 5"-7" range is drastically lower than the cost of a pair of microdisplays, thanks to the surging popularity of smartphones & tablet computers. By making use of readily available displays intended for smartphone/tablet manufacturers, Oculus were able to bring their first Development Kit (DK1) to market for researchers & enthusiasts at a price of only $300, but still providing substantially wider FOV than the vast majority of existing HMDs (even those with vastly higher price points).

For comparison, examples of consumer-grade commercial HMDs that use the twin OLED microdisplay approach, the Sony HMZ-T1, which launched with a price of ¥60,000 ($800 at exchange rates of the time) & its successor the HMZ-T2 which launched with a price of ¥70,000 ($900 at exchange rates of the time), provide 45 horizontal FOV/51.6 diagonal & no head tracking (intended primarily as a personal 3D cinema experience), whilst Oculus' DK1 provides more than 90 horizontal & 110 diagonal FOV. Furthermore, the DK1 integrates a head tracking solution operating at a rate of 1kHz & providing best in class accuracy. Combined with advances in both hardware & software tasked with producing 3D graphics, the user experience of Oculus' HMD offerings is promising to finally deliver on the promises of 30 years previous.

The March 2014 acquisition of Oculus by Facebook[2] for $2 billion[3] & Oculus partnership with Samsung, one of the world's leading display manufacturers, which has already led to the release of an innovative VR HMD that makes use of an existing smartphone as its display[4], lends hope that this wave of VR hype won't suffer the fate of its 90's cousin.

*****Maybe talk about what other HMDs there were actually available to me on the market? Vuzix 1200/900/whatever?**

[2] `https://www.facebook.com/zuck/posts/10101319050523971`
[3] `http://www.theguardian.com/technology/2014/jul/22/facebook-oculus-rift-acquisition-virtual-reality`
[4] `https://www.oculus.com/gear-vr/`

5.2.1 The Oculus Rift DK1 & Unity Game Engine

The OVW group took delivery of an Oculus Rift DK1 from the first batch of units shipped to the EU, in August 2013. The immersive experience of using the DK1, thanks to its wide FOV, fast & accurate head tracking, stereoscopic 3D & novelty compared to traditional 2D displays, easily met the requirements of the display aspect of the Mirrorshades platform to exceed that of VTW in terms of user experience.

At this early stage in the DK1's release, the best supported software platform in terms of API provision & integration was the Unity game engine. After experience with modifying the Second Life client with the VTW project, it was decided prudent to convert the OVW group's OpenSim model of St Salvator's chapel into a Unity compatible format, rather than embarking upon further modification to the Second Life client to support the DK1.

One deciding factor in this deliberation was the more stringent performance requirements for an enjoyable HMD experience compared to those of a traditional desktop/handhend display experience; when using a HMD such as the DK1, a high & smooth framerate is required to avoid a kind of motion sickness referred to as 'simulator sickness', with Oculus' official guidelines being for Rift applications to *"run at a frame rate equal to or greater than the Rift display refresh rate"*[5] which in the case of the DK1 is 60Hz. Due to the possibly ephemeral nature of Second Life content, where users are free to create, modify & destroy content in real time, Second Life as a 3D platform suffers in terms of performance compared to game engines such as Unity due to not being able to exploit techniques such as occlusion culling [72] as these require an offline processing phase that depends upon environmental content to be static & unchanging. The OVW group's experience in presenting Second Life/OpenSim content on a range of different hardware did not point to good odds of managing to render the St Salvator's chapel scene at 60fps, especially when considering that stereoscopic rendering introduces an overhead even when the total resolution of the two side-by-side images is no greater than the single monoscopic image. As Mirrorshades is a mobile application & the computer producing the visuals may have to be worn & carried by the user, the specification of this client may also be limited compared to those that the group has used in alternative deployments.

*****Some fps graphs of Second Life/OpenSim content with different hardware?**

5.2.2 Modifying the DK1 for See Through Video

The Oculus Rift DK1 covers the user's entire view, such that they cannot see any of their real world surroundings whilst wearing it, & it does not feature any camera provision to allow a mediated view of the real world to be presented to the user. As such, it was necessary to modify the DK1 to provide such capability. When choosing cameras for this task, there were several desired ideal features;

- resolution & refresh rate that match (or exceed) those of the DK1,
- sensor aspect ratio that matches that of the DK1's display halves,
- combined lens focal length & sensor dimension to provide wide FOV (ideally matching the FOV of the DK1),
- ease of integration with the Unity platform.

The PS3 Eye camera met most of these requirements. It's resolution is only 640x480 pixels, whilst each half of the DK1's display is 640x800 pixels, however unusually for a USB camera it is capable of running at 60fps (the refresh rate of the DK1). The aspect ratio of the 640x480 sensor is 4:3, which although not identical to the 5:4 aspect ratio of each eye's 640x800 'half' of the DK1 screen is closer than the 16:10 or 16:9 aspect ratio of a 'widescreen' camera sensor. Furthermore, once dismantled to its bare PCB it features mounting holes for a standard S-mount (M12x0.5mm) lens mount commonly used for CCTV cameras, allowing alternative focal length lenses to be easily fitted.

[5] `http://static.oculus.com/sdk-downloads/documents/Oculus_Best_Practices_Guide.pdf`

A very early test with the PS3 Eye & the DK1[6] was performed by simply attaching a single unmodified PS3 Eye camera to the top of the DK1 (figure 5.9), with its stock lens set to its 'wide' setting (75°, presumably diagonal, FOV[7]). One purpose of this test was to explore the suitability of Unity's `WebCamTexture`[8] feature for integrating the stream from a USB camera into a 3D application. In this early test, the mediated RW video stream was rendered to a small 'floating' window that moved with the user's head (figure 5.10), allowing the user to view both environments at once, with the real environment in their peripheral whilst they were attending to the virtual. Whilst an interesting concept, the decision was made to instead render the mediated RW stream to the full DK1 screen so as to allow the user to better observe their real environment thanks to the larger image & higher resolution, with the small floating window likened more to the VTW approach of PR than an experience that allows true immersion in both environments. A second benefit of this switching approach is that it helps to mitigate any detrimental affect of latency in the camera image(s) not matching that of the virtual image(s).

Figure 5.9: First monoscopic see through hardware.

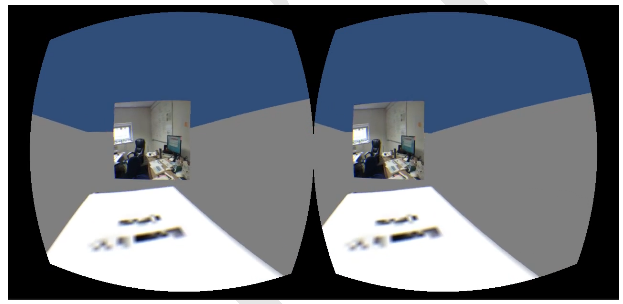


Figure 5.10: Early 'floating' window see through video.

A pair of PS3 Eye cameras were dismantled, removing their outer plastic housing & stock lenses then fitting S-mount lens mounts. Ideally, the lenses used would provide the same FOV as the Rift itself is capable of displaying, such that the mediate RW stream from the cameras could be displayed at the full size of the Rift & 'match' the FOV of whatever virtual content would alternatively be displayed. However there is a trade off with lenses between focal length & distortion; shorter focal lengths mean a wider FOV, however they also introduce more distortion which is not necessarily corrected by the shader that the Rift uses to compensate for the distortion of its own plastic lenses through which the image is viewed.

The PS3 Eye has a '1/4" type' sensor which is only an indication of its true dimensions[9] & as Sony has not published the actual dimensions of the sensor we adopt the typical 1/4" type dimensions[10] of 4.5mm diagonal, 3.6mm horizontal, 2.7mm vertical for calculating FOV estimations. Empirical accounts of very short focal length S-mount lenses mounted to the PS3 Eye camera indicated that the distortion becomes very high beneath 2.1mm[11]. Table 5.1 gives the diagonal, horizontal & vertical FOV of the widest readily available S-mount lenses.

Whilst 1.7mm lenses would provide almost identical FOV to the Rift's display (105.9° diagonal for the cameras, 110° diagonal for the Rift) the amount of distortion introduced would likely be of such an extent that the experience of viewing the mediate RW environment would be degraded more by distortion than by limited/non-matching FOV of longer focal length lenses, unless the lens' distortion was compensated in a separate stage. However, using a lens with a short enough focal length to provide a FOV as wide as the Rift isn't strictly necessary as, when wearing the Rift, the edges of the image presented to each eye are not necessarily visible to the user, especially if the Rift's adjustable distance from the eyes is adjusted such

[6] https://www.youtube.com/watch?v=tS0FGZxQzCU
[7] http://uk.playstation.com/media/247868/7010571PS3EyeWeb_GB.pdf
[8] http://docs.unity3d.com/ScriptReference/WebCamTexture.html
[9] http://www.dpreview.com/glossary/camera-system/sensor-sizes
[10] http://www.photoreview.com.au/tips/buying/unravelling-sensor-sizes
[11] http://peauproductions.com/store/index.php?main_page=index&cPath=26_4

Focal length (mm)	Diagonal FOV (°)	Horizontal FOV (°)	Vertical FOV (°)
2.5mm	84	71.5	56.7
2.1mm	93.9	81.2	65.5
2.0mm	96.7	84	68
1.9mm	99.6	86.9	70.8
1.8mm	102.7	90	73.7
1.7mm	105.9	93.3	76.9

Table 5.1: FOV of various focal lengths resolving onto a 1/4" type sensor.

that it sits at its furthest position. Such adjustment is actually prudent, as using the Rift at its maximum extension from the eyes ensures maximum compatibility & comfort with users & also removes a variable between users compared to if each user is permitted to chose the extension themselves. Thus the choice of lens can be dictated by identifying the FOV required to fill the portion of the Rift's images that are visible when the headset is extended to its maximal position, rather than by matching the Rift's overall FOV, possibly allowing the use of lenses with focal length long enough that the distortion they introduce is not bad enough to require a separate correction phase.

Experiments revealed that with the DK1 set to its maximum extension, the area of the images visible to the user was wider than that provided by 2.5mm lenses (84° diagonal) when scaled correctly & narrower than that provided by 2.1mm lenses (93.9° diagonal) when scaled correctly. Without easy availability of a lens with a focal length between 2.5mm & 2.1mm it was decided to make use of the 2.1mm lenses. Figure 5.11 shows the 2.5mm lens (right) & 2.1mm lens (left) mounted to the PS3 Eye PCBs via S-mount lens mounts, while figure 5.12 shows the FOV of the selected 2.1mm lenses scaled upon the wider FOV of the DK1's images - as previously mentioned, with the DK1 at its furthest extension, users cannot perceive the area outwith the mediated camera image.

Figure 5.11: S-mount lenses on PS3 Eye camera PCBs.

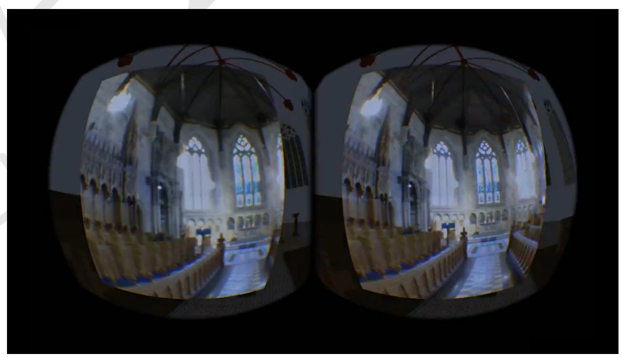


Figure 5.12: FOV comparison between DK1 & 2.1mm lenses.

The PS3 Eye cameras were mounted to the DK1 by modifying the 3D printable sensor mount design released by the University of Southern California Institute for Creative Technologies[12]. The modified mount comprised a base piece (figure 5.13) that clips securely over the front of the DK1 & a slotted plate (figure 5.14) onto which the PS3 Eye cameras are mounted. These parts were 3D printed using a MakerBot Replicator 2X[13] & then combined using epoxy resin. The combination is shown attached to the DK1 by figure 5.15. The slots in the slotted plate are spaced to match the mounting holes of the PS3 Eye PCB, such that the cameras can be attached by metal stand-offs (figure 5.16) & can then be easily moved left & right to alter

[12]http://projects.ict.usc.edu/mxr/diy/oculus-sensor-mount/

[13]http://store.makerbot.com/replicator2x

the distance between them to account for different interpupillary distances of different users. Figure 5.17 shows how one camera is mounted upside down to allow enough clearance for the PCBs to be moved close enough together to accommodate short interpuillary distances.

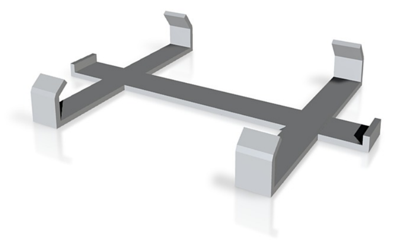


Figure 5.13: Camera mount base.

Figure 5.14: Camera mount slotted plate.

Figure 5.15: Camera mount attached to DK1.

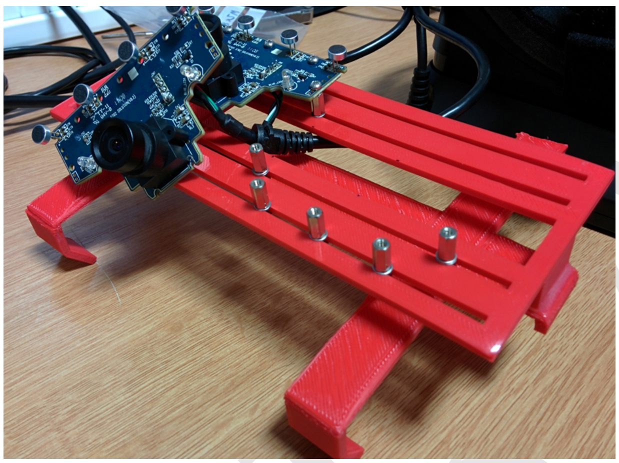


Figure 5.16: Cameras mounted using stand-offs.

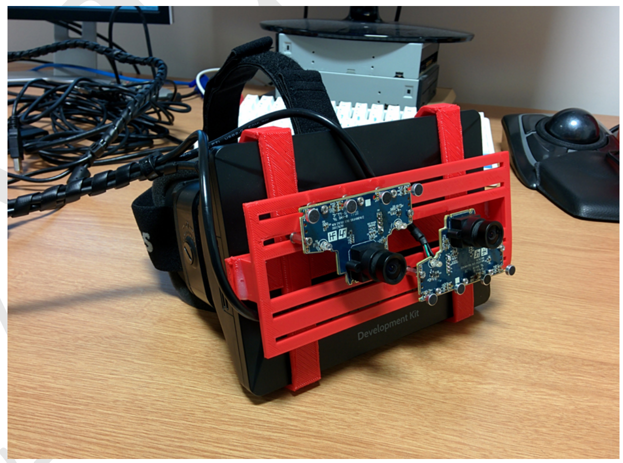


Figure 5.17: Two PS3 Eye cameras mounted on DK1.

Although the initial integration test with a single PS3 Eye camera revealed easy accessibility of the camera within Unity, using two PS3 Eye cameras proved temperamental. Unity's `WebCamTexture` support identifies webcams via their 'name' as provided by their driver. In the case of the PS3 Eye using the driver provided by Code Laboratories[14] (this third party driver must be used as no official Windows driver is available with Sony only marketing the PS3 Eye for use with their PS3 console) an issue arises where both cameras present the same name to Unity & the second camera overwrite the reference to the first, only allowing access to a single camera. Figure 5.18 shows this issue, that whilst Windows' device manager successfully identifies both cameras independently, Unity's `WebCamTexture.devices()` function returns a reference to only one (the `BisonCam, NB Pro` entry is the laptop's internal webcam). A partial solution to this issue was presented by a community provided Unity package[15], which allowed the setup up to be successfully tested within a departmental building[16].

An oversight in the design of the camera mounts was realised by when William Steptoe later released details of his 'AR Rift' project[17]. Although the DK1's overall screen has a resolution of 1280x800 in a

[14] `https://codelaboratories.com/products/eye/driver/`
[15] `http://tips.hecomi.com/entry/20130731/1375279561` (Japanese)
[16] `https://www.youtube.com/watch?v=oy5NqqDtkJ4`
[17] `http://willsteptoe.com/post/66968953089/ar-rift-part-1`

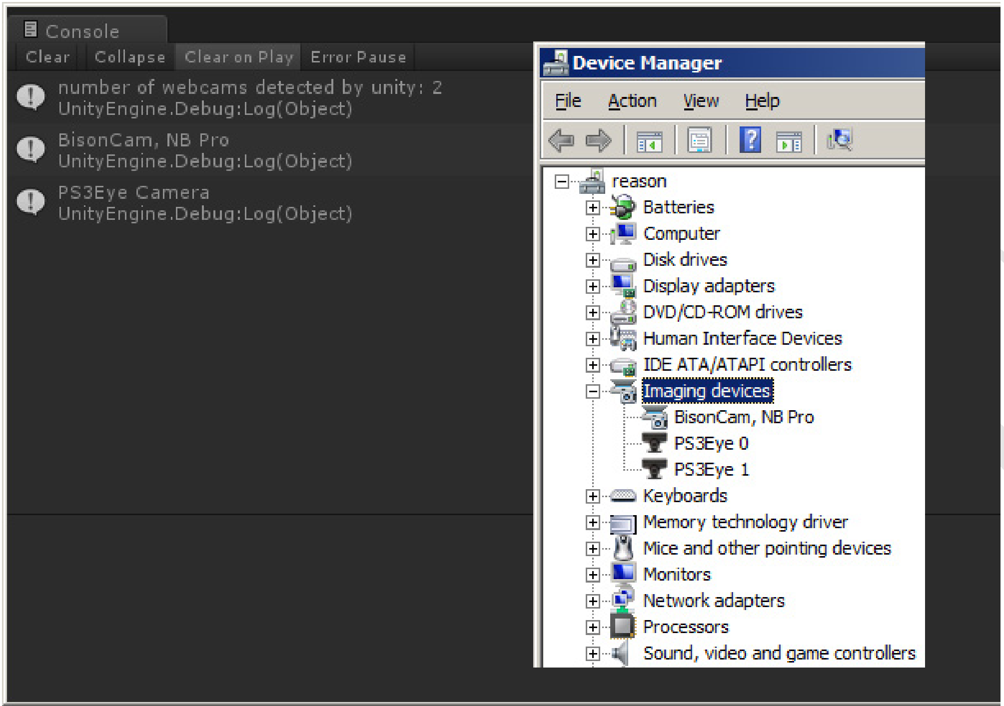


Figure 5.18: Unity failing to stat multiple PS3 Eye cameras.

'horizontal' 16:10 aspect ratio, each 'half' of this screen as presented individually to each eye has a resolution of 640x800 in a 'vertical' 4:5 aspect ratio. Thus to best match the aspect ratio of a 4:3 camera sensor, such as that of the PS3 Eye, to each half of the DK1's screen, that camera should be oriented in a portrait orientation rather than the landscape orientation employed by this project with the PS3 Eye cameras. Thus new mounting hardware was designed & printed, by further modification of the USC's original 3D designs, allowing for vertical mounting of the PS3 Eye cameras. This new design is shown in figure 5.19 (the recessed section in the centre of the clip allows for the heads of bolts to clear the front of the DK1) & the assembled units are shown attached to the DK1 in figure 5.20. Additionally soon after this point, the metal stand-offs that had been used to mount the camera PCBs to the clips (see figure 5.21) were replaced with a combination of rubber washers & threaded bolts (see figure 5.22) both to reduce the discrepancy in the mediated RW images caused by the distance between the camera sensors & the user's eyes (by reducing this distance) & to allow for finer alteration of the orientation of the cameras.

Unfortunately the PS3 Eye naming solution was temperamental at best & two camera compatibility was frequently lost. It was decided prudent to therefore replace the PS3 Eye cameras with alternatives, rather than attempting to glean a solution to their reliable compatibility with Unity. Using Steptoe's project as a guide, a pair of Logitech C310[18] cameras were sourced. Whilst the stated refresh rate of the C310 is only 30Hz, half that of the PS3 Eye, it supports a resolution of 1280x960, which is higher than that of the PS3 Eye & of each half of the DK1's display. Thus the switch from the PS3 Eye cameras to the C310 represented a sacrifice in framerate, but an increase in resolution. Empirically the increase in resolution was however indiscernible, likely due to the effect of the DK1's optics reducing the visual acuity of its display, whilst the reduction in framerate was more prominently noticeable.

The C310 cameras received the same attention as the PS3 Eye cameras; they were dismantled & outfitted with S-mount lens mounts. As the sensor in the C310 is also of the 1/4" type, the FOV provided by the 2.1mm lenses on the C310 cameras will be comparable to that of the same lenses mounted to the PS3 Eye

[18]http://www.logitech.com/en-gb/product/hd-webcam-c310

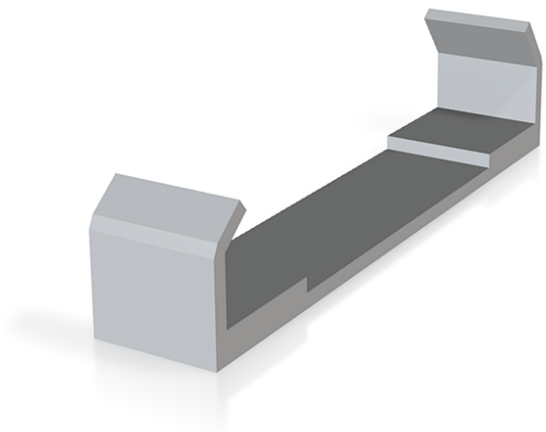


Figure 5.19: Updated camera mount.

Figure 5.20: Two PS3 Eye cameras using updated mounts.

Figure 5.21: Updated mount with stand-offs.

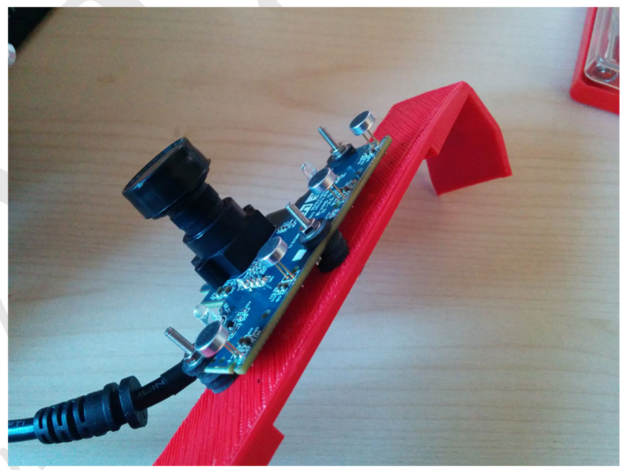


Figure 5.22: Updated mount with rubber washers.

cameras. Due to the lack of mounting holes present on the C310 PCB, the PCBs were set into a thin sheet of thermoplastic (figure 5.23) which was then attached to the 3D printed clips with the same rubber washer & threaded bolt arrangement as the PS3 Eye cameras. The assembled DK1 + dual C310 solution is shown by figures 5.24 (3/4 view), 5.25 (profile view) & 5.26 (detail view).

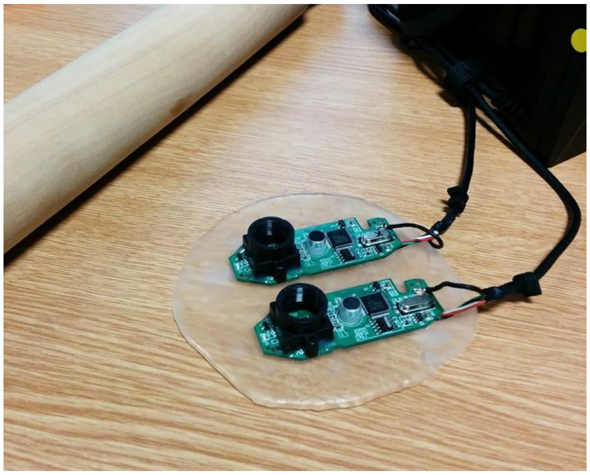


Figure 5.23: Setting C310 PCBs into thermoplastic.

Figure 5.24: Two C310 mounted to DK1 (3/4).

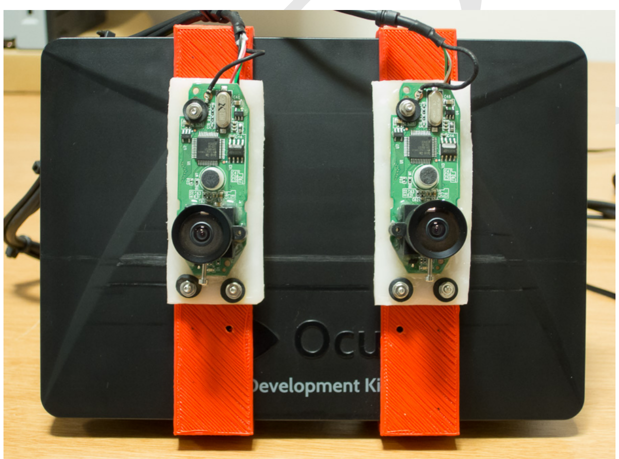


Figure 5.25: Two C310 mounted to DK1 (front).

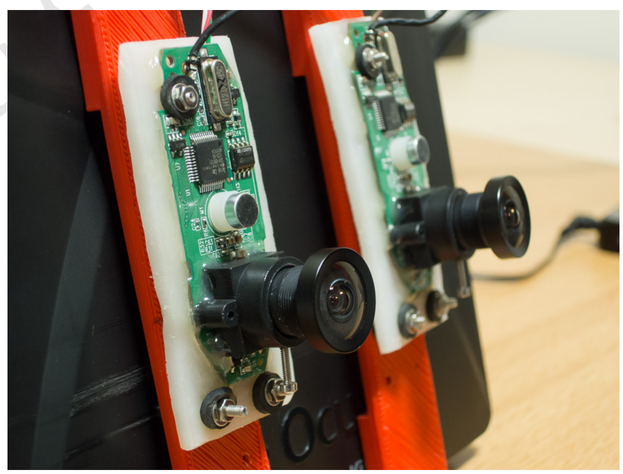


Figure 5.26: Two C310 mounted to DK1 (detail).

