rection 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 would reliably break reception. This reduced the theoretical maximum performance of the unit to 2.5m CEP, with observed performance being lower.

Figure 3.34 depicts an aerial view of the St Andrews cathedral ruins, oriented with North upwards; the blue line represents the planned route, red the route recorded by the MAX-6 receiver and green the route recorded by the smartphone while walking the planned route.

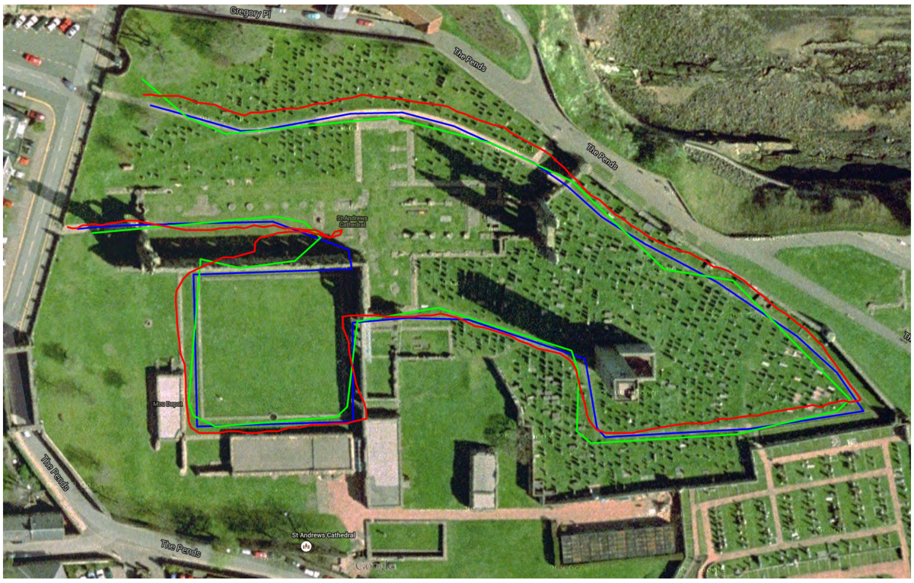

Figure 3.34: Planned and recorded paths at St Andrews cathedral (complete track).

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

The MAX-6 achieved 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 3.29 and in the shadows cast in figure 3.34) which provides an effective obstruction to line-of-sight to half of the sky (and thus substantially impairing reception of signals from GPS satellites) when in proximity to it. This issue has been encountered in some earlier sitsim experiments [97]. When considering just the sub-track shown in figure 3.35, 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 $7.23e^{-05\circ}$ ($\pm$8.05m N/S, $\pm$4.47m E/W), with the smartphone still behind with $8.99e^{-05\circ}$ ($\pm$10.01m N/S, $\pm$5.56m E/W). Again the Hausforff distance between the receivers showed low correlation between the inaccuracies, at $6.43e^{-05\circ}$ ($\pm$7.12m N/S, $\pm$3.98m E/W).

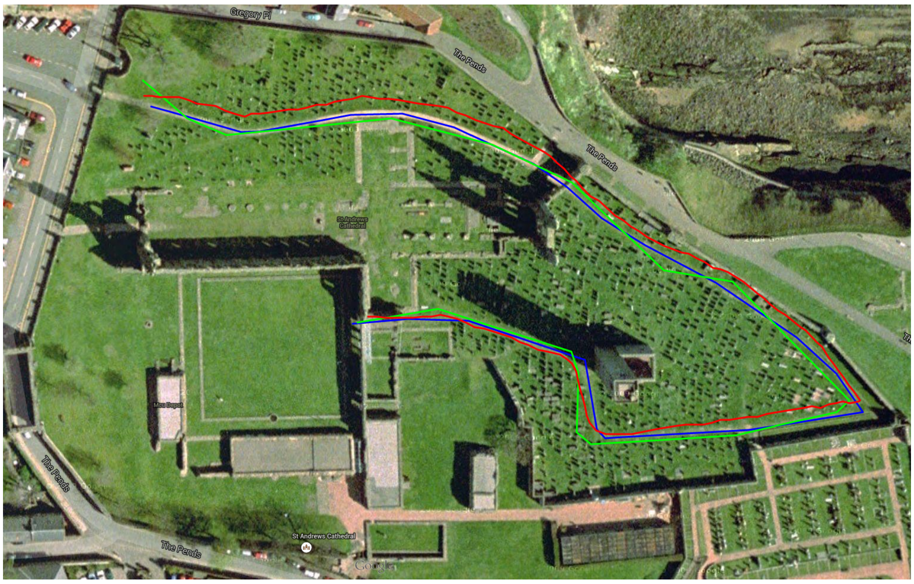

Figure 3.35: Planned and recorded paths at St Andrews cathedral (first sub track).

When analyzing the sub-track in the vicinity of the nave (see figure 3.36) it can be seen that although the MAX-6 outperformed the smartphone in terms of Hausdorff distance this relationship is misleading as the smartphone track corresponded more closely in shape to the planned route even if it did stray further from it 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 the 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 (defined for the MAX-6 by the Dynamic Platform Model chosen).

In addition to the accuracy of the position tracking it is also important to consider the frequency and granularity of these data. Even if the position data used by a freeform explorative parallel reality system were extremely accurate, the experience of using that platform would be poor if these data were reported too infrequently, as it would either lead to 'jumpy' movement where the virtual view had to move a substantial distance to match each newly reported real position, or a reliance upon dead-reckoning to predict the user's movement between subsequent data. Likewise even with accurate and frequently reported position data, if the granularity of these data is not especially fine then the experience of using the platform will be negatively impacted by an inability to make small real movements and see them reflected as similarly small virtual movements when trying to pay attention to specific aspects of the environments.

Figure 3.36: Planned and recorded paths at St Andrews cathedral (second sub track).

Throughout the test route the HTC One S only reported 27 positions. This would have resulted in extremely large virtual movements if used for VTW and the low granularity of these positions (as seen in figure 3.37) would have meant that the user would've found it frustratingly difficult to match real world movements to virtual world equivalents in any sort of freeform exploration scenario. The MAX-6 performed substantially better in these regards, reporting 251 positions along the same route and with substantially higher granularity (also shown in figure 3.37).

However when the MAX-6 readings were integrated into the VTW platform and it was tested in its complete form at the cathedral, even though subsequent positions reported by the MAX-6 were usually no more than 1-3m away, they did not 'settle' and keep the virtual view in the same position when standing still. Instead new readings in this 1-3m range would continue to be reported and the virtual view would continue to move even while the user was standing stationary in the real world. Adjusting the high pass filter on incoming position data to remedy this situation led to a worse experience when moving, as virtual position would only update in jumps of multiples of the high pass value.

3.6.3 Graphical Performance

VTW averaged framerates between 20 and 25 frames per second (fps) with the modified Second Life client's quality option set to the 'Low' position during testing at the cathedral site. Figure 3.38 shows average framerates of the client's different quality options when standing at two different positions within the cathedral site; one 'indoor' position from the centre of the nave and one

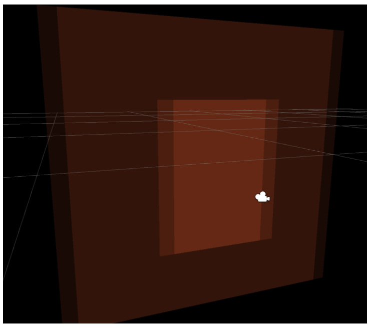

Figure 4.28: Camera and backing planes in Unity.

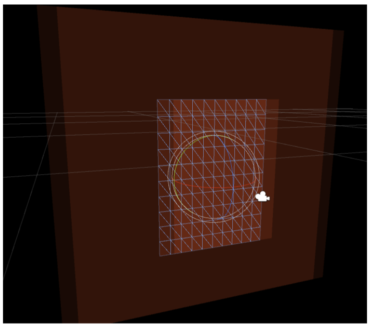

Figure 4.29: Left camera plane in Unity.

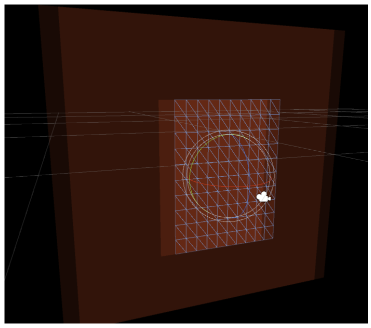

Figure 4.30: Right camera plane in Unity.

interpupillary distance that the user inputs to the Oculus configuration utility. By placing each of these two planes in a separate layer and 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 and 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 highlighted in figure 4.29 while the right virtual camera sees only the camera plane shown highlighted in figure 4.30.

