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ViewNet Reference Network Survey

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ABSTRACT

A network of forty-seven reference points has been setup in and around the Merchant Ventures building at the University of Bristol. Each reference point comprises a magnetic drift nest designed to hold a ½ inch tooling ball. The network of reference points was surveyed using laser tracker to locate the tooling ball centre coordinates to an uncertainty of approximately 0.3 mm. In addition, the coordinates of reference features in the building such as door and window frame corners were measured using the laser tracker. The reference point network was used to enable the reference features to be measured within a consistent coordinate frame. The measurement uncertainty associated with the reference feature coordinates is estimated to be 2 mm (k = 2).

The reference features and reference points will be used by the ViewNet project for characterisation of the various sensor technologies employed by the project.

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By Dr John Greenwood, Knowledge Leader, Engineering Measurement Team

Contents

Figures

Tables

1 Introduction

1.1 The ViewNet Project

ViewNet is a two-year research project co-funded by the Technology Strategy Board. It is a collaborative research project led by 3C Research and comprising the University of Bristol, Toshiba Research Europe, Sepura, Ordnance Survey, ST Microelectronics, Thales Research and Technology, National Physical Laboratory, TRW Conekt, Comsine and the Home Office Scientific Development Branch.

Emergency services personnel often enter a scene without adequate maps, or building schematics. At present, movements and details about the area are reported back to a control centre, which collates the information then directs the response. This is inefficient and time consuming. A system that could efficiently capture accurate information about the current state of an environment would be invaluable. The ViewNet project is developing a wireless sensor network to provide distributed localisation and mapping with a view to efficiently map local environments and their conditions, particularly those encountered inside buildings.

The objective of ViewNet is to develop a technical demonstrator system that shows a networked group of operatives mapping the inside of a building using simultaneous localisation and mapping techniques.

The project involves fusing 3D information from several devices, including inertial sensors such as gyroscopes and accelerometers, with on-body cameras, ultra wideband radio positioning and GPS. As teams of operatives explore an area, the local data each member collects is linked and collated via a wireless network. Each team member therefore contributes data to a large 3D model, using a combination of Computer Vision (Visual SLAM) and sensor fusion techniques. These pieces are then fused together to produce a virtual global map of the environment. This generates a virtual 3D map into which users can embed information, such as tagging the location of a fingerprint. This tag will be displayed to other ViewNet handsets in the local area, efficiently disseminating critical information.

1.2 Visual SLAM

Simultaneous Location And Mapping (SLAM) is a technique that is concerned with the problem of building a map of an unknown environment by a mobile robot and simultaneously navigating the environment using the map. Originally, the data used to generate these maps came from, for example, rotation sensors on the robot wheels or proximity sensors etc.

The ViewNet project uses a variation on SLAM called Visual SLAM. Visual SLAM uses real-time processing of video camera images, rather than other sensor data, to build the maps. The technique uses computer vision algorithms to identify and track easily identifiable features in the field of view of a moving camera. The map is built up as these features come into and go through the camera's field of view. Suitable features are typically high-contrast edges or corners that are easily identified in an image, such as corners of doorframes and table edges. To an extent, the type of feature employed can be tuned by software parameters.

1.3 Reference Network Survey Requirements

Visual SLAM is effectively a triangulation technique. The 3D coordinates of the features are encoded into two angles represented by (x, y) coordinates in the image plane of a moving camera. The challenge is to use this data to locate and track the motion of the camera in six degrees-of-freedom – location and orientation – in a meaningful way as it moves through the environment. As with all triangulation based measurement techniques, scale must be introduced into the system, as the angle data alone is independent of scale.

The ViewNet system has several ways of introducing scale, for example using the GPS or Ultra-Wide Band (UWB) systems. However, the GPS only functions outside buildings and the UWB system has limited accuracy. The accuracy of the maps and location information produced by the ViewNet system will depend on how well the data from the various sensors can be fused and on the quality of the data.

There is a requirement, therefore, to verify the performance of the ViewNet system against some independent reference. To this end, NPL, in collaboration with the University of Bath, has installed and calibrated a network of reference *points* and *features* throughout part of the Merchant Ventures Building at the University of Bristol. The requirements for the reference network were as follows:

1. The network should include many visual SLAM compatible *reference features* - fixed parts of the structure of the building;
2. The reference features should be located within a consistent coordinate frame;
3. The locations of the reference features should be established to an uncertainty of the order of a few centimetres. The accuracy requirement is not well defined at the time of writing and is likely to depend on the intended applications of the ViewNet system;
4. The reference features should be spread throughout the upper and lower floors of the atrium.

2 Reference Features & Network

The Visual SLAM system is optimised for the detection of high-contrast features, like corners and edges, such as those that may be found around doors, windows or furniture in a typical indoor environment. An example of a reference feature is shown in Figure 1. The objective of the reference network survey was to measure, with sub-centimetre accuracy, a number of suitable *reference features* spread throughout the volume of interest within the Merchant Ventures Building. The areas surveyed were the main entrance from Woodland Road, the reception area, the upper and lower floors of the atrium and the corridor leading to the toilets on the lower floor.

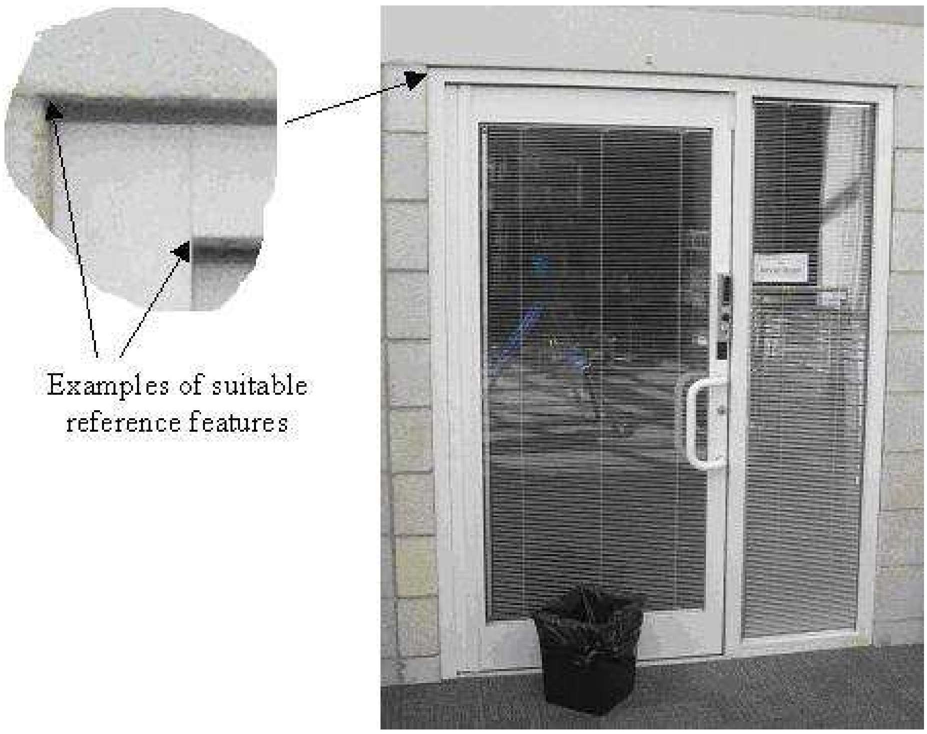


Figure 1 An example of reference features - the corners of the Arnold Room doorframe.

The measurements were performed using a laser tracker - a high accuracy coordinate measuring instrument that uses a combination of a tracking laser interferometer and/or laser-based absolute distance meter and two angle encoders to track and locate the coordinates of a spherically mounted retro-reflector target (SMR).

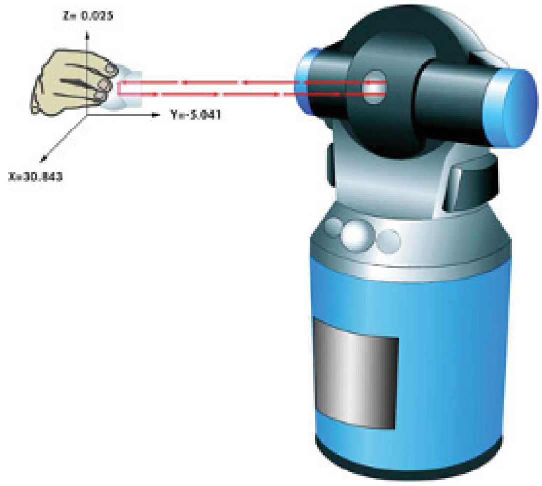


Figure 2 A laser tracker following a retroreflector.

Figure 3 A Spherically Mounted Retroreflector (SMR).

The requirement to spread the reference features throughout the upper and lower floors of the atrium meant that it was not possible to measure them all from one location. It was therefore necessary to reposition the tracker several times to view the entire volume of interest. To maintain a consistent coordinate frame when the tracker was moved, a network of *reference points* was established. The reference points were spread throughout the volume such that several were visible from all tracker positions. In this way, measurements of common reference points from different tracker positions could be used to locate the tracker in a consistent coordinate frame.

The reference point network comprised forty-seven magnetic ½ inch “drift nests” similar to those shown in Figure 4.

Figure 4 a pair of ½ inch drift nests.

Each drift nest comprises a cylindrical metallic base with a conical recess in the top. The recess is equipped with a magnet at the bottom that is used to hold a ½ inch diameter spherical insert that forms the target. The reference point coordinates are defined at the centre of the sphere. In operation, the spherical insert can be either a precision tooling ball or an SMR. The former is suitable for use with a number of systems including visual SLAM, the latter is specifically designed for use with a laser tracker.

Each drift nest was uniquely labelled with the identifier Pi ($1 \leq i \leq 48$). Note that due to a labelling error there was no $P42$.

2.1 Reference Features

Suitable reference features were identified on the following structures:

- The main entrance to the building – external and internal door frames
- Room 2.01 door surround
- Corners around the upper and lower floor lift entrances
- The Arnold Room doorframe
- Room 2.11 Door/Window surround
- Room 2.16 Door surround
- The red painted panel adjacent to the entrance to Room 2.16
- The doorframe around the door leading off the atrium balcony to the Set Squared area
- A window to Room 1.15
- Room 1.07 door surround
- Room 1.11 door surround
- Room 1.06 doorframe
- The red painted panel by the Room 1.06 door.
- The bottom corners of the lower floor wall below the red painted panel
- The ‘fake’ window on the lower floor near the fire extinguishers
- Along the power conduit on the wall on the lower floor
- The corners between the floor and the walls by the fire extinguishers on the lower floor

In addition to the features listed above, some points coinciding with UWB base stations were measured. A representation of the complete network, including reference points (red markers) and reference features, constructed from the coloured lines, is shown in Figure 5.

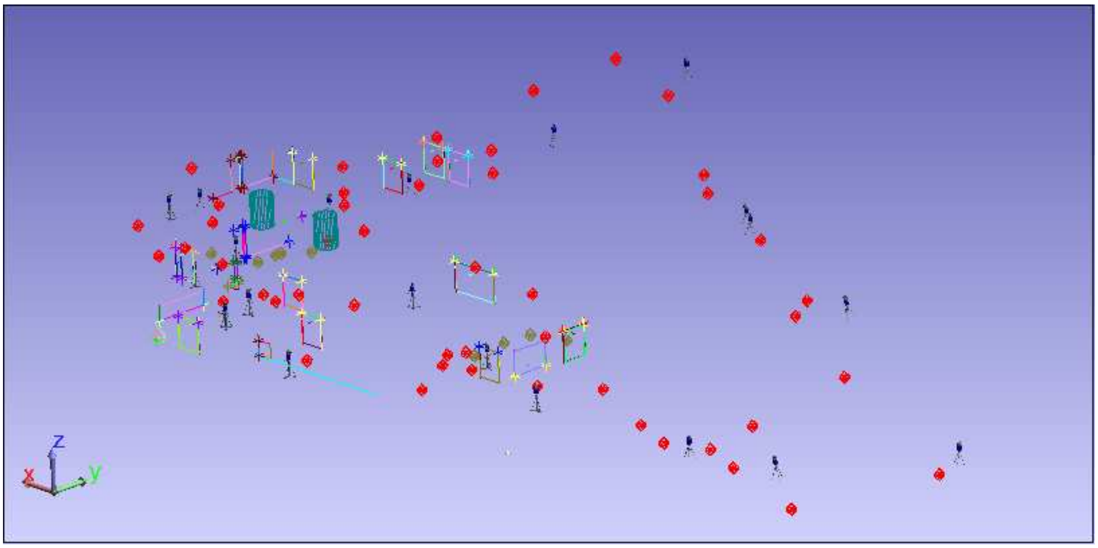


Figure 5 The reference point network (red markers) and the reference features (lines etc).

Note that in Figure 5, all the reference features are on the left of the network. The network was extended out through a corridor on the lower floor (bottom right of Figure 5) onto Woodland Road, then back up the road to the main building entrance. This was done to help tie the network together, to bring in measurements of two Ordinance Survey points located on the pavement and to establish a few reference points on the outside of the building. The two cylinders represent the two pillars on the upper level. These were measured and included in the data set to aid orientation.

3 Measurement Procedure

The drift nests were first fixed at strategic points on walls and ceilings both outside and inside the Merchant Ventures Building. The positions of the reference points were chosen such that from any position within the measured volume there would be several nests visible from each laser tracker position. Inside the building, hot-melt adhesive was used to fix the nests whereas on the outside of the building a weatherproof adhesive was used. The drift nests were left in place as a permanent reference network for future use.

3.1 Reference Points

The reference point locations were then surveyed using the laser tracker and a software package, SpatialAnalyzer (version 2009.5.12). The survey was carried out as follows. The tracker was positioned at a number of carefully chosen positions *T*1, *T*2…*T*n. At each position the coordinates of all visible drift nests were measured. At some of these tracker positions features of the building such as doorframes, window frames *etc* were also measured.