5.2.3 Switchable Stereoscopic See Through Video with Unity

Unity's `WebCamTexture` support was used to gain access to the C310 video streams within Unity. Due to better provisioned drivers, there was no issue with Unity obtaining references to both C310 as there had been with two PS3 Eye cameras. These video streams were applied to a pair of planes, of matching orientation & aspect ratio to the video stream, that are situated perpendicular to the two virtual cameras of the Oculus Unity prefab. This is shown by figure 5.27 in which the smaller portrait planes in the centre of the image are those onto which the camera streams are rendered.

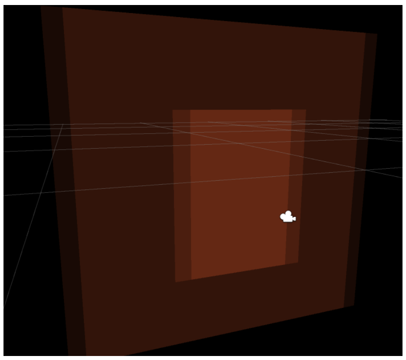


Figure 5.27: Camera & backing planes.

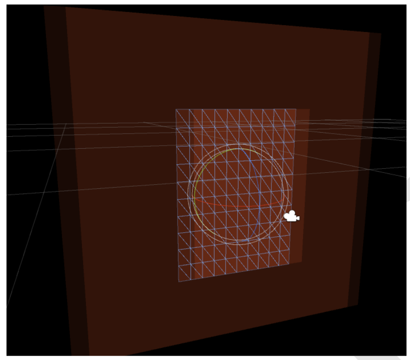


Figure 5.28: Left camera plane.

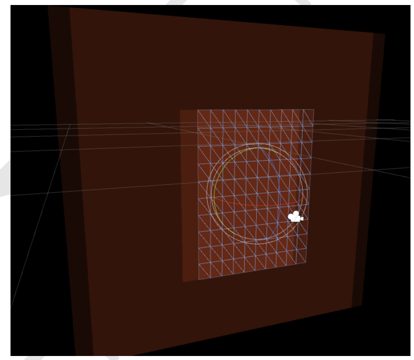


Figure 5.29: Right camera plane.

It can be seen that these planes overlap considerably as they are only horizontally spaced the same amount as the virtual cameras are spaced (see also figure 5.30), which is derived from the interpupillary distance that the user inputs to the Oculus configuration utility. By placing each of these two planes in a separate layer & setting the culling mask of the virtual cameras to cull/not-cull these layers appropriately (such that the left virtual camera culls the layer of the right plane but not the left plane & the right virtual camera culls the layer of the left plane but not the right plane) the appropriate virtual camera only sees the appropriate webcam image, even though they overlap - the left virtual camera sees only the camera plane shown by figure 5.28 while the right virtual camera sees only the camera plane shown by figure 5.29.

As the Mirrorshades platform required the user to be able to control which environment they are perceiving, either real or virtual, the visibility of these camera planes (& the virtual environment behind them) must thus be controllable. The opacity of the camera planes is therefore linked to the control mechanisms, however because the camera planes do not completely fill the DK1's FOV (see section 5.2.2 & figure 5.12) two further, larger, planes are situated behind the camera planes which cover the entire FOV of the DK1. The opacity of these planes is also linked to the control mechanisms, such that when the user operates the control mechanism in a manner to view VR, they are completely transparent to allow VR visual stimuli to pass, but when the user operates the control mechanism in a manner to see RW, they become opaque in order to prevent any RW visual stimuli from passing around the camera planes.

The arrangement of these planes in relation to the virtual cameras is shown by figure 5.31, where it can be seen that the smaller camera planes do not fill the virtual cameras' frustum due to the lower FOV of the C310 than of the DK1. Figure 5.32 shows a space between the camera planes & the backing planes, required to avoid a rendering bug that arose when the planes were placed together.

5.2.4 Latency of DK1 See Through Video Solution

Measurement of the end-to-end latency of the C310 solution was performed by placing the DK1, with the lens cups removed, in front of a LCD monitor displaying a timer[19]. In this context, end-to-end latency

[19] `http://www.flatpanels.dk/monitortest_inputlag_dk.php`

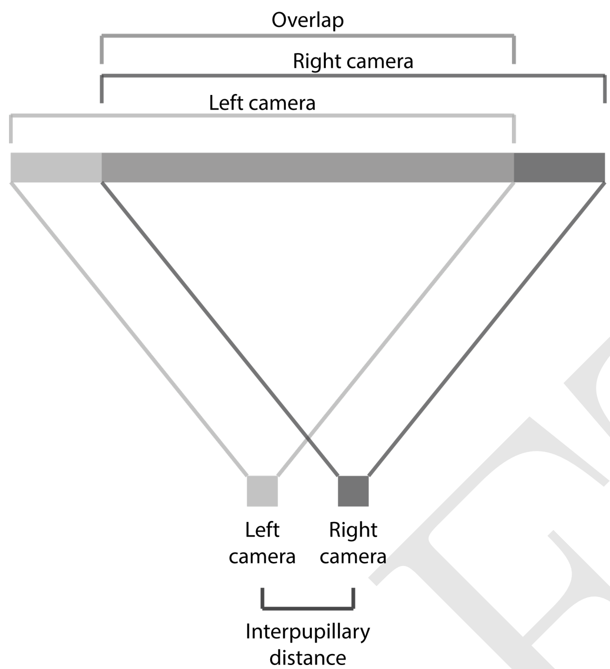


Figure 5.30: Overlap between camera planes.

refers to the time taken for a visible change in the scene in front of the DK1 (in this instance, the image upon the monitor) to be reflected by a comparable change upon the DK1's display. This figure accounts for latency introduced by the C310 cameras themselves, by the Unity engine & by the DK1's display. A digital camera was set up on a tripod behind the monitor & DK1, such that it could record both the monitor & the milliseconds value on the DK1's screen. The digital camera was set at a sufficiently high ISO as to record video at 50fps with a shutter speed of 1/4000 of a second.

Both the monitor & the DK1's screen refresh at 60Hz, each frame lasting for 16.67ms, whilst a 1/4000 of a second shutter on a camera means that the shutter is open for 0.25ms. The response time of the monitor (quoted by the manufacturer as 8ms grey-to-grey) was evidently much higher than that of the Rift, as the tenths & even hundredths digit on the monitor was usually legible in each frame of the video whereas on the Rift the hundredths & thousandths digits were always illegible. Thus to determine the latency of the DK1 + camera setup using Unity, adjacent video frames were identified where a transition from one tenth digit to the next was legible enough on the Rift's display & the hundredths/thousandths digits were legible enough on the monitor, such as the pair shown by figures 5.33 & 5.34. From these values, it can be inferred that the tenths digit on the DK1's screen (visible through the right eyecup hole) changed from 9 (figure 5.33) to 0 (figure 5.34) sometime between 181ms (figure 5.33) & 198ms (figure 5.34) on the monitor, which represents a latency of between 181ms & 198ms. Out of 11 pairs of frames like this, 7 pairs showed this 181-198ms latency, while 4 showed 198-215ms latency as in figures 5.35 & 5.36.

In addition to video frames, still photographs taken at the same 1/4000 of a second shutter speed gave some better legible stills which corroborated this 181-251ms figure. This figure is substantially greater than the 30-60ms figure often quoted[20] as the upper limit for an acceptable VR experience, however how much it affects a relatively 'slow' style of interaction such as that of applying PR to a cultural heritage site versus that of a 'fast' application such as a competitive twitch game is open to interpretation from experimental results.

[20] `https://www.oculus.com/blog/the-latent-power-of-prediction/`

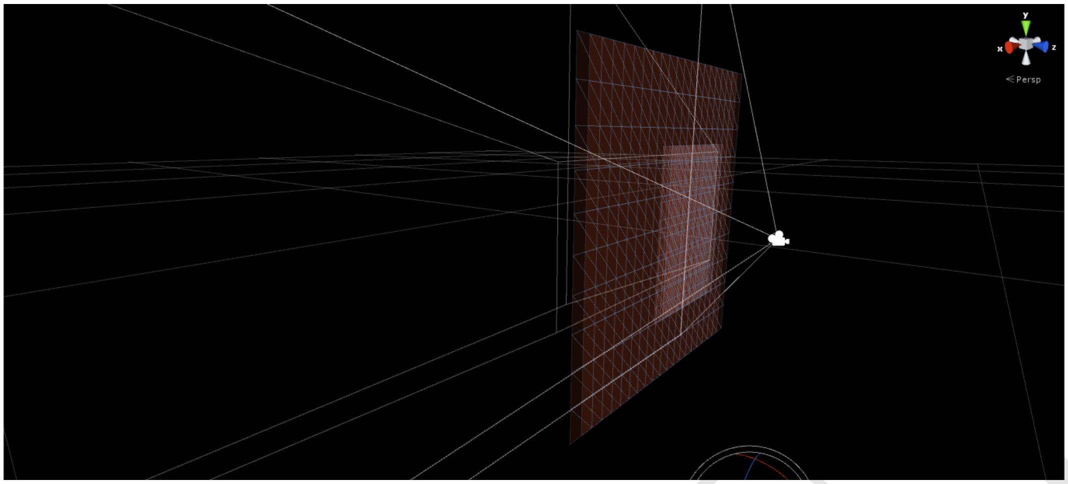


Figure 5.31: Arrangement of camera planes & backing planes.

5.2.5 Constraints of DK1 See Through Solution

Whilst the FOV of the image produced by the C310 is sufficient to fill the area of the DK1's screen visible when extended to its furthest position, there are other aspects of the camera solution to consider, including the depth of field (DoF) of the camera solution & the fixed convergence of the cameras.

Due to the fact that depth of field of an image captured by a camera increases both as lens focal length & sensor size decreases, combining a short focal length lens (such as the 2.1mm used in the solution) with a small sensor (such as the 1/4" type used in the solution) results in a plenty sufficient depth of field when looking through the DK1 with C310 so as not to feel markedly different in this respect to viewing in the same lighting conditions with bare eyes.

With regards to convergence, when viewing an object in the real world the eyes rotate such that the perpendicular axes that bisect each eye converge at the point that one is looking at. This results in disparity between the images produced by each eye, as each sees the object from a different angle due to the physical distance between the eyes. This disparity leads to stereopsis which is one of the contributing factors that leads to our ability to perceive depth. Oculus exploit this situation with their HMDs, by presenting a slightly different image to each eye, allowing virtual objects to appear at varying distances behind or in front of the virtual display.

For a stereo camera video see through solution, however, the convergence between the cameras is fixed, unless one were to implement a complex system employing eye tracking to dynamically physically reorient the cameras to match the orientation of the eyes. Thus one can either chose to mount the cameras parallel to each other, such that their optical axes never converge/converge at infinity, or to fix them 'toed-in' such that they converge at a non infinite distance.

With parallel cameras, any object captured by the cameras at infinity will be cast to the virtual screen. However any object captured by the cameras closer than infinity will be cast in front of the virtual screen with negative parallax. Viewing an entire scene in this manner is uncomfortable & should be avoided. With toed-in cameras, objects behind the convergence point will be rendered with positive parallax & will appear to be behind the virtual screen, whilst objects before the convergence point will be rendered with negative parallax & will appear to be in front of the virtual screen.

With toed-in cameras, the distance of the convergence point from the user should be chosen to sit somewhere in the middle of the environment & task. For Mirrorshades, this distance was set by trial & error to be somewhere in the region of 15 to 20ft, which resulted in the most comfortable & natural feeling experience when engaging in the sort of behaviour of a visitor to a cultural heritage site such as St Salvator's chapel, which involves mainly observing aspects of the building & architecture in this sort of distance range.

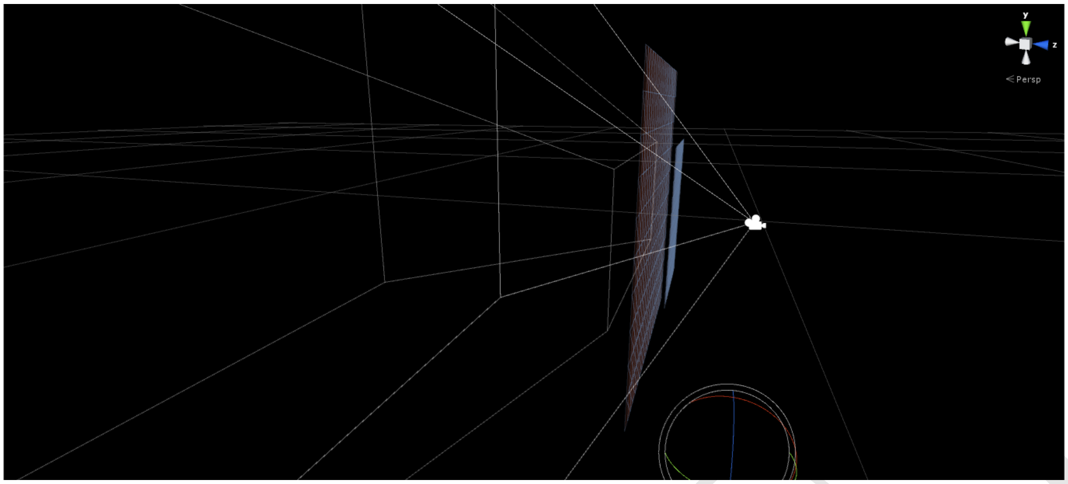


Figure 5.32: Spacing between camera planes & backing planes.

Figure 5.33: vid1.jpg

Figure 5.34: vid2.jpg

Figure 5.35: vid3.jpg

Figure 5.36: vid4.jpg

Toed-in cameras lead to both depth plane curvature, which causes objects at the corners of the image to appear further away than those toward the centre, & , keystone distortion, which causes vertical discrepancy between each image, as the cameras' sensors are oriented in different planes, such that for one camera an image will appear larger at one side than the other, whilst for the other camera the image will appear larger on the other side [77]. As with depth plane curvature, keystone distortion is worse toward the corners.

Figure 5.37: still1.jpg

Figure 5.38: still2.jpg

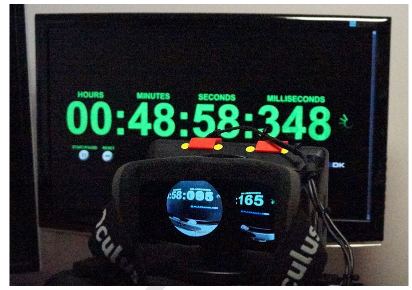


Figure 5.39: still3.jpg

It should also be noted in this discussion that the DK1's combination of optics & rendering shader means that the user's eyes focus at infinity. This is intentional, as focussing on far away plane is less strenuous than focussing on one closer, especially one only a few inches from the eyes. However this has the effect that the user is focussing their eyes at infinity, whilst perceiving objects at varying distances between them & infinity. This is a caveat inherent to the DK1 that cannot be avoided, however it should be noted that this is an additional degradation to the user's view of their RW environment whilst using the experimental setup, compared to viewing the RW environment directly.

A further consideration is the discrepancy between the cameras' sensors & the users' eyes, caused due to the fact that the cameras must be mounted to the front of the DK1 & thus several inches in front of the user's eyes. This has the effect of making the user experience viewing the real world from several inches in front of where their eyes truly are (as if their eyes were 'on stalks'), whilst viewing VR through the same setup does not have this effect. The distance between the sensors & the user's eyes was reduced when iterating from the first mounting mechanism with metal stand-offs (figure 5.40) to the second mechanism with rubber washers (figure 5.41), however with the interaction style of Mirrorshades where the user is predominantly focussed on observing objects & architecture 15-20ft away from them the discrepancy is not particularly noticeable - it is when trying to manipulate objects much closer to the eyes that the discrepancy becomes prominent.

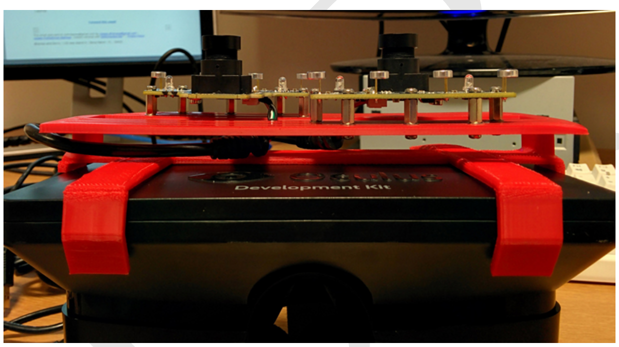


Figure 5.40: Early mounts, large eye/sensor distance.

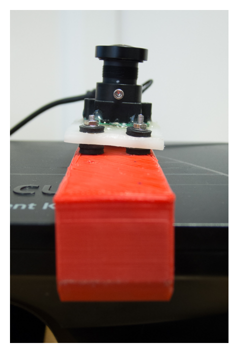


Figure 5.41: Later mounts, smaller eye/sensor distance.

5.3 Indoor Positioning Systems

For outdoor applications, GPS represents a suitable solution for the vast majority of position tracking requirements. Global coverage & the ability to scale accuracy as required, from many metres with a basic GPS receiver such as those integrated into smartphones, to a few metres with SBAS augmentations & further to as little as 10cm with the deployment of Differential GPS (DGPS) beacons, has led to GPS occupying the role of the ‘go to’ solution where position tracking is required for an outdoor application. For indoor applications however, there is no single technology or solution that provides similar coverage or suitability as GPS does outside: a large number of different technologies have been employed to produce Indoor Positioning Systems (IPS), which are summarised in figure 5.2.

Technology	Typical Accuracy	Typical Coverage (m)	Typical Measuring Principle	Typical Application
Cameras	0.1mm – dm	1 – 10	angle measurements from images	metrology, robot navigation
Infrared	cm – m	1 – 5	thermal imaging, active beacons	people detection, tracking
Tactile & Polar Systems	µm – mm	3 – 2000	mechanical, interferometry	automotive, metrology
Sound	cm	2 – 10	distances from time of arrival	hospitals, tracking
WLAN / WiFi	m	20 – 50	fingerprinting	pedestrian navigation, LBS
RFID	dm – m	1 – 50	proximity detection, fingerprinting	pedestrian navigation
Ultra-Wideband	cm – m	1 – 50	body reflection, time of arrival	robotics, automation
High Sensitive GNSS	10 m	‘global’	parallel correlation, assistant GPS	location based services
Pseudolites	cm – dm	10 – 1000	carrier phase ranging	GNSS challenged pit mines
Other Radio Frequencies	m	10 – 1000	fingerprinting, proximity	person tracking
Inertial Navigation	1 %	10 – 100	dead reckoning	pedestrian navigation
Magnetic Systems	mm – cm	1 – 20	fingerprinting and ranging	hospitals, mines
Infrastructure Systems	cm – m	building	fingerprinting, capacitance	ambient assisted living

Table 5.2: Overview of IPS technologies, from [2].

Because of this diversity in technology, with different IPS solutions covering various swathes of the continuums of accuracy & coverage (see figure 5.42), introducing a host of performance & suitability considerations, it is necessary to carefully consider the requirements of the application (see figure 5.43) & then choose the best suited of the many different IPS approaches. Unsurprisingly, selection of a particular IPS usually leads to balancing these requirements in a trade-off, as each of the challenges of indoor positioning effects each technology more or less than others [78].

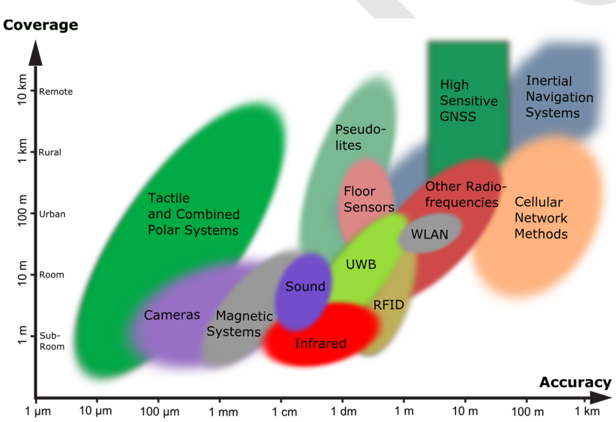


Figure 5.42: IPS technologies plotted against their accuracy & coverage, from [2].

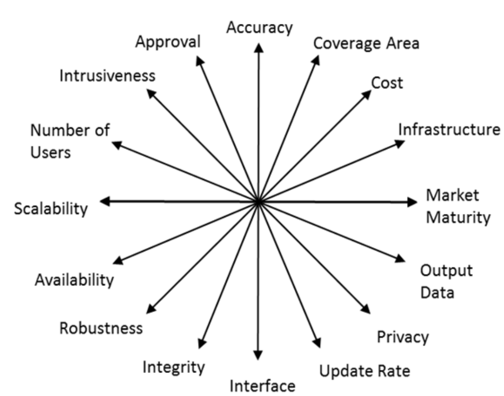


Figure 5.43: Requirements parameters of IPS, from [2].

5.3.1 IPS Requirements for Mirrorshades

The positional accuracy of the IPS used for the Mirrorshades platform needs to be substantially higher than that of the GPS solution used for VTW. As a pedestrian application wherein the user walks through doorways (whether real or virtual) & observes multiple rooms within a building, it is necessary to achieve a level of accuracy that allows, for example, reliably discerning between adjacent rooms, between a doorways & their surrounding walls & for approximating position within rooms & corridors.

Coverage required depends largely upon the size of the cultural heritage site that Mirrorshades is deployed to. However it is prudent to select an IPS that can scale quite arbitrarily from small scenarios (perhaps of a small village church) to substantially larger scenarios (such as a cathedral similar to that at St Andrews), such that the suitability of the platform isn't restricted to sites of particular sizes.

A high update frequency is not especially important to Mirrorshades. The envisaged style of interaction is one wherein users walk relatively slowly through the environments, as they wish to observer & take in their surroundings. Updates in the range of several hz will be sufficient, especially if users are attending more to their real environment than the equivalent virtual environment when actively moving around (which is to be encouraged, as one cannot walk through a RW obstacle as one can a VR one). Similarly, low latency is not critical. Even if the IPS takes a few seconds to 'catch up' with the user, because the user is committed to a deliberate study & comparison of their real & virtual surroundings they are not going to be foiled in their task if they find they have to wait momentarily when switching from real to virtual views.

Cost represents a more concrete restriction for Mirrorshades, as the costs of installing & using different IPS range drastically. For example, an IPS that locates users via propagation modelling/empirical fingerprinting/pathloss of WiFi signals can make use of existing WiFi infrastructure installed in a building & use nothing more expensive than a smartphone carried by the mobile user. Conversely, using a motion capture suit as an IPS solution will incur substantial costs for each suit, with additional costs for the supporting infrastructure. In a similar vein to the vision of Mirrorshades, an existing project combined the Oculus Rift HMD with an Xsens MVN motion capture suit, allowing participants to walk around a virtual environment of the same layout & dimensions as their real environment[21], but without any video see-through of the real environment. The use of a motion capture suit allowed extremely accurate positional tracking, however as a *"complete standard Xsens MVN system is available at around €50,000"*[22] & requires a not insubstantial setup phase of the participant donning the suit, it is unsuitable for a virtual heritage scenario where budget is likely to be substantially more limited & where visitors are unlikely to be willing to don a complex motion capture suit in order to explore the site. To illustrate a real world comparison of the trade off between costs, accuracy, frequency, etc. of different IPS technologies, considering the departmental building shown by **??**, *"To cover ground floor and have room level accuracy in each room + tracking in the corridors, the cost would be ca. $25,000"*[23] for a commercial ultrasonic IPS.

Reliance upon deployed infrastructure such as beacons & markers needs to be avoided for Mirrorshades, as most cultural heritage sites will not allow the installation of any such infrastructure into the site/environment, or may only allow strictly temporary infrastructure to be deployed. Approaches that require extensive infrastructure to be deployed, or for which the deployment & calibration phase of infrastructure is long & thus not suitable for temporary deployments, are therefore unusable. Similarly, intrusiveness of the IPS used for Mirrorshades needs to be considered such that the IPS does not drastically affect the user's ability to observe the real & virtual sites around them.

Robustness of all aspects of a virtual heritage system is critical for enjoyment & beneficial experience by the user. Visitors to a cultural heritage site, especially if they are only visiting for a short period of time in passing, are not going to be pliant to waiting for a malfunctioning virtual heritage system to right itself. Furthermore, many virtual heritage systems are installed in situations in which the on-site staff do not have the technical knowledge or experience to troubleshoot & repair them, so these systems must be robust enough to continue successful operation for extended periods of time without intervention by knowledgeable administration.

[21] `https://www.youtube.com/watch?v=LtMfrkRqlRs`

[22] Personal correspondence with Xsens EMEA Entertainment Business Manager.

[23] Personal correspondence with Sonitor Technologies Vice President Sales and Business Development EMEA & APAC.

5.3.2 PlayStation Move

An initial technology investigated for suitability as an IPS for use with Mirrorshades was PlayStation Move (PSMove), a game controller platform released by Sony for use with their PlayStation 3 console. The platform comprises a hand held controller which contains inertial sensors & has a plastic sphere on its end that is illuminated from within by a RGB LED. A bundled webcam, the PlayStation Eye (referred to as 'PS3 Eye', 'PS3Eye' & 'PSEye' among the literature & community) uses vision tracking to track the controller's position in relation to the camera. Through use of the PSMove API [79], the PSMove platform can be used by a regular computer, by making use of the OpenCV[24] computer vision project.

Whilst the PSMove has been used successfully for pedestrian position tracking in previous projects, included those that used an Oculus Rift HMD[25], it quickly became apparent when auditioning the platform that it only performs reliably when in very dimly lit conditions. Even the relatively dim scene shown by figure 5.44 (see also) represented too much ambient light for reliable tracking, so the suitability of the platform for use at a cultural heritage site was removed.

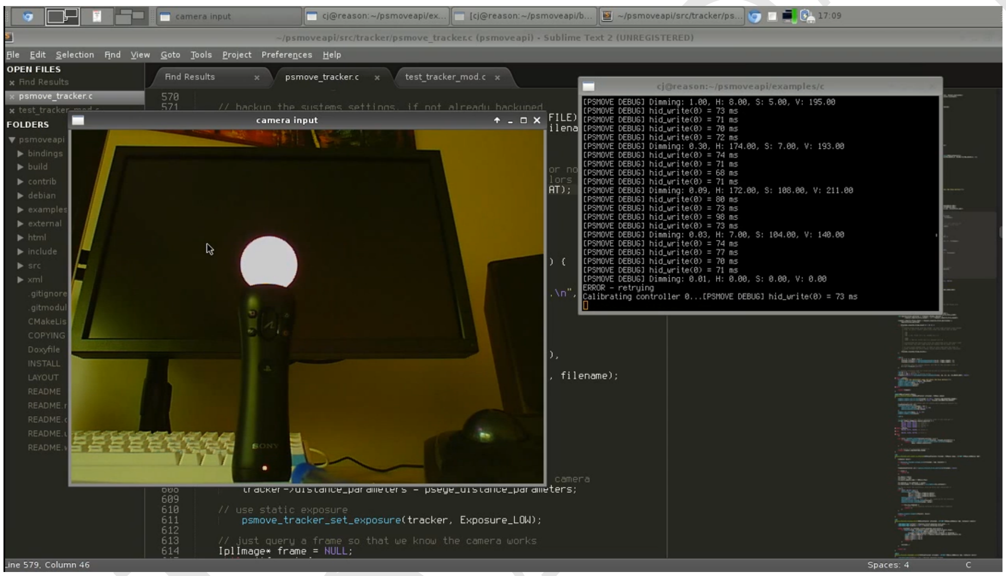


Figure 5.44: PSMove failing to locate even in dim conditions.