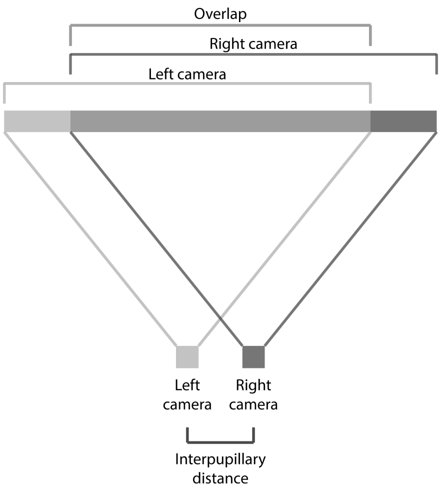

Figure 4.31: Visualisation of overlap between camera planes.

As the Mirrorshades platform needed to allow the user to control which environment they are perceiving, either real or virtual, the visibility of these camera planes (& the virtual environment behind them) had to be controllable. The opacity of the camera planes was linked to the control mechanisms, however because the camera planes do not completely fill the DK1's FOV (see section 4.3.2 and figure 4.13) two further, larger planes were situated behind the camera planes to cover the entire FOV of the DK1. The opacity of these planes was also linked to the control mechanisms, such that when the user operates the control mechanism in a manner to view VR, they become 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 to prevent any RW visual stimuli from passing around the camera planes. Even though these areas around the mediated camera streams are not strictly viewable, the ambient light that they would produce could be detrimental to the viewing of the RW camera streams.

The arrangement of these planes in relation to the virtual cameras is shown by figure 4.32, where it can be seen that the smaller camera planes do not fill the virtual cameras' frustum due to the narrower FOV of the C310 with 2.1mm lenses than of the DK1. Figure 4.33 shows a space between the camera planes and the backing planes, required to avoid a rendering bug that arose with planes situated so close together.

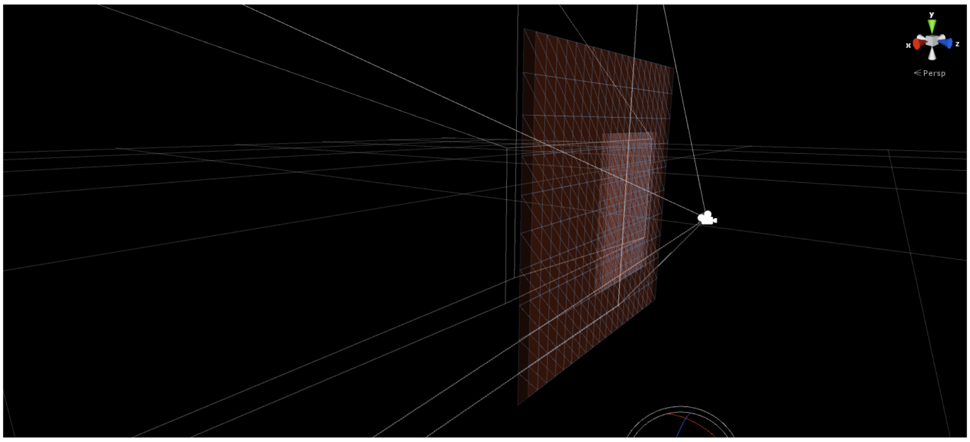

Figure 4.32: Arrangement of camera planes and backing planes in Unity.

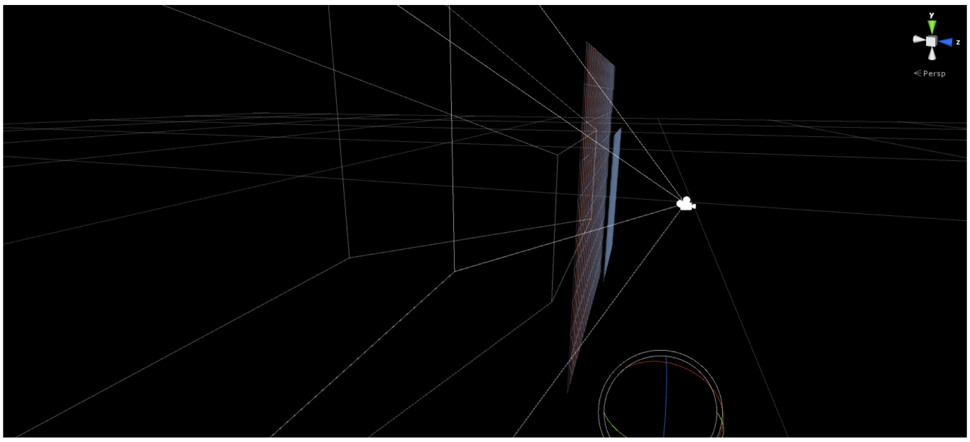

Figure 4.33: Spacing between camera planes and backing planes in Unity.

5.3.4 Log Data

For the seated VR scenario log data were recorded while each participant was engaging with the VR chapel in the seated position and using the Xbox controller to navigate the VR environment. For the parallel reality scenario log data were recorded throughout the whole experiment, such that data are available both for the periods in which they were observing the RW chapel via the DK1 and cameras, and the periods in which they were observing the VR chapel after performing a transition.

Comparing seated and parallel reality scenarios

When looking at either scenario's data as a whole (the VR section of the seated VR scenario and both RW and VR periods of the parallel reality scenario) it is immediately evident that participants looked to their sides and turned their heads horizontally (yaw) far more than they looked above and beneath themselves by tilting their heads vertically (pitch). An example of this relationship is shown by figure 5.5 which shows pitch and yaw plotted against time for participant 6, for both the seated VR scenario and the parallel reality scenario. With the seated VR scenario on the left of the pair of plots and the parallel reality scenario on the right, the variance in yaw is substantially greater in both than the variance in pitch.

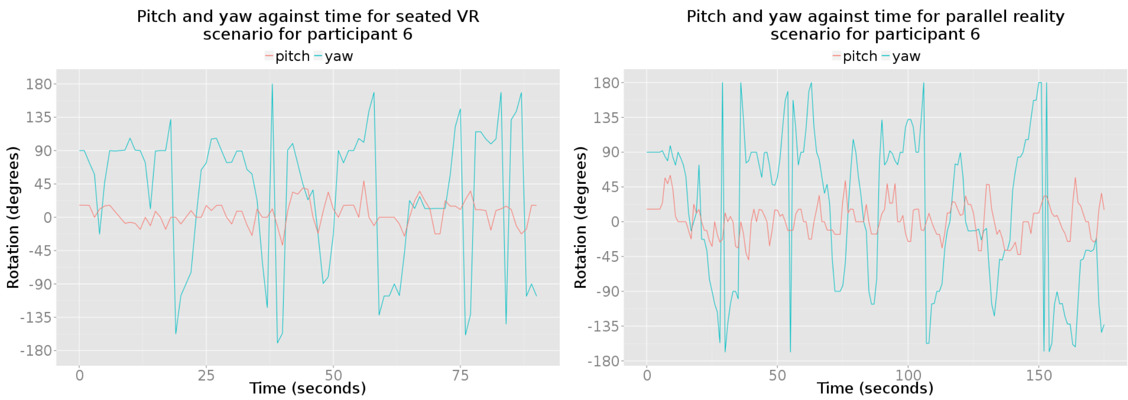

Figure 5.5: Pitch and yaw against time for participant 6 in seated VR and parallel reality scenarios.

This relationship is reflected in calculations of the standard deviation in pitch and yaw across both scenarios, shown by table 5.2 for the seated VR scenario and table 5.3 for the parallel reality scenario. For all participants for which the data are available the standard deviation in yaw is substantially higher than that in pitch. This relationship can largely be explained by the simple fact that there is more to observe in the chapel(s) at ground level than above eye level or down at the ground, however with the marked difference in the appearance of the chapel roof (stone in the VR reconstruction and wood in the RW chapel today) a smaller difference between pitch and yaw variance might have been expected for both scenarios.

and standing still, their willingness to perform larger head movements returned as they no longer had to contend with obstacle avoidance.