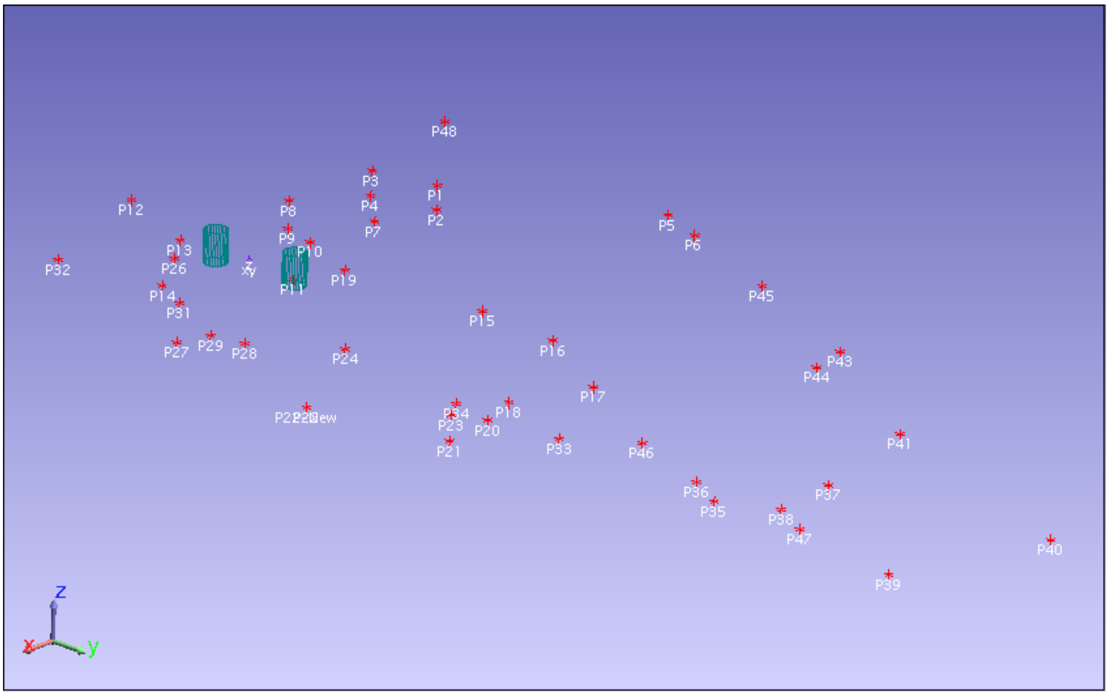


Figure 6 The 47 reference points. The two cylinders represent the columns on the upper floor of the atrium.

The measurements made from the first tracker position used an arbitrary coordinate frame. For subsequent tracker positions, the procedure adopted was to initially measure three or more nests that had already been measured and to use this data to locate the tracker in the original coordinate frame using a least-squares fitting method. All subsequent measurements made from that position were then in the same coordinate system as the original data. This approach ensured a consistent coordinate frame was used throughout the building. Figure 7 shows measurements taken from two positions with five common points used to align the coordinate systems.

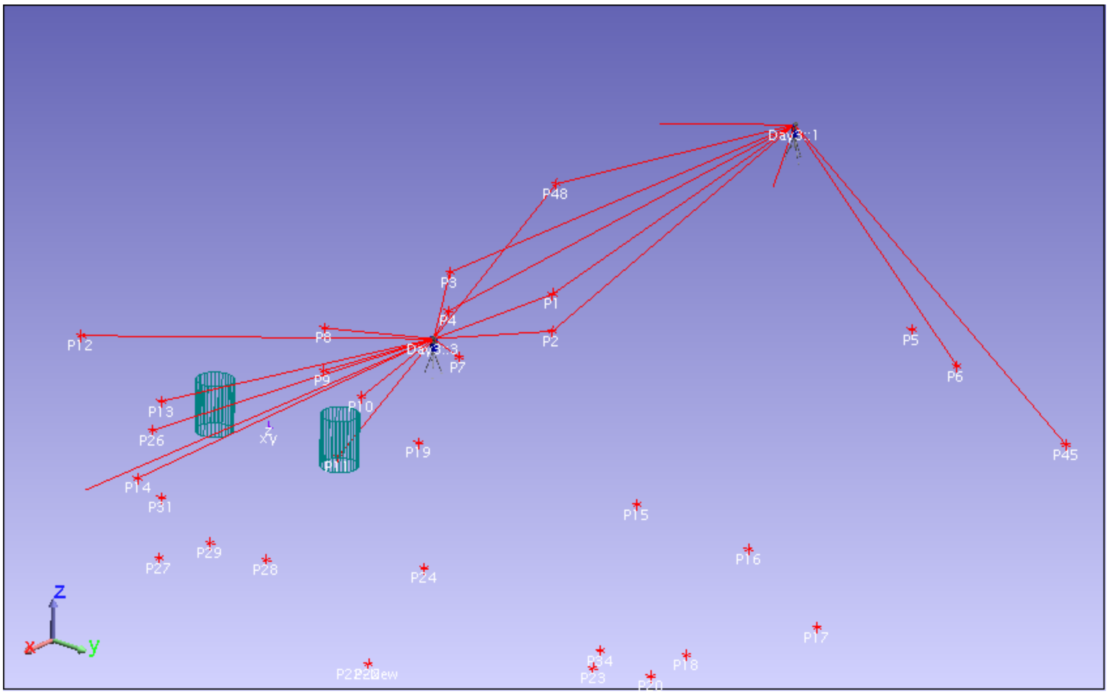


Figure 7 Measurements from two laser tracker positions showing several overlapping points.

Tracker locations were chosen to ensure sufficient overlap between the reference points measured from each tracker position. The complete network is shown in Figure 8 and Figure 9.

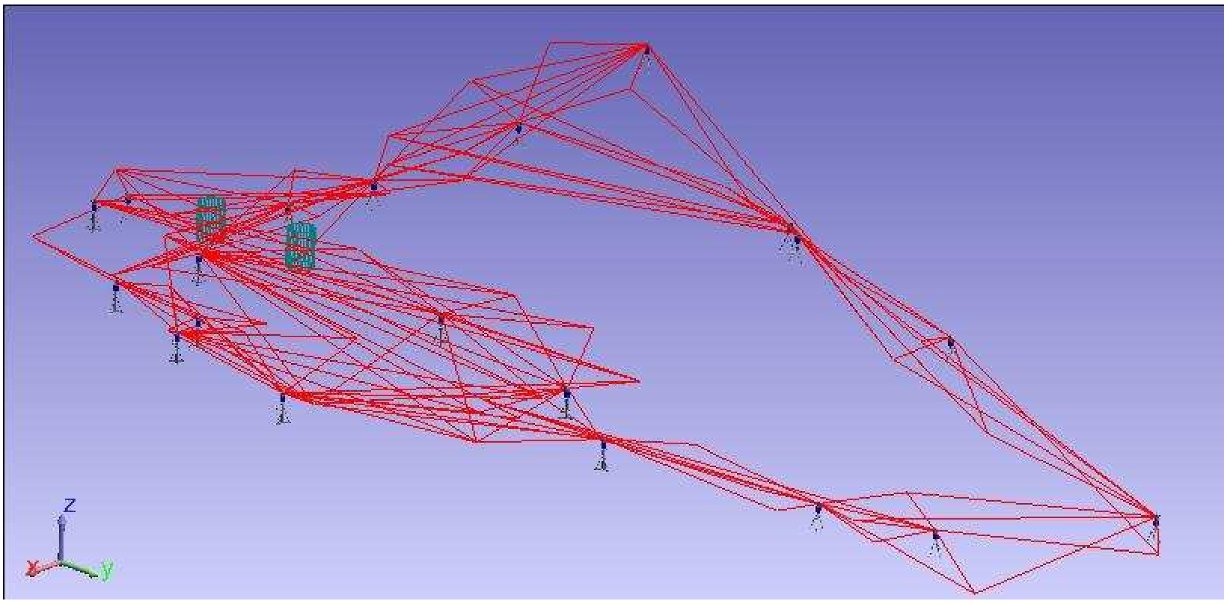


Figure 8 View of the complete reference point network showing strong links between the measurements taken from each tracker location.

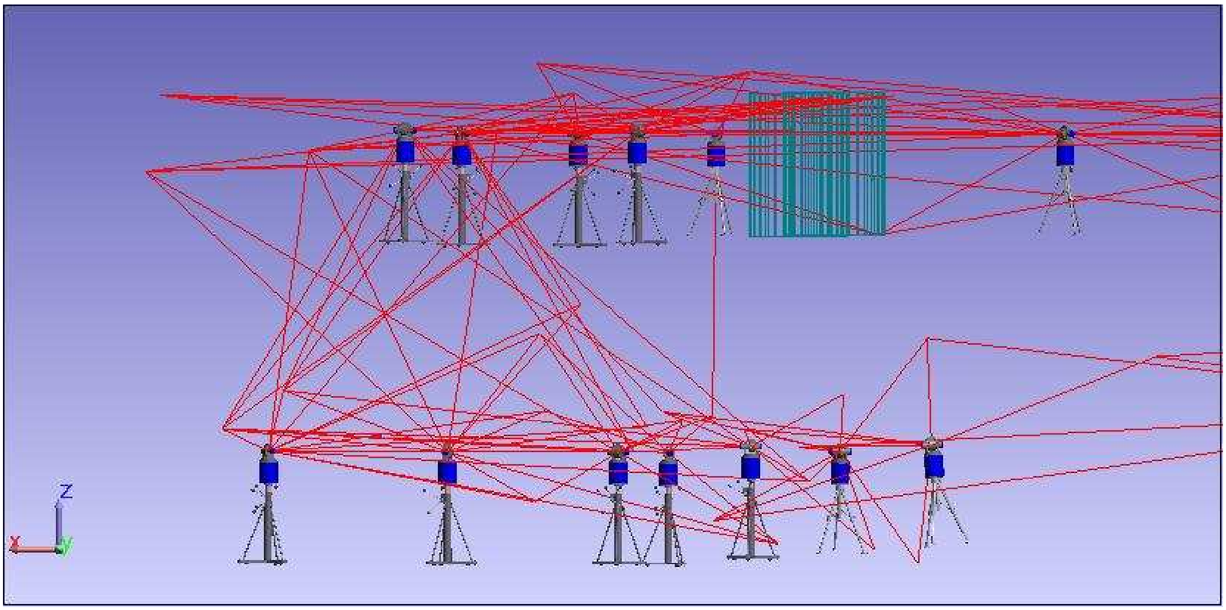


Figure 9 View of network from one end of the atrium showing the strong links between the upper and lower floors.

Table 1 shows which reference points were measured from which tracker positions. Note that data from tracker positions T1 and T2 were discarded; they were simple part of a trial run.

	Tracker Position ID																			
Point ID	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22
P1																■	■	■	■	
P2																■	■	■	■	
P3														■	■	■	■	■		
P4														■	■	■	■	■		
P5													■	■	■		■			
P6														■	■	■	■			
P7				■														■	■	■
P8	■																	■	■	
P9	■																	■	■	
P10	■																	■	■	
P11	■			■														■	■	
P12	■	■		■														■	■	■
P13				■														■	■	■
P14	■	■																■	■	
P15	■	■	■	■																
P16	■	■	■																	
P17	■	■	■	■	■															
P18	■	■	■		■	■			■											■
P19	■	■	■	■																
P20	■				■															
P21	■	■	■		■	■			■											
P22								■												

	Tracker Position ID																			
	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22
P22-new	■	■	■		■	■	■		■											
P23	■		■		■	■			■											
P24	■				■	■														
P25	■					■	■											■	■	
P26	■	■	■			■												■	■	
P27					■	■	■													
P28					■	■		■												
P29					■	■	■	■												
P30						■	■	■												
P31					■	■	■	■												
P32							■	■												■
P33			■		■				■	■										
P34			■						■	■	■									
P35									■	■										
P36									■	■	■									
P37										■	■	■								
P38										■	■	■								
P39										■	■	■								
P40											■	■	■							
P41												■	■	■	■					
P42																				
P43												■	■	■						
P44													■	■	■					
P45												■	■	■	■	■				
P46									■	■										
P47										■	■									
P48															■	■	■	■		

Table 1 Reference points measured from each tracker position.

3.2 Reference Features

Measurements of the reference features were made either directly with a 1½ inch SMR or a combination of a 1½ inch SMR with an edge tool. The SMR on its own was used for measuring, for example, internal corners where a window frame meets the glass pane. The SMR/edge tool combination was used to measure points along the edges of doorframes *etc*.

Figure 10 The edge tool being used to measure a doorframe.

Visual SLAM requires high contrast corners to be used as reference features, however, the laser tracker cannot measure the coordinates of a corner (point) directly, so each feature was constructed from a number of lines, each of which was constructed from several measured points. So, for example, the corner of a doorframe was located by measuring several points along the two meeting edges. From these points, two lines were constructed and the intersection of these two lines was calculated.

The reference point network was designed to be as strong as practicable with as much overlap between measurements from each tracker position as possible without the need for an excessive number of tracker positions. The layout of the atrium was such that it was possible to tie together the upper and lower levels of the network at several positions.

The network was also extended to the outside of the building through the lower floor exit onto the pavement on Woodland Road and back up to the main entrance of the building. This was done to provide some additional fixed reference points outside the building and to help tie the network together. However, analysis of the data has shown that this additional data had little effect on the overall accuracy of the network due to the narrowly constrained route taken around the outside of the building and the lack of any line of sight back into the building between the exit and entrance.

Reference features were measured at the following locations:

- The main entrance on Woodland Road
- Room 1.06 door
- Room 1.07 door
- Room 1.11 door
- Room 1.15 door
- Red wall panel on lower floor by room 1.06 entrance
- Fake Window on lower floor

- Lower floor lift
- Upper floor lift
- Arnold room door
- Room 2.01 door
- Room 2.11 door
- Room 2.16 door
- Red wall panel on upper floor
- Set Squared door

In addition, the corners of the four grills on the lower floor of the atrium were measured so that they could be used to define a track or path that could be followed during testing of the ViewNet systems.

4 Post-processing & Results

After all data had been collected, it was processed in two ways: firstly, the complete data set was bundled using the Unified Spatial Measurement Network (USMN) function within SpatialAnalyzer; secondly the individual points measured around the reference features were processed to locate the coordinates of the features. During this processing stage, corrections were applied for probe offsets – the radius of the SMR and the thickness of the edge tool. This resulted in a data set comprising measured points, constructed lines and planes and constructed feature coordinates.