5.3.3 Indoor Atlas

During the evaluation phase of different IPS & their suitability to the envisaged Mirrorshades platform, Finnish startup IndoorAtlas[26] released the first public beta of their indoor positioning technology that uses the magnetometers found in smartphones to locate a user within a magnetic 'fingerprint' of a particular building, taking inspiration from animals, such as the spiny lobster, that are able to determine their position in addition to their direction from the Earth's magnetic field [80]. A spin out from research at the University of Oulu in 2009 [81, 82], with a similar project undertaken by Media Lab researchers in 2011 [83], IndoorAtlas exploits how the Earth's magnetic field is distorted by both natural & man-made sources. Indoors, these distortions come from building materials, especially in structures employing a framework of metal beams, but also from electrical cabling, HVAC ducting, etc. By recording a map of these distortions in an offline

[24] `http://opencv.org/`
[25] `http://projects.ict.usc.edu/mxr/blog/project-holodeck-wows-in-dublin/`
[26] `https://www.indooratlas.com/`

mapping phase, producing a fingerpint of the magnetic field around a building, the location of a user can be deduced by comparing the readings from their smartphone's magnetometer to this fingerprint in real time.

IndoorAtlas promised to be a good match for the IPS requirements of the Mirrorshades platform. In particular, the lack of dependence upon any deployed infrastructure such as ultrasound beacons or visual tracking targets suits the deployment area of Mirrorshades well, as most cultural heritage sites will not be amenable to the deployment of such hardware. Furthermore, the reliance upon only a smartphone held by the user means that coverage is only limited by the area that has prior been mapped in an offline mapping phase, allowing the positioning to scale to arbitrarily large indoor cultural heritage sites. This dependence upon only a smartphone also meets the low cost requirement of the Mirrorshades platform, as mid to high end smartphones with sensitive magnetometers can be purchased for just a few hundred dollars.

The major concern at this point was whether the building materials employed in the construction of cultural heritage sites such as chapels, castles & cathedrals would create great enough distortions to the Earth's magnetic field for IndoorAtlas to provide its boasted accuracy (which would be sufficient to discern between adjacent rooms, between doorways & their surrounding walls & estimate position within rooms & corridors). These building materials are largely various types of stone, along with wood, a far cry from the metal framework that permeates most modern buildings. Whilst initial tests of the IndoorAtlas beta technology within a departmental building[27,28] of roughly 40m & 30m tall were promising, this was a modern building with a steel beam structure & an abundance of computing infrastructure & its associated cabling & cooling provision. Figure 5.45 shows the results of one of these tests, with each red dot representing a position reported by the IndoorAtlas platform while walking around the building at a slow walking pace ($< 1\text{ms}^{-1}$, akin to how a visitor to a cultural heritage site might walk.

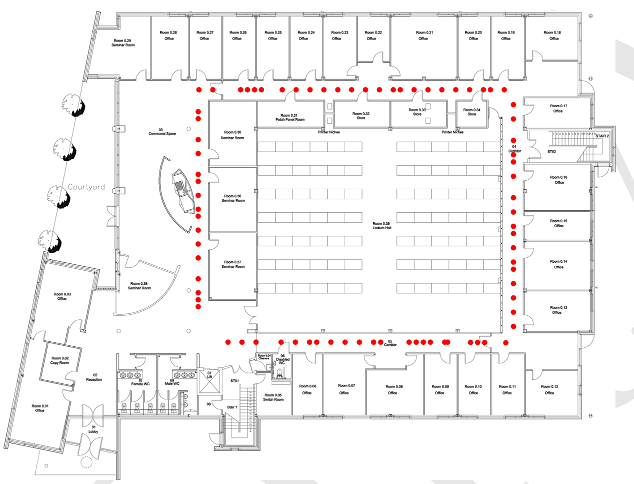


Figure 5.45: Positions reported by IndoorAtlas.

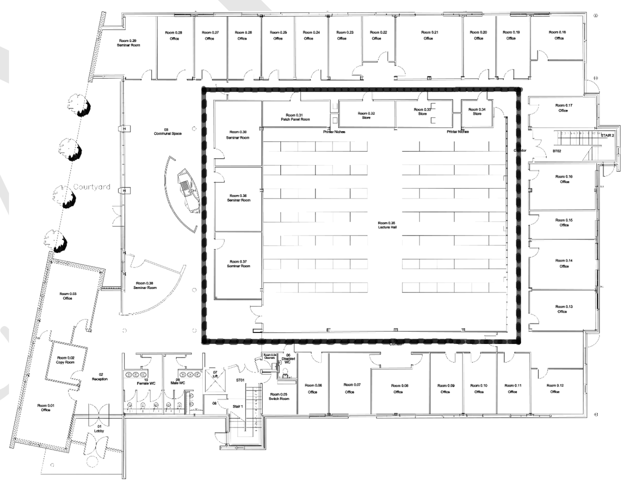


Figure 5.46: Route mapped during offline phase.

It should be noted that the IndoorAtlas technology only reports positions upon routes that have been previously mapped in an offline mapping phase; for the test results shown by figure 5.45, this offline mapping phase comprised walking the route shown by the thick black line in figure 5.46 several times. In the following test, had the user deviated from this route, IndoorAtlas would still have reported them as being somewhere upon it; it would not attempt to extrapolate their position into unmapped territory. This is presumably because the scale of distortions in the Earth's magnetic field is quite fine grained, supported by the fact that many of the black dots are less than a meter apart, thus extrapolation would not fair well. This is an important aspect to take into account when performing the offline mapping phase, as one must map sufficient paths to cover all possible places & routes that a user may walk. For locations comprised mainly of corridors & small rooms, this is not an issue, however for a location that contains a large open space in which the user

[27] https://www.youtube.com/watch?v=l-eIvzpScRs
[28] https://www.youtube.com/watch?v=9hc2zEeQJXQ

is free to meander, a more involved mapping process in which the entire space is systematically covered by back & forth routes that progress across the space is required.

Initial testing of IndoorAtlas at St Salvator's chapel proved surprisingly successful, with the platform able to track the smartphone accurately throughout the building even without any obvious overbearing metal content in the structure or its furnishings. Figure 5.47 shows the set of positions reported by the IndoorAtlas platform whilst walking throughout the chapel, which is roughly 30m across, after an offline mapping phase that mapped the routes shown in figure 5.48.

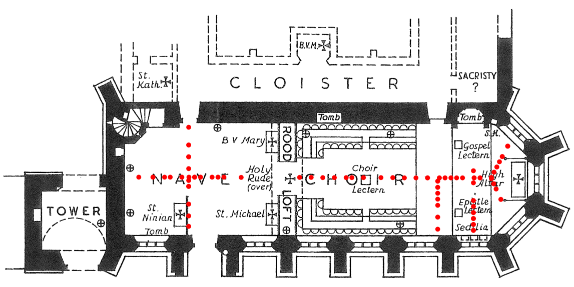


Figure 5.47: Preliminary testing of IndoorAtlas in St Salvator's chapel.

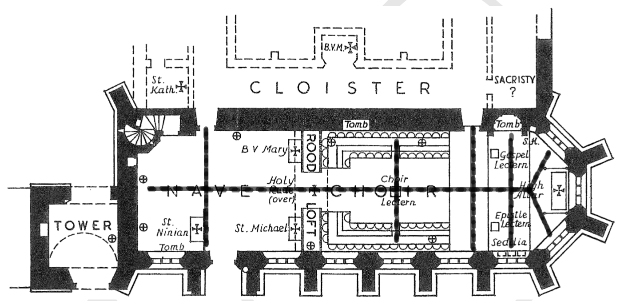


Figure 5.48: Routes mapped during offline phase.

Upon closer inspection of the building, metal grating that runs along the ground along the central aisle, representing much of the horizontal movement in figure 5.47 & shown in figure 5.49 & figure 5.50 in detail, which also extends to the open area in front of the altar as shown in figure 5.51, may explain this unexpectedly high performance, however in other areas such as when walking to either side of the altar (far right of figures 5.47 & 5.48) there were no obvious sources, as seen in figure 5.52, of magnetic interference to account for the maintained accuracy. Possible less obvious explanations could be the ferromagnetic properties of certain types of stone used in the building's construction & the presence of electrical lighting & audio systems installed into the chapel (loudspeaker & light fixture visible in figure 5.53), which presumably make use of electrical cables routed throughout the building.

Figure 5.49: Chapel aisle, flanked by gratings.

Figure 5.50: Grating detail.

Figure 5.51: Gratings before altar.

Figure 5.52: No obvious metal around altar.

Figure 5.53: Loudspeaker & electric light fixture.

5.4 Mobile Client

Although the Unity engine allows for executables to be built for myriad platforms, including popular mobile platforms such as Android, iOS & Windows Phone, at the time of Mirrorshades' development the only platforms upon which Oculus' Unity integration for the DK1 was available were Windows & Mac OS standalone & community efforts to support the DK1 on Android were at a rudimentary stage of functional head tracking but no distortion shader[29]. Thus the mobile client used for the Mirrorshades platform was a small Windows laptop computer, an 11" Clevo W110ER with an Intel i7-3632QM 4-core/8-thread processor, Nvidia GT 650M graphics card & 16GiB system memory, to be worn in a satchel that would also serve to hold other hardware & cables required for the platform to operate.

Since the development of Mirrorshades, Oculus' have partnered with Samsung to produce the Samsung Gear VR, a device that combines Samsung's Galaxy Note 4 smartphone with a HMD housing containing lenses & head tracker, to produce a mobile VR HMD. Although not available at the time of the development & experimentation with Mirrorshades, Gear VR now represents an ideal platform for a PR system such as Mirrorshades to be implemented upon. Whilst the graphical quality of the visuals of a smartphone based approach may not match those of a laptop powered approach, the physical modality of the Gear VR is ideal for a mobile application such as the PR exploration of a cultural heritage site, as even in a more graceful setup as those used during Mirrorshades experiments the reliance upon a separate HMD, laptop, smartphone & control device make for a physical modality not suited for anything but research in the lab or field. As Gear VR is based around an Android smartphone it would not only remove the requirement for separate HMD & client to produce its visuals, as the hardware & software provision to operate IndoorAtlas is already present within the Note 4 & the Gear VR HMD housing even features an input area that would negate the requirement for the user to carry a separate control device to perform transitions between their real & virtual environments.

5.4.1 Integrating IndoorAtlas & Unity

Due to the role of the mobile client being filled by a laptop computer, position data obtained via IndoorAtlas using an Android smartphone had to be relayed to the laptop. Modifications were made to an IndoorAtlas SDK beta example app, such that it submits position data to a remote MySQL database server via a PHP/HTTP POST mechanism. This not only allows the mobile client to determine its position by polling the database server for the most up-to-date data, but also allows for remote logging (unrestricted by local storage

[29] `https://www.youtube.com/watch?v=pO2Vt8CuxsA`

on the smartphone) & for other applications to easily make use of the location data; during development, a Web based visualisation of the position data was used for both the department building (figure 5.54) & St Salvator's chapel (figure 5.55). These Web pages render the position of the user as a red mark using a relative position `div` & served as a source of diagnostic information that was quickly accessible from any platform.

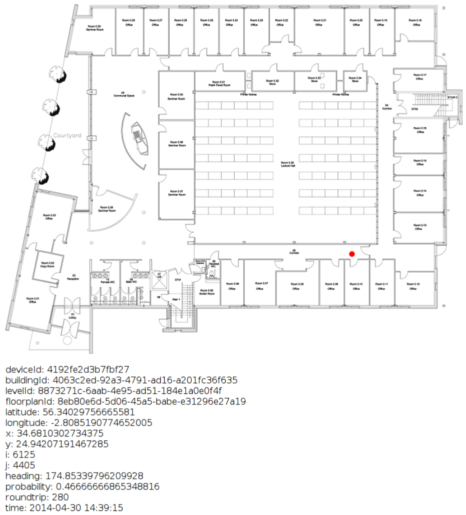


Figure 5.54: foo

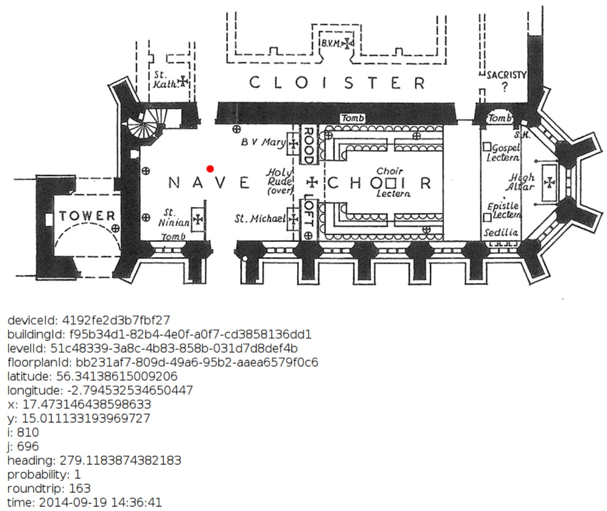


Figure 5.55: bar

Translating RW positions reported by IndoorAtlas into VR positions within the Unity environments is performed in a similar same way as RW positions reported by GPS were translated into VR positions within the OpenSim environment in section 4.4, except that the myriad formats that position data are reported by the IndoorAtlas API negates the requirement to use the haversine formula. As well as providing indoor positions in the form of longitude & latitude pairs, the API also provides positions as offsets from the origin of the floorplan image file used when performing the offline mapping phase, in both pixels & meters. Thus, instead of deriving the displacement between the anchor point & the user's position by using haversine to calculate great circle distances between pairs of longitude & latitude, the displacement is instead obtained by simply adding/negating the position of the user reported in meters from the position of the anchor point also in meters. This approach is possible with IndoorAtlas as the use of a floorplan image provides a frame of reference, that can be indexed by 2D pixel coordinates & converted into meters using a pixels-per-meter value, that did not exist with the GPS approach adopted for VTW that requires no offline mapping phase.

Using IndoorAtlas reported positions in Unity is configured & achieved by a combination of two scripted objects. One object, the anchor point, simply contains fields for the entry & storage of the RW position information of the anchor point (see figure 5.57). In the Unity environment this object can be rendered with no texture or collider, such that it does not interfere with the environment in any way, but by using a dedicated object for the anchor point rather than attaching the script to another object, the anchor point object itself can be moved throughout the environment to the correct VR position instead of the user having to enter these details in addition to the corresponding RW ones & this inferred position then used in the calculations.

Thanks to the ability of the Unity engine to build applications for myriad platforms, the integration of IndoorAtlas IPS into Unity could be tested within the department building using a pair of Android smartphones[30] before moving on to the full DK1 based setup. This can be seen in figure 5.56, where the smartphone in the right hand (a Google Nexus 4) is running the modified IndoorAtlas SDK beta example app, POSTing position data to the remote MySQL server, while the smartphone in the left hand (a Google

[30] `https://www.youtube.com/watch?v=i3lEnXZMjms`

Nexus 5) is running a Unity application that depicts a top-down view of the user's current position within a 3D model of the department building.

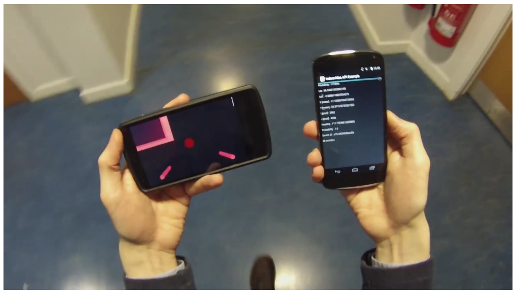


Figure 5.56: Anchor point (yellow) & avatar position (red).

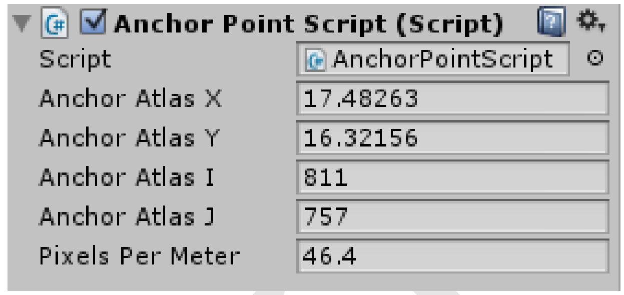


Figure 5.57: RW anchor point settings in Unity.

5.5 Transitions Between RW & VR

Attending to visual stimuli from the RW environment via the cameras is required for the user to safely move around. Delay in IndoorAtlas reporting their position & inaccuracies in these 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 likely, especially in a cultural heritage scenario, that many RW obstacles won't have equivalent VR representations. Whilst one can walk through a virtual wall, the same is not true of a real one!

Thus the 'default' view through the DK1 must display enough of the view through the cameras for the user to safely navigate their environment, including any obstacles within it (whether these are static objects or dynamic objects such as other humans). For the user to alternatively view through the DK1 a scene that is more, or completely, virtual, thus requires a transition to be performed in which the visual stimuli presented to the user via the DK1 are changed from the default view to the new view.

As discussed in section 3.8, when a user experiences such a transition from viewing the visual stimuli of one environment (or combination of environments) to viewing the visual stimuli from another environment (or different combination of environments), this will have an effect upon their sense of presence - a break in presence. When experiencing a transition between an environment that is predominantly real & one that is predominantly virtual, as depicted by figure 3.18, this break is expected to manifest with a temporary increase in conceptual/abstract reasoning (a movement upon the focus access from presence towards absence), as the user compares & contrasts the visual stimuli that they are now perceiving from the new environment to those that they were just perceiving from the previous environment until they can successfully position & relate the new against the old, accompanied with a temporary increase in wakefulness as they have to more consciously consider the environment presented to them rather than passively receiving it.

The manner in which these transitions are performed is expected to have an effect upon the severity of these breaks. The transitions can be performed differently in two regards;

1. The starting & ending position upon the locus axis;
2. The implementation of replacing one set of visual stimuli with the other.

At the extremes, performing an immediate switch from 100% real to 100% virtual is expected to cause the worst break. Performing a slow transition between 100% real & 100% virtual is expected to cause a lesser break. Performing a transition from a combination environment to a non combination environment is expected to cause a lesser break than performing a transition between two non combination environments.

In order to best implement PR for situations such as cultural heritage, ascertaining the optimum manner in which to perform transitions between the constituent environments is important. As such, a number of different transition methods have been implemented.

Whilst in the first phase of user studies, which intended to test the basic concept of a mobile PR system in a cultural heritage scenario, the users only had access to a single type of transition, latter user studies actively compared different transitions within groups. Whilst some of these transitions were performed by the system, outwith of the users' control, the majority were controlled by user triggers. It was thus necessary to provide the user with a control modality with which they could trigger from a set of transitions.

Ideally this control methodology would be something that would not detract from the user's ability to process the visual stimuli they received from the DK1 & as the camera solution mounted to the DK1 is set up in a manner such that looking at things close to the user (such as a control) in order to differentiate between controls would be uncomfortable due to the heightened negative parallax (see section 5.2.5), a control modality that could be quickly learned & then used by touch/memory was preferable.

The mobile phone was auditioned, however with only a single input device (a featureless screen, with no touch feedback for different sections & the difficulty of discerning areas by looking due to the cameras, plus the fact we don't want to have to look) it was decided against.

For another interface to be used, it would have to be usable by a single hand. Although placing the smartphone in a pocket, or in the satchel, was attempted, it had a severe negative impact on the performance of IndoorAtlas, so holding it in a hand is required.

An Xbox 360 controller was chosen to accomplish this goal. When held with just the right hand, the controller features multiple push buttons & an analogue trigger accessible to the thumb & first finger. These buttons are easily distinguishable from each other via touch, due to their simple geometric layout.

reference for the fundamentals of HCI, buttons size/shape/placement, etc.

Releasing the button/trigger causes the 'default' (thee camera feeds) to be displayed again.

5.5.1 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 5.58 illustrates this scenario.

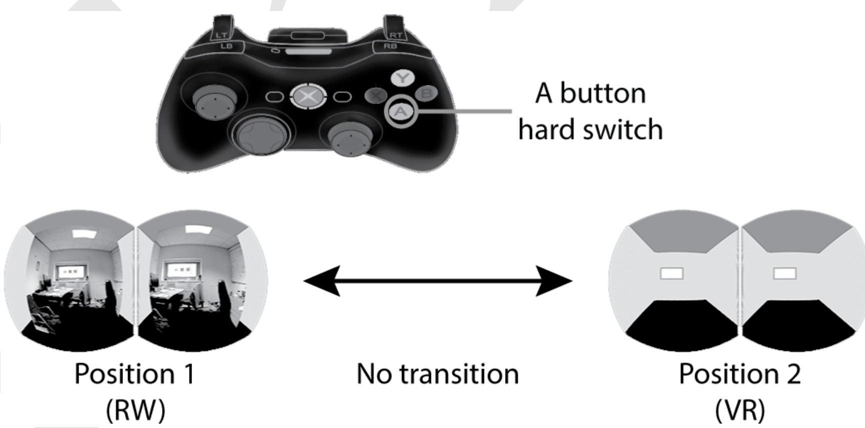


Figure 5.58: Hard switch.

5.5.2 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 5.59 illustrates this scenario.

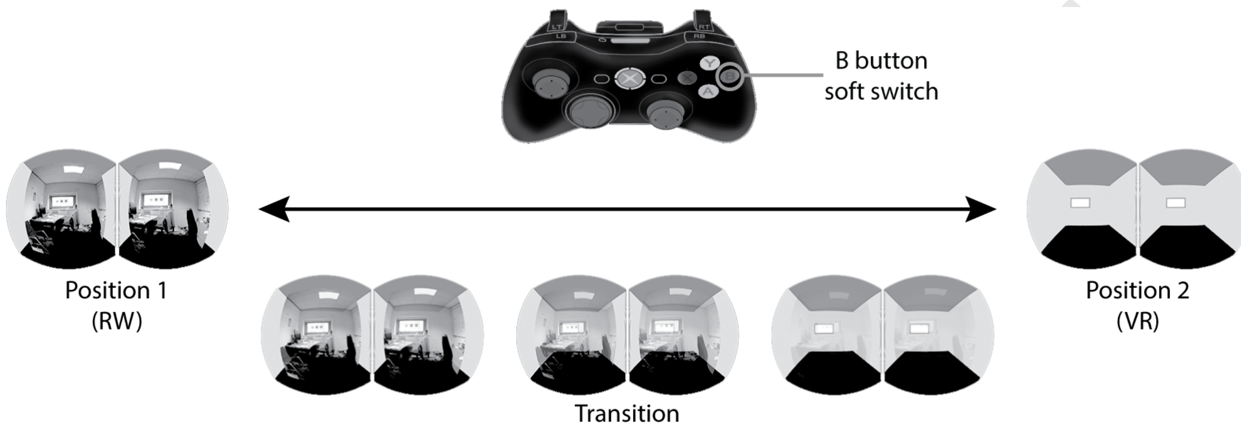


Figure 5.59: Switch with linear interpolation.

5.5.3 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 5.60 illustrates this scenario.

5.5.4 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 5.61 illustrates this scenario, where `i` represents the interval between switches & `d` represents the duration of the switch from RW to VR.

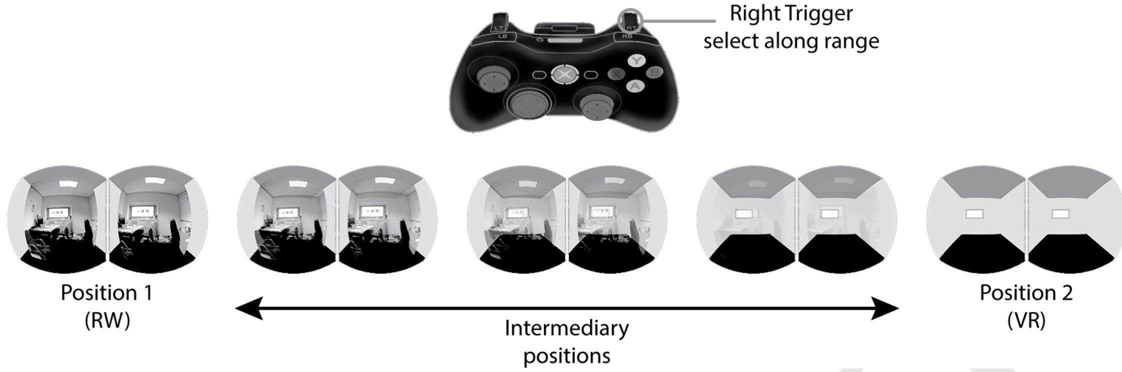


Figure 5.60: Analogue selectable opacity.

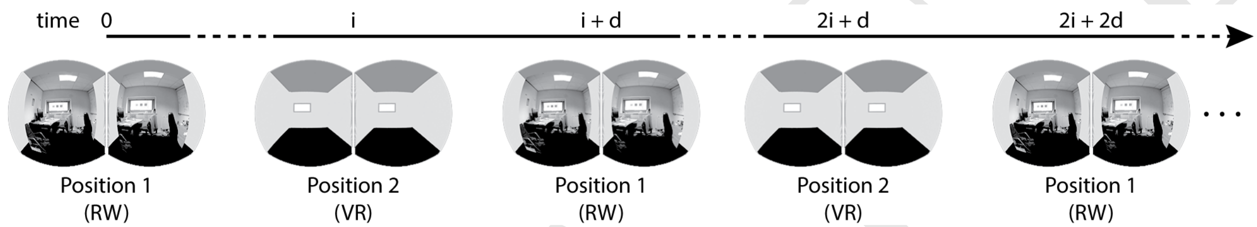


Figure 5.61: Periodic hard switches.

5.5.5 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 5.62 illustrates this scenario in combination with a hard switch (from section 5.5.1) 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.

5.6 Bring it all together

Figure 5.63 presents an overview of the integration of components that made up the Mirrorshades platform as used in user studies

implementation of the Mirrorshades platform design for use in the chapel investigations.