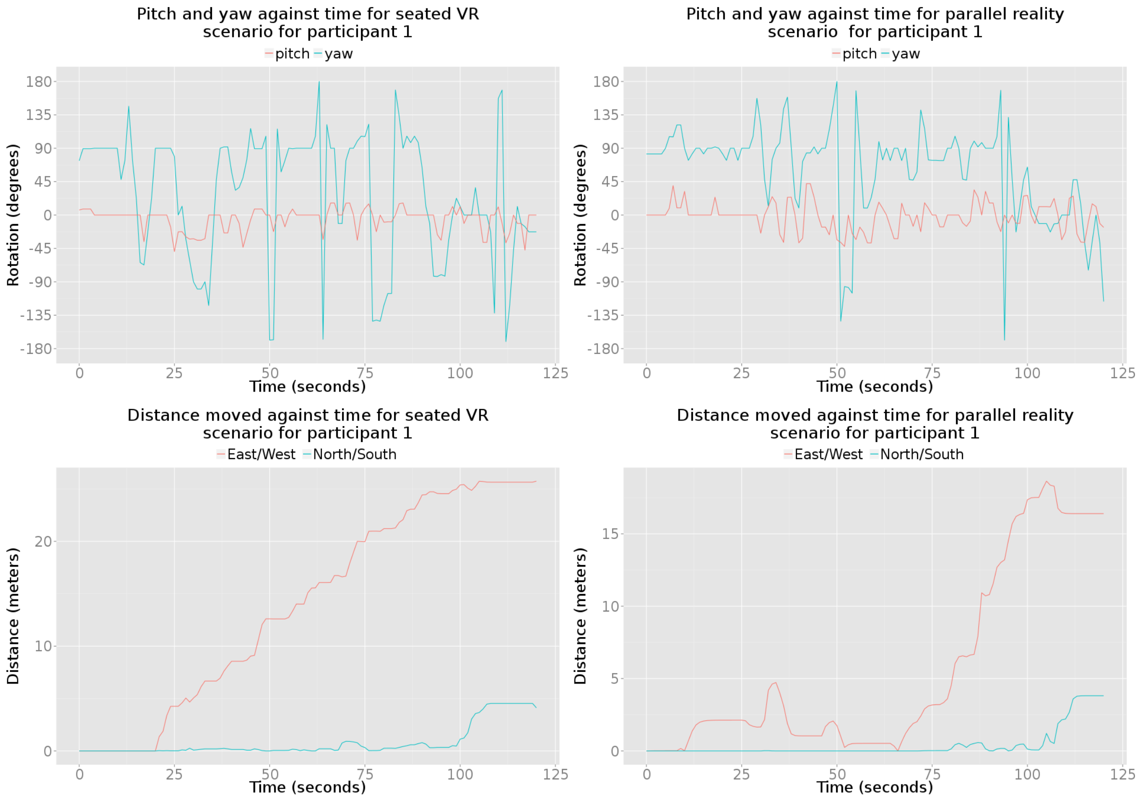

Figure 5.6: Pitch and yaw against time, aligned with distance moved against time, for participant 1 in both scenarios.

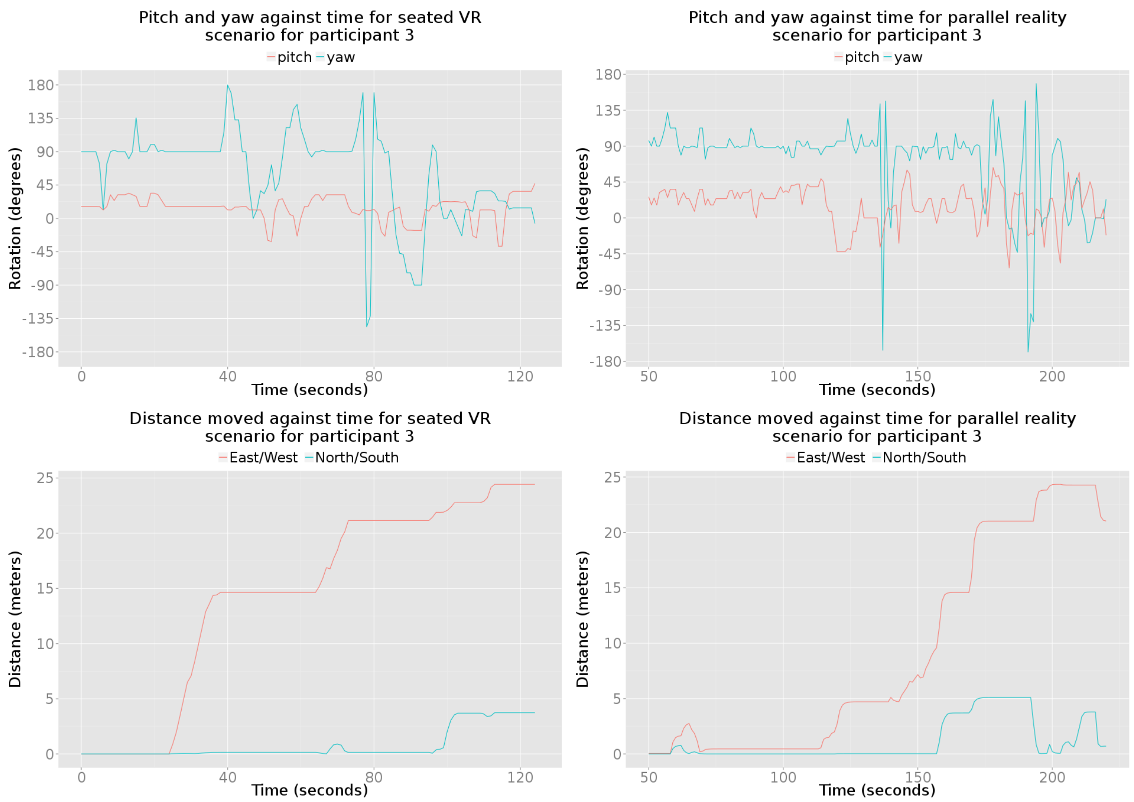

Figure 5.7: Pitch and yaw against time, aligned with distance moved against time, for participant 3 in both scenarios.

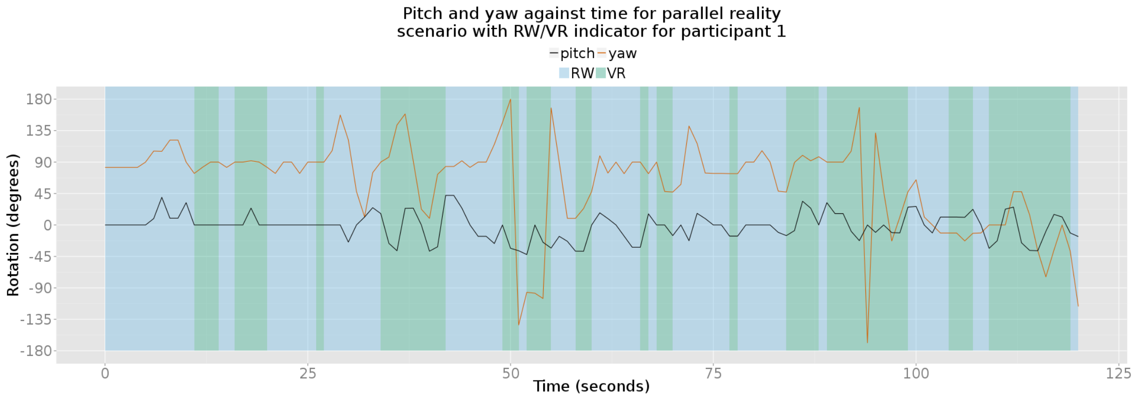

Figure 5.10: Pitch and yaw against time for participant 1 in parallel reality scenario, showing RW/VR periods.

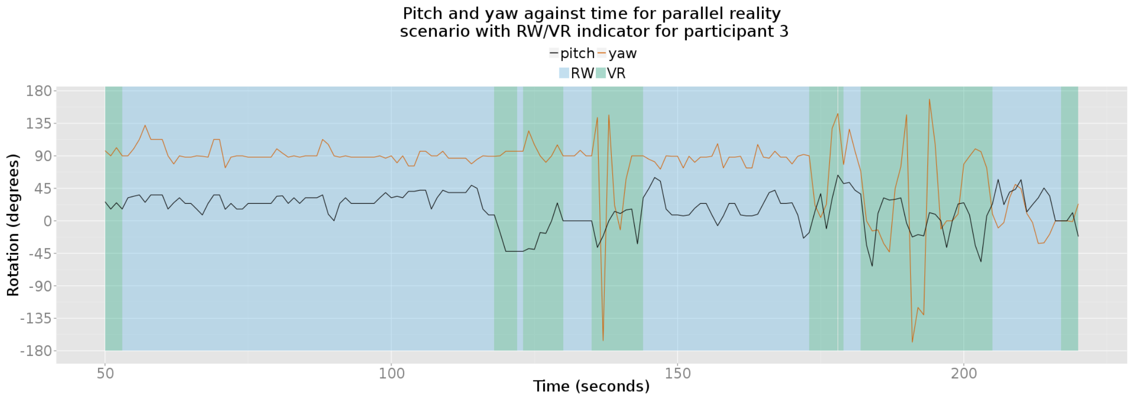

Figure 5.11: Pitch and yaw against time for participant 3 in parallel reality scenario, showing RW/VR periods.