In addition, a new coordinate frame was constructed that was aligned approximately with the existing coordinate frame used by the UWB system.

Finally, the data set was compared with the measurements of the reference points made by the Ordinance Survey and transformed into their global coordinate system.

A more detailed explanation of these processes and the results obtained is given in the following sections along with a detailed explanation of the contents of the SpatialAnalyzer file that contains the processed data. The SpatialAnalyzer file and SpatialAnalyzer viewer software will be made available to the project team with this report.

4.1 SpatialAnalyzer File Contents

Data is stored in SpatialAnalyzer in *Collections*. Each collection can contain *Instruments*, *Point Groups* and other constructed elements such as *Planes*, coordinate *Frames*, *Lines*, *Cylinders etc.* Point Groups can contain either measured or constructed points.

The ViewNet Survey results are all contained within a file called "ViewNet Survey with OS Data.xit". The measured points are stored within two collections called *Day2* and *Day3* respectively. The point groups within these collections are arranged by tracker position. The point groups are named to reflect the tracker position and the reference features that were measured from the tracker location. If reference points only - no reference features - were measured from a particular tracker position, then the point groups was simply named "*Tnn*", where *nn* refers to the tracker position 3 to 22 (data from tracker positions 1 and 2 were taken for trial purposes only and not used in the final processing). If reference features were also measured from a tracker position then additional point groups were included in the data. The name of these point groups includes the name of the reference features being measured. For example, from tracker position 5, reference points were measured and features on the door frame to Room 2.16, the red panel by Room 2.16 door and the door through to the Set Squared area were measured. The data file therefore contains point groups *T5*, *T5 Room 2.16 Door*, *T5 Red Panel by R2.16* and *T5 Set Squared Door*.

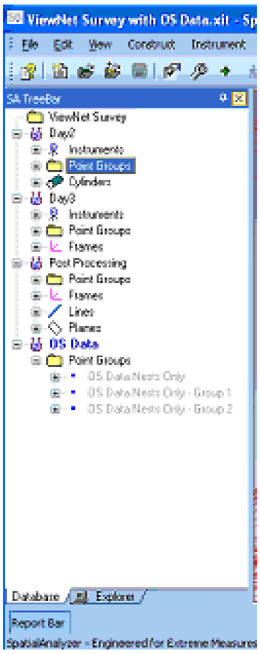


Figure 11 A view of the SpatialAnalyser file showing the individual data Collections on the left of the window.

Each point group contains a number of measured points. The naming convention used was as follows:

Reference points (drift nests) were labelled *P*1 to *P*48 corresponding to the drift nest ID. Points used for constructing reference features were given descriptive names. For example, the points used to construct a line representing the right-hand block-work edge of the doorframe to Room 2.16 were named "*R2.16 Right Block 1*", "*R2.16 Right Block 2*", *etc*.

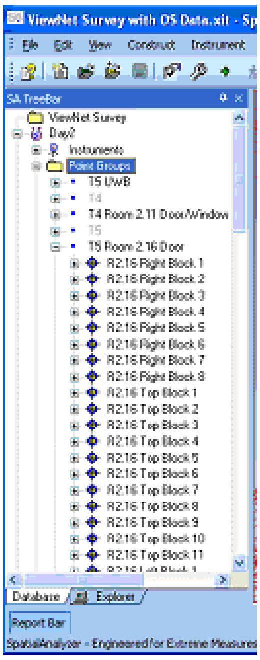


Figure 12 Another view of the data collections showing an expanded view of a set of Point Groups with one group expanded to show the individual points within the group.

The *Post Processing* collection shown in Figure 11 was used to store all constructed features – lines points, planes etc that were used to construct the points representing the reference features. The OS data collection contains the reference point data provided by the Ordinance Survey.

Note that all data in this file is post-USMN best-fit.

4.2 Coordinate Frames

The coordinate data for the Reference Points and Reference Features is given below in two coordinate frames.

4.2.1 Arbitrary Coordinate Frame

This coordinate frame was based on the internal coordinate frame of the laser tracker in the first position surveyed. It does not relate to any physical features of the building. This was the working coordinate frame for the survey.

4.2.2 UWB Coordinate Frame

This coordinate frame was constructed to simplify comparison between data obtained from the different sensor systems used by the ViewNet project. This coordinate frame is nominally the same as that defined for the UWB system.

The UWB Coordinate frame has the origin at the lower left hand corner of the atrium when viewed from the top of the stairs. A coordinate system was constructed that nominally matched this frame. Measured points on the walls and lower floor of the atrium were used to construct three planes, shown in Figure 13, that define the coordinate frame. The XZ plane is shown as cyan was constructed from reference points on the wall – points *P*14, *P*18, *P*21, *P*22-new and *P*25. The *yz* plane, shown orange, was constructed form points round the door to room 2.16. The *xy* plane, shown as pale green, was constructed from points measured on the five square grids on the lower floor – points *TA*1-4, *TB*1-4, *TC*1-4 and *TD*1-4. The origin of the coordinate frame is depicted by the large red/green/blue arrows.

Note that the UWB frame is left-handed.

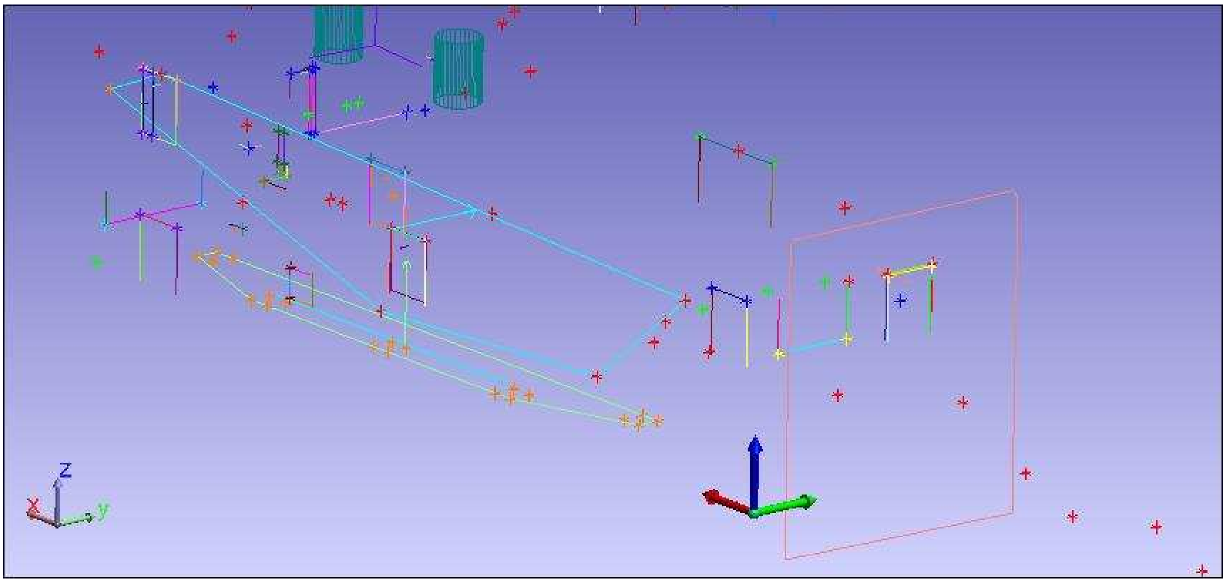


Figure 13 Construction of the UWB Coordinate Frame.

4.3 Reference Points

Although care had been taken to re-locate the tracker in the arbitrary coordinate frame each time it was moved, this method is prone to increased uncertainty propagating through the network as it is built-up due to uncertainties in the individual tracker location calculations. The USMN functions within SpatialAnalyzer provide the ability to effectively minimise this uncertainty build-up by simultaneously adjusting the complete data set to obtain the best fit of the individual data sets to each other. This function has the added benefit of providing uncertainty estimates for the fitted data points.

The complete data set was processed by USMN. This revealed a single measurement that had a residual of 4.18 mm. This point (one measurement of *P*27) was eliminated by setting its weight to zero, and the data re-processed.

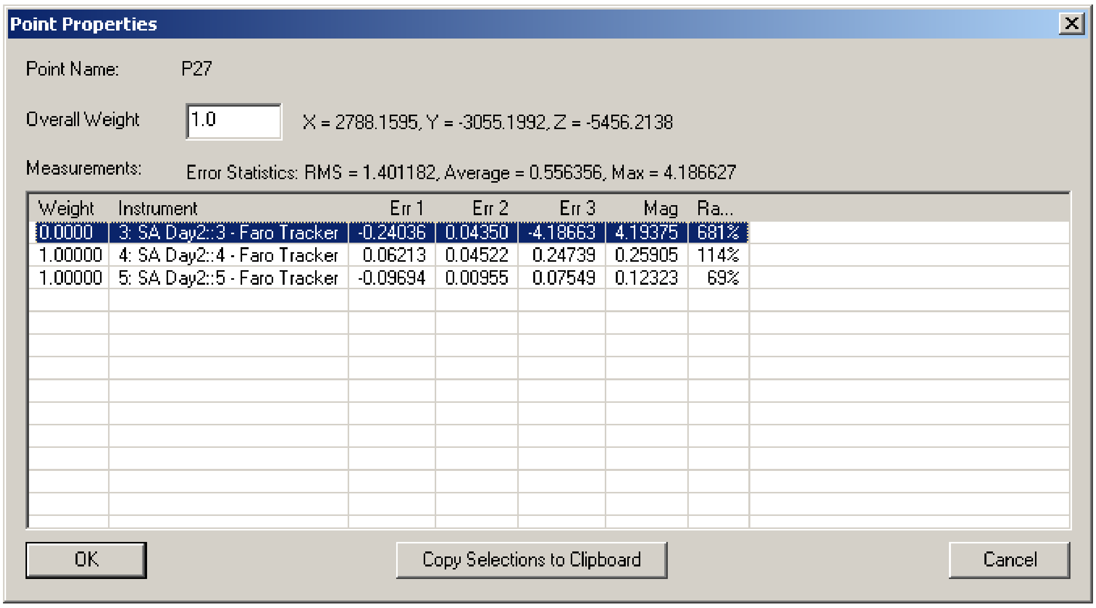


Figure 14 Removing one measurement of *P*27 from the USMN fit by setting its weight to zero.

Further examination of the data revealed fifteen further outliers. So the weighting of the data associated these measurements was reduced from 1.0 to 0.2 and the data re-processed. The magnitude of the residuals of the fit for all forty-seven reference points was thus reduced to between 0.31 mm and 0.028 mm.

The reference point coordinates and their respective coordinate uncertainties ($k=1$) are shown in Table 2. The uncertainties listed in Table 2 are colour-coded – green for an uncertainty less than 0.1 mm, amber for between 0.1 and 0.2 mm and red for greater than 0.2 mm.

	Coordinates /mm			Coordinate uncertainty /mm			
Point	***x***	***y***	***z***	***u(x)***	***u(y)***	***u(z)***	***u(mag)***
P1	-16878.2	-43.9	271.6	0.02	0.04	0.05	0.06
P2	-16926.8	-57.5	-1284.7	0.02	0.04	0.05	0.07
P3	-15952.0	-4406.5	244.4	0.03	0.04	0.05	0.07
P4	-15905.0	-4401.3	-1343.6	0.03	0.03	0.05	0.06
P5	-25341.9	10866.9	-750.9	0.06	0.05	0.16	0.18
P6	-21109.5	16681.5	668.0	0.08	0.05	0.13	0.16
P7	-10248.8	881.8	-44.6	0.02	0.02	0.04	0.05
P8	-7918.6	-3911.0	548.7	0.02	0.02	0.03	0.04
P9	-7913.9	-3910.4	-1219.6	0.02	0.02	0.03	0.04
P10	-3777.6	1444.3	480.2	0.02	0.02	0.03	0.04
P11	-2304.4	1566.2	-1507.8	0.02	0.02	0.03	0.04
P12	-392.4	-9789.4	911.5	0.02	0.02	0.03	0.04
P13	2750.9	-3098.2	1034.8	0.03	0.03	0.04	0.06
P14	8338.9	455.6	564.6	0.02	0.03	0.03	0.04
P15	-2537.9	16317.4	553.8	0.03	0.02	0.04	0.05
P16	-2994.6	21544.5	23.1	0.03	0.03	0.05	0.06
P17	2210.1	29391.8	593.8	0.03	0.02	0.03	0.04

	Coordinates /mm			Coordinate uncertainty /mm			
Point	*x*	*y*	*z*	*u(x)*	*u(y)*	*u(z)*	*u(mag)*
P18	6125.2	26165.8	-258.4	0.02	0.02	0.03	0.04
P19	-1649.5	6122.9	537.7	0.03	0.02	0.04	0.05
P20	1120.3	20208.6	-4351.3	0.05	0.04	0.06	0.09
P21	6505.3	21935.7	-3811.4	0.03	0.02	0.04	0.05
P22-new	7413.8	11351.4	-4381.7	0.02	0.02	0.03	0.04
P23	1324.8	17483.3	-4721.6	0.04	0.03	0.04	0.06
P24	2103.7	9619.7	-2534.8	0.02	0.02	0.03	0.04
P25	8549.1	-2012.5	-571.9	0.02	0.02	0.03	0.04
P26	3343.9	-3017.1	31.3	0.02	0.02	0.02	0.03
P27	2787.9	-3055.7	-5456.3	0.02	0.01	0.02	0.03
P28	2632.9	2183.9	-4112.1	0.02	0.02	0.02	0.04
P29	-828.1	-3538.2	-6087.9	0.02	0.02	0.03	0.04
P30	593.7	1979.2	-4254.5	0.02	0.02	0.03	0.04
P31	2708.2	-3041.3	-2967.9	0.02	0.01	0.02	0.03
P32	153.9	-14917.2	-4183.0	0.03	0.02	0.04	0.05
P33	-1270.2	23814.9	-5159.5	0.04	0.03	0.05	0.06
P34	895.0	17471.5	-4126.3	0.04	0.03	0.04	0.07
P35	-2246.6	35374.7	-6172.8	0.07	0.04	0.11	0.13
P36	-315.0	35600.5	-4384.6	0.06	0.04	0.11	0.13
P37	-3023.1	43636.7	-3043.6	0.09	0.03	0.16	0.19
P38	-1116.1	41628.4	-4651.5	0.08	0.04	0.15	0.17
P39	156.1	51398.4	-5742.5	0.11	0.04	0.22	0.25
P40	-6416.5	58367.2	-3308.4	0.13	0.04	0.28	0.31
P41	-12949.0	40530.4	-3216.8	0.11	0.05	0.20	0.23
P43	-16325.0	32636.9	-1051.9	0.10	0.05	0.17	0.20
P44	-17627.7	29703.6	-3215.9	0.10	0.05	0.16	0.20
P45	-20610.3	22606.2	-784.8	0.09	0.05	0.15	0.18
P46	-1785.8	29928.4	-3862.6	0.05	0.03	0.08	0.09
P47	-2884.3	41627.2	-6367.7	0.08	0.04	0.15	0.17
P48	-26791.4	-8222.6	-505.0	0.04	0.06	0.17	0.19

Table 2 Reference point coordinates (arbitrary coordinate frame) and coordinate uncertainties (1σ).