5.6.1 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 **??**);
- a USB battery pack, to power the HMD;

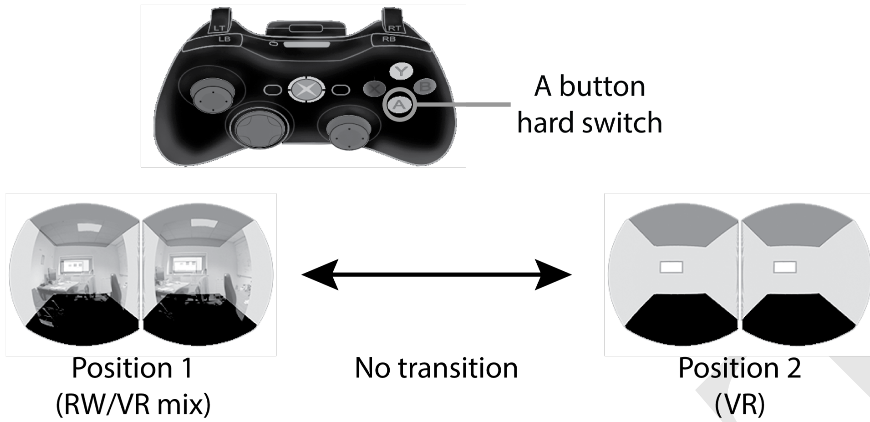


Figure 5.62: Hard switch from reduced maximum opacity.

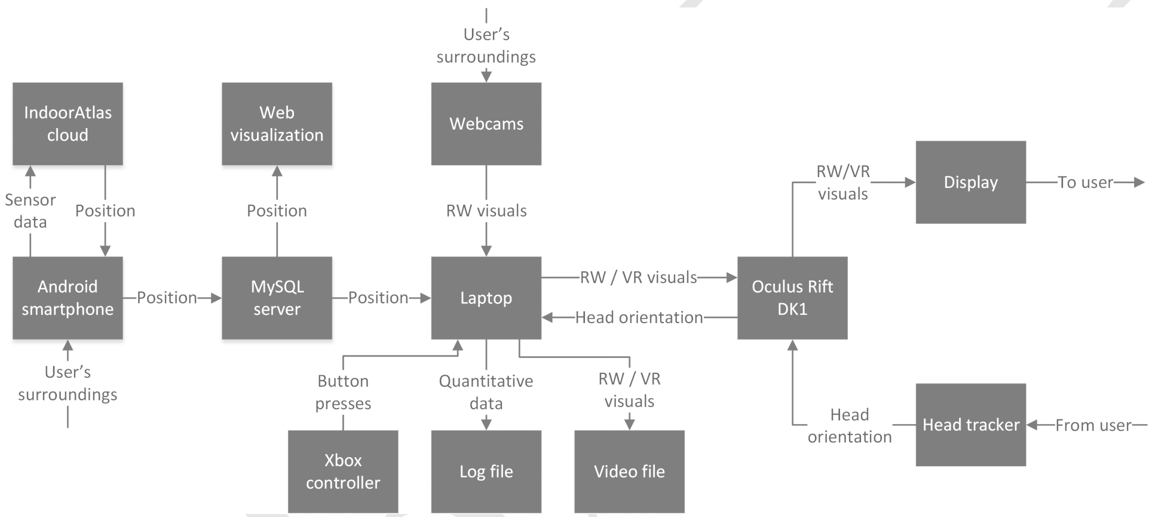


Figure 5.63: Implementation of Mirrorshades platform.

- 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.

5.6.2 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 [84] (figure 6.1 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;

Figure 5.64: Mirrorshades hardware.

Figure 5.65: Detail of control box.

- a Unity application that runs on the laptop.

5.6.3 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.

5.7 Putting it all together

This lot should come after the section on designing/implementing the different transition types.

First time trying it all together - Rift with cameras & controller, phone providing position data `https://www.youtube.com/watch?v=oy5NqqDtkJ4` screenshots

First time trying it at St Salvator's (myself, just headset video) `https://www.youtube.com/watch?v=W4oPIHIr9Z4` screenshots

First time trying it at St Salvator's with other people (Ariana & Alan) `https://www.youtube.com/watch?v=pvGV5dCjt4U` screenshots

6

Mirrorshades - Evaluation

Final video `https://www.youtube.com/watch?v=UsDRPjDwr8A` screenshots

6.0.1 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 6.1 shows the 1450-1460 layout of the chapel (including the paths that the IPS has been prepared upon).

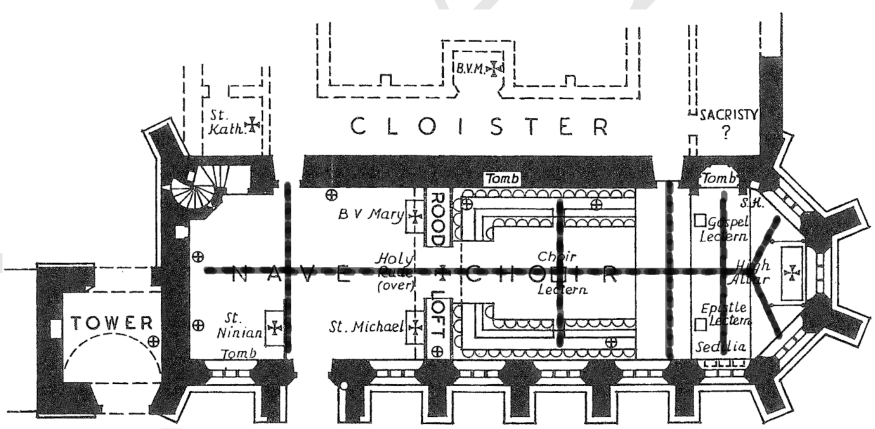


Figure 6.1: Floor plan of St Salvator's chapel, with IPS routes.

6.1 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.

6.1.1 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.

6.1.2 Evaluation Techniques

Evaluation will be performed via a short structured interview & completion of the System Usability Scale (SUS) [85].

6.1.3 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.

6.1.4 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 6.1 will be employed, encouraging participants to encounter multiple different scenarios of moving, remaining stationary, etc.

6.1.5 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 [41]. 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 [38], 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) [86] (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 5.5.5)
- `<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 5.5.4)
- `<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.

Figure 6.2: participant-f.png

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

6.2 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.

Figure 6.3: participant-m.png

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 [49] & thus this investigation serves to compare Mirrorshades with previous applications virtual reality content to these contexts.

6.3 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) [85] questionnaire, included as Appendix 6.5 & 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.

6.4 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 **??** 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.

6.5 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.

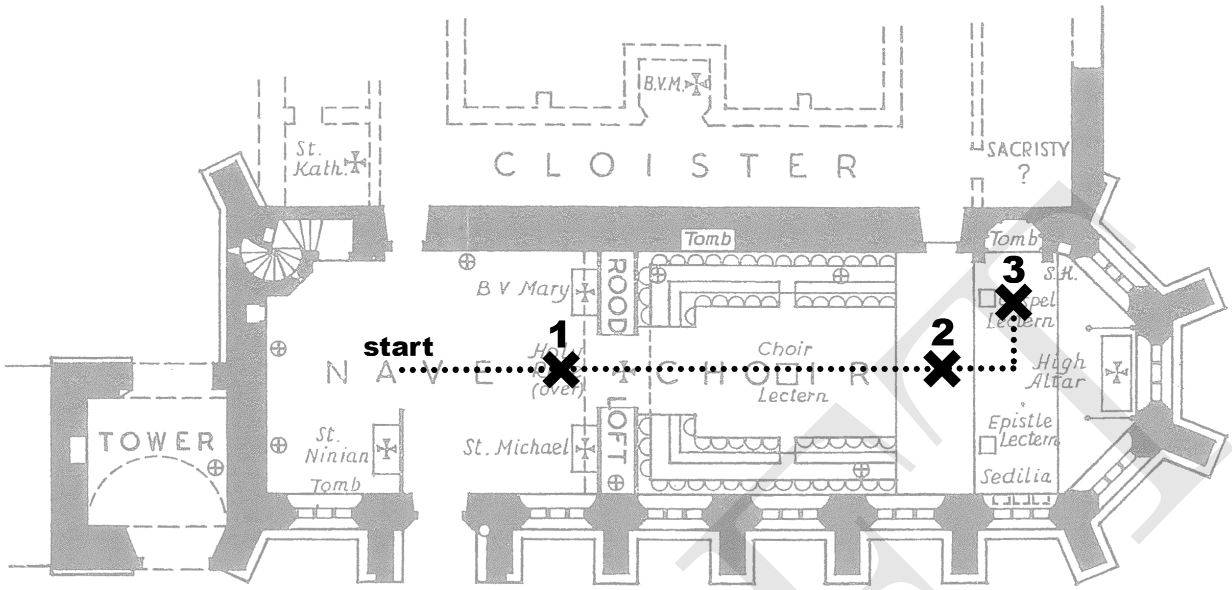


Figure 6.4: The path & positions within the chapel that participants are instructed to attend to.

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 & 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.

6.6 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.

6.7 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)

6.8 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

6.9 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’

6.10 Phase 1 Results

6.10.1 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.

6.10.2 SUS

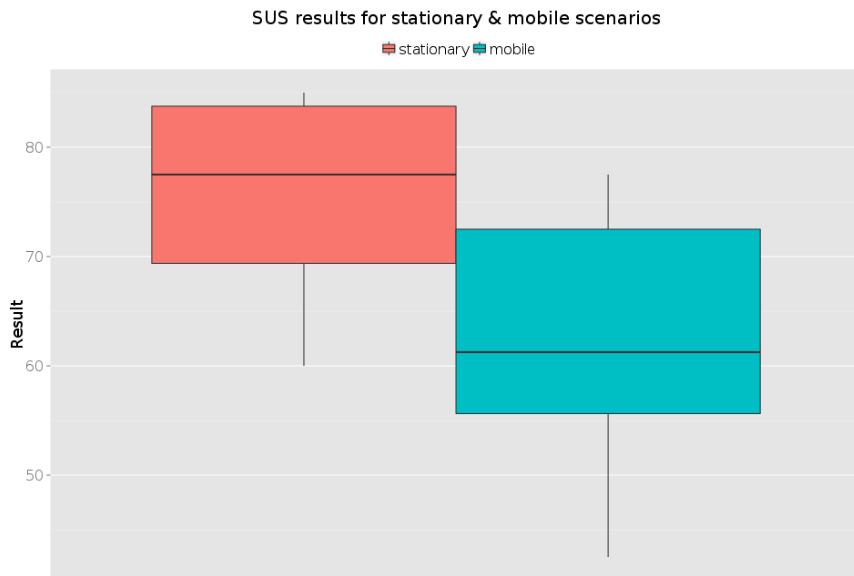


Figure 6.5: SUS results.

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.

6.10.3 12-item Questionnaire

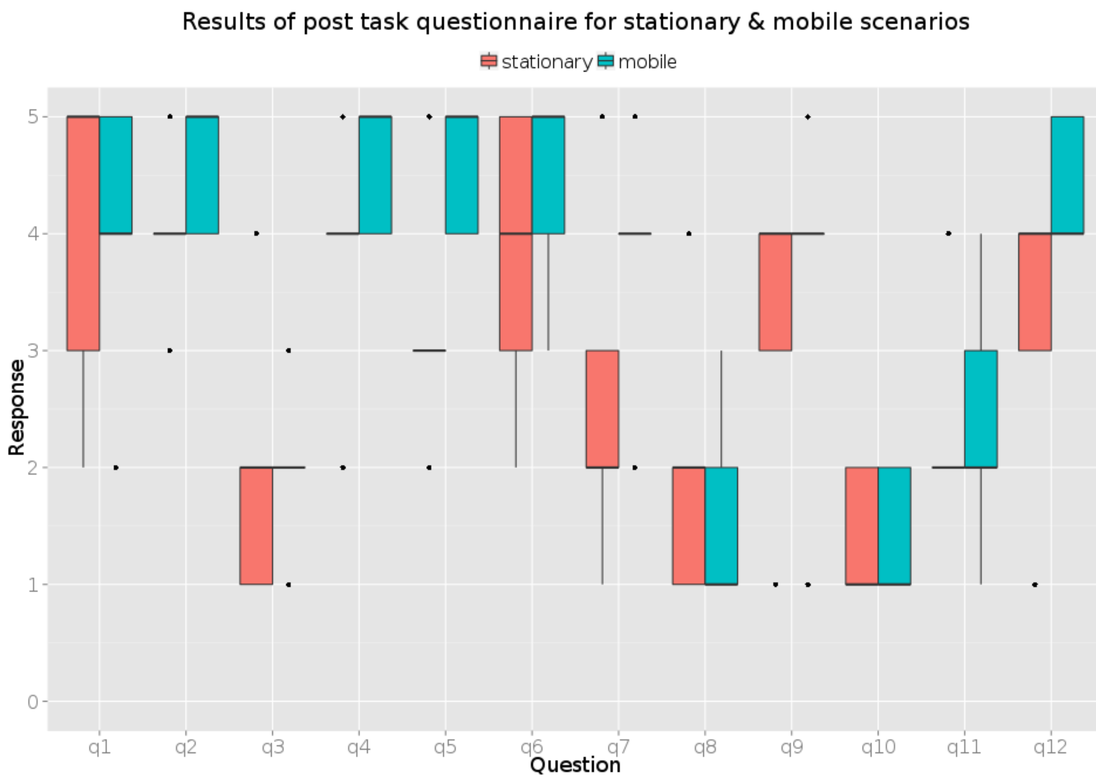


Figure 6.6: 12-item questionnaire results.

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).

6.10.4 Participant 1

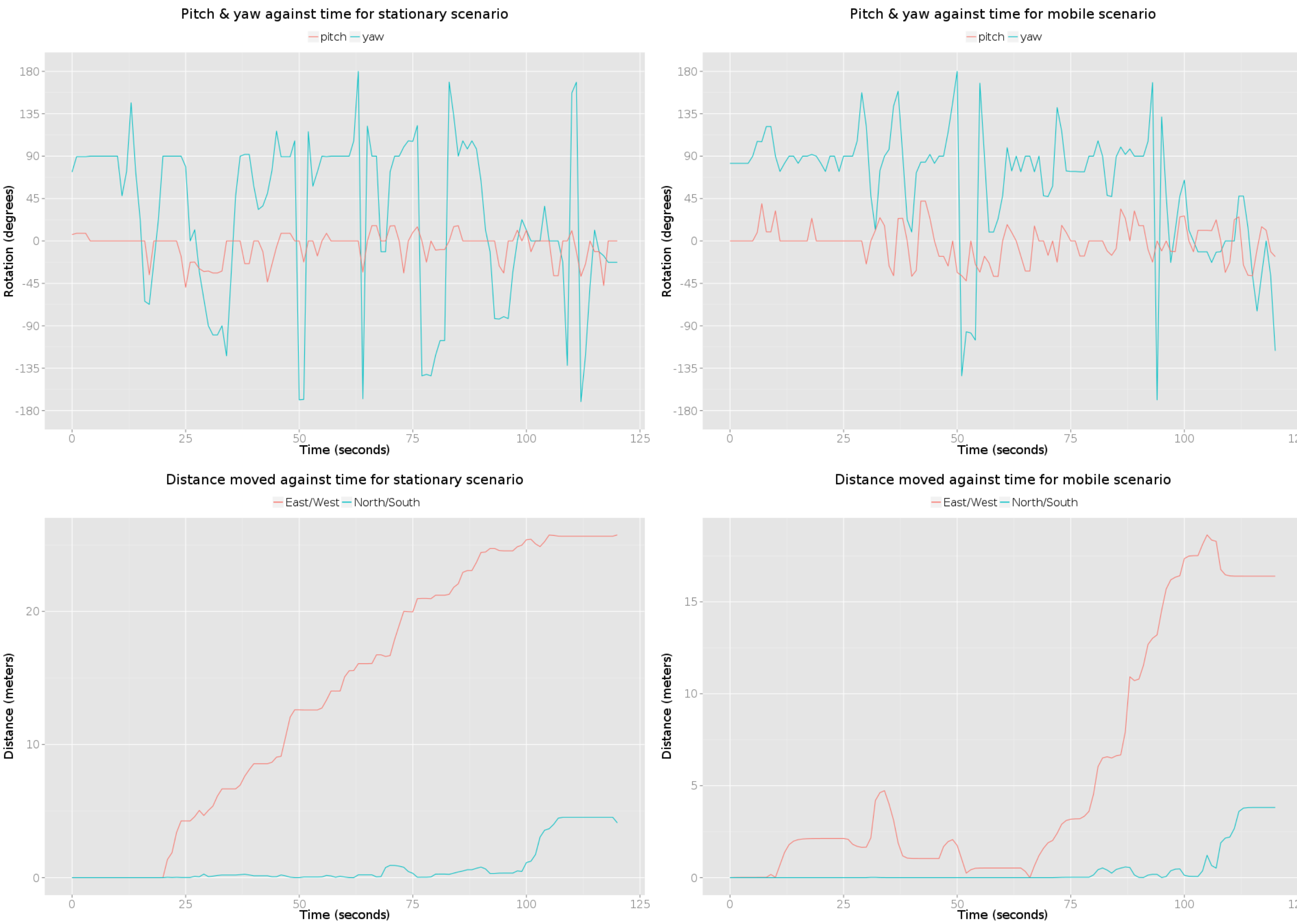


Figure 6.7: Some images, yah.

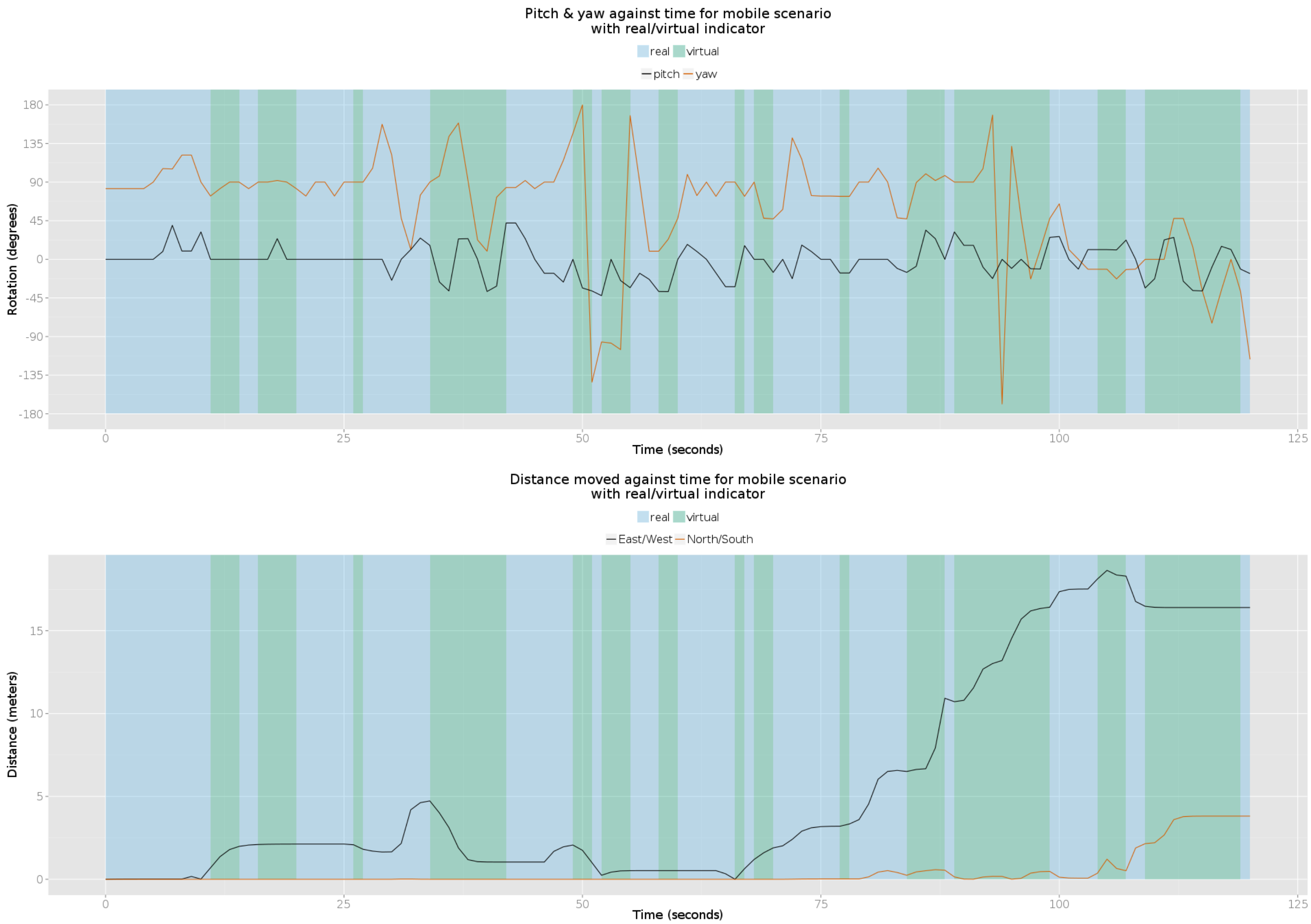


Figure 6.8: Some images, yah.

6.10.5 Participant 3

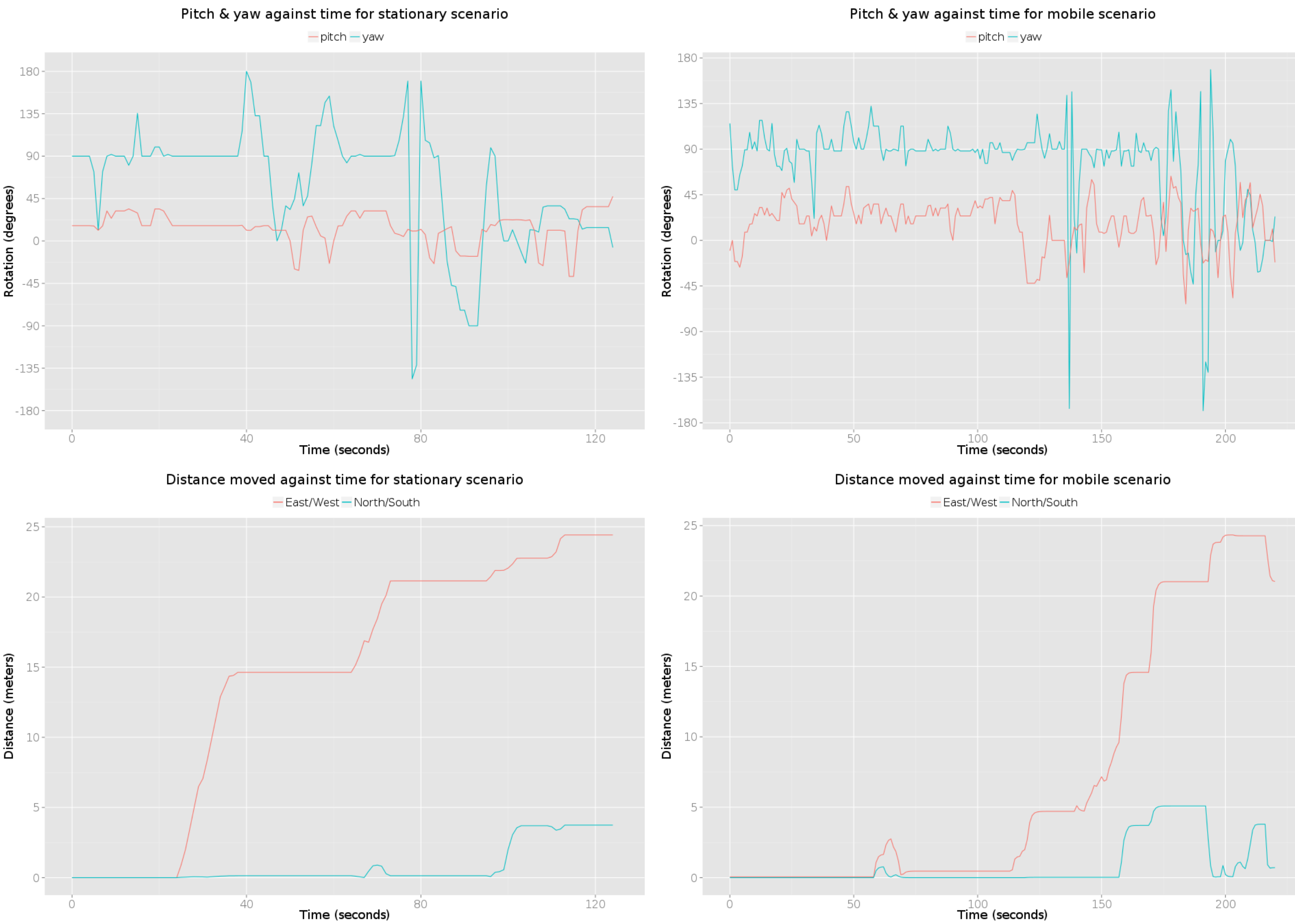


Figure 6.9: Some images, yah.