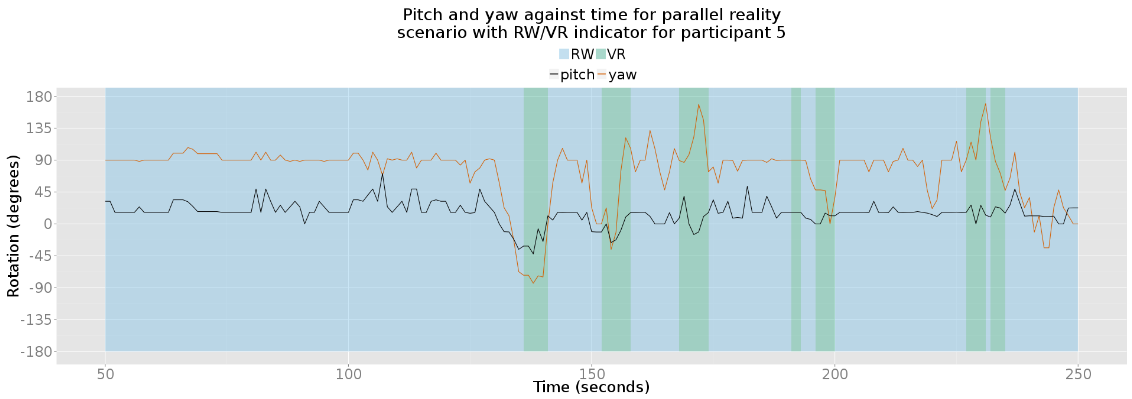

Figure 5.12: Pitch and yaw against time for participant 5 in parallel reality scenario, showing RW/VR periods.

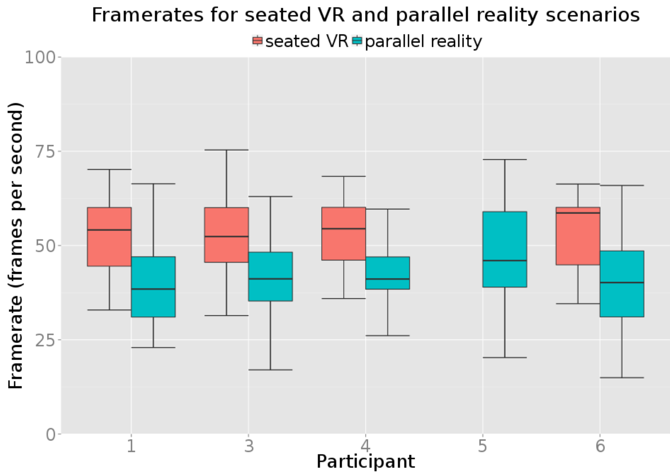

Figure 5.13: Framerates for both seated VR and parallel reality scenarios for all participants.

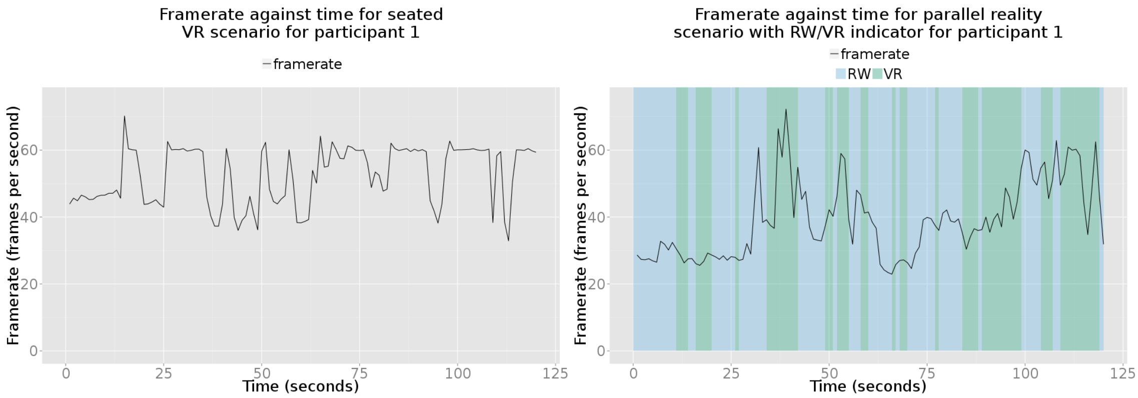

Figure 5.14: Framerate against time for seated VR scenario (left) and parallel reality scenario (right) for participant 1.

Instead of varying according to whether the participant was observing RW or VR, the variance in framerate in the parallel reality scenarios instead varies more in accordance to what part of the chapel the participant was directing their view toward and whether they were moving or standing still. Certain parts of the 3D model are substantially more complex in terms of the number of virtual objects (and thus the number of draw calls required) and rendering moving graphics has an overhead compared to rendering a static scene. Comparing the parallel reality plot from figure 5.14 (right) to the plot of distance moved against time for the same participant in figure 5.6 (bottom right) hints at this relationship. The seated VR scenario plot (figure 5.14 left) shows periods in which framerate reached and was capped at the 60fps enforced by vsync.

5.3.6 IndoorAtlas Performance

Interview transcripts and video recordings of participants completing the parallel reality scenario indicate that the accuracy of the IndoorAtlas position data were largely perceived as being very

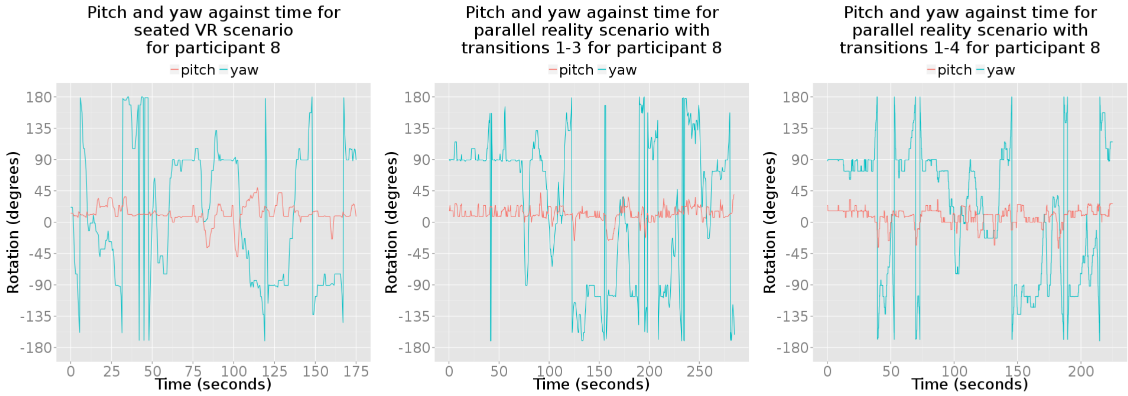

Figure 6.3: Pitch and yaw against time for participant 8 in seated VR and both parallel reality scenarios.

Participant	Pitch (°)	Yaw (°)
7	13.013	87.822
8	13.917	94.436
9	12.039	87.956
10	no data	no data
11	no data	no data
12	no data	no data
13	no data	no data

Table 6.1: Standard deviation in pitch and yaw for seated VR scenario.

Participant	Pitch (°)	Yaw (°)
7	no data	no data
8	10.253	102.254
9	13.734	84.076
10	17.833	84.578
11	11.540	76.445
12	19.635	74.696
13	22.095	91.827

Table 6.2: Standard deviation in pitch and yaw for parallel reality scenario with transitions 1-3 (RW and VR periods combined).

Participant	Pitch (°)	Yaw (°)
7	no data	no data
8	11.493	89.531
9	12.365	95.144
10	14.059	90.429
11	8.354	82.279
12	22.202	75.425
13	19.530	62.321

Table 6.3: Standard deviation in pitch and yaw for parallel reality scenario with transitions 1-4 (RW and VR periods combined).

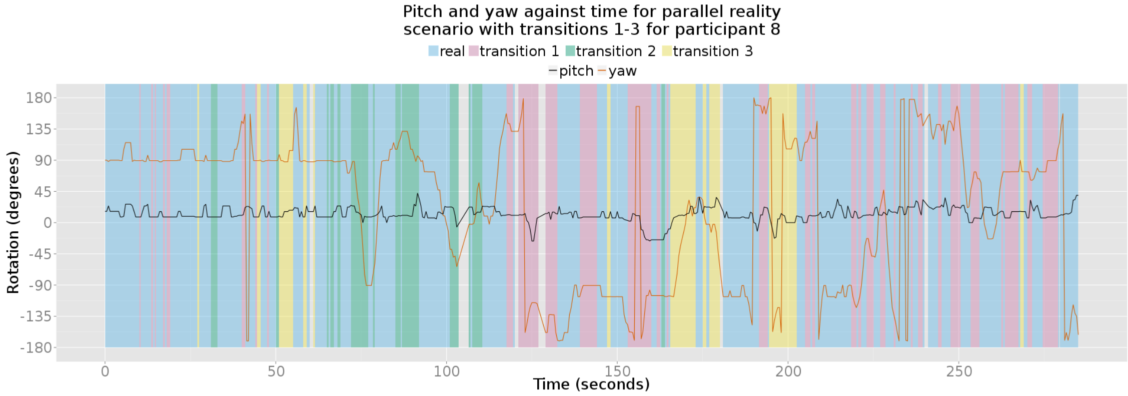

Figure 6.6: Pitch and yaw against time for participant 8 in scenario 1-3, showing RW/VR transitions.