Table 3 shows the reference point coordinates in the UWB coordinate frame.

	UWB Coordinate Frame /mm		
Point	*x*	*y*	*z*
P1	27782.4	25031.6	6684.3
P2	27795.1	25086.5	5128.2
P3	32205.7	24461.4	6663.8
P4	32207.4	24419.4	5075.6
P5	16225.0	32588.7	5664.4
P6	10768.9	27895.3	7057.0
P7	27396.5	18350.2	6344.9
P8	32360.9	16413.2	6941.5
P9	32364.2	16414.4	5173.2

Point	UWB Coordinate Frame /mm		
	x	***y***	***z***
P10	27358.1	11853.0	6847.9
P11	27359.7	10381.5	4855.1
P12	38827.9	9385.9	7293.4
P13	32412.6	5711.4	7391.9
P14	29323.3	-144.1	6896.1
P15	12633.9	9414.4	6884.5
P16	7388.1	9448.7	6343.7
P17	-13.7	3624.6	6880.5
P18	3520.0	-13.9	6022.9
P19	22866.9	9353.3	6888.3
P20	9060.9	5470.0	1959.2
P21	7773.9	-38.8	2478.1
P22	18398.0	-86.6	1928.5
P23	11794.5	5487.8	1594.3
P24	19691.1	5340.0	3796.1
P26	32381.7	5117.1	6386.4
P27	32386.0	5692.8	900.6
P28	27148.3	5419.1	2233.6
P29	32575.7	9338.0	281.6
P31	32360.3	5762.8	3389.3
P32	43993.1	9273.0	2208.6
P33	5274.7	7563.8	1150.6
P34	11770.3	5915.1	2191.0
P35	-6324.2	7605.6	114.7
P36	-6396.5	5656.1	1896.3
P37	-14628.1	7700.9	3228.0
P38	-12469.0	5968.0	1618.5
P39	-22101.9	3913.6	501.9
P40	-29584.1	9893.0	2941.3
P41	-12334.3	17846.1	3093.3
P43	-4743.9	21842.0	5286.4
P44	-1921.3	23384.9	3133.1
P45	4906.9	26923.5	5589.4
P46	-863.0	7579.0	2435.6
P47	-12607.4	7736.3	-92.1
P48	35134.2	35576.3	5957.3
P22-new	18398.1	-86.5	1928.5

Table 3 Reference point coordinates in the UWB coordinate frame.

4.3.1 Reference Point Coordinate Uncertainty

The reference point coordinate uncertainty reported in Table 2 were calculated by USMN based on the fit of the data after outlier rejection. This takes into account the nominal uncertainty of the instrument and the effects of the environment on the stability of the instrument and the building/nest locations. The uncertainty quoted represents one standard deviation (1σ).

4.4 Reference feature coordinates

The coordinates of the reference features were computed from point measurements on edges forming the features. Lines and/or planes were fitted to the points as appropriate and tool offsets were applied to compensate for the radius of the SMR and thickness of the edge tool. The planes and lines were then used to construct points representing the features of interest. For example, Figure 15 shows two planes and the points they were constructed from that were measured around the blockwork edges of the Arnold Room door and the UPVC window frame next to the door. Figure 16 shows the same planes with the reference points constructed from their corners – Top Left and Top Right of the block work frame and the four corners of the UPVC frame round the window to the right of the door. Figure 17 shows the actual features represented in Figure 15.

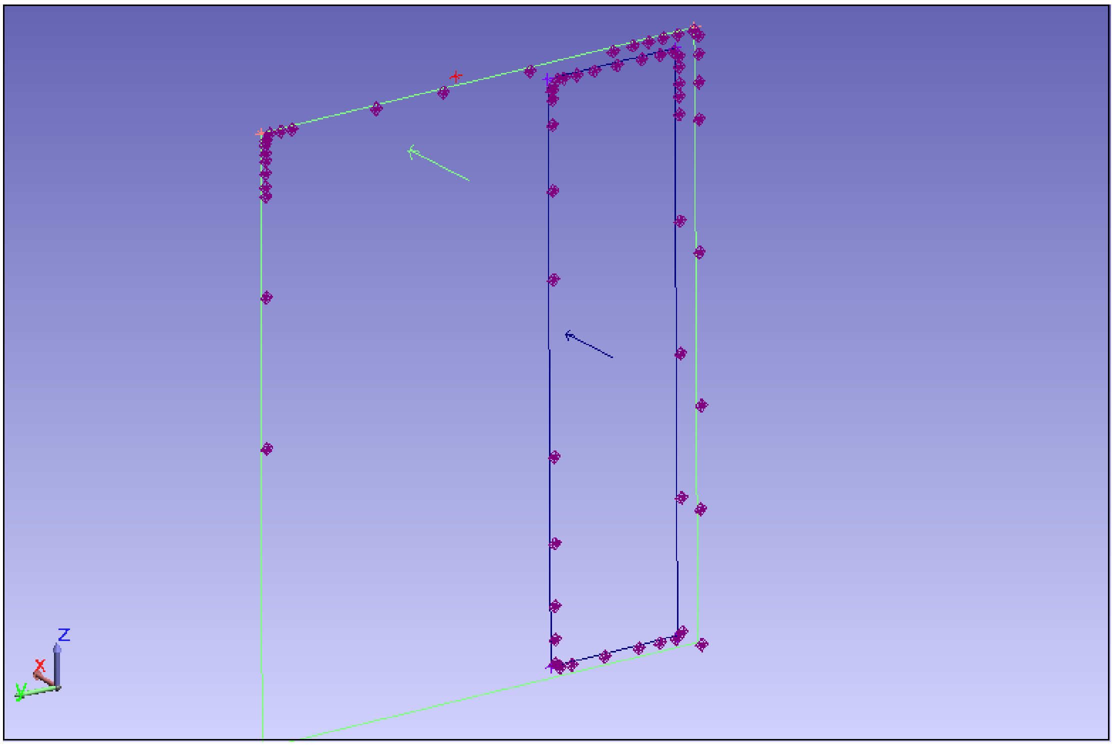


Figure 15 Raw data points measured around the Arnold room door and the planes constructed from them. The corners of the planes represent the reference features.

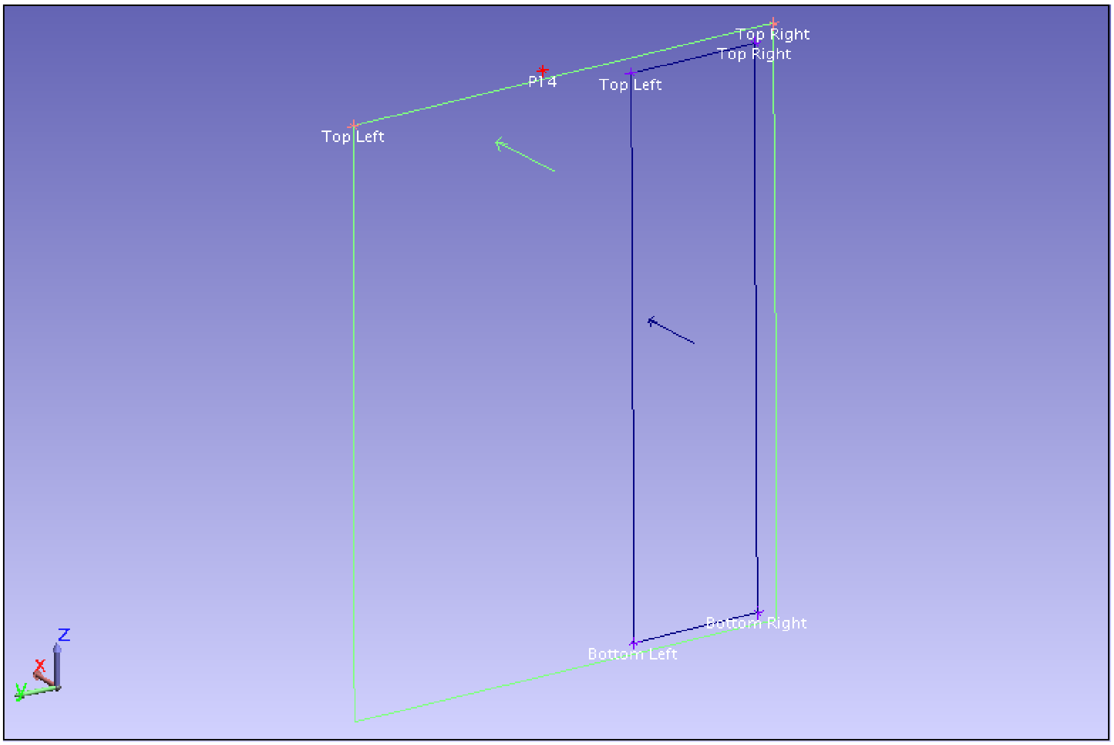


Figure 16 The planes used to construct the reference features located around the Arnold Room door. The larger plane represents the edges of the block work frame. The smaller plane represents the edges of the UPVC window frame. The Reference features (corners) are labelled.

Figure 17 The reference features around the Arnold Room door. Top corners of block work and the corners of the window frame.

Arnold Room Window Frame Point Name	Arbitrary Coordinate Frame /mm			UWB Coordinate Frame /mm		
	x	***y***	***z***	***x***	***y***	***z***
Bottom Left	8404.8	89.1	-1557.5	29698.1	-173.0	4774.5
Bottom Right	8449.0	-394.6	-1557.3	30183.8	-178.0	4775.7
Top Left	8404.9	88.3	462.2	29694.9	-179.8	6794.2
Top Right	8449.2	-395.9	460.7	30181.1	-184.8	6793.7

Table 4 Arnold Room Door Reference Feature Coordinates.

The same methods were used to locate the reference features depicted in the following figures. The Feature names used in the Figures refer to the names used to record data in the SpatialAnalyzer files.

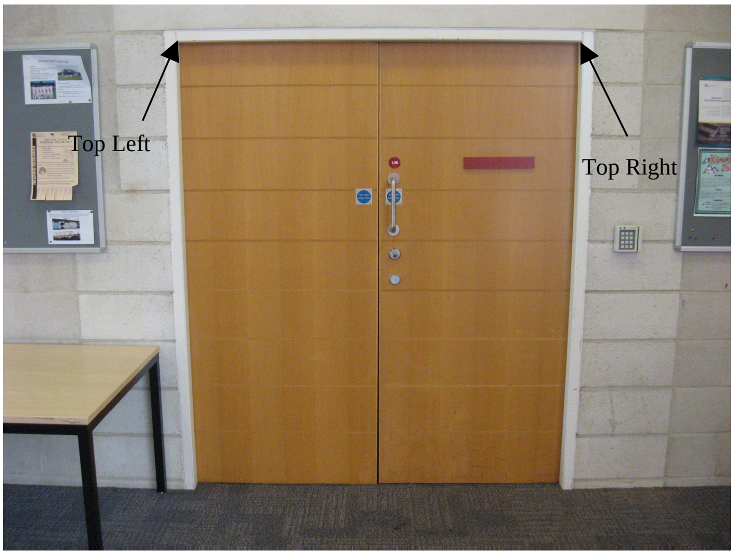


Figure 18 Features round Room 1.06 door. Outside corners of wooden frame.

Room 1.06 Door Wooden Frame Point Name	Arbitrary Coordinate Frame /mm			UWB Coordinate Frame /mm		
	x	*y*	*z*	*x*	*y*	*z*
Top Left	-1054.1	-1689.3	-4317.8	30711.1	9407.9	2048.3
Top Right	-1203.8	17.7	-4314.2	28997.6	9419.0	2048.6

Table 5 Room 1.06 Door Reference Feature Coordinates.

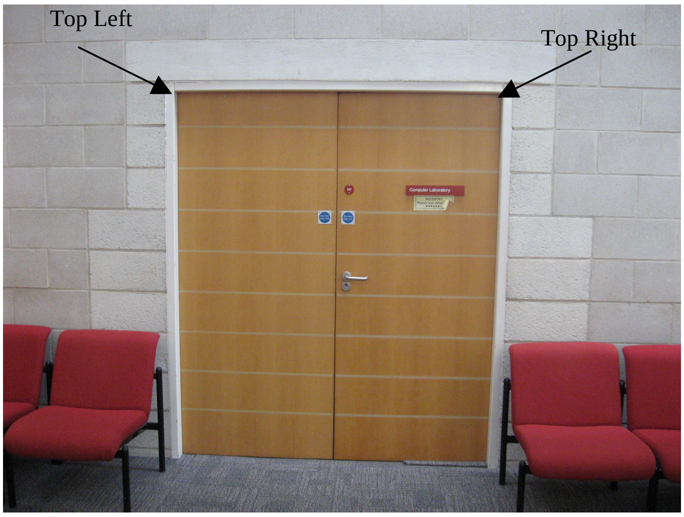


Figure 19 Features on Room 1.07 door. Outside corners of wooden frame.

Room 1.07 Door Point Name	Arbitrary Coordinate Frame /mm			UWB Coordinate Frame /mm		
	x	*y*	*z*	*x*	*y*	*z*
Top Left	2425.1149	4577.7193	-4306.8065	24745.99	5433.274	2034.301
Top Right	2275.0801	6282.9488	-4301.7286	23034.21	5444.909	2036.067

Table 6 Room 1.07 Door Reference Feature Coordinates.