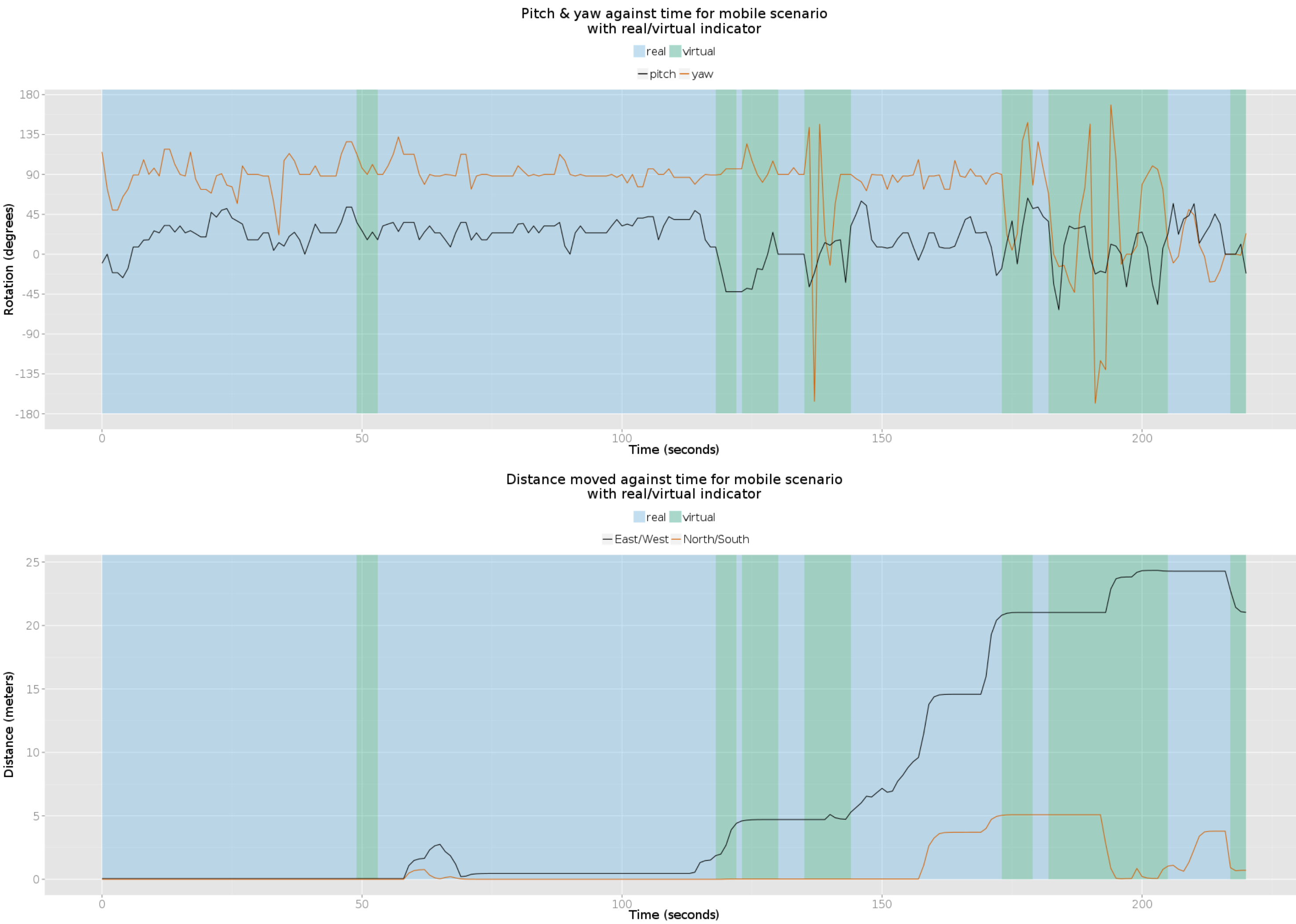
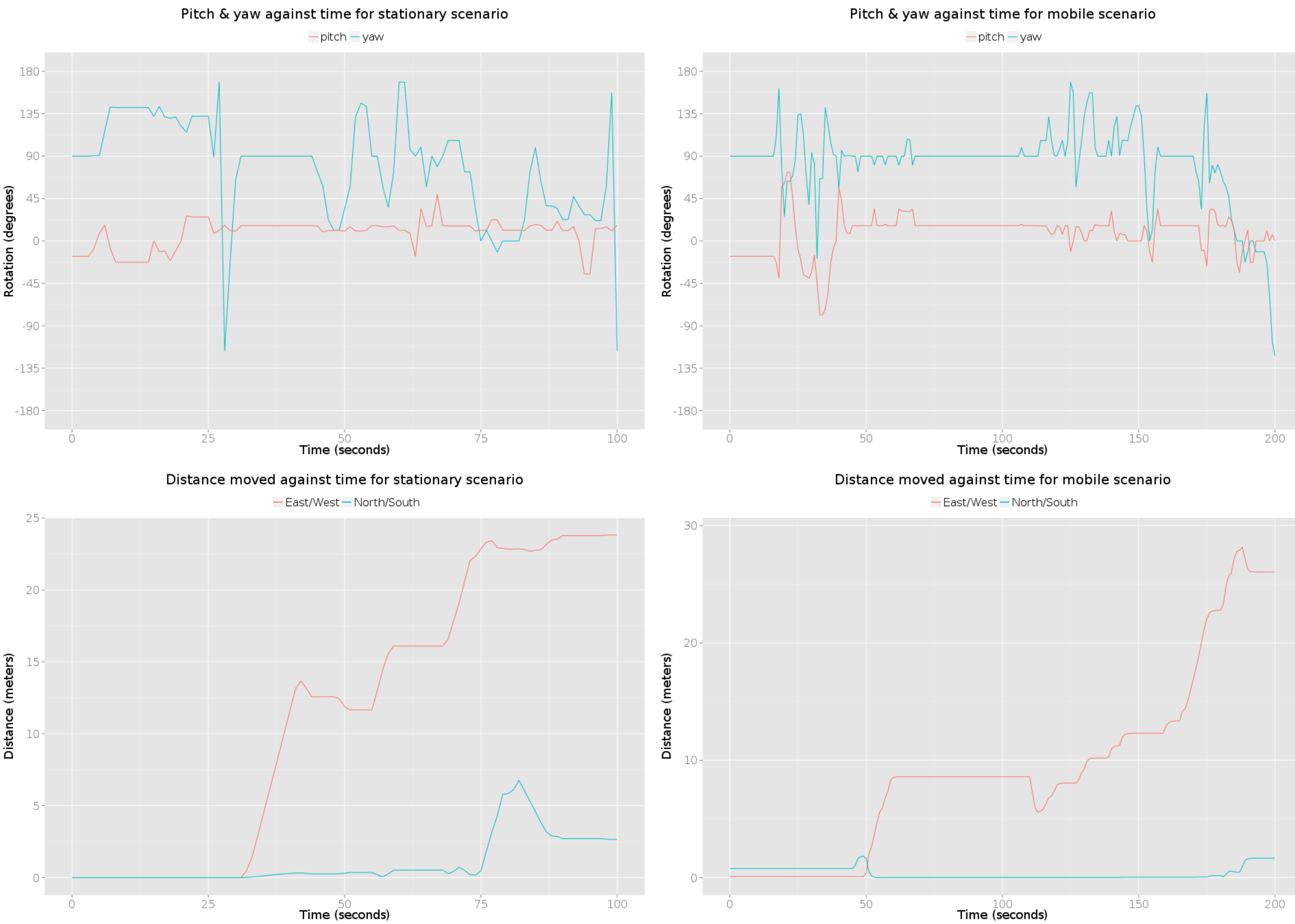


Figure 6.10: Some images, yah.

6.10.6 Participant 4



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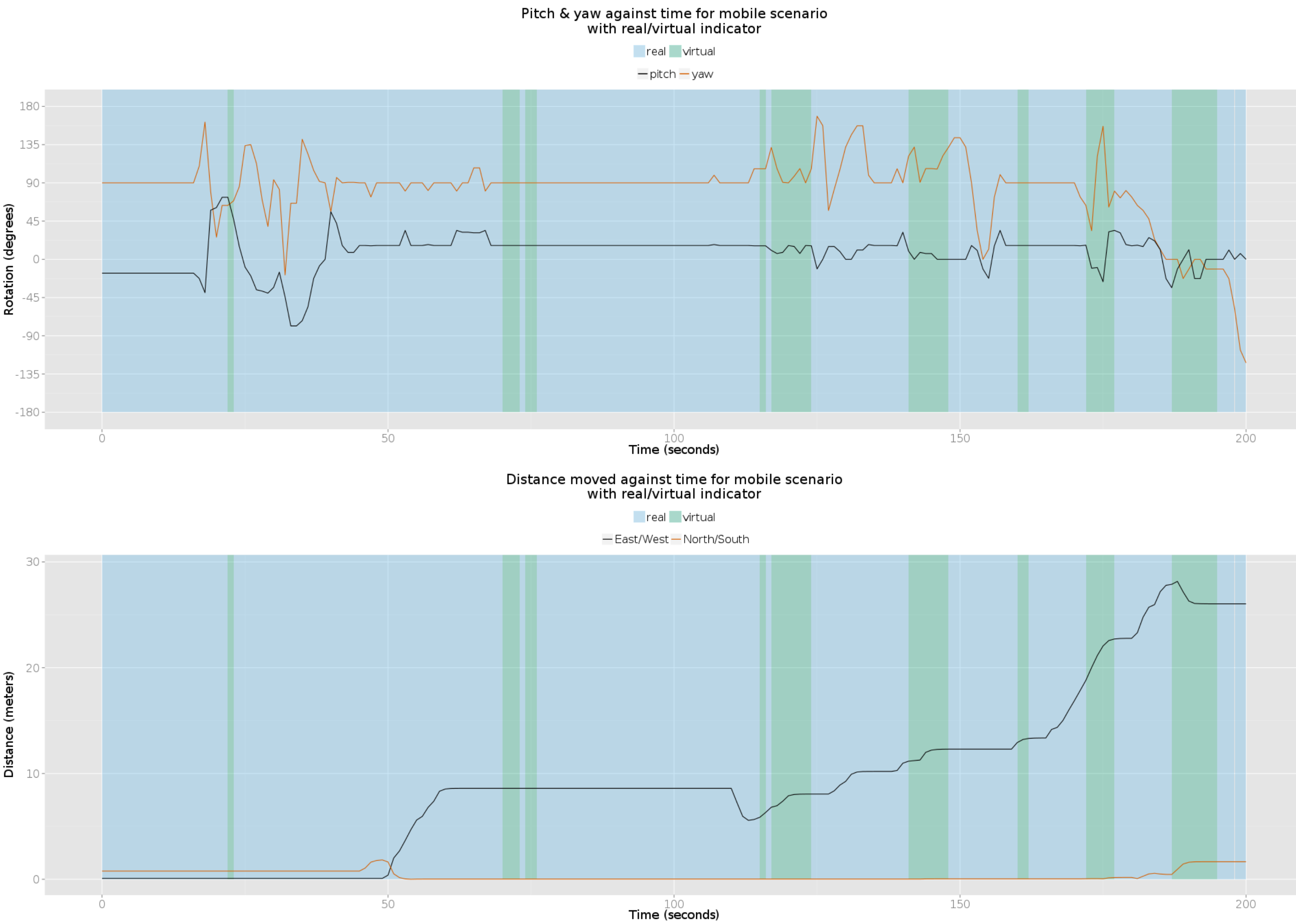
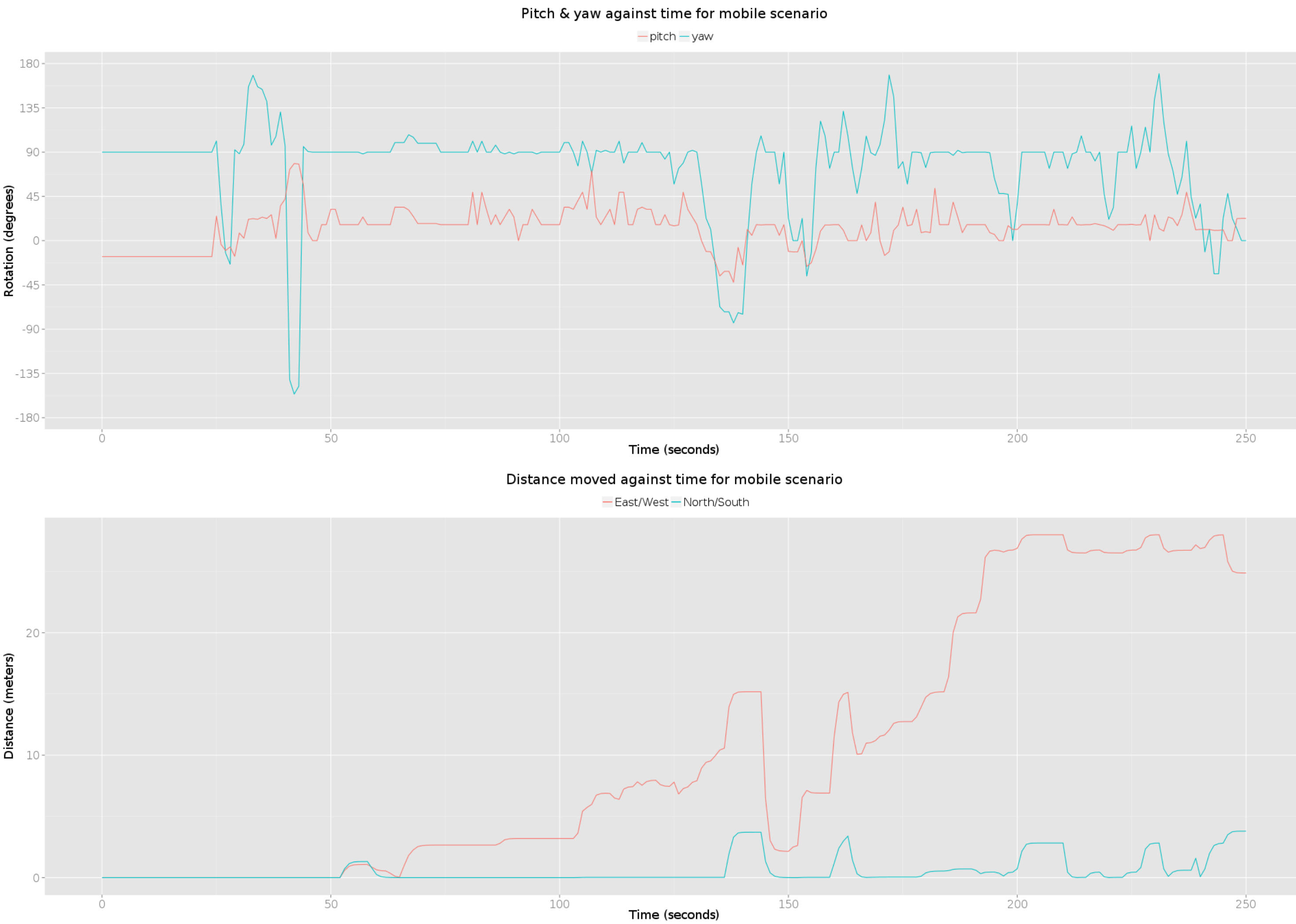


Figure 6.12: Some images, yah.

6.10.7 Participant 5



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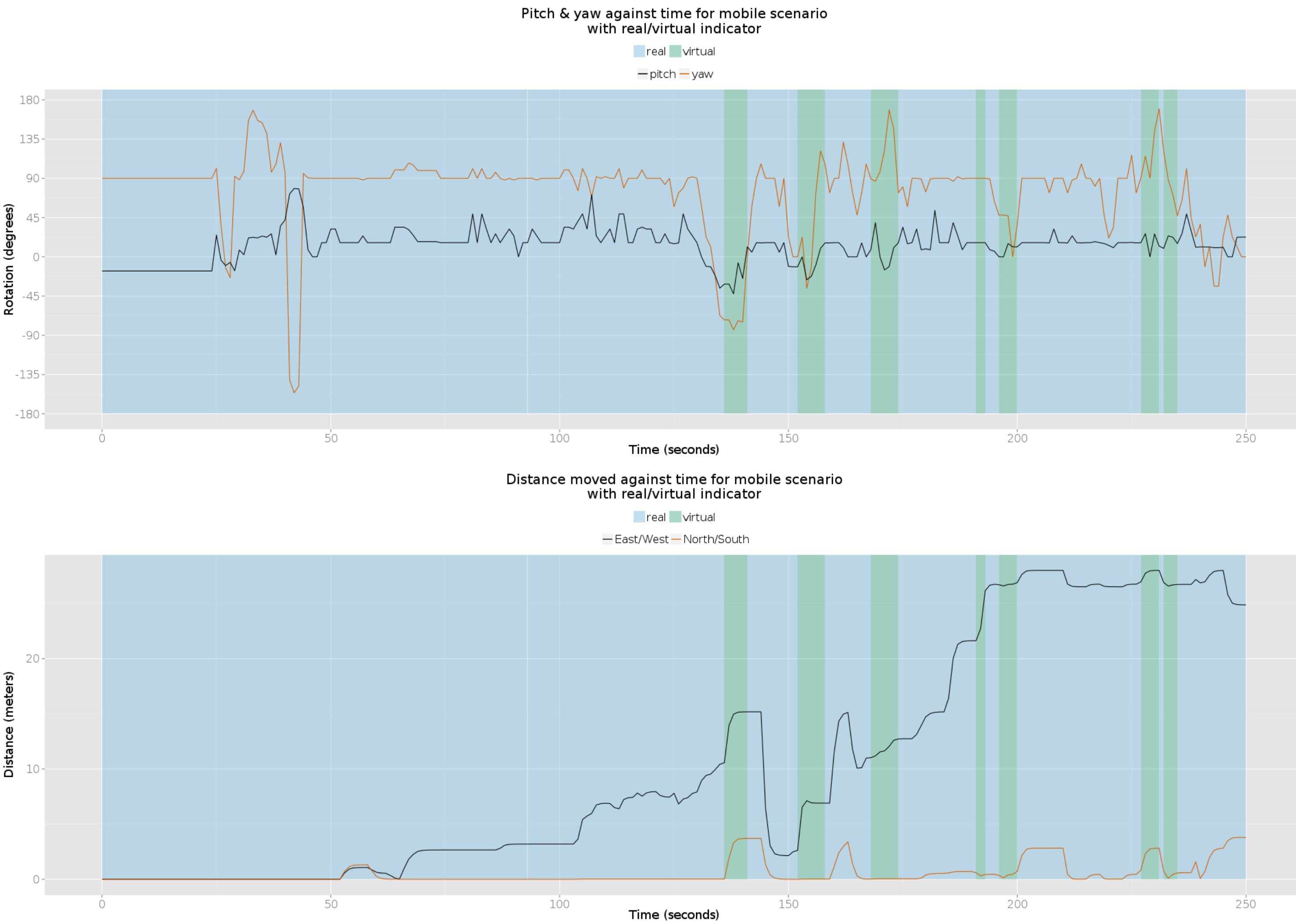

Figure 6.14: Some images, yah.

6.10.8 Participant 6

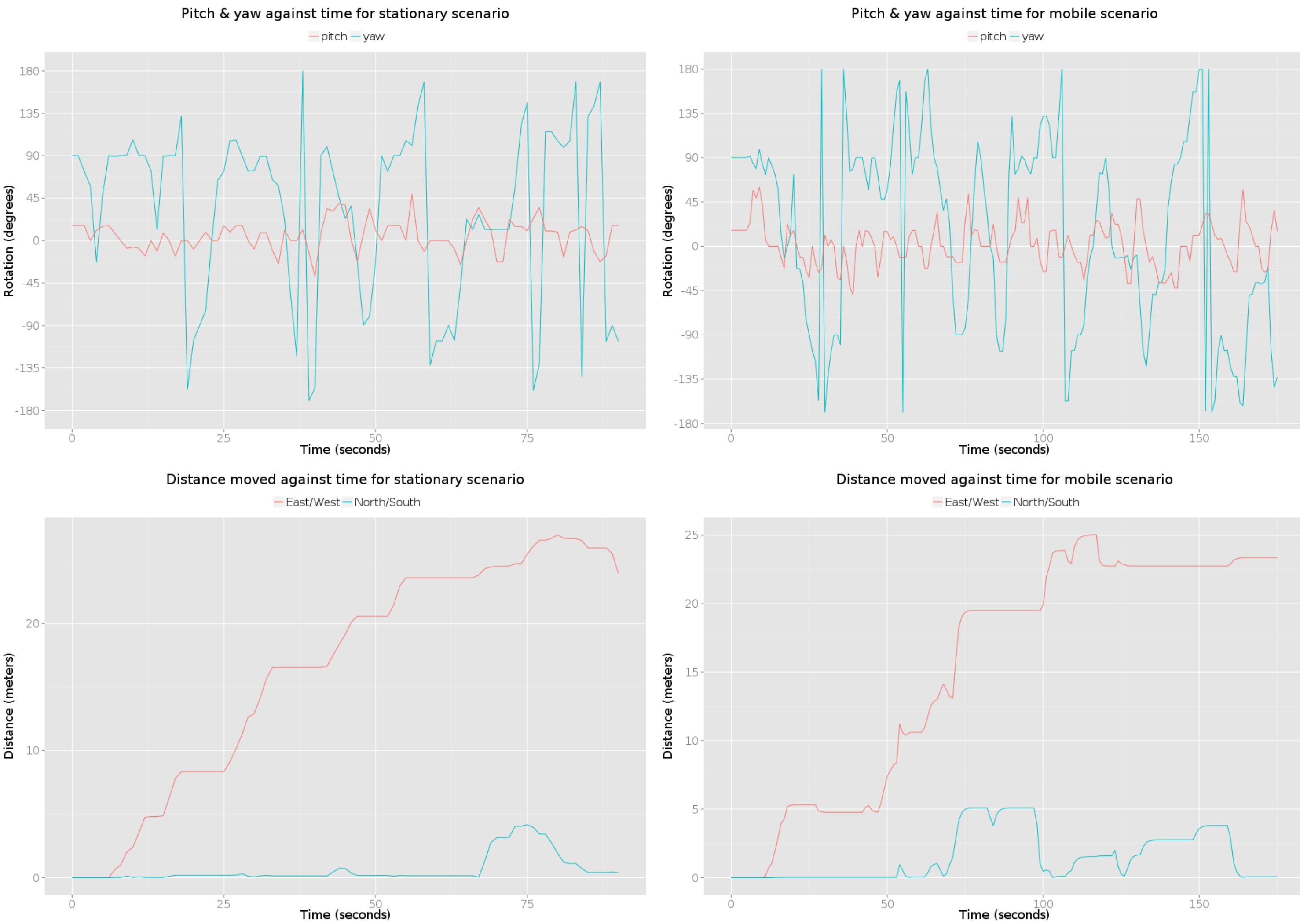

Figure 6.15: Some images, yah.

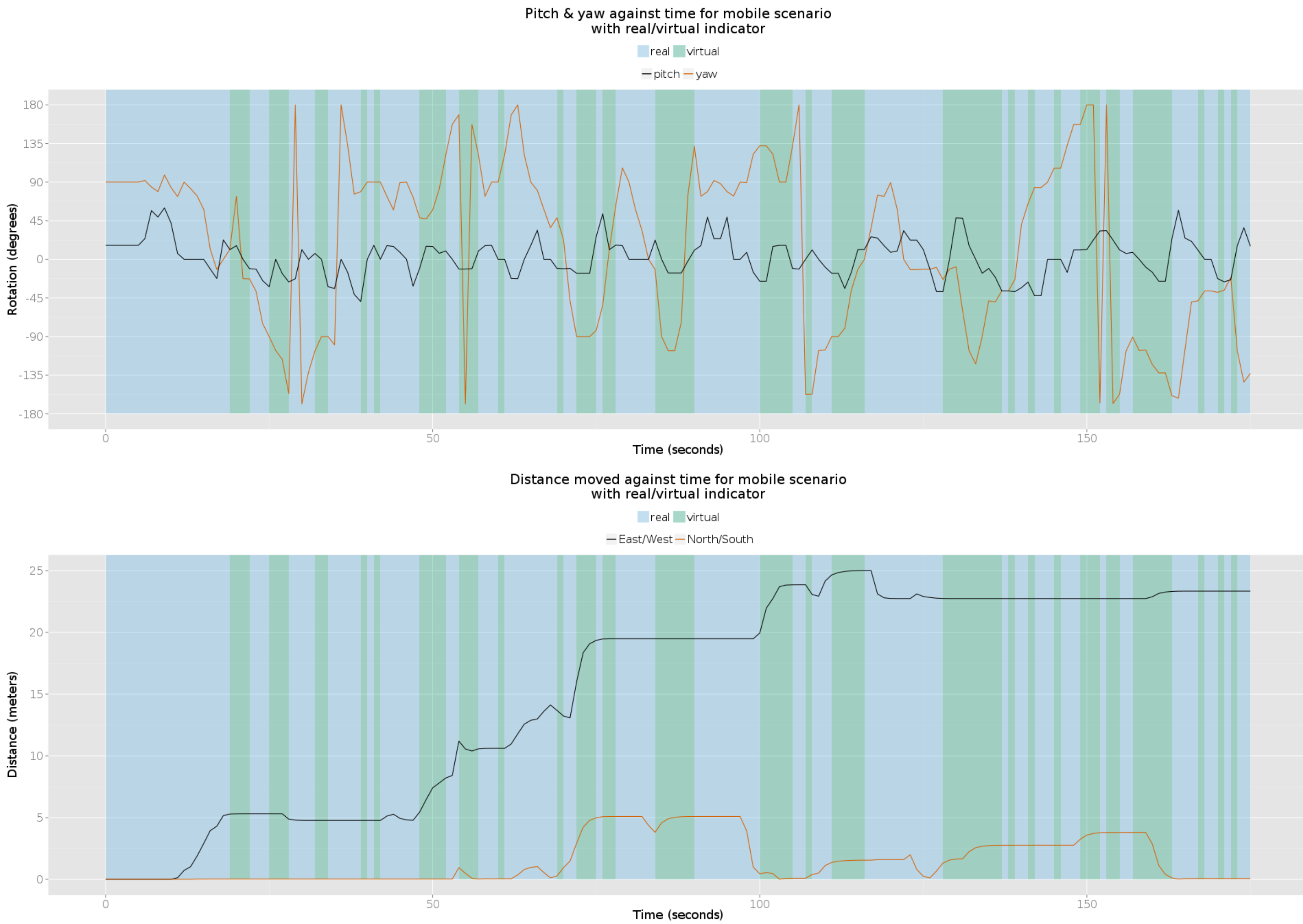

Figure 6.16: Some images, yah.

6.11 Phase 2.1 Results

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Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

Nulla malesuada porttitor diam. Donec felis erat, congue non, volutpat at, tincidunt tristique, libero. Vivamus viverra fermentum felis. Donec nonummy pellentesque ante. Phasellus adipiscing semper elit. Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo. Maecenas lacinia. Nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem. Sed lacinia nulla vitae enim. Pellentesque tincidunt purus vel magna. Integer non enim. Praesent euismod nunc eu purus. Donec bibendum quam in tellus. Nullam cursus pulvinar lectus. Donec et mi. Nam vulputate metus eu enim. Vestibulum pellentesque felis eu massa.