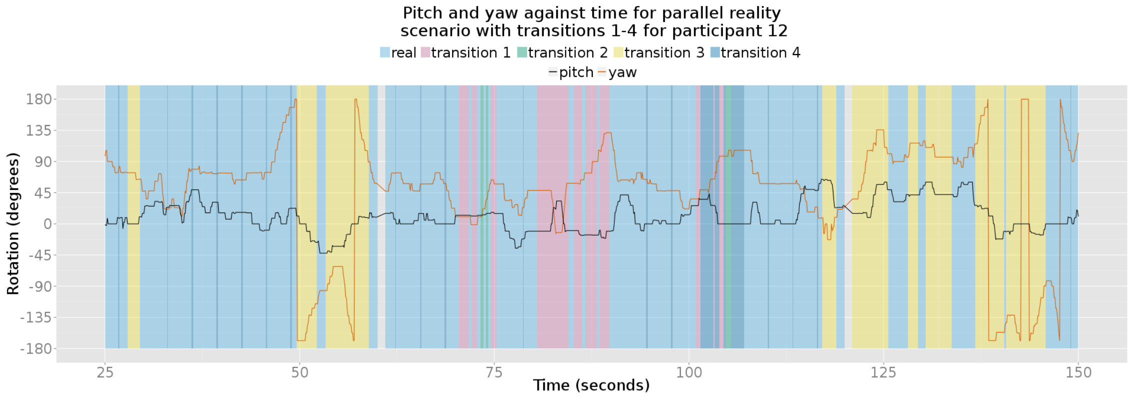

Figure 6.7: Pitch and yaw against time for participant 12 in scenario 1-4, showing RW/VR transitions.

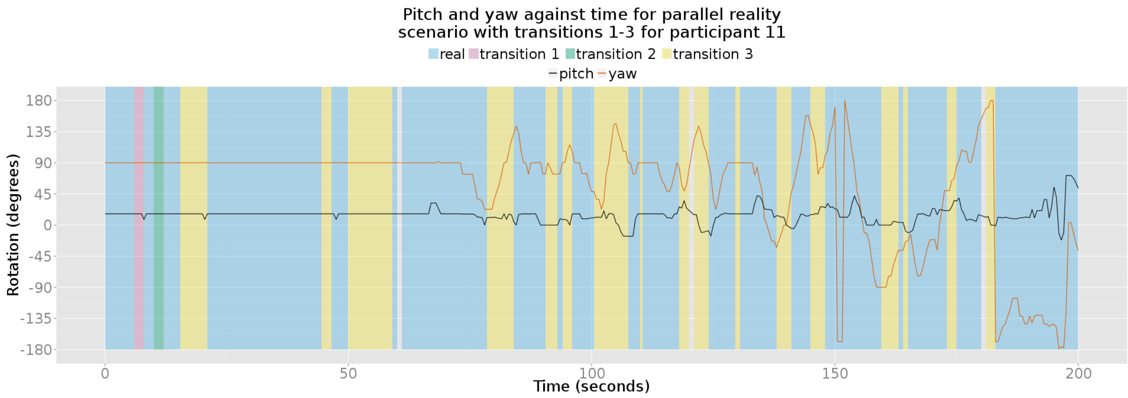

Figure 6.8: Pitch and yaw against time for participant 11 in scenario 1-3, showing RW/VR transitions.

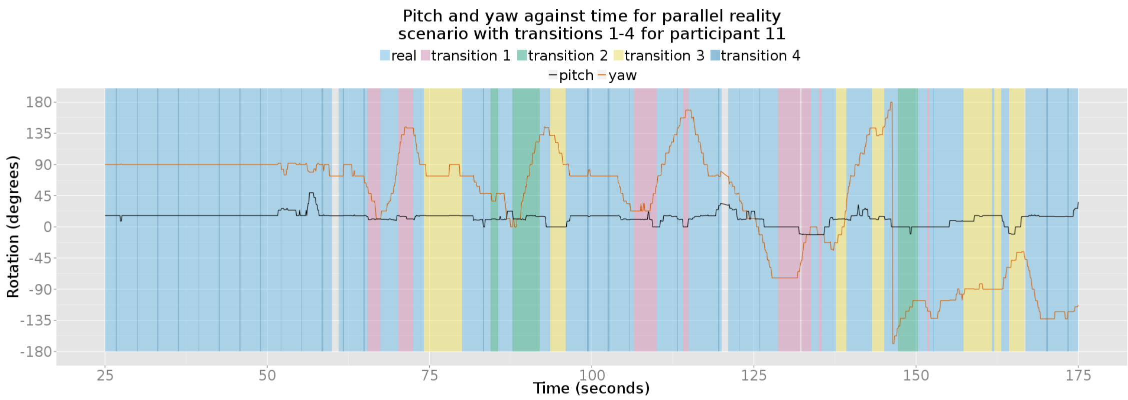

Figure 6.9: Pitch and yaw against time for participant 11 in scenario 1-3, showing RW/VR transitions.

Other participants continued to use all available transition styles throughout a session, such as participant 13 during scenario 1-3 (figure 6.10). This was one of the longest individual sessions, with the participant exploring the RW and VR chapels in tandem in parallel reality via the Mirrorshades platform for over 8.5 minutes. During the interview s/he reported preferring transition 3 via the right trigger [RT], which is corroborated by the data. S/he triggered this transition more than transition 1 or 2 (25 times total, compared to 20 for transition 1 and 14 for transition 2) and spent longer perceiving VR via transition 3 than the others (103 seconds total compared to 81.5 seconds for transition 1 and 20 seconds for transition 2, with a mean of 4.12 seconds for each period using transition 3, 4.075 seconds for transition 1 and 1.429 seconds for transition 2).

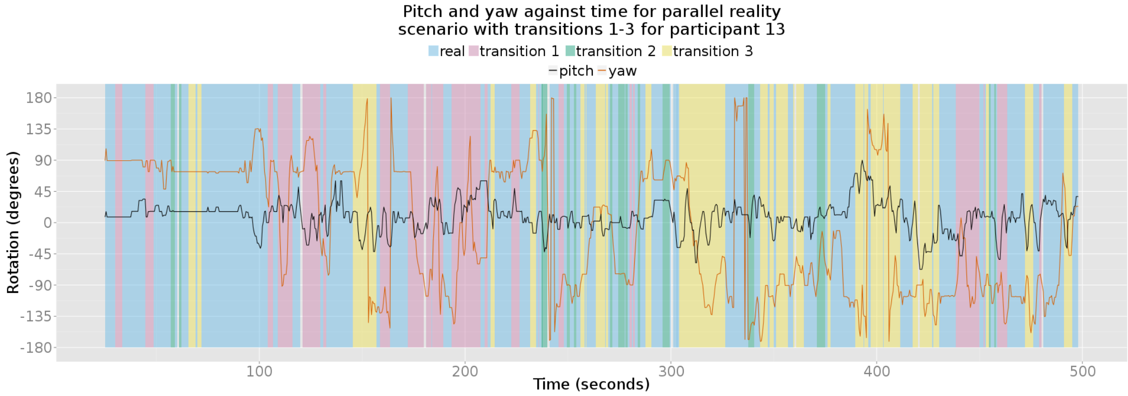

Figure 6.10: Pitch and yaw against time for participant 13 in scenario 1-3, showing RW/VR transitions.

Walking and Head Movement

As seen in the results to the stage 1 evaluation, there is also a correlation in the stage 2.1 results between position and change in head movement, with several participants displaying greater variance in head pitch and yaw while standing still than when walking with the DK1. This is true for both parallel reality scenarios; as an example figure 6.11 shows pitch and yaw against time above, aligned with distance moved against time below, for participant 8 performing scenario 1-3. Figure 6.12 shows the same arrangement for participant 9 performing scenario 1-4. Especially after taking into consideration the slight lag in IPS data, the stationary periods starting around 120, 160, 200 and 240 seconds in figure 6.11 and those starting around 70, 150 and 210 seconds in figure 6.12, all closely coincide with pronounced variance in yaw.