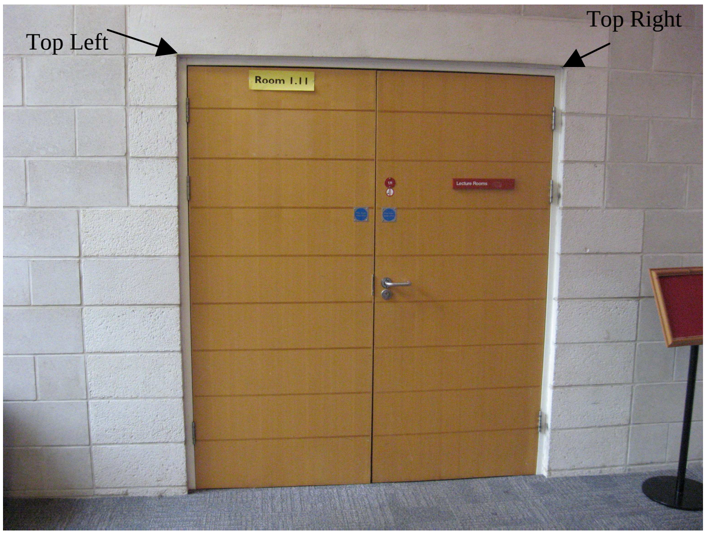


Figure 20 Features on Room 1.11 door. Outside corners of block work.

Room 1.11 Door Block Point Name	Arbitrary Coordinate Frame /mm			UWB Coordinate Frame /mm		
	x	*y*	*z*	*x*	*y*	*z*
Top Left	8285.4	1345.3	-4246.6	28441.6	-146.6	2083.1
Top Right	8438.9	-460.1	-4250.3	30253.6	-153.6	2082.9

Table 7 Room 1.11. Door Reference Feature Coordinates.

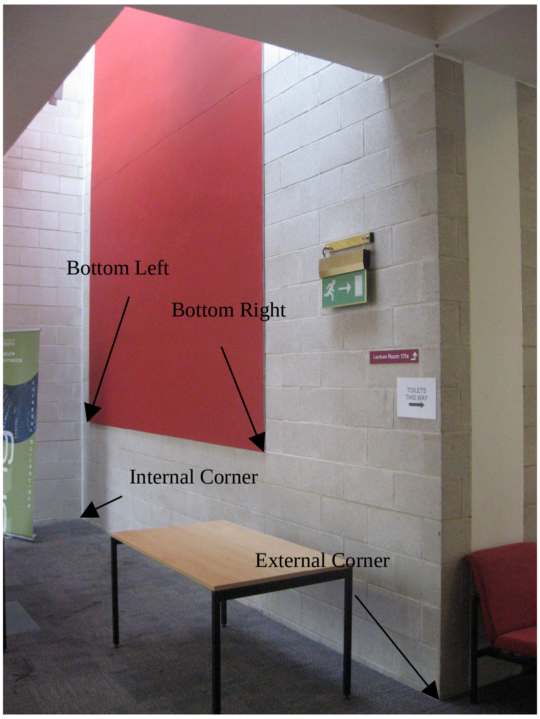


Figure 21 Features round the Red Panel on the lower floor. The bottom corners of the wall and the two bottom corners of the red panel.

Room 1.06 Door Wooden Frame	**Arbitrary Coordinate Frame /mm**			**UWB Coordinate Frame /mm**		
Point Name	***x***	***y***	***z***	***x***	***y***	***z***
Top Left	-1054.1	-1689.3	-4317.8	30711.1	9407.9	2048.3
Top Right	-1203.8	17.7	-4314.2	28997.6	9419.0	2048.6

Table 8 Coordinates of Reference Features by Red Panel on lower floor

Figure 22 Features on the False Window on the lower floor. Corners of the glass pane.

False Window	**Arbitrary Coordinate Frame /mm**			**UWB Coordinate Frame /mm**		
Point Name	***x***	***y***	***z***	***x***	***y***	***z***
Bottom Left	-675.9	-6240.9	-5570.5	35280.9	9403.1	804.5
Bottom Right	-701.3	-5933.9	-5569.4	34972.8	9403.6	805.0
Top Left	-673.9	-6242.9	-4575.1	35281.0	9398.0	1799.9
Top Right	-699.4	-5936.7	-4574.4	34973.8	9398.7	1800.0

Table 9 Coordinates of reference Features by False Window on Lower Floor.

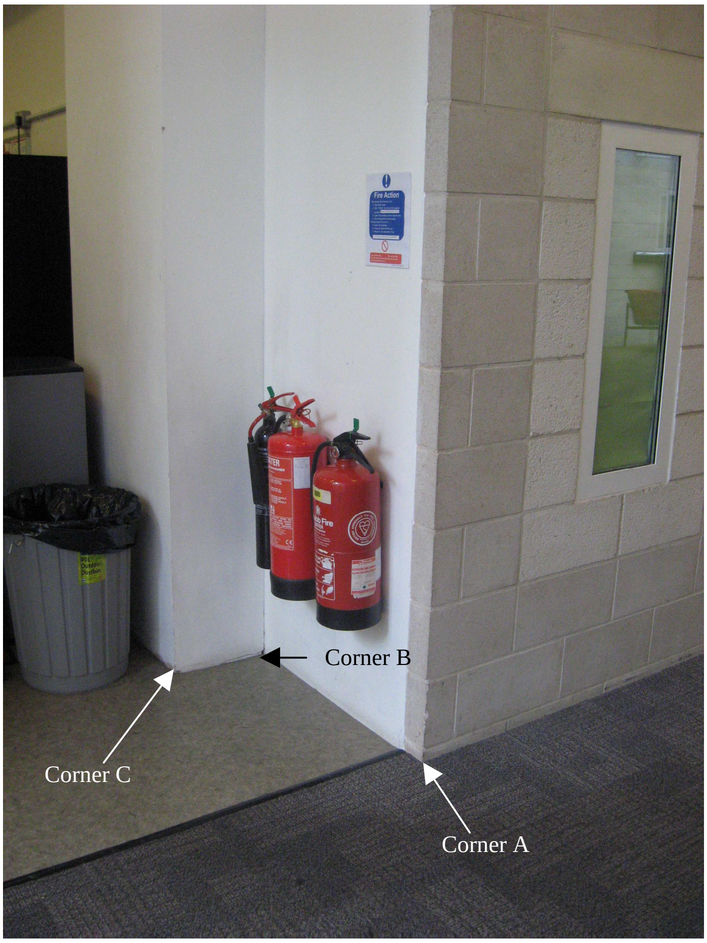


Figure 23 Corners by False Window on lower floor.

Corners by False Window	Arbitrary Coordinate Frame /mm			UWB Coordinate Frame /mm		
Point Name	*x*	*y*	*z*	*x*	*y*	*z*
Corner A	-606.1	-6871.0	-6355.6	35916.0	9387.2	20.5
Corner B	-1541.5	-6950.8	-6368.9	35920.0	10326.0	10.4
Corner C	-1505.2	-7311.4	-6365.3	36282.3	10318.9	14.7

Table 10 Coordinates of Reference Features by False Window.

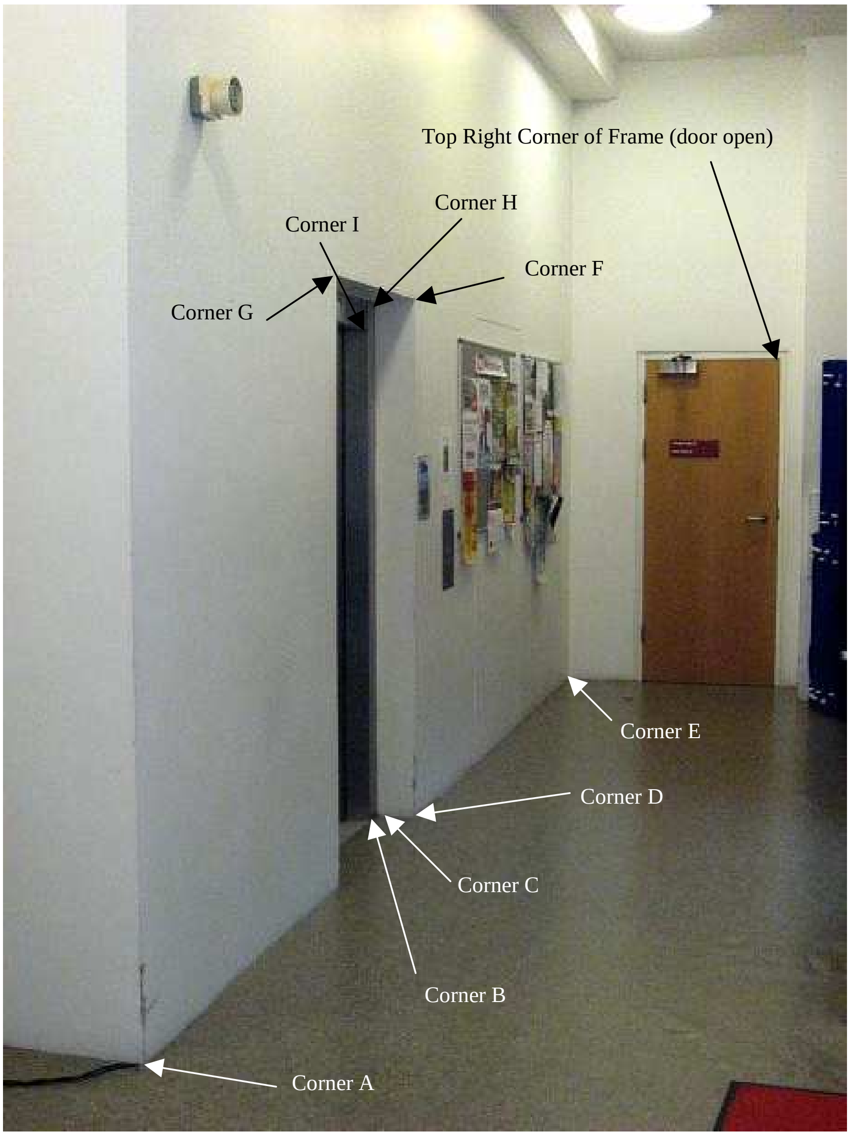


Figure 24 Features by lower floor lift.

Corners by Lower Floor Lift	Arbitrary Coordinate Frame /mm			UWB Coordinate Frame /mm		
Point Name	x	y	z	x	y	z
Corner A	-2124.9	-9932.1	-6363.8	38844.4	11148.6	24.0
Corner B	-4620.4	-10313.9	-6361.1	39023.1	13666.8	35.5
Corner C	-4720.7	-10322.5	-6360.7	39023.5	13767.4	36.2
Corner D	-4742.8	-10159.7	-6364.9	38859.5	13776.3	31.7
Corner E	-8430.2	-10474.7	-6361.9	38875.3	17477.0	47.2
Corner F	-4745.5	-10160.7	-4239.4	38856.1	13771.9	2157.3
Corner G	-3737.8	-10072.8	-4233.0	38849.9	12760.4	2160.3
Corner H	-4723.4	-10324.9	-4240.2	39021.6	13763.2	2156.7
Corner I	-4623.2	-10315.9	-4360.7	39020.9	13663.0	2035.8

Table 11 Coordinates of Reference Features by Lower Floor Lift.

Figure 25 Room 1.15 Window. Corners of glass pane.

Room 1.15 Window Glass/Frame Point Name	Arbitrary Coordinate Frame /mm			UWB Coordinate Frame /mm		
	x	*y*	*z*	*x*	*y*	*z*
Bottom Right	7819.7	6936.6	-5077.2	22832.7	-131.8	1241.5
Top Right	7820.4	6935.0	-4093.7	22832.3	-135.7	2225.1

Table 12 Coordinates of Reference Features on Room 1.15 Window.

Figure 26 Feature on Room 2.11 Door/Window surround.

Room 2.11 Door/Window Border Point Name	Arbitrary Coordinate Frame /mm			UWB Coordinate Frame /mm		
	x	*y*	*z*	*x*	*y*	*z*
Top Left	-2380.8	14413.6	515.1	14544.3	9412.0	6849.6
Top Right	-2701.1	17964.2	529.5	10979.4	9444.1	6857.1

Table 13 Coordinates of Reference Features on Room 2.11 Door/Window Frame.

Figure 27 Feature on Room 2.16 door.

Room 2.16 Door Block Point Name	Arbitrary Coordinate Frame /mm			UWB Coordinate Frame /mm		
	x	*y*	*z*	*x*	*y*	*z*
Top Left	-1103.9	29133.5	548.3	-24.2	6948.8	6846.0
Top Right	701.4	29279.9	547.3	-24.2	5137.6	6839.0

Table 14 Coordinates of Reference Features on Room 2.16 Door frame.

Figure 28 Features on Red Panel on upper floor by Room 2.16 door.

The two bottom corners (not visible in the picture).

Red Panel by Room 2.16 Door Point Name	Arbitrary Coordinate Frame /mm			UWB Coordinate Frame /mm		
	x	*y*	*z*	*x*	*y*	*z*
Bottom Left	2252.1	29395.7	-1268.9	-10.6	3588.7	5017.6
Bottom Right	4957.4	29614.6	-1259.4	-10.0	874.5	5018.0

Table 15 Coordinates of Reference Features on Red Panel on Upper Floor.

Figure 29 Features on the 'Set Squared' Door. The top outer corners of the frame.

Set Squared Door	Arbitrary Coordinate Frame /mm			UWB Coordinate Frame /mm		
Point Name	*x*	*y*	*z*	*x*	*y*	*z*
Top Left	6106.8	27549.8	513.6	2137.5	-110.1	6792.0
Top Right	5954.3	29259.0	515.8	421.6	-96.3	6790.8

Table 16 Coordinates of Reference Featured on Door to Set Squared Area.

Figure 30 Feature round the Main entrance doors. The top corners of the left and right doorframes.