6.11.1 Participant 7

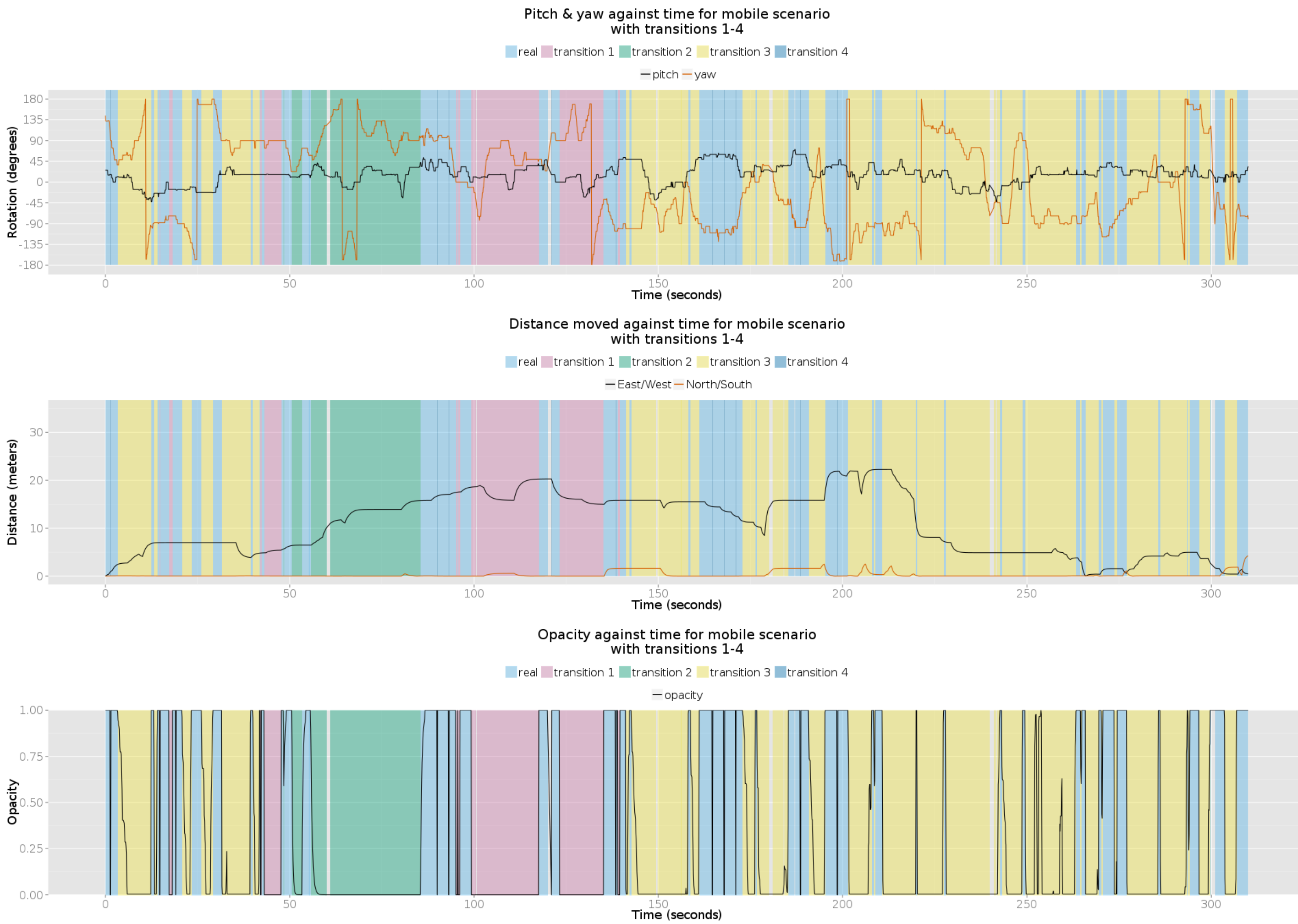
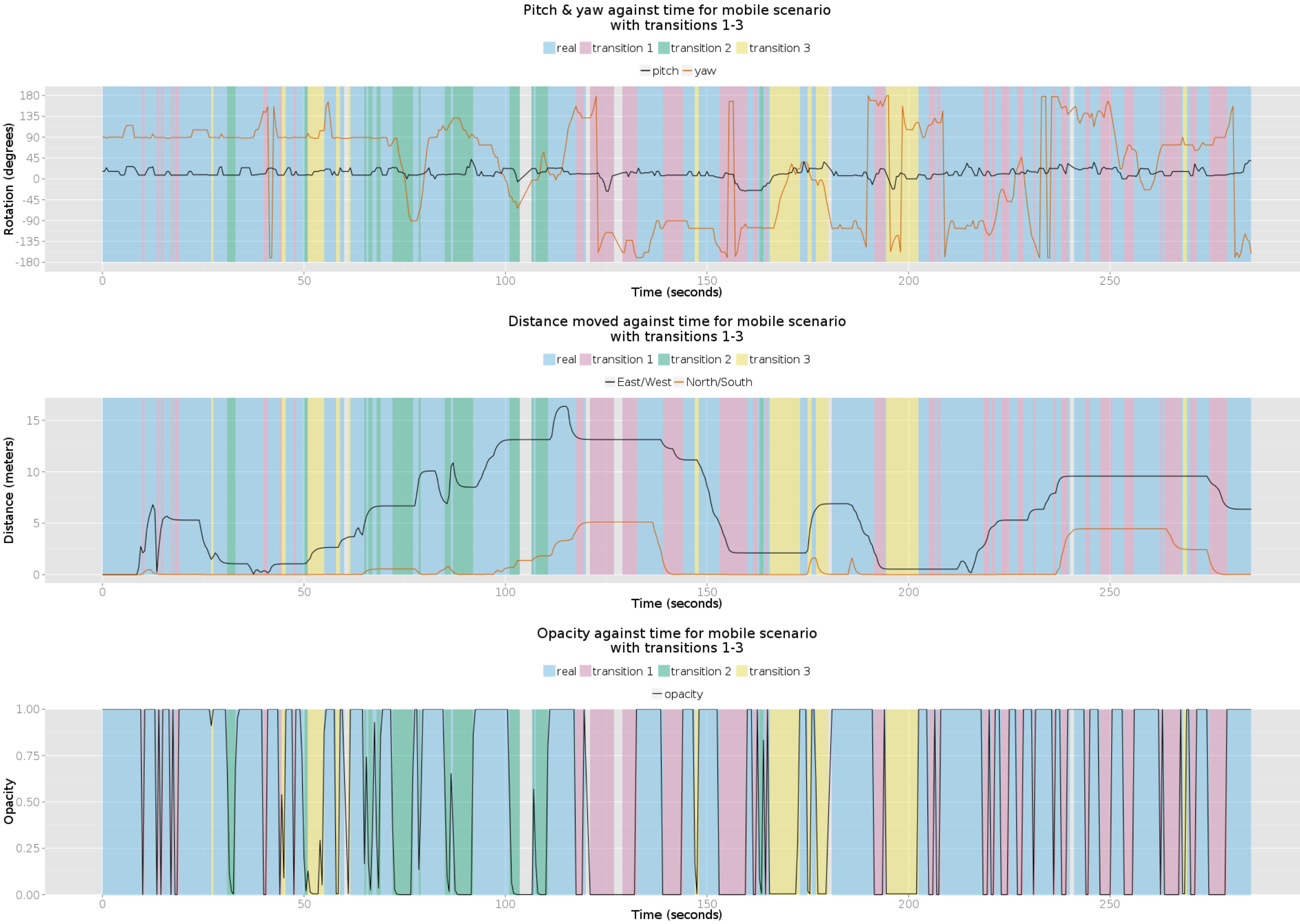


Figure 6.17: Some images, yah.

6.11.2 Participant 8



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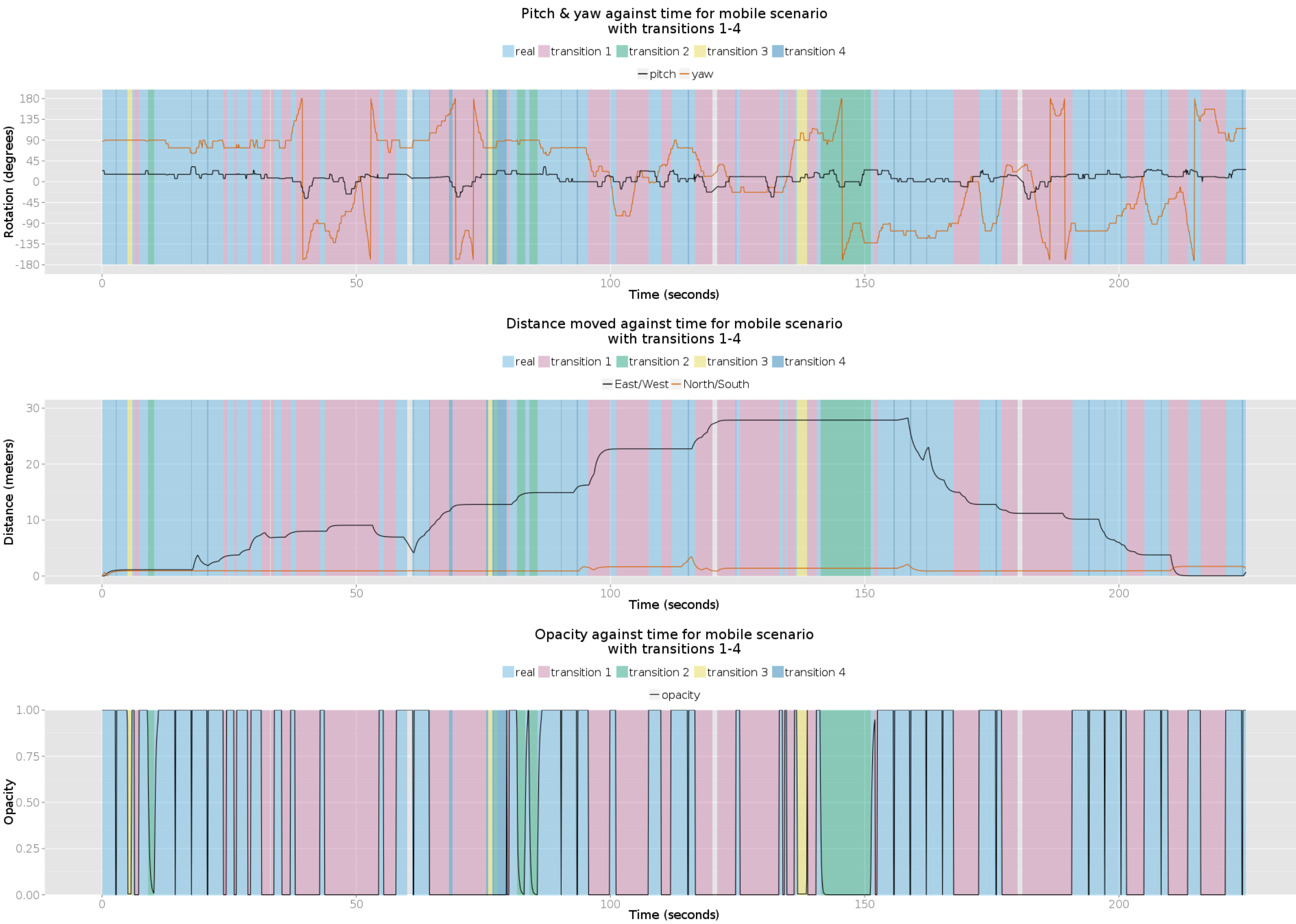

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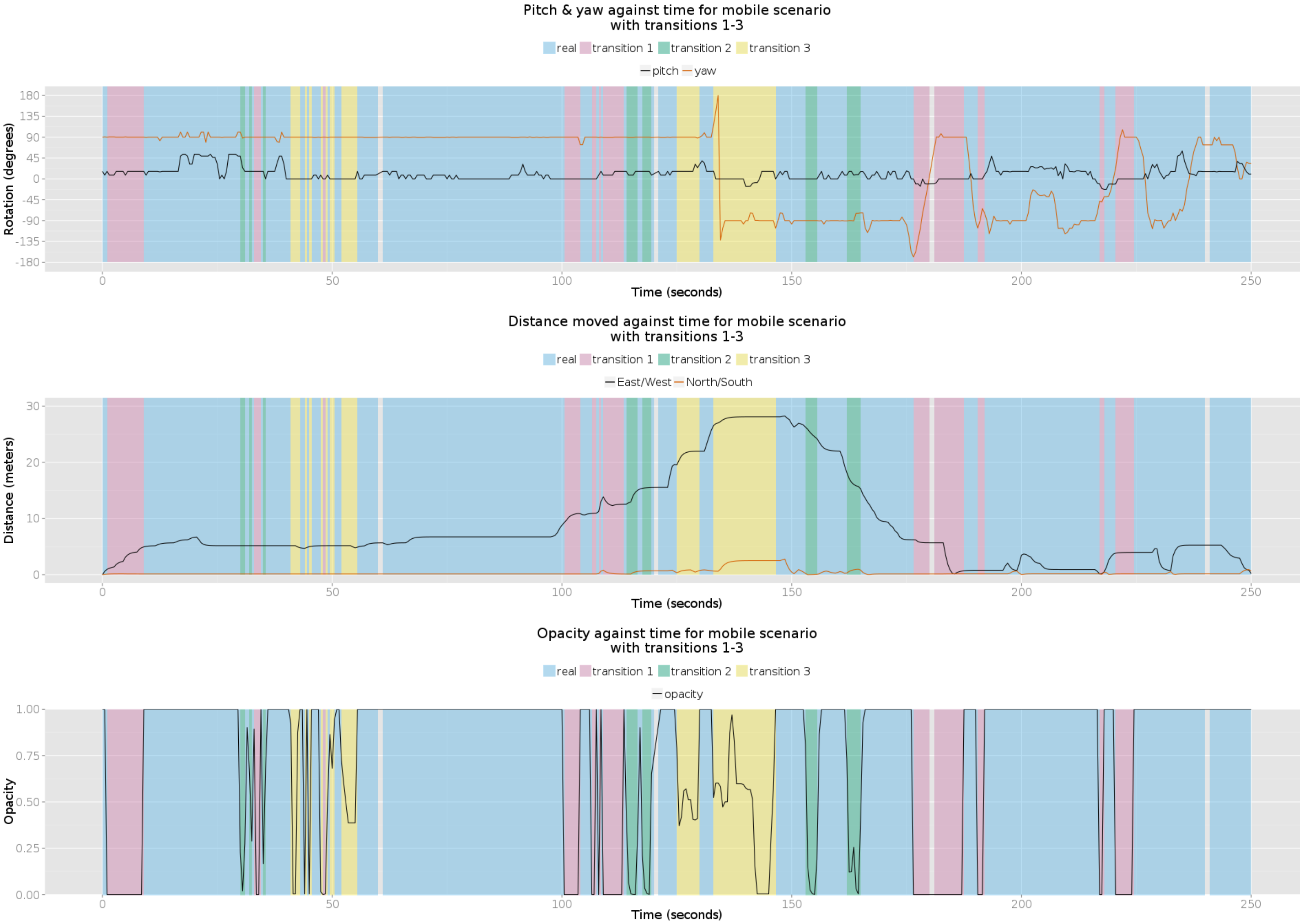
6.11.3 Participant 9



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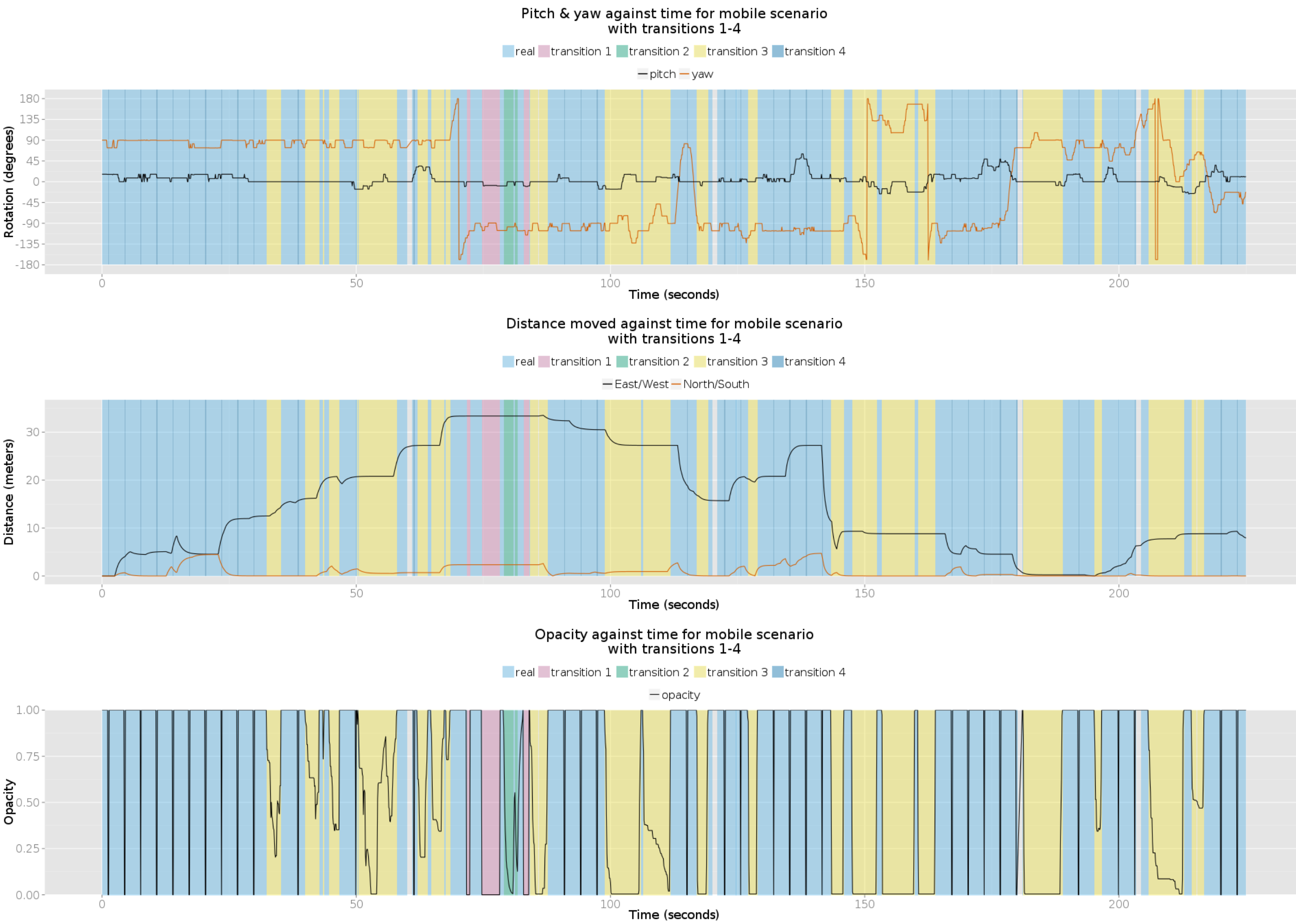

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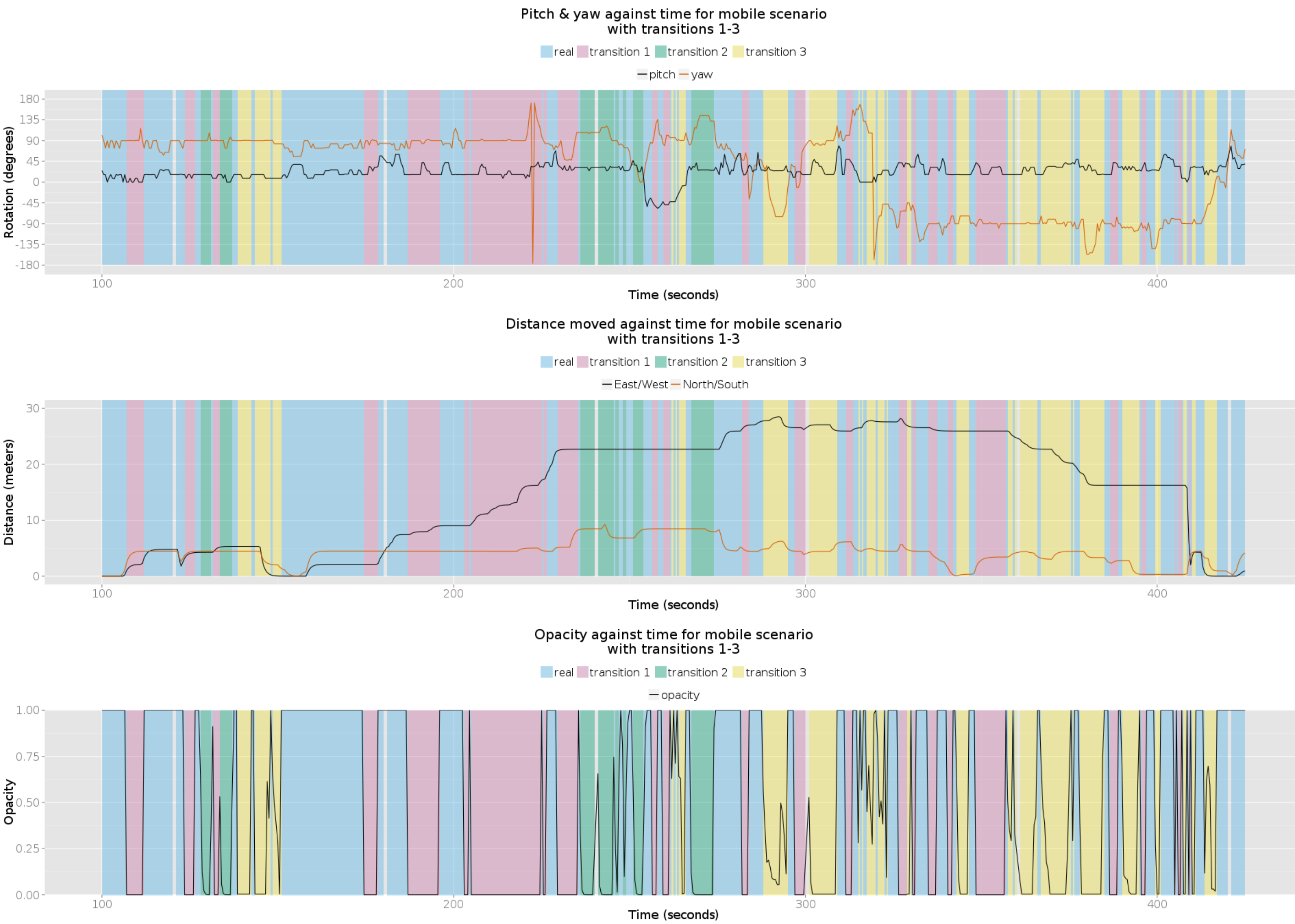
6.11.4 Participant 10



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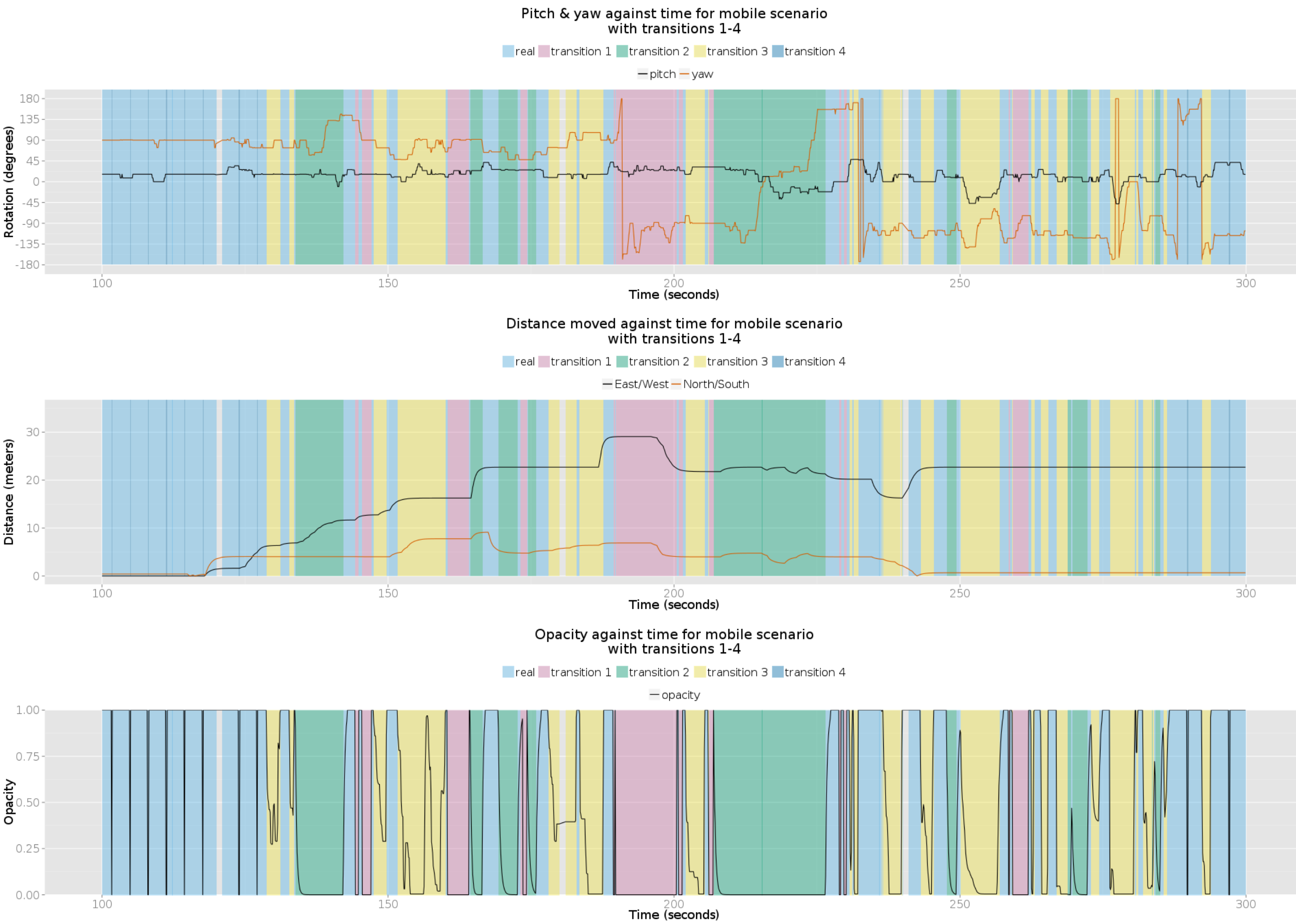
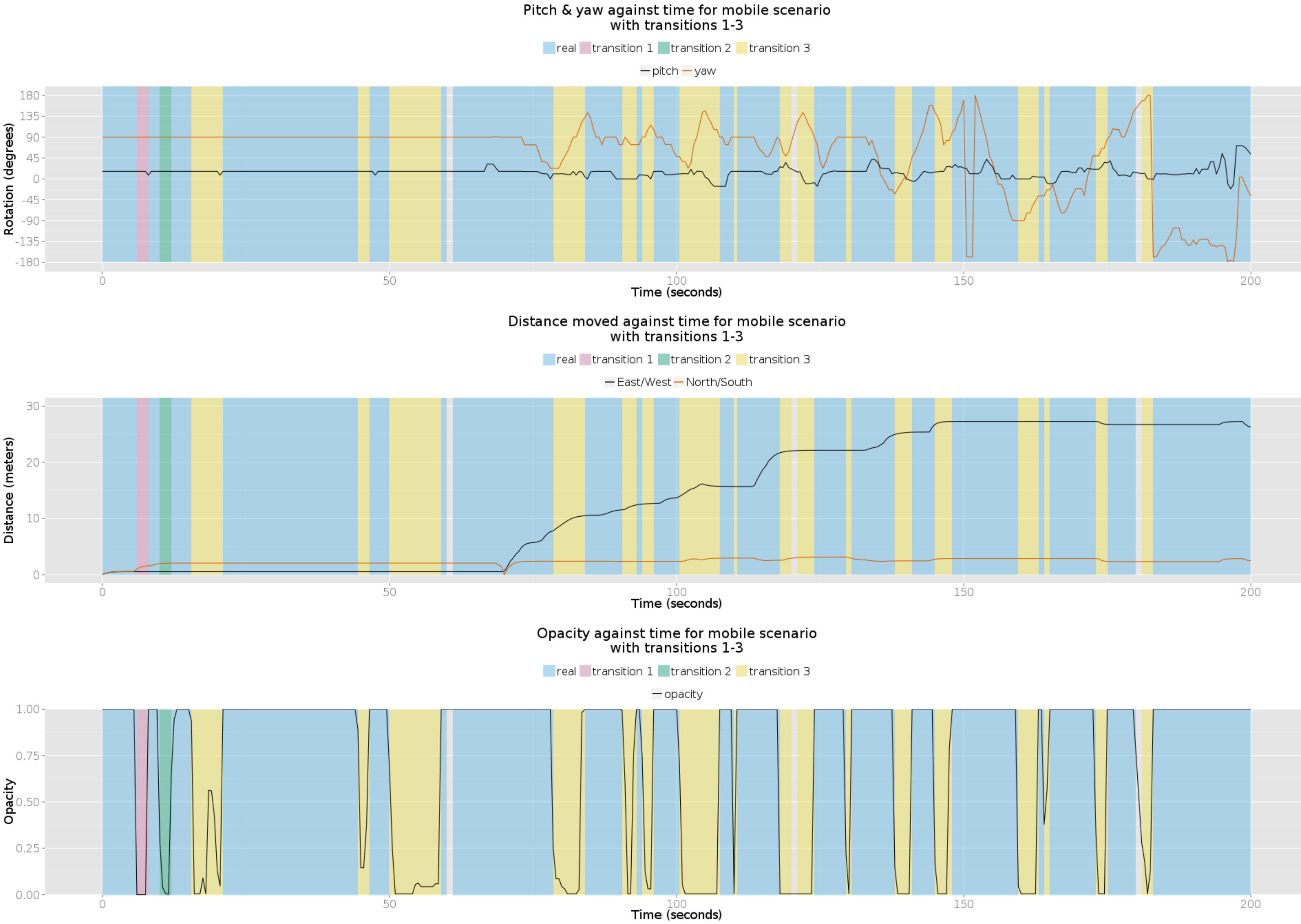


Figure 6.23: Some images, yah.