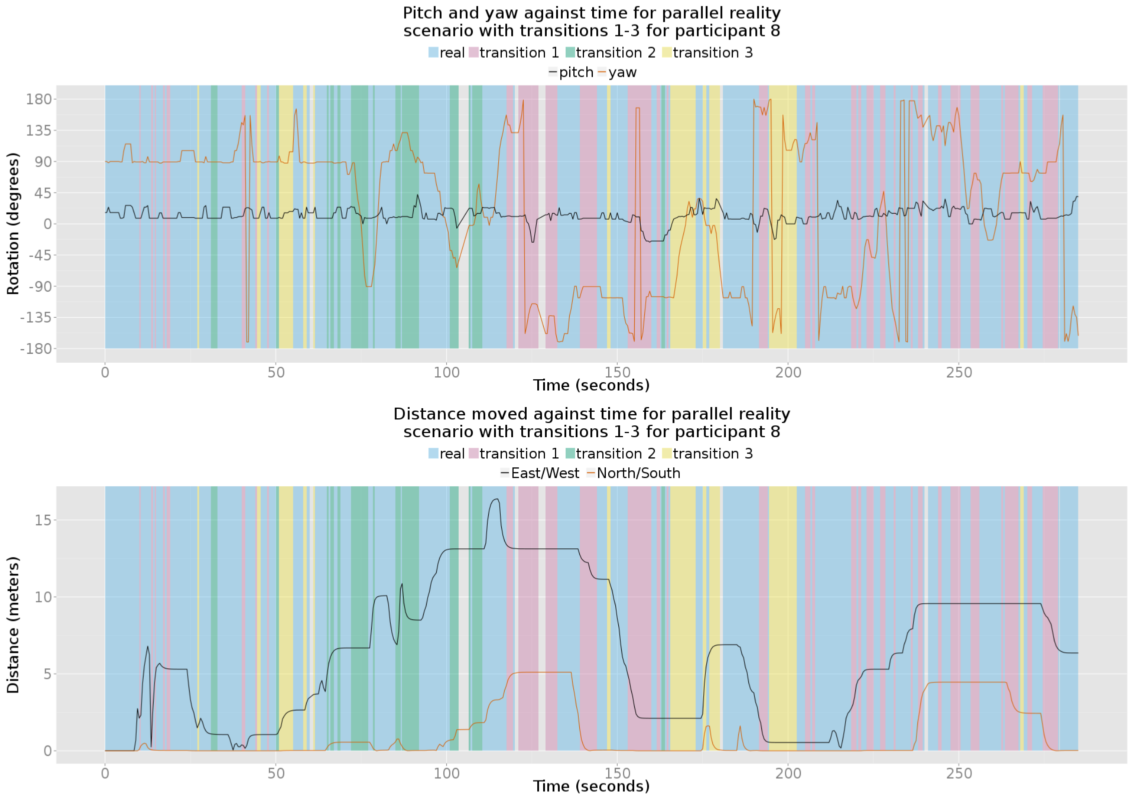

Figure 6.11: Pitch and yaw against time aligned with distance moved against time for participant 8 in scenario 1-3, showing RW/VR transitions.

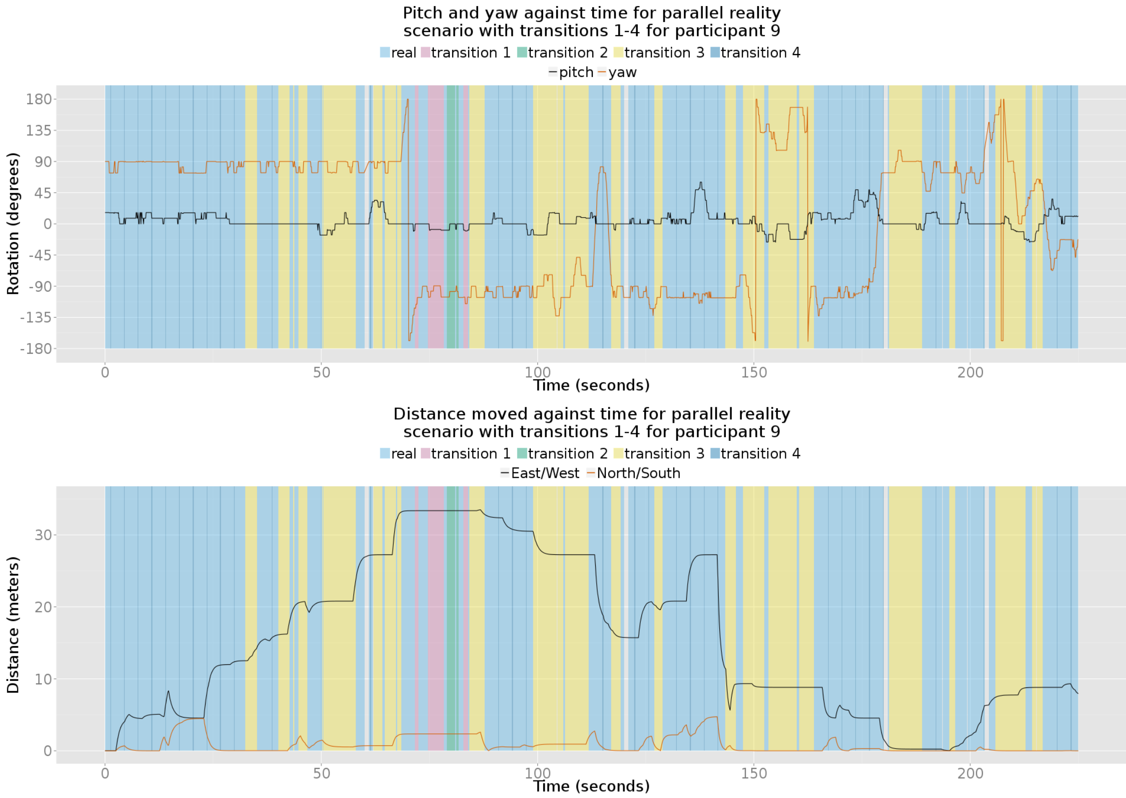

Figure 6.12: Pitch and yaw against time aligned with distance moved against time for participant 9 in scenario 1-4, showing RW/VR transitions.

Use of Intermediary Opacities

Confirming responses during the post task interviews, several participants made use of the analogue selectable transition (transition 3, accessed via the right trigger [RT]) to view both RW and VR environments together, by pausing with the trigger partially depressed. Figures 6.13 and 6.14 show examples, for participants 10 and 12 respectively undertaking scenario 1-4, of the opacity of the objects upon which the camera feeds were rendered. An opacity of 1.0 means that the camera feeds were completely opaque and that the participant was thus perceiving 100% RW visual stimuli, while an opacity of 0 means that the camera feeds were invisible and that the participant was perceiving 100% VR visual stimuli. As well as using the analogue selectable transition to view both environments at once, there are incidents where it seems that the participant used it to control the speed at which a transition from 100% RW to 100% VR was performed. We can see that participant 10 (figure 6.13) uses transition 3 at around 250 seconds to perform a transition to a 100% VR view, but at a slower rate than the linear interpolated transition such as can be seen taking place just before at around 245 seconds. This greater level of control in how quickly transitions were performed was raised in interviews as one reason why this particular transition was favoured by participants.

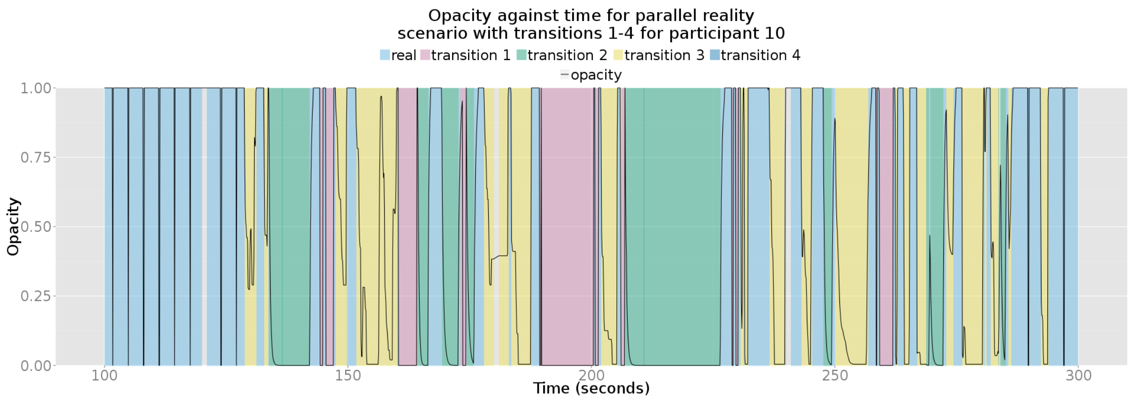

Figure 6.13: Opacity of camera objects against time for participant 10 in scenario 1-4, showing RW/VR transitions.