Main Entrance Door Left Wooden Frame	**Arbitrary Coordinate Frame /mm**			**UWB Coordinate Frame /mm**		
Point Name	***x***	***y***	***z***	***x***	***y***	***z***
Top Left	-14929.8	13.1	456.3	27882.9	23084.5	6862.7
Top Right	-14762.5	-1789.8	447.6	29693.4	23063.5	6857.4
Main Entrance Door Right Wooden Frame	**Arbitrary Coordinate Frame /mm**			**UWB Coordinate Frame /mm**		
Point Name	***x***	***y***	***z***	***x***	***y***	***z***
Top Left	-14720.9	-2233.5	448.7	30139.0	23057.9	6859.4
Top Right	-14558.8	-4036.1	448.3	31948.8	23042.1	6862.5

Table 17 Coordinates of Reference Features on Main Entrance Doors.

Figure 31 Features on Main Entrance Inner Left Door.

Inner Main Entrance Door Left Point Name	Arbitrary Coordinate Frame /mm			UWB Coordinate Frame /mm		
	x	*y*	*z*	*x*	*y*	*z*
Top Left	-11006.7	-3682.2	387.7	31883.4	19473.3	6789.8
Top Right	-11147.8	-1979.5	391.8	30174.9	19476.1	6790.5

Table 18 Coordinates of Reference Features on Inner Door of Main Entrance.

Figure 32 Features on Room 2.01 door surround.

Room 2.01 Door Block Point Name	Arbitrary Coordinate Frame /mm			UWB Coordinate Frame /mm		
	x	*y*	*z*	*x*	*y*	*z*
Top Left	-7464.9	-8393.1	472.5	36865.2	16323.7	6873.8
Top Right	-7618.5	-6590.3	471.5	35055.8	16331.0	6869.3

Table 19 Coordinates of Reference Features on Room 2.01 Door Frame.

Figure 33 Features around the lift door in the upper floor.

Corners by Lift Door on Upper Floor	Arbitrary Coordinate Frame /mm			UWB Coordinate Frame /mm		
Point Name	***x***	***y***	***z***	***x***	***y***	***z***
Corner A	-2136.2	-9923.1	-1636.5	38825.2	11143.3	4751.3
Corner B	-4735.7	-10140.1	-1644.3	38831.3	13751.8	4752.2
Corner C	-4722.1	-10328.7	-1646.6	39020.3	13753.5	4750.3
Corner D	-4624.9	-10320.2	-1645.7	39019.7	13656.0	4750.9
Corner E	-7297.3	-10352.7	-1643.8	38836.0	16322.2	4761.3
Corner F	-4744.4	-10160.2	475.0	38846.4	13755.0	6871.6
Corner G	-3746.5	-10076.4	478.9	38843.6	12753.6	6872.2
Corner H	-4728.6	-10331.7	477.3	39018.7	13753.1	6874.2
Corner I	-4627.6	-10322.9	356.6	39018.3	13652.1	6753.2

Table 20 Coordinates of Reference Features round Upper Floor Lift.

4.4.1 Reference feature coordinate uncertainty

The uncertainty in the reference feature coordinates is not as easily derived as for the directly measured reference points (see section 4.3.1). This is because the reference feature coordinates are constructed from lines and planes, which are themselves constructed by least-squares fit to measured points. In many cases, the points are measured on ill-defined surfaces or rough edges, for example the block work round doorframes. As a result of this, the residuals of the fit of measured points to constructed lines and planes used to construct the reference feature points are in some cases of the order of 1 mm to 2 mm.

An examination of a cross section of the residuals of the fitted lines and planes showed RMS residuals ranging up to a maximum of 1.9 mm. If one assumes that the residuals examined are typical residuals across all the fitted lines and planes and that the uncertainty in the individual points was at least a factor of two worse than the uncertainty achieved for the reference points due to the least-squares fitting process, then one can reasonably estimate that the likely uncertainty of the constructed reference points is no more than 1 mm.

The expanded uncertainty (k = 2) is therefore 2 mm.

Note that this uncertainty applies to the measurements made at the time. It does not include any drift of relative position of the reference features due to movement of the building due, for example, to temperature change or other effects.

A definitive uncertainty calculation for each constructed reference feature coordinate is possible but is considered too labour intensive given the accuracy requirement of the project.

4.5 UWB Base Stations and Receivers

In addition to the reference points and features, the approximate positions of ultra-wide-band (UWB) base units and receivers were also measured.

The UWB Receiver locations were all on the railing round the upper part of the atrium. Three were located at the top of the stairs as indicated in Figure 34, and another three were located at the other end of the atrium.

The UWB base unit positions were on top of the cupboard by the Arnold Room door (*BU*2), the base of the column across the landing from the Arnold Room door (*BU*0) and at the far end of the balcony at floor level (*BU*1).

Figure 34 Approximate locations of UWB receivers 1-3.

Weighted USMN UWB Point Name	Arbitrary Coordinate Frame /mm			UWB Coordinate Frame /mm		
	x	*y*	*z*	*x*	*y*	*z*
UWB1	2675.7	3032.1	-624.3	26299.6	5296.1	5719.5
UWB2	3152.0	3069.2	-628.8	26301.1	4818.5	5713.3
UWB3	4690.2	3192.2	-627.3	26303.0	3275.3	5709.7
UWB4	721.8	25913.7	-593.3	3334.9	5393.2	5705.8
UWB5	2821.8	25841.2	-590.8	3577.0	3306.0	5701.8
UWB6	5569.8	26325.4	-589.9	3316.6	527.9	5692.9

Table 21 Coordinates of UWB Receivers.

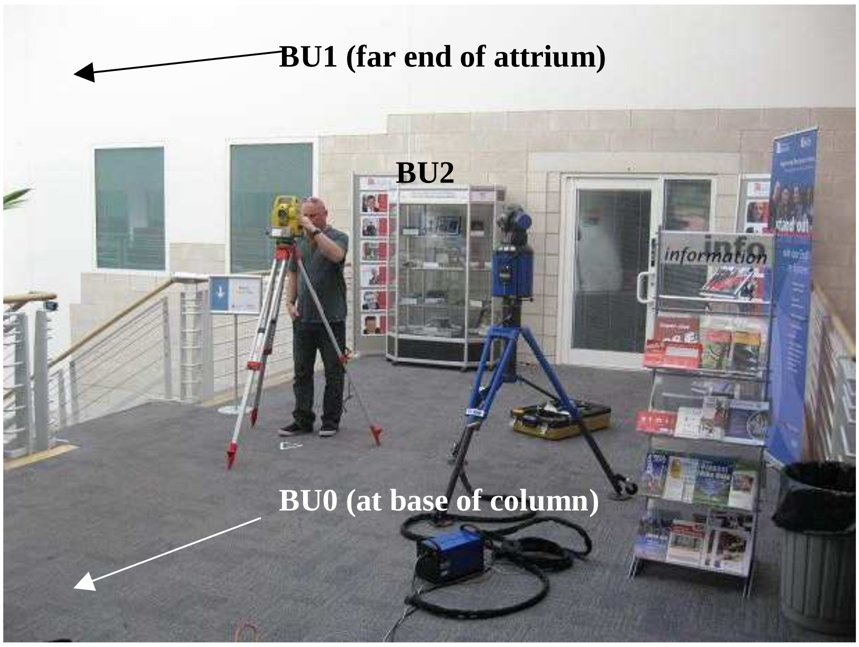


Figure 35 Locations of UWB Base Units.

Weighted USMN BU Point Name	Arbitrary Coordinate Frame /mm			UWB Coordinate Frame /mm		
	x	*y*	*z*	*x*	*y*	*z*
BU0	-444.1	2151.7	-1599.9	26926.7	8480.2	4755.7
BU1	-1948.5	26203.1	-1564.8	2832.4	8034.7	4742.2
BU2	7690.6	2322.3	510.2	27410.4	351.3	6839.5

Table 22 Coordinates of UWB Base Stations.

4.6 Track Points

Some additional points were measured on the lower floor of the atrium to be used to define a track or path that could be followed when testing the ViewNet systems. The points measured were the corners of the five grid plates in the floor of the atrium.

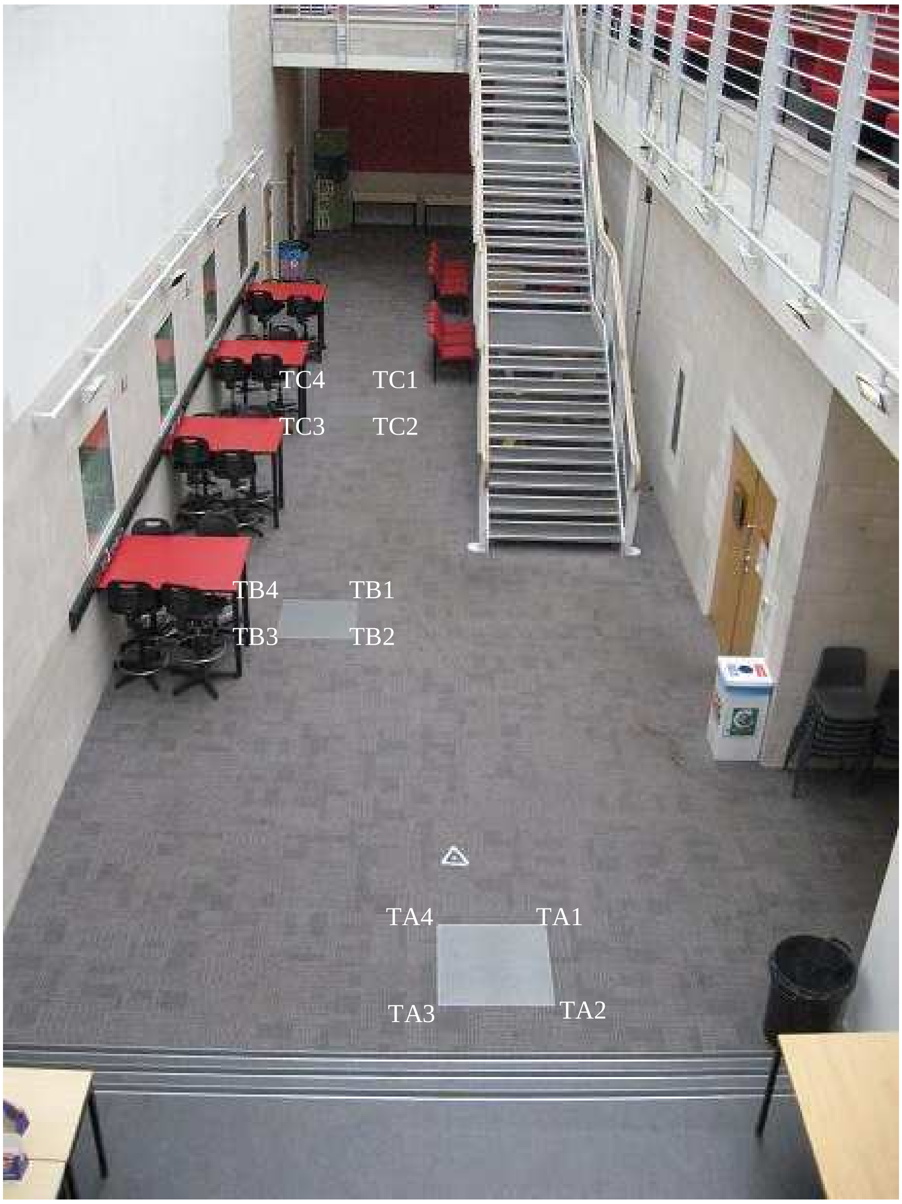


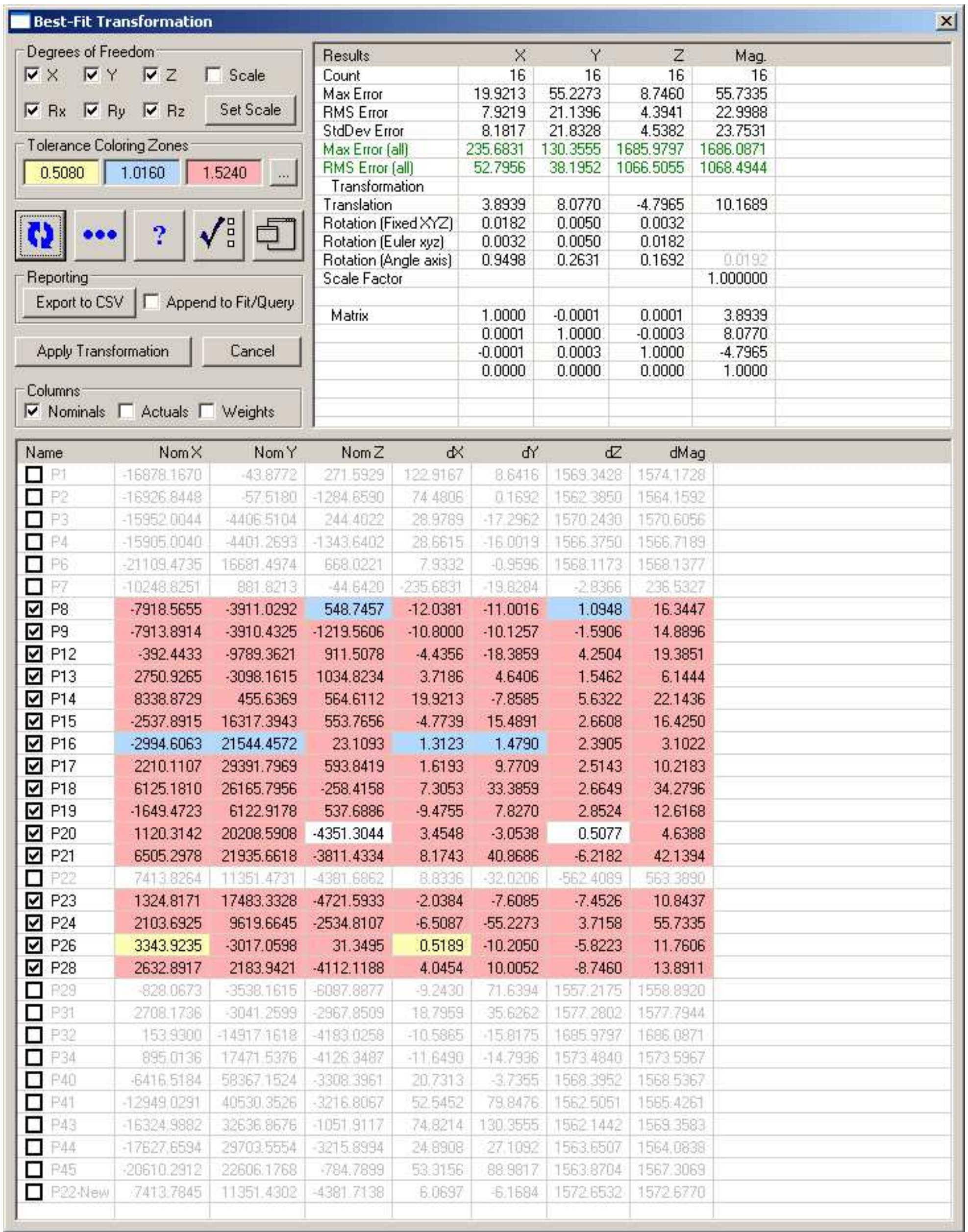
Figure 36 The corners of the plates in the floor were used as Reference Features to define a Track. Only three of the five plates are easily discernable in this picture. The point labels for the other two plates follow the same naming pattern – TD1-4 and TE1-4.