6.11.5 Participant 11



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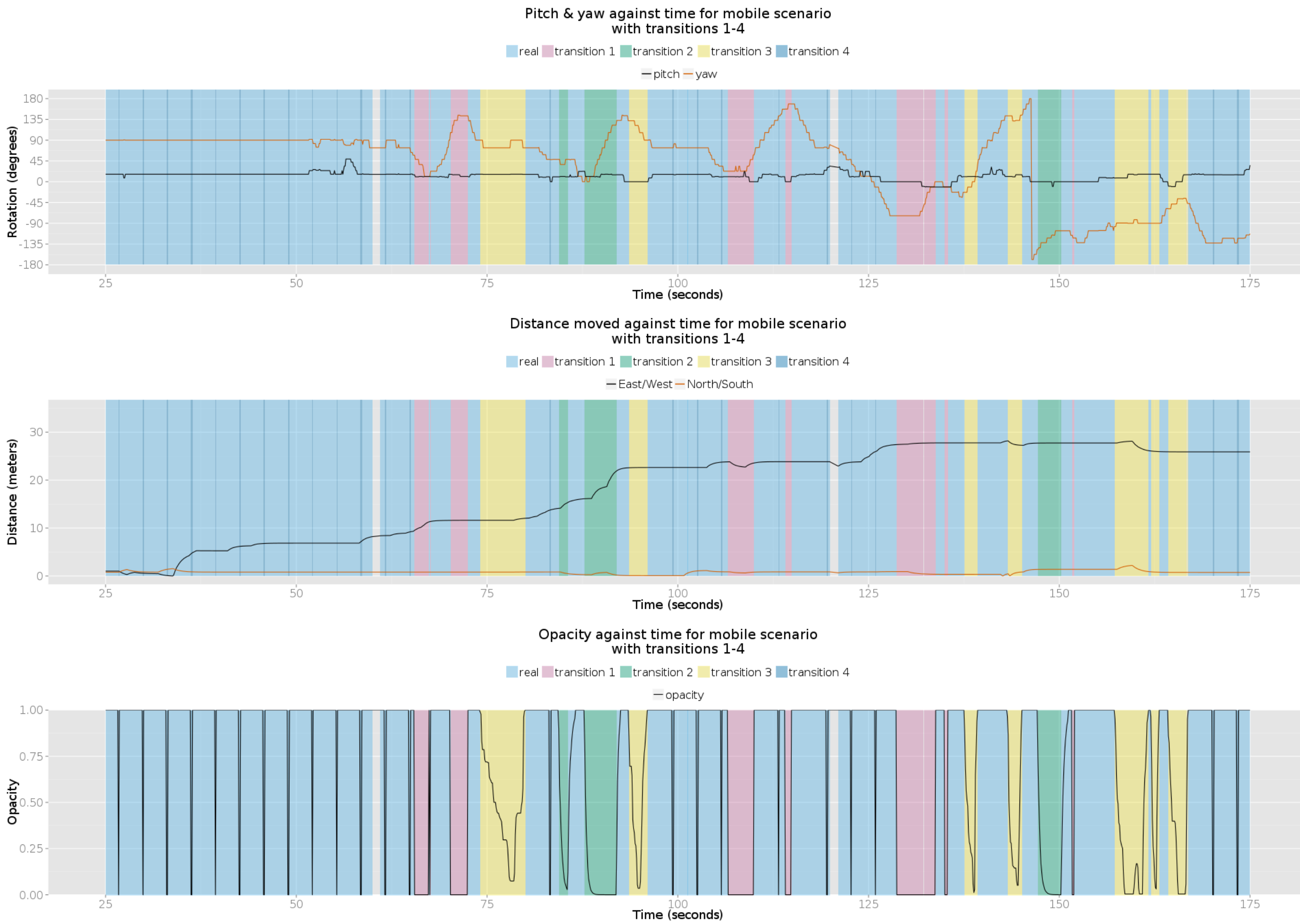
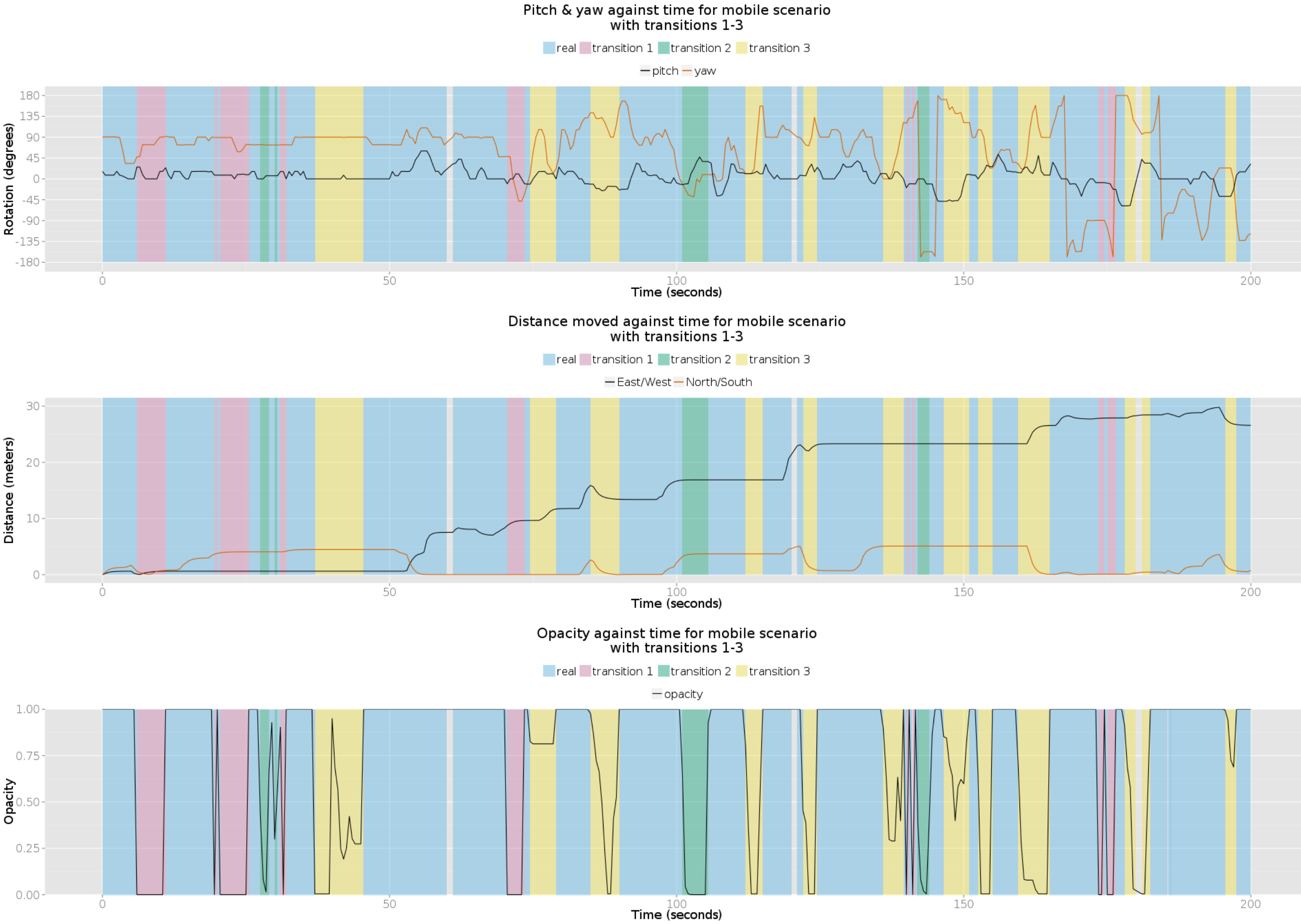


Figure 6.25: Some images, yah.

6.11.6 Participant 12



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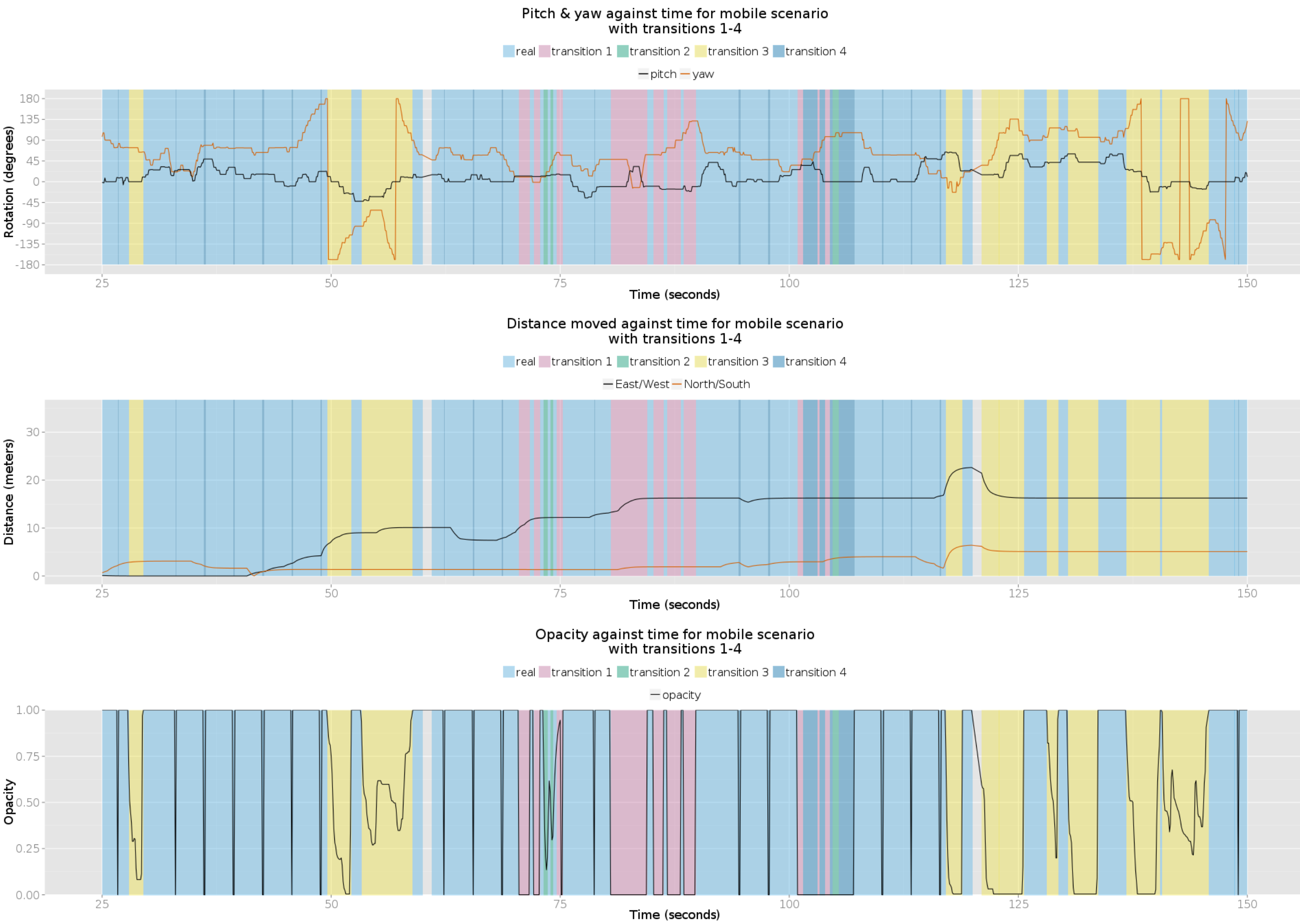
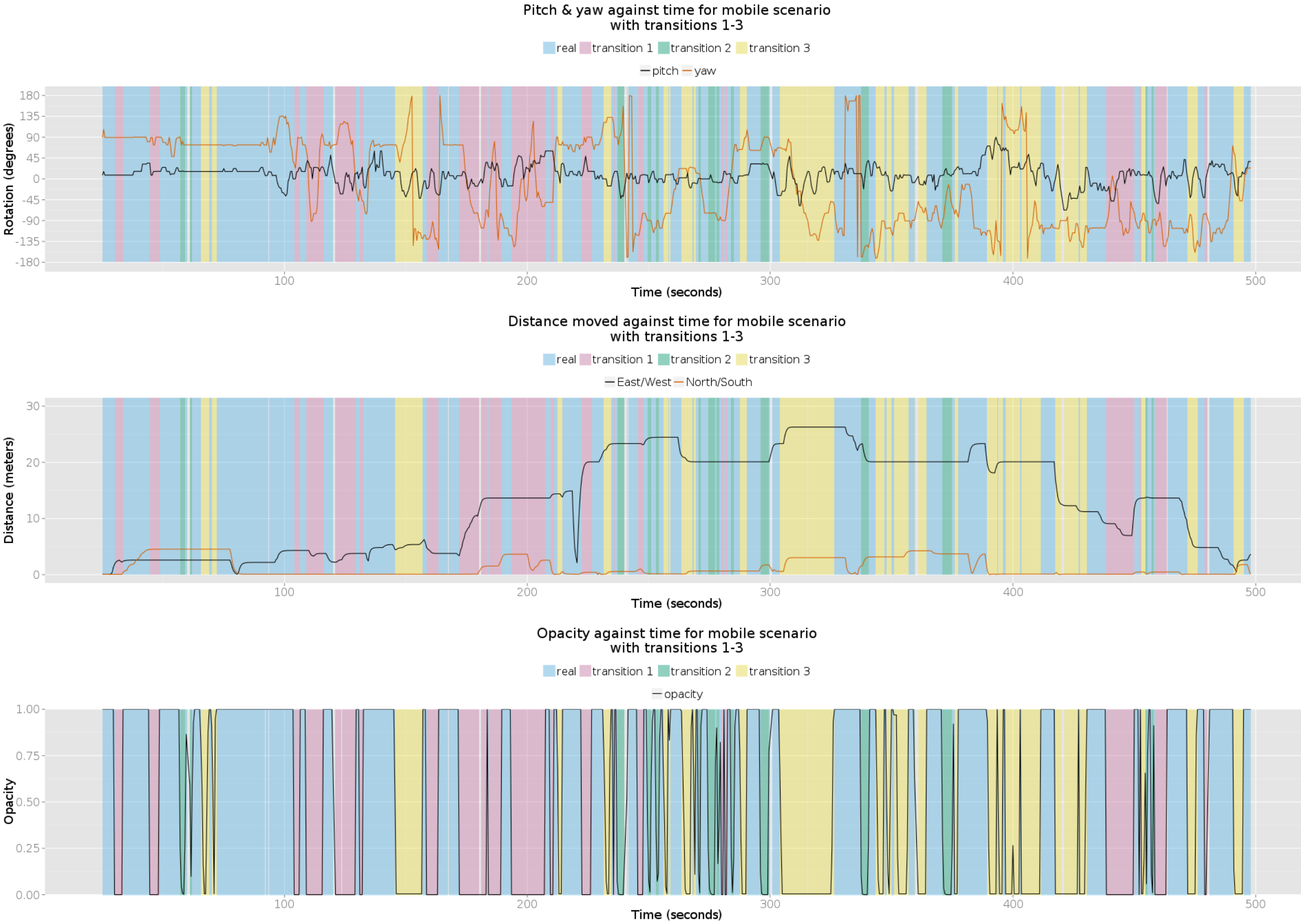


Figure 6.27: Some images, yah.

6.11.7 Participant 13



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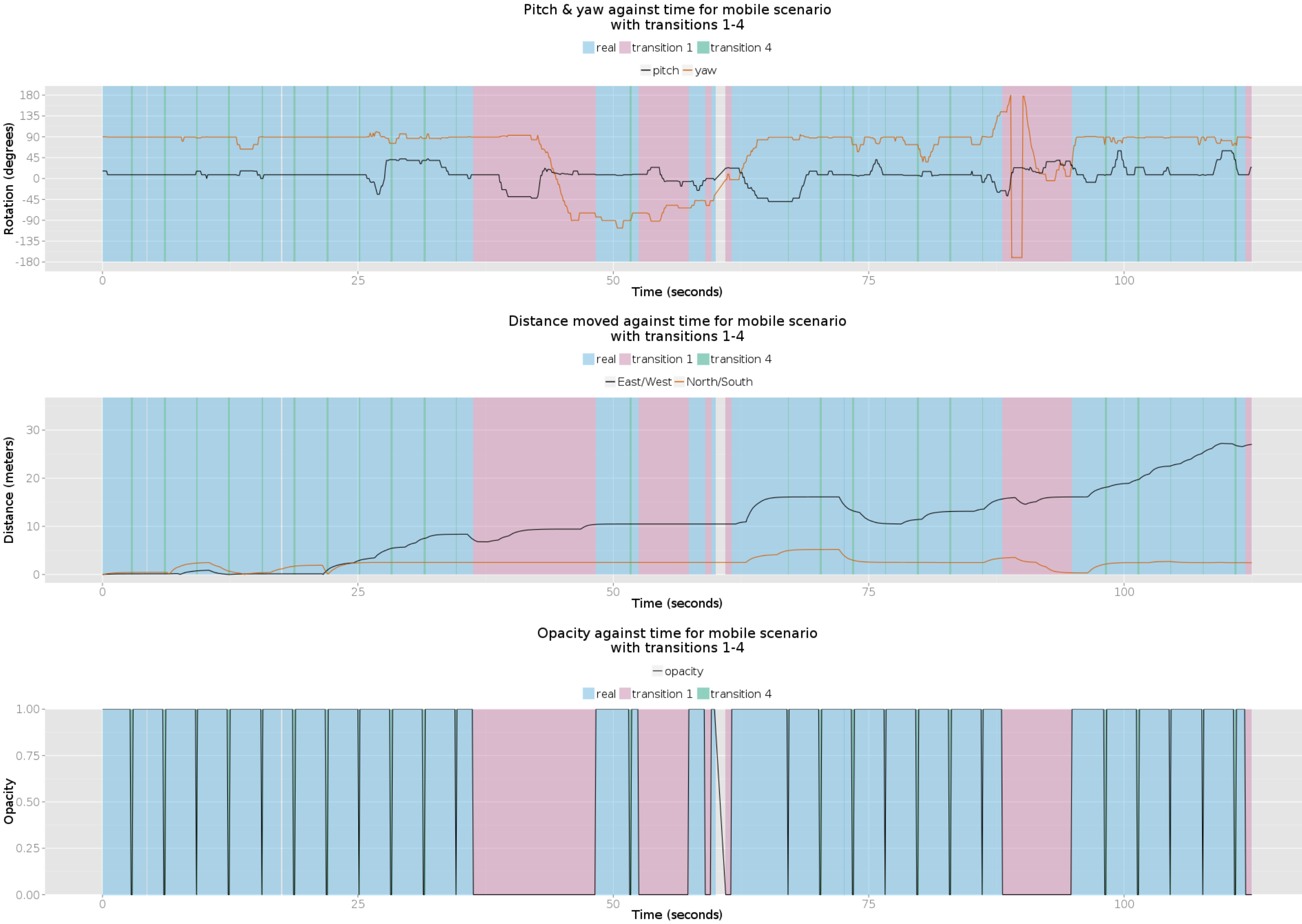


Figure 6.29: Some images, yah.

6.12 Phase 2.2 Results

6.12.1 Participant 14

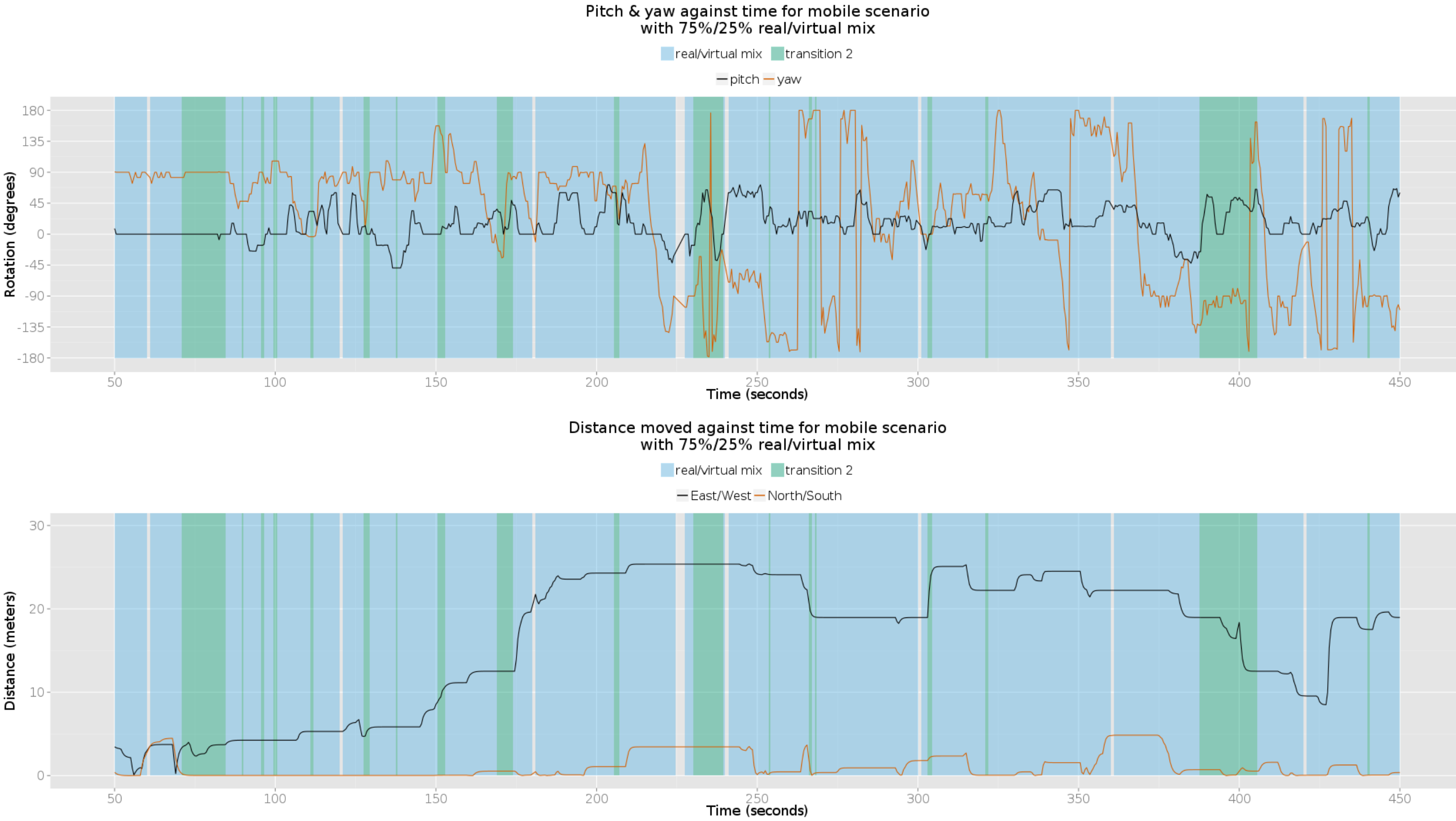


Figure 6.30: Some images, yah.