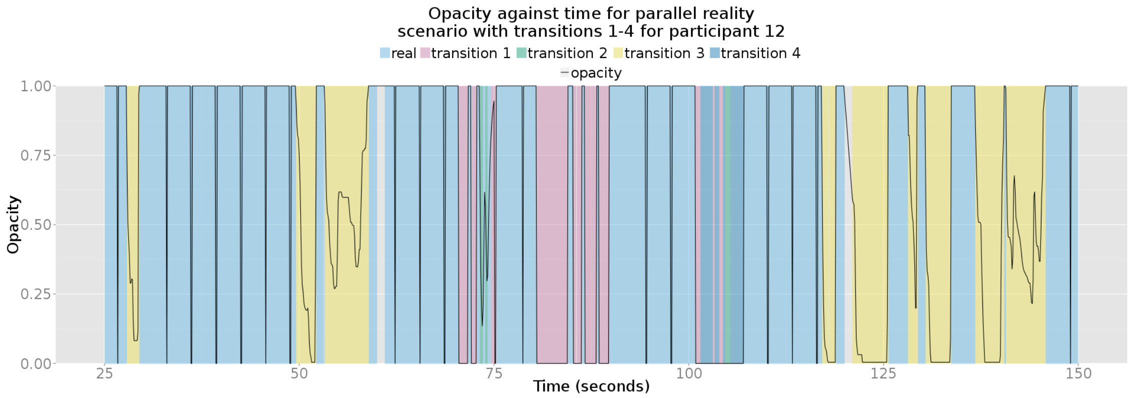

Figure 6.14: Opacity of camera objects against time for participant 12 in scenario 1-4, showing RW/VR transitions.

6.4.4 IPQ

IPQ results were scaled from the -3 to +3 range used by the questionnaires to the 0 to 6 range used to express results herein. The reversed items (SP2, INV3 and REAL1) had their results appropriately reversed. Tables 6.6, 6.7 and 6.8 show the mean and standard deviation for SP, INV and REAL respectively for the all of the scenarios (seated VR scenario, scenario 1-3 and scenario 1-4).

Scenario	Mean	Standard deviation
seated	4.6	0.780
1-3	4.133	1.093
1-4	4.133	0.532

Table 6.6: Means and standard deviations of SP for all stage 2.1 scenarios.

Scenario	Mean	Standard deviation
seated	4.166	1.393
1-3	2.666	1.125
1-4	1.958	1.308

Table 6.7: Means and standard deviations of INV for all stage 2.1 scenarios.

Scenario	Mean	Standard deviation
seated	2.208	1.134
1-3	1.917	1.339
1-4	1.917	1.080

Table 6.8: Means and standard deviations of REAL for all stage 2.1 scenarios.

Scenario	SP3		INV2	
	mean	sd	mean	sd
seated	4.5	1.472	4	1.673
1-3	2.5	2.160	2.8	1.643
1-4	3.5	1.633	1	0.707

Table 6.9: Means for SP3 and INV2 for all stage 2.1 scenarios.

The seated VR scenario produced baseline IPQ results for a seated, full immersion HMD based VR experience in which RW stimuli are intentionally suppressed from the user. SP and INV results for this scenario were relatively high, while the REAL results were low. This does not come as much of a surprise, as the graphical quality of the VR chapel reconstruction used throughout

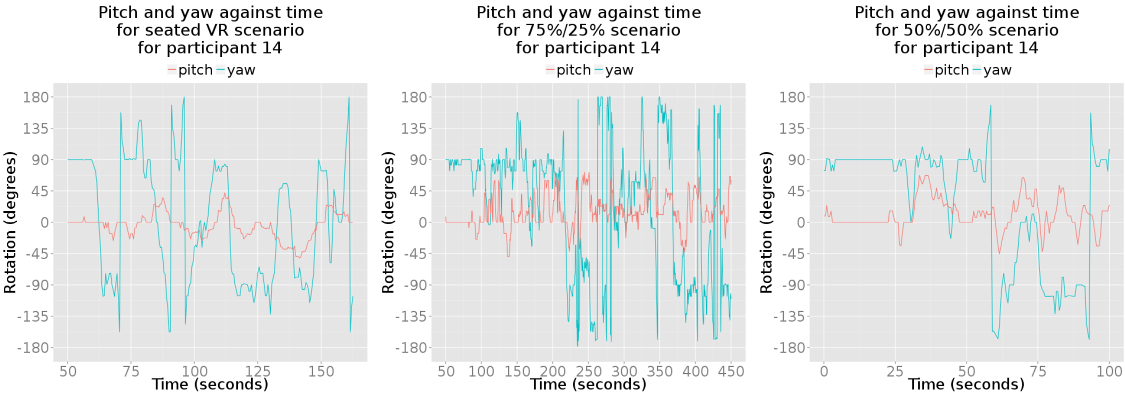

Figure 6.21: Pitch and yaw against time for participant 14 in seated and both parallel reality scenarios.

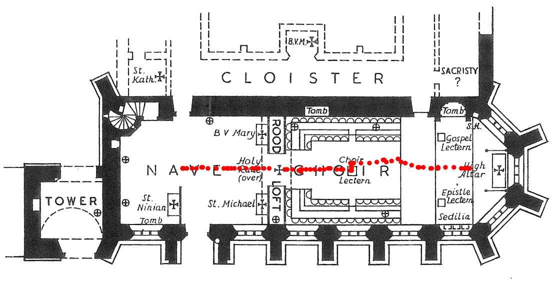

Figure 6.22: Position data during seated VR scenario for participant 16.

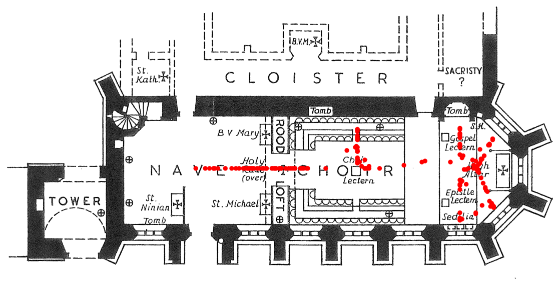

Figure 6.23: Position data during 50/50 scenario for participant 16.

Whilst one explanation for this behaviour, as touched upon in section 5.3.4, is simply that the combination of real and virtual altar in the parallel reality scenarios drew the participants' attention more than just the virtual altar in the seated VR scenario did, enough to warrant the challenge of the steps, an additional observation herein presents a somewhat intriguing possibility. Many visitors to the chapel display a heightened reverence for the altar, not approaching it too closely nor stepping up to the platform it stands upon, presumably due to an overbearing assumption that it may be construed as disrespectful or against socially accepted etiquette to do so. However with a view that is constantly a mix of a real and a virtual environment, as in the parallel reality scenarios in this stage of the evaluation, it is conceivable that this reduced clarity or less 'real' seeming nature of the altar, along with the increased interest of the combined real and virtual views, could have led participants to feel more comfortable than non parallel reality visitors to approach it more closely and even to mount its platform.

Comparing Between 75/25 and 50/50 Scenarios

Observations that come to light when comparing log data between the two parallel reality scenarios are that all of the participants performed fewer transitions in the 50/50 scenario than in the 75/25 scenario, with the ratio between time spent in RW and VR environments showing that participants spent comparatively less time viewing VR in the 50/50 scenario than the 75/25 scenario. These values are summarised in tables 6.10 and 6.11 for the 75/25 and 50/50 scenarios respectively, while figures 6.24 and 6.25 visualise this relationship using participant 16 as an example when performing the 75/25 scenario and 50/50 scenario respectively.

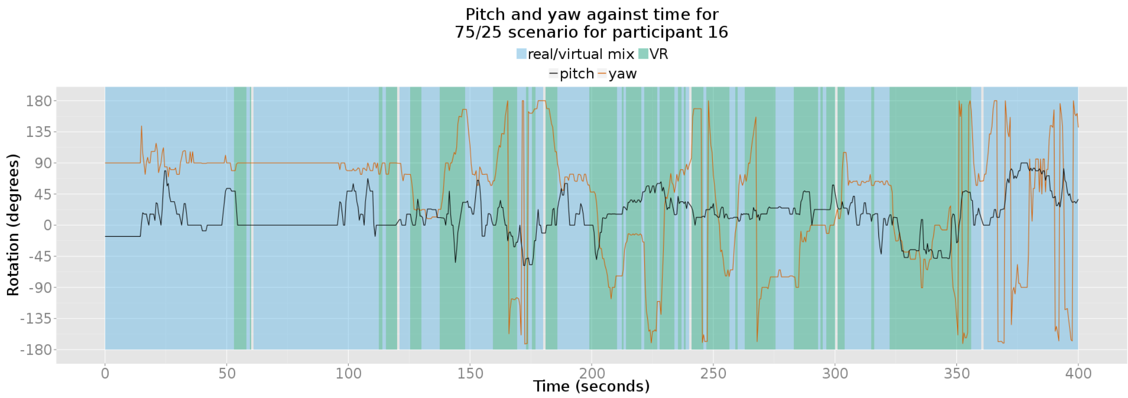

Figure 6.24: Pitch and yaw against time for participant 16 in 75/25 scenario, showing default/VR transitions.