Weighted USMN Track Point Name	**Arbitrary Coordinate Frame /mm**			**UWB Coordinate Frame /mm**		
	x	***y***	***z***	***x***	***y***	***z***
TA1	3071.7	19477.1	-6291.1	9951.6	3590.7	14.8
TA2	3017.8	20223.1	-6288.8	9203.7	3584.0	15.7
TA3	3751.0	20281.5	-6291.1	9204.8	2848.6	10.9
TA4	3813.5	19539.5	-6294.7	9949.4	2846.2	8.8
TB1	4949.7	15120.3	-6295.7	14446.0	2071.1	14.0
TB2	4896.5	15859.8	-6296.2	13704.6	2064.3	12.0
TB3	5626.6	15924.6	-6294.0	13699.1	1331.4	11.7
TB4	5693.9	15183.6	-6295.3	14443.1	1324.2	11.9
TC1	5462.1	9150.8	-6305.5	20437.4	2043.1	15.8
TC2	5402.6	9882.9	-6306.9	19702.9	2043.3	13.0
TC3	6139.1	9947.9	-6304.7	19697.7	1303.9	12.6
TC4	6207.2	9206.0	-6304.9	20442.7	1296.1	13.9
TD1	5976.5	3171.3	-6315.9	26438.9	2014.0	17.1
TD2	5922.2	3917.0	-6314.5	25691.3	2007.8	17.0
TD3	6658.9	3973.3	-6312.5	25694.7	1268.9	16.6
TD4	6721.0	3226.9	-6312.4	26443.7	1267.4	18.1
TE1	4863.8	-1448.8	-6322.2	30953.9	3496.6	24.6
TE2	4798.6	-701.9	-6320.0	30204.2	3501.2	25.3
TE3	5553.0	-642.6	-6321.2	30206.1	2744.5	21.6
TE4	5605.5	-1386.7	-6320.6	30952.0	2752.3	23.7

Table 23 Coordinates of Reference Features used to define a Track.

5 Comparison between NPL and OS data

The reference points setup by NPL were also surveyed by the Ordinance Survey using a total station. An attempt to compare the two independent data sets has been made using the Best-Fit transformation facility in SpatialAnalyzer.



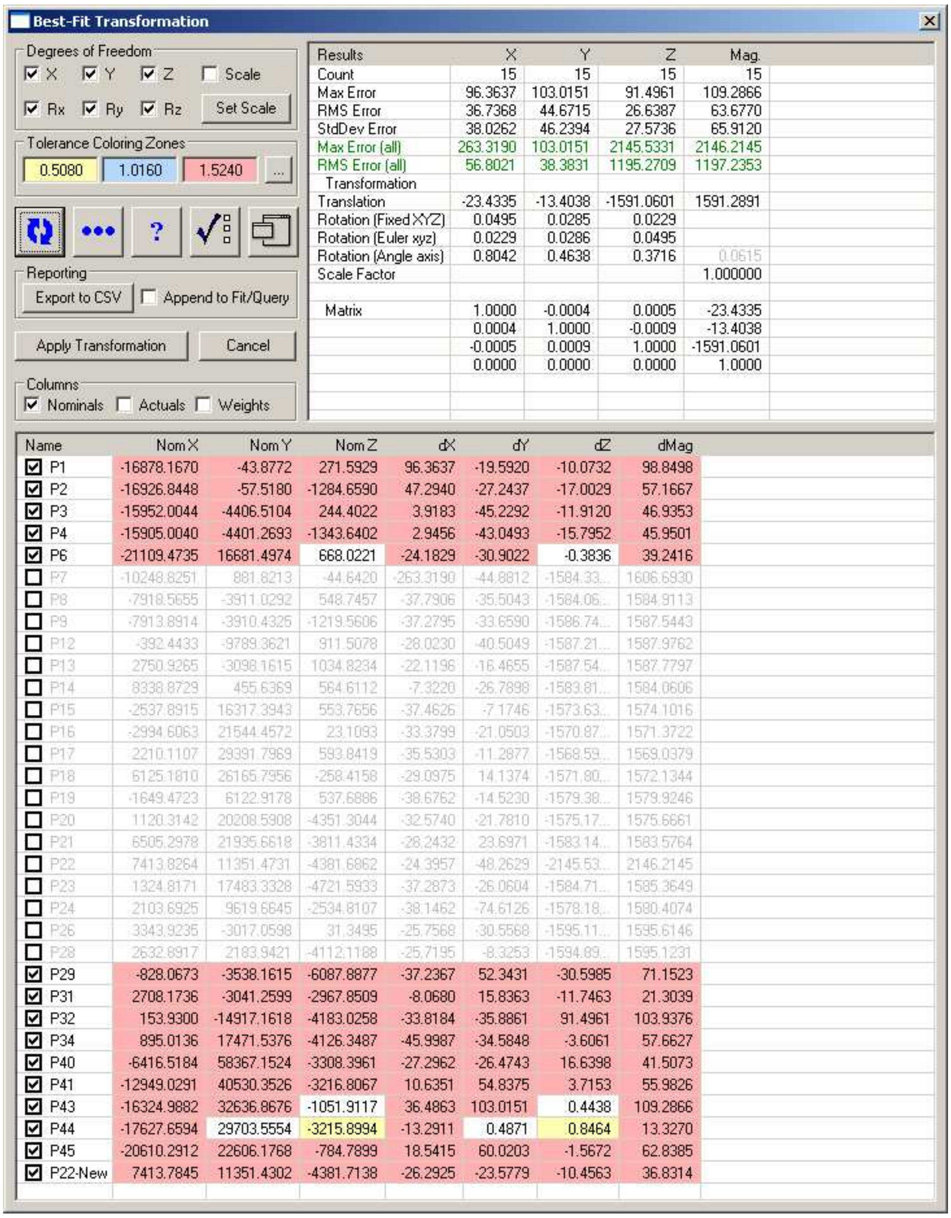
Results	X	Y	Z	Mag.
Count	16	16	16	16
Max Error	19.9213	55.2273	8.7460	55.7335
RMS Error	7.9219	21.1396	4.3941	22.9988
StdDev Error	8.1817	21.8328	4.5382	23.7531
Max Error (all)	235.6831	130.3555	1685.9797	1686.0871
RMS Error (all)	52.7956	38.1952	1066.5055	1068.4944
Transformation				
Translation	3.8939	8.0770	-4.7965	10.1689
Rotation (Fixed XYZ)	0.0182	0.0050	0.0032	
Rotation (Euler xyz)	0.0032	0.0050	0.0182	
Rotation (Angle axis)	0.9498	0.2631	0.1692	0.0192
Scale Factor				1.000000
Matrix	1.0000	-0.0001	0.0001	3.8939
	0.0001	1.0000	-0.0003	8.0770
	-0.0001	0.0003	1.0000	-4.7965
	0.0000	0.0000	0.0000	1.0000

Name	Nom X	Nom Y	Nom Z	dX	dY	dZ	dMag
P1	-16878.1670	-43.8772	271.5929	122.9167	8.6416	1569.3428	1574.1728
P2	-16926.8448	-57.5180	-1284.6590	74.4806	0.1692	1562.3850	1564.1592
P3	-15952.0044	-4406.5104	244.4022	28.9789	-17.2962	1570.2430	1570.6056
P4	-15905.0040	-4401.2693	-1343.6402	28.6615	-16.0019	1566.3750	1566.7189
P6	-21109.4735	16681.4974	668.0221	7.9332	-0.9596	1568.1173	1568.1377
P7	-10248.8251	881.8213	-44.6420	-235.6831	-19.8284	-2.8366	236.5327
P8	-7918.5655	-3911.0292	548.7457	-12.0381	-11.0016	1.0948	16.3447
P9	-7913.8914	-3910.4325	-1219.5606	-10.8000	-10.1257	-1.5906	14.8896
P12	-392.4433	-9789.3621	911.5078	-4.4356	-18.3859	4.2504	19.3851
P13	2750.9265	-3098.1615	1034.8234	3.7186	4.6406	1.5462	6.1444
P14	8338.8729	455.6369	564.6112	19.9213	-7.8585	5.6322	22.1436
P15	-2537.8915	16317.3943	553.7656	-4.7739	15.4891	2.6608	16.4250
P16	-2994.6063	21544.4572	23.1093	1.3123	1.4790	2.3905	3.1022
P17	2210.1107	29391.7969	593.8419	1.6193	9.7709	2.5143	10.2183
P18	6125.1810	26165.7956	-258.4158	7.3053	33.3859	2.6649	34.2796
P19	-1649.4723	6122.9178	537.6886	-9.4755	7.8270	2.8524	12.6168
P20	1120.3142	20208.5908	-4351.3044	3.4548	-3.0538	0.5077	4.6388
P21	6505.2978	21935.6618	-3811.4334	8.1743	40.8686	-6.2182	42.1394
P22	7413.8264	11351.4731	-4381.6862	8.8336	-32.0206	-562.4089	563.3890
P23	1324.8171	17483.3328	-4721.5933	-2.0384	-7.6085	-7.4526	10.8437
P24	2103.6925	9619.6645	-2534.8107	-6.5087	-55.2273	3.7158	55.7335
P26	3343.9235	-3017.0598	31.3495	0.5189	-10.2050	-5.8223	11.7606
P28	2632.8917	2183.9421	-4112.1188	4.0454	10.0052	-8.7460	13.8911
P29	-828.0673	-3538.1615	-6087.8877	-9.2430	71.6394	1557.2175	1558.8920
P31	2708.1736	-3041.2599	-2967.8509	18.7959	35.6262	1577.2802	1577.7944
P32	153.9300	-14917.1618	-4183.0258	-10.5865	-15.8175	1685.9797	1686.0871
P34	895.0136	17471.5376	-4126.3487	-11.6490	-14.7936	1573.4840	1573.5967
P40	-6416.5184	58367.1524	-3308.3961	20.7313	-3.7355	1568.3952	1568.5367
P41	-12949.0291	40530.3526	-3216.8067	52.5452	79.8476	1562.5051	1565.4261
P43	-16324.9882	32636.8676	-1051.9117	74.8214	130.3555	1562.1442	1569.3583
P44	-17627.6594	29703.5554	-3215.8994	24.8908	27.1092	1563.6507	1564.0838
P45	-20610.2912	22606.1768	-784.7899	53.3156	88.9817	1563.8704	1567.3069
P22-New	7413.7845	11351.4302	-4381.7138	6.0697	-6.1684	1572.6532	1572.6770

Figure 37 Results of comparison between NPL and one group of the OS data using Best-Fit Transform in SA.

When all the Reference Point data from NPL's survey and the OS survey were compared, the data sets did not match. By trial and error, it was found that the best fit between the NPL and OS data was obtained if the OS data was split into groups, then the groups could be individually fitted to the NPL data. Figure 37 shows the quality of the fit for one group of OS data, namely points *P*8, *P*9, *P*12-*P*21, *P*23, *P*24, *P*26 and *P*28.

A similar quality of fit was obtained with the second group, points *P*1-*P*4, *P*6, *P*29, *P*31-*P*32, *P*34, *P*40-*P*45 and *P*22-new.