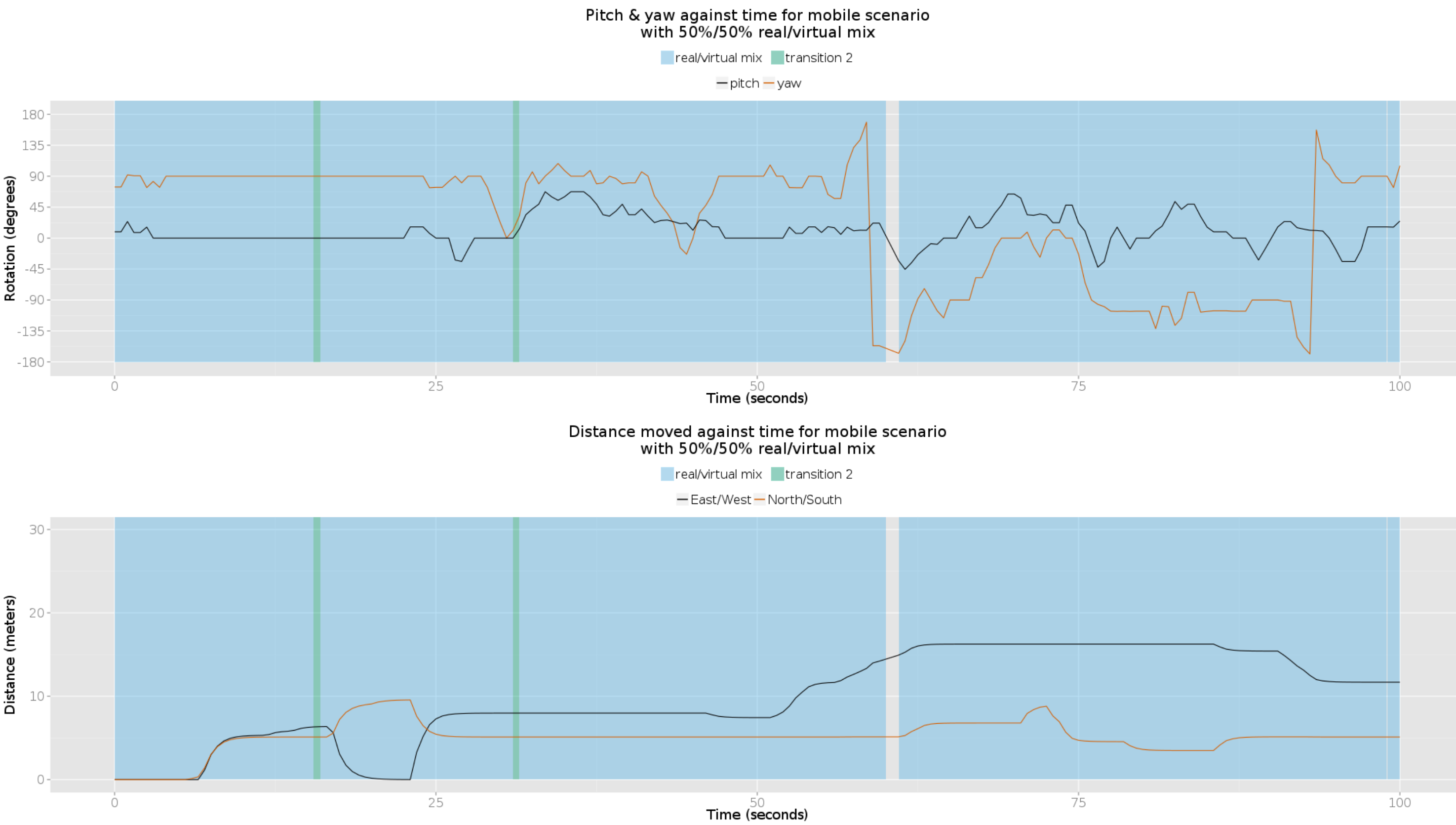
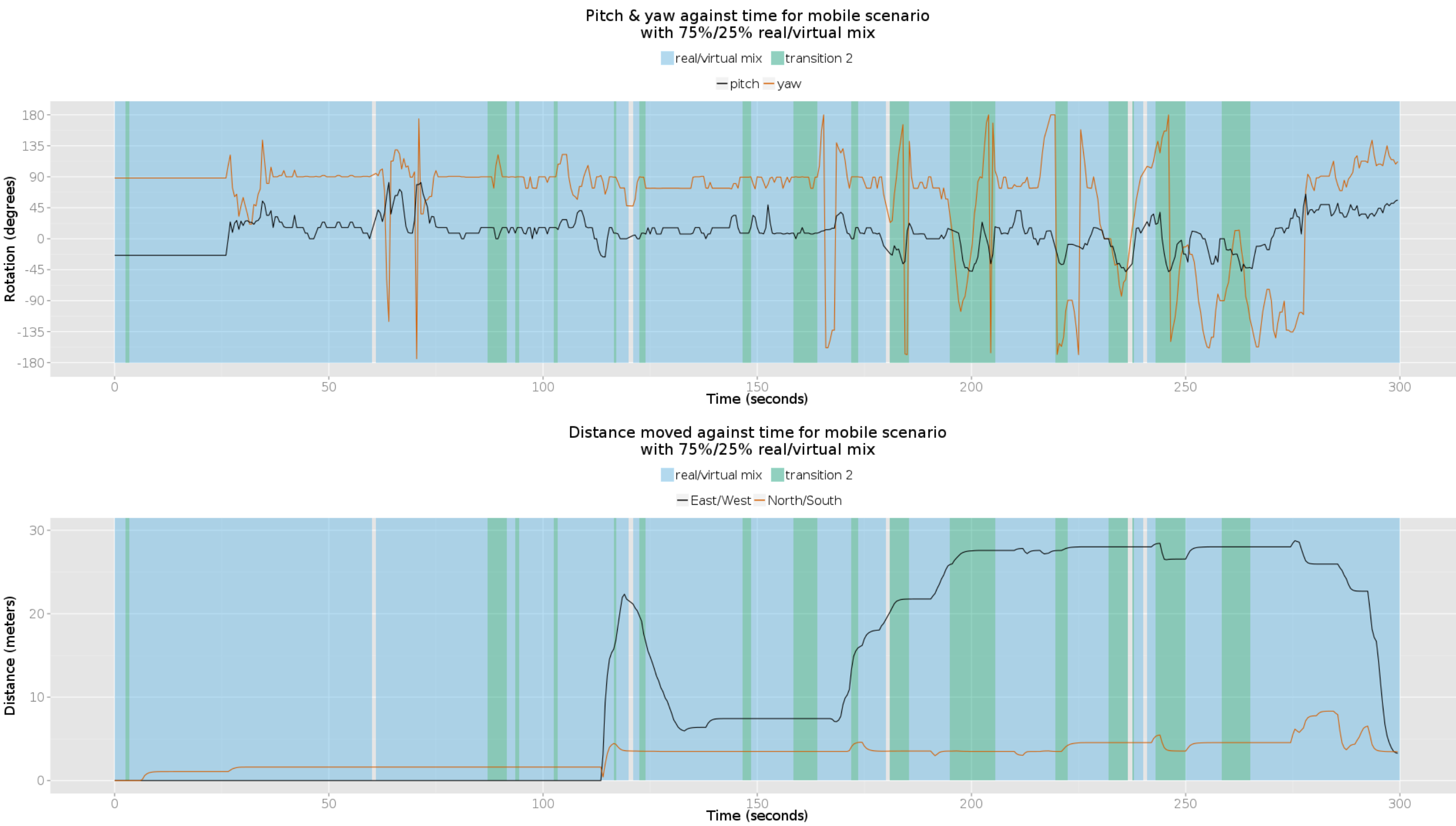


Figure 6.31: Some images, yah.

6.12.2 Participant 15



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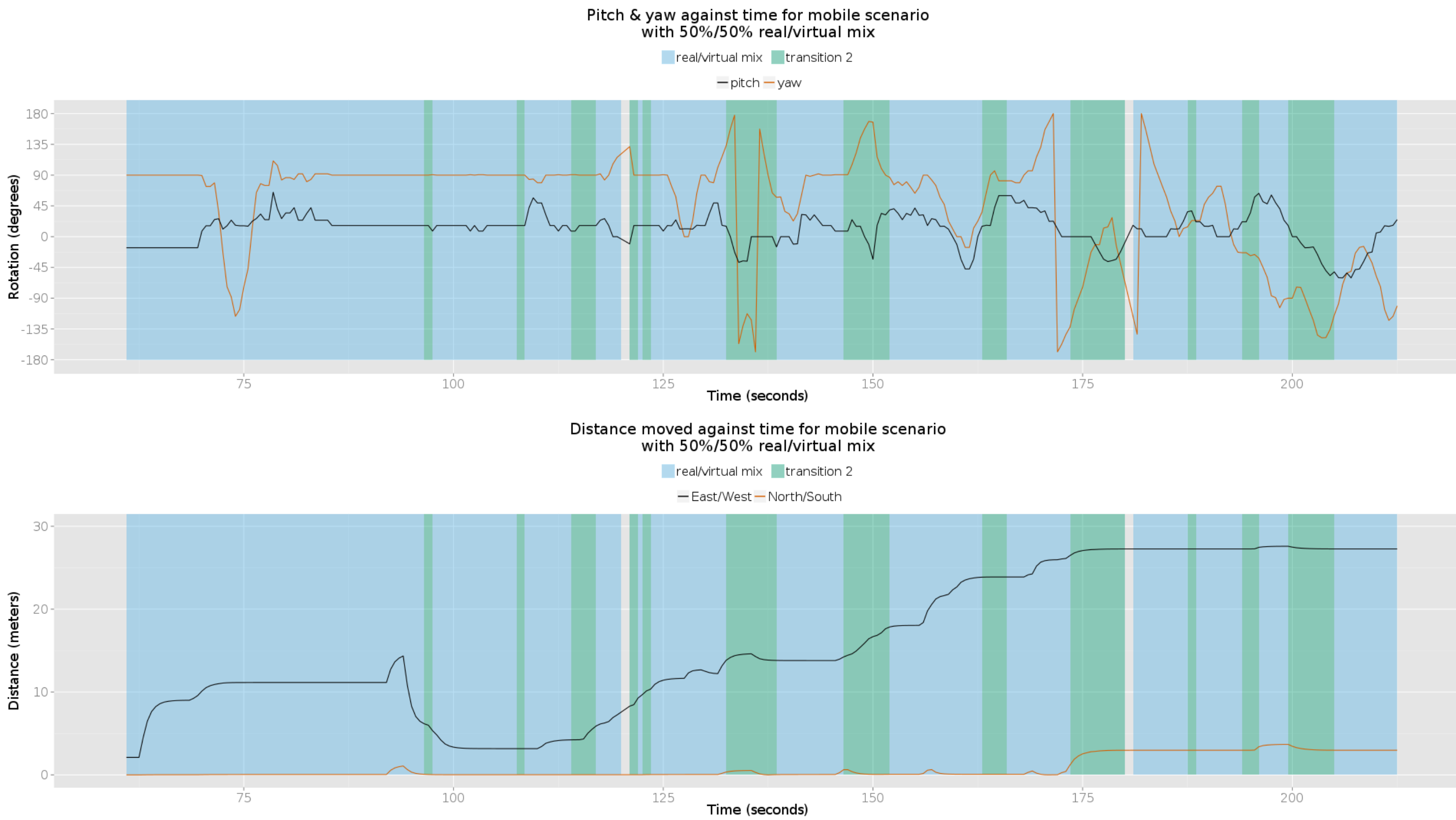

Figure 6.33: Some images, yah.

6.12.3 Participant 16

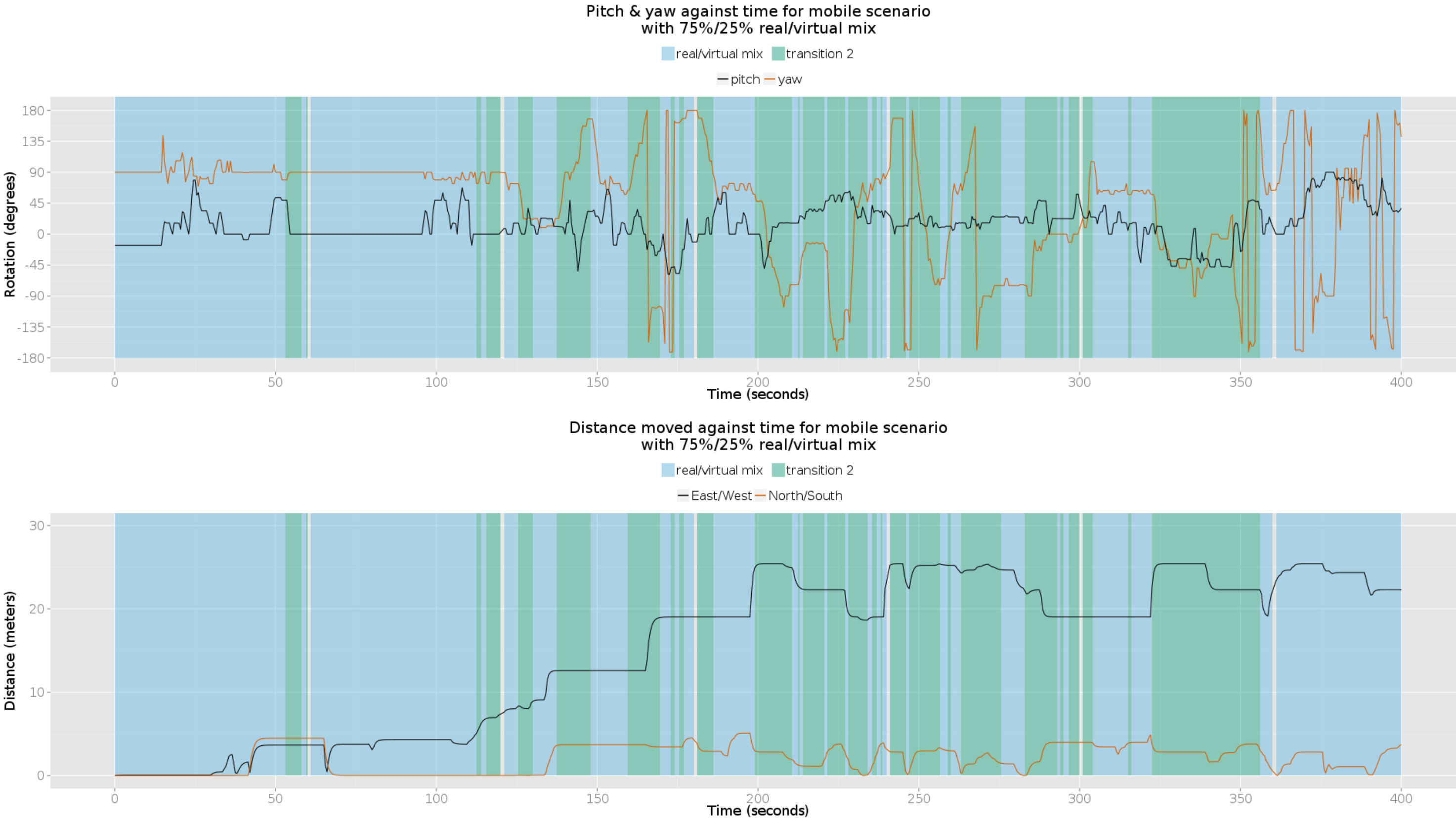

Figure 6.34: Some images, yah.

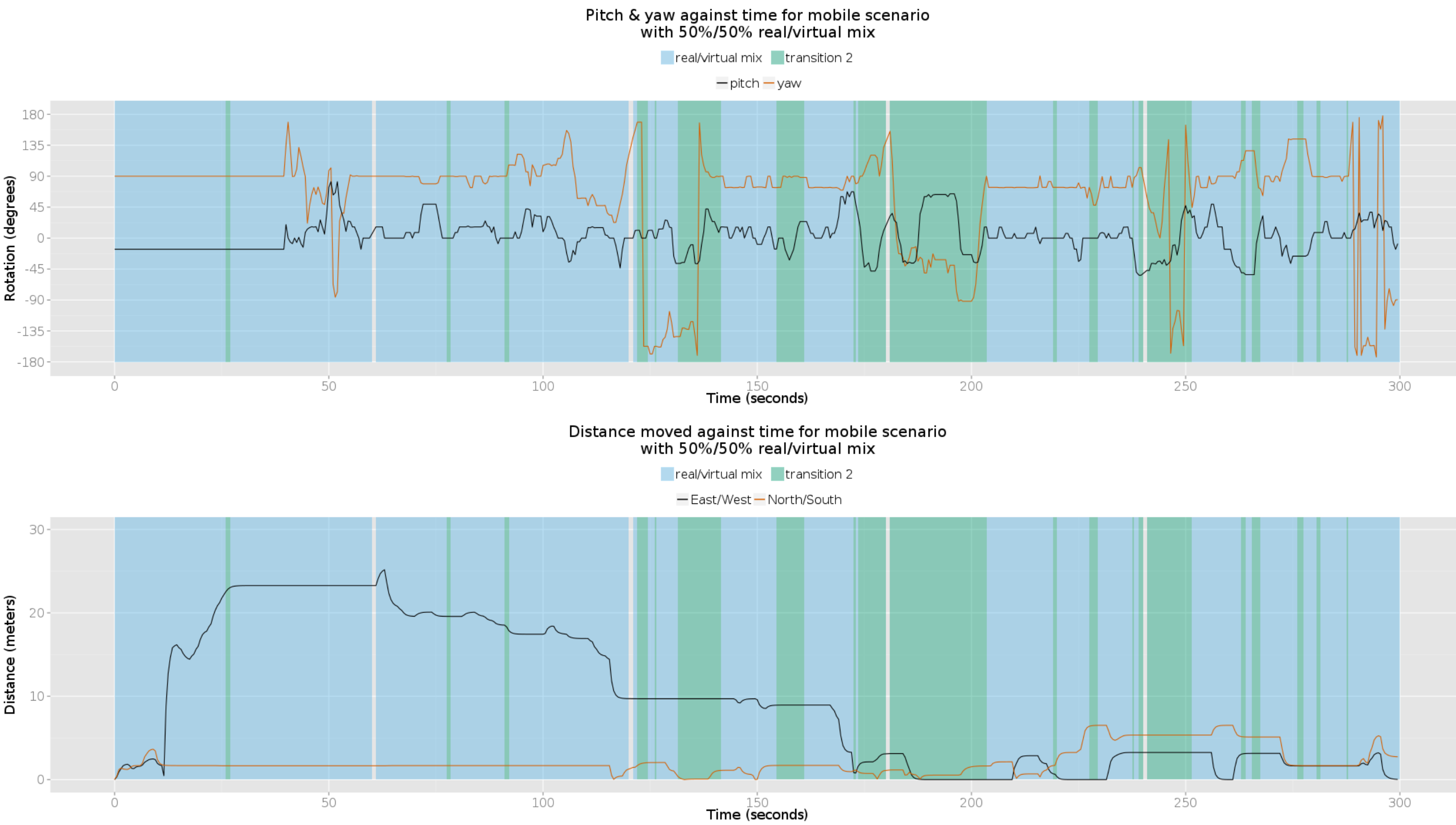

Figure 6.35: Some images, yah.

6.12.4 Participant 17

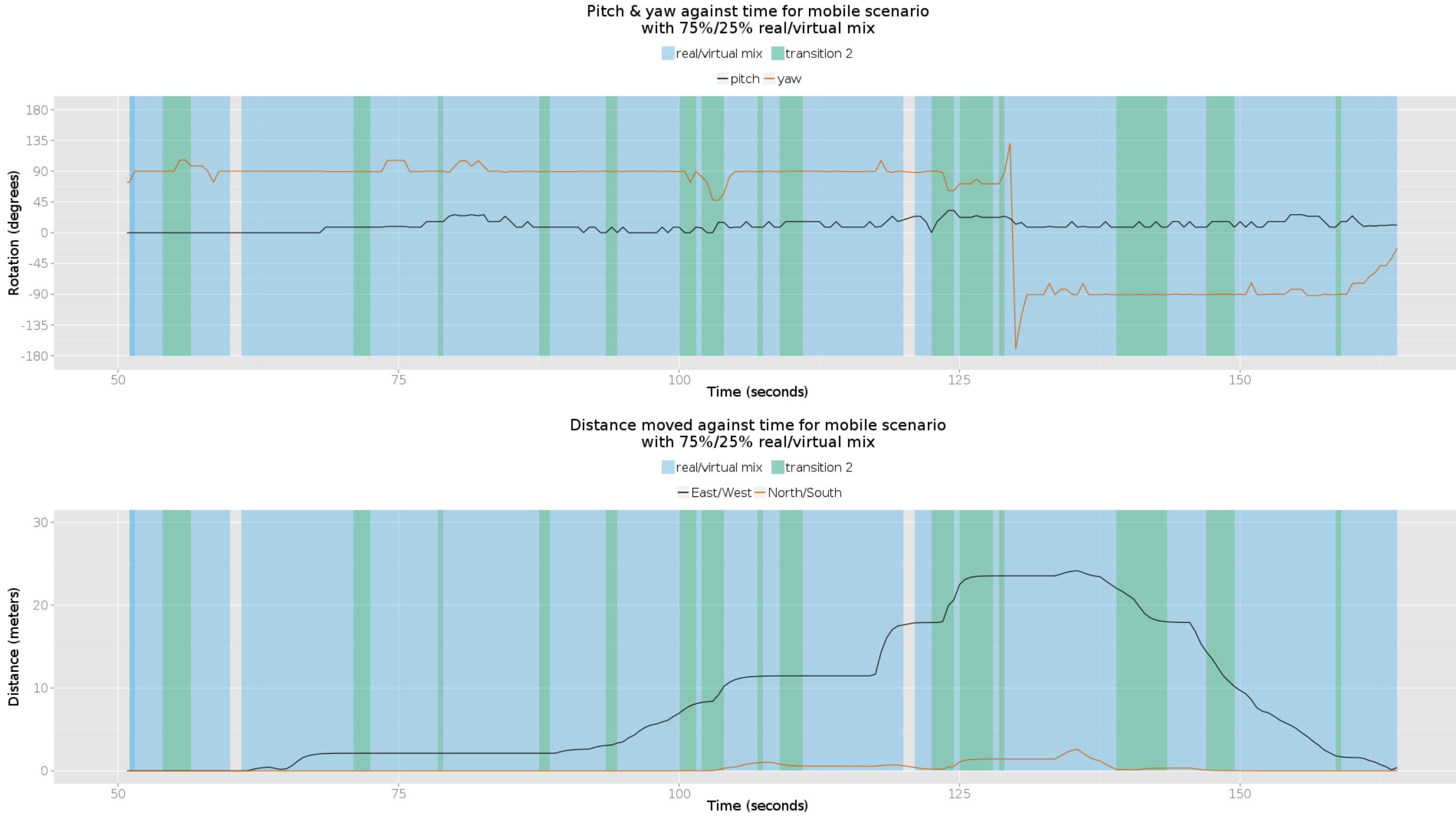

Figure 6.36: Some images, yah.

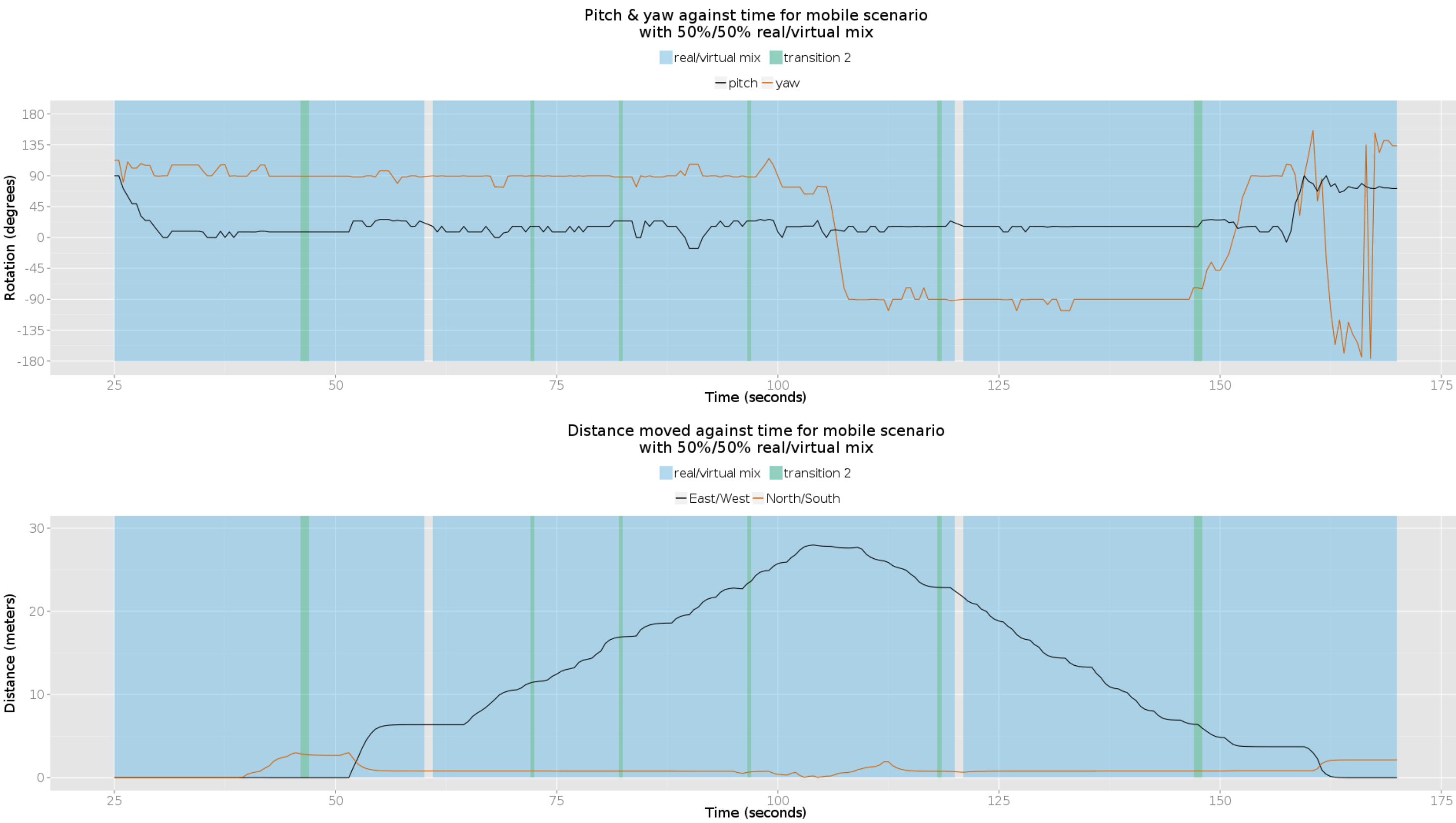

Figure 6.37: Some images, yah.

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.

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