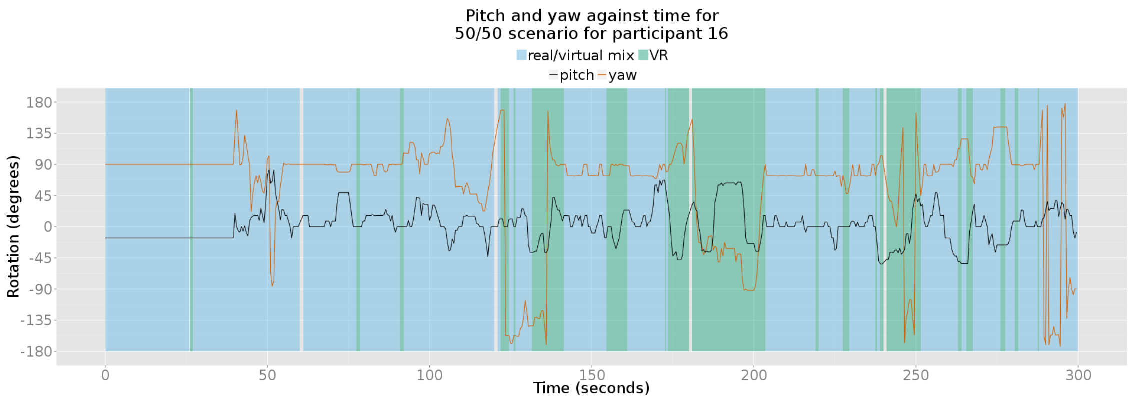

Figure 6.25: Pitch and yaw against time for participant 16 in 50/50 scenario, showing default/VR transitions.

In combination with interview feedback these log data are explained by the notion that the 50/50 scenario was more engaging, with participants not finding it necessary to perform transitions to VR as frequently in order to perceive enough VR stimuli to engage with it.

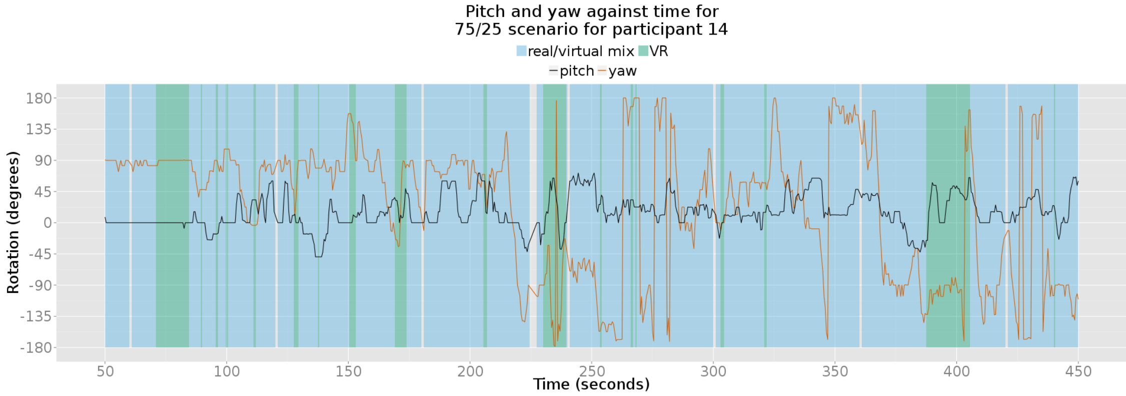

Figure 6.26: Pitch and yaw against time for participant 14 in 75/25 scenario, showing default/VR transitions.

Walking and Head Movement

Concerning the relationship between variance in head pitch and yaw compared to whether participants were actively walking, most participants exhibited similar behaviour to previous stages of evaluation with maximum variance restricted to periods in which they were standing still.

Participant 17 exhibited extremely restricted head movement (figure 6.27), only moving their head from looking straight ahead in the direction of movement upon reaching the altar end of the chapel and turning around to return. Intuitively one might suppose that for a participant who did not feel sure of themselves when walking with the apparatus, not having a 100% RW view may have resulted in this static head behaviour as they would have needed to focus all of their attention on what reduced amount of the RW environment they could see in order to successfully navigate. However this participant did not report any such lack of surety in the interview, although did mention performing fewer transitions in the 50/50 scenario as they were *"trying to make sure I didn't bump into anything"*. Reviewing the video recordings and ShadowPlay footage of this participant completing the 75/25 scenario showed them to walk comfortably and deliberately. The mostly static head activity is therefore as likely to be attributable to simple disinterest with the environments or misunderstanding of the purpose of the scenarios as to any restricting aspect of the apparatus or experience.

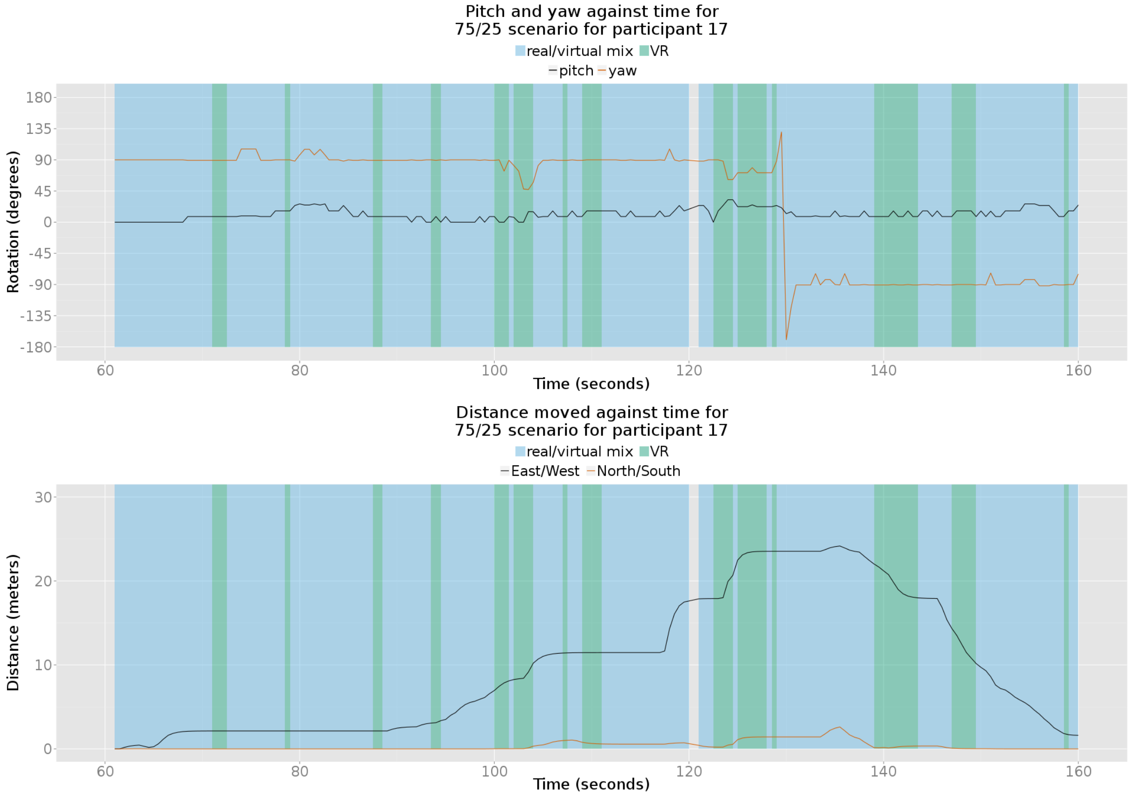

Figure 6.27: Pitch and yaw against time aligned with distance moved against time for participant 17 in 75/25 scenario, showing default/VR transitions.

6.6.4 IPQ

When considering the IPQ results for stage 2.2 participants the seated VR scenario presents very similar results for all of SP, INV and REAL (tables 6.12, 6.13 and 6.14 respectively) to the seated VR scenario from stage 2.1 (tables 6.6, 6.7 and 6.8). This was to be expected and confirms these values as good baseline IPQ results for a seated VR experience at the chapel.

SP was reduced in the 75/25 scenario to a level slightly lower than that in both parallel reality scenarios in stage 2.1, while in the 50/50 scenario there was a marked increase in SP to a level (4.7) above any other scenario in either stage, including the seated VR scenarios. This hints toward the optimistic expectation of a good parallel reality experience resulting in reduced INV but increased SP compared to a seated VR scenario, by representation of bodily actions within the RW environment leading to an increase in experienced spatial presence within the (spatially equivalent) VR environment.

INV was reduced in the 75/25 scenario and further reduced in the 50/50 scenario, as was to be expected. Interestingly however, the INV results for both parallel reality scenarios in stage 2.2 were notably higher than those for the parallel reality scenarios of stage 2.1, a discrepancy that is not contained within the higher INV for the traditional VR scenario in stage 2.2 compared to