Results	X	Y	Z	Mag.
Count	15	15	15	15
Max Error	96.3637	103.0151	91.4961	109.2866
RMS Error	36.7368	44.6715	26.6387	63.6770
StdDev Error	38.0262	46.2394	27.5736	65.9120
Max Error (all)	263.3190	103.0151	2145.5331	2146.2145
RMS Error (all)	56.8021	38.3831	1195.2709	1197.2353
Transformation				
Translation	-23.4335	-13.4038	-1591.0601	1591.2891
Rotation (Fixed XYZ)	0.0495	0.0285	0.0229	
Rotation (Euler xyz)	0.0229	0.0286	0.0495	
Rotation (Angle axis)	0.8042	0.4638	0.3716	0.0615
Scale Factor				1.000000
Matrix	1.0000	-0.0004	0.0005	-23.4335
	0.0004	1.0000	-0.0009	-13.4038
	-0.0005	0.0009	1.0000	-1591.0601
	0.0000	0.0000	0.0000	1.0000

Name	Nom X	Nom Y	Nom Z	dX	dY	dZ	dMag
P1	-16878.1670	-43.8772	271.5929	96.3637	-19.5920	-10.0732	98.8498
P2	-16926.8448	-57.5180	-1284.6590	47.2940	-27.2437	-17.0029	57.1667
P3	-15952.0044	-4406.5104	244.4022	3.9183	-45.2292	-11.9120	46.9353
P4	-15905.0040	-4401.2693	-1343.6402	2.9456	-43.0493	-15.7952	45.9501
P6	-21109.4735	16681.4974	668.0221	-24.1829	-30.9022	-0.3836	39.2416
P7	-10248.8251	881.8213	-44.6420	-263.3190	-44.8812	-1584.33...	1606.6930
P8	-7918.5655	-3911.0292	548.7457	-37.7906	-35.5043	-1584.06...	1584.9113
P9	-7913.8914	-3910.4325	-1219.5606	-37.2795	-33.6590	-1586.74...	1587.5443
P12	-392.4433	-9789.3621	911.5078	-28.0230	-40.5049	-1587.21...	1587.9762
P13	2750.9265	-3098.1615	1034.8234	-22.1196	-16.4655	-1587.54...	1587.7797
P14	8338.8729	455.6369	564.6112	-7.3220	-26.7898	-1583.81...	1584.0606
P15	-2537.8915	16317.3943	553.7656	-37.4626	-7.1746	-1573.63...	1574.1016
P16	-2994.6063	21544.4572	23.1093	-33.3799	-21.0503	-1570.87...	1571.3722
P17	2210.1107	29391.7969	593.8419	-35.5303	-11.2877	-1568.59...	1569.0379
P18	6125.1810	26165.7956	-258.4158	-29.0975	14.1374	-1571.80...	1572.1344
P19	-1649.4723	6122.9178	537.6886	-38.6762	-14.5230	-1579.38...	1579.9246
P20	1120.3142	20208.5908	-4351.3044	-32.5740	-21.7810	-1575.17...	1575.6661
P21	6505.2978	21935.6618	-3811.4334	-28.2432	23.6971	-1583.14...	1583.5764
P22	7413.8264	11351.4731	-4381.6862	-24.3957	-48.2629	-2145.53...	2146.2145
P23	1324.8171	17483.3328	-4721.5933	-37.2873	-26.0604	-1584.71...	1585.3649
P24	2103.6925	9619.6645	-2534.8107	-38.1462	-74.6126	-1578.18...	1580.4074
P26	3343.9235	-3017.0598	31.3495	-25.7568	-30.5568	-1595.11...	1595.6146
P28	2632.8917	2183.9421	-4112.1188	-25.7195	-8.3253	-1594.89...	1595.1231
P29	-828.0673	-3538.1615	-6087.8877	-37.2367	52.3431	-30.5985	71.1523
P31	2708.1736	-3041.2599	-2967.8509	-8.0680	15.8363	-11.7463	21.3039
P32	153.9300	-14917.1618	-4183.0258	-33.8184	-35.8861	91.4961	103.9376
P34	895.0136	17471.5376	-4126.3487	-45.9987	-34.5848	-3.6061	57.6627
P40	-6416.5184	58367.1524	-3308.3961	-27.2962	-26.4743	16.6398	41.5073
P41	-12949.0291	40530.3526	-3216.8067	10.6351	54.8375	3.7153	55.9826
P43	-16324.9882	32636.8676	-1051.9117	36.4863	103.0151	0.4438	109.2866
P44	-17627.6594	29703.5554	-3215.8994	-13.2911	0.4871	0.8464	13.3270
P45	-20610.2912	22606.1768	-784.7899	18.5415	60.0203	-1.5672	62.8385
P22-New	7413.7845	11351.4302	-4381.7138	-26.2925	-23.5779	-10.4563	36.8314

Figure 38 Comparison between NPL data and the second group of OS data. NomX, NomY and NomZ are the NPL results, dX, dY, dZ are the differences between the NPL and OS coordinates and dMag is the distance between the NPL and OS points.

Points *P*7 and *P*22 did not appear to fit into either group.

The two sub-sets of the OS data appear to be separated in the vertical (*z*) direction by approximately 1570 mm to1580 mm. At the time of writing, no explanation for this observation has been found.

5.1 Repeat measurements

To attempt to resolve the issue of the misfit between the NPL and OS data, we returned to Bristol in October 2009 to re-measure a selection of points. For these measurements a different instrument was used – an API T3 laser tracker.

The points chosen for re-measurement were chosen from the two distinct groups identified above, and were spread throughout the upper and lower floors of the attrium. Measurements were made from four tracker positions and the data bundled using USMN as previously. All measurements were included in the bundle. The results of the bundle are shown in Figure 39.

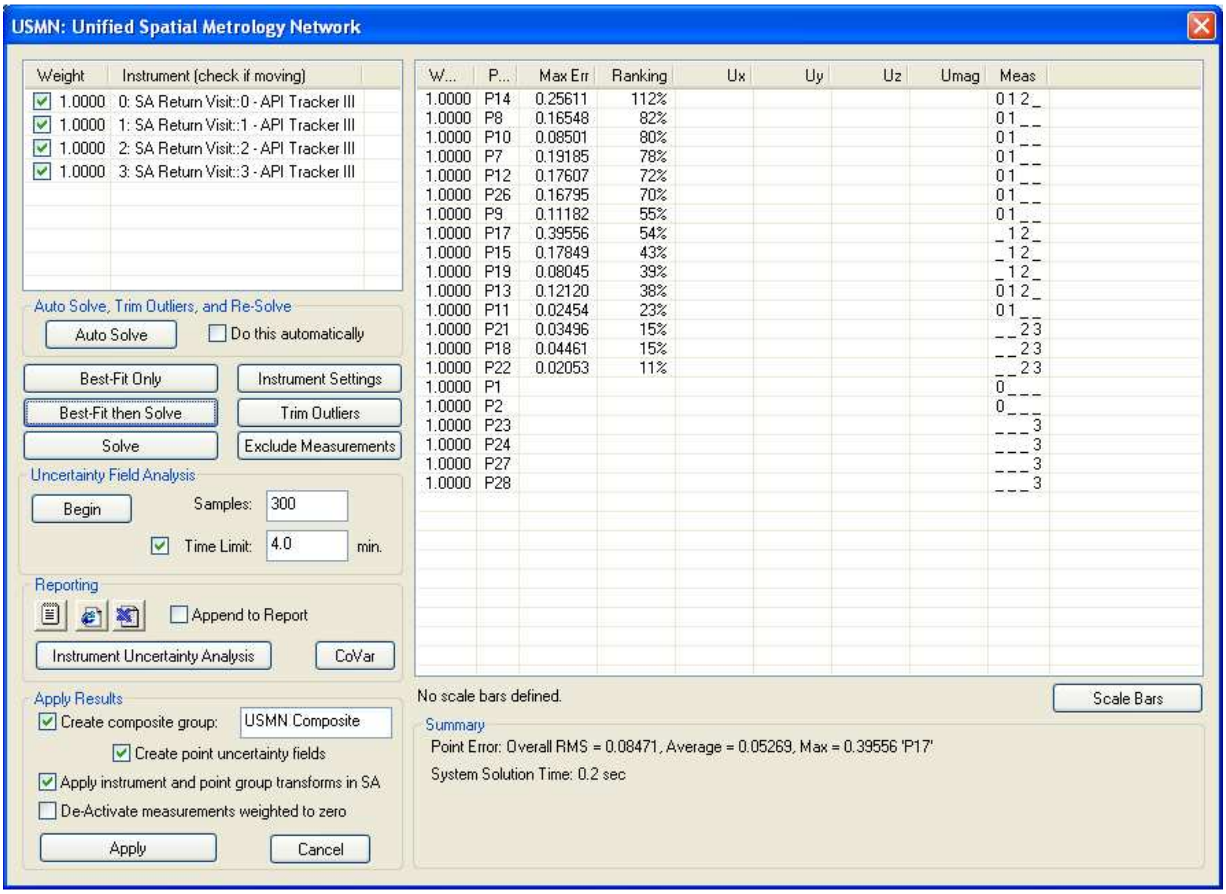
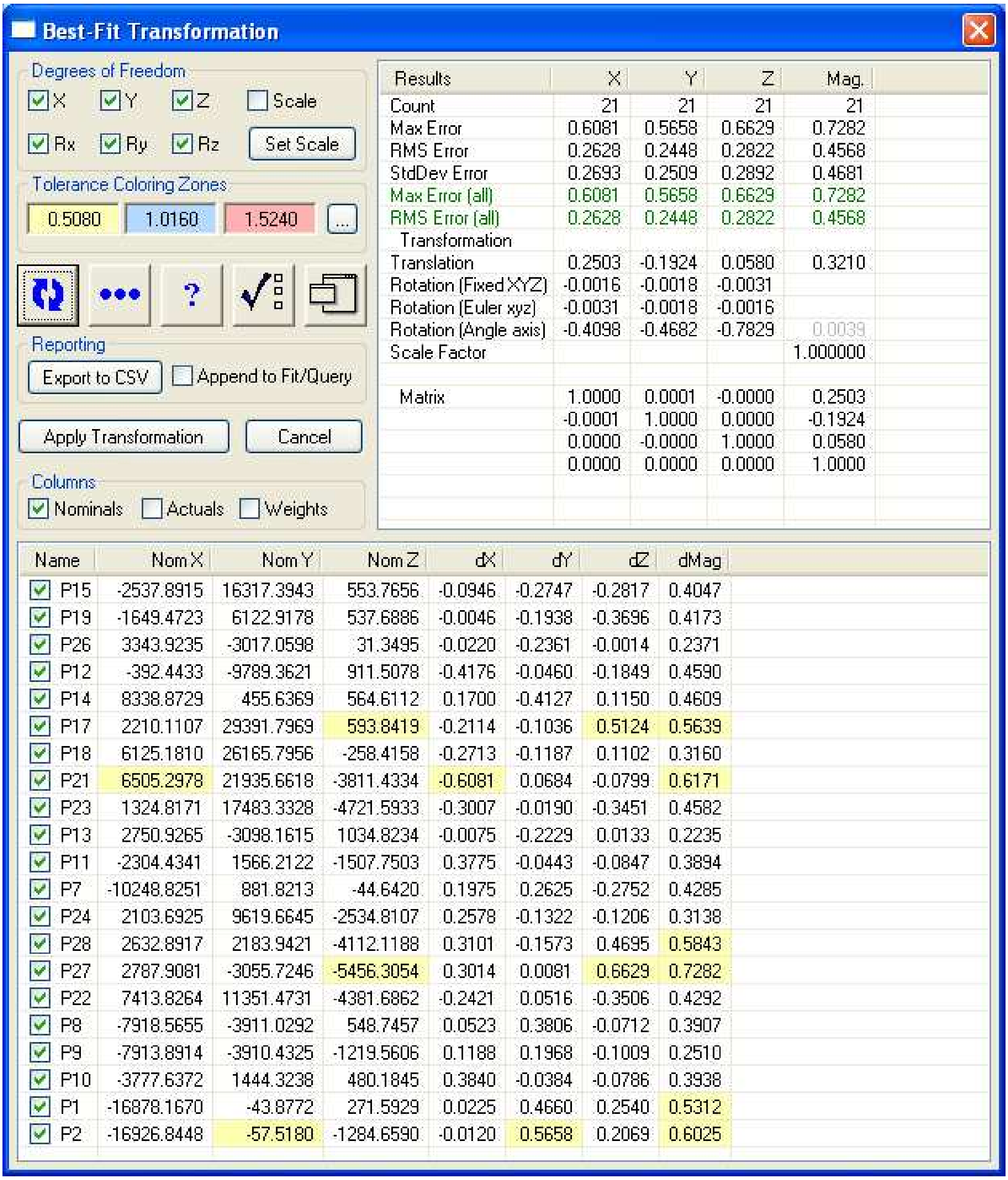


Figure 39, USMN output for the repeated measurements.

The composite points generated from the bundled new measurements were then fitted to the corresponding composite points from the original measurements. The results of the best fit are shown in Figure 40.



Results	X	Y	Z	Mag.
Count	21	21	21	21
Max Error	0.6081	0.5658	0.6629	0.7282
RMS Error	0.2628	0.2448	0.2822	0.4568
StdDev Error	0.2693	0.2509	0.2892	0.4681
Max Error (all)	0.6081	0.5658	0.6629	0.7282
RMS Error (all)	0.2628	0.2448	0.2822	0.4568
Transformation				
Translation	0.2503	-0.1924	0.0580	0.3210
Rotation (Fixed XYZ)	-0.0016	-0.0018	-0.0031	
Rotation (Euler xyz)	-0.0031	-0.0018	-0.0016	
Rotation (Angle axis)	-0.4098	-0.4682	-0.7829	0.0039
Scale Factor				1.000000
Matrix	1.0000	0.0001	-0.0000	0.2503
	-0.0001	1.0000	0.0000	-0.1924
	0.0000	-0.0000	1.0000	0.0580
	0.0000	0.0000	0.0000	1.0000

Name	Nom X	Nom Y	Nom Z	dX	dY	dZ	dMag
P15	-2537.8915	16317.3943	553.7656	-0.0946	-0.2747	-0.2817	0.4047
P19	-1649.4723	6122.9178	537.6886	-0.0046	-0.1938	-0.3696	0.4173
P26	3343.9235	-3017.0598	31.3495	-0.0220	-0.2361	-0.0014	0.2371
P12	-392.4433	-9789.3621	911.5078	-0.4176	-0.0460	-0.1849	0.4590
P14	8338.8729	455.6369	564.6112	0.1700	-0.4127	0.1150	0.4609
P17	2210.1107	29391.7969	593.8419	-0.2114	-0.1036	0.5124	0.5639
P18	6125.1810	26165.7956	-258.4158	-0.2713	-0.1187	0.1102	0.3160
P21	6505.2978	21935.6618	-3811.4334	-0.6081	0.0684	-0.0799	0.6171
P23	1324.8171	17483.3328	-4721.5933	-0.3007	-0.0190	-0.3451	0.4582
P13	2750.9265	-3098.1615	1034.8234	-0.0075	-0.2229	0.0133	0.2235
P11	-2304.4341	1566.2122	-1507.7503	0.3775	-0.0443	-0.0847	0.3894
P7	-10248.8251	881.8213	-44.6420	0.1975	0.2625	-0.2752	0.4285
P24	2103.6925	9619.6645	-2534.8107	0.2578	-0.1322	-0.1206	0.3138
P28	2632.8917	2183.9421	-4112.1188	0.3101	-0.1573	0.4695	0.5843
P27	2787.9081	-3055.7246	-5456.3054	0.3014	0.0081	0.6629	0.7282
P22	7413.8264	11351.4731	-4381.6862	-0.2421	0.0516	-0.3506	0.4292
P8	-7918.5655	-3911.0292	548.7457	0.0523	0.3806	-0.0712	0.3907
P9	-7913.8914	-3910.4325	-1219.5606	0.1188	0.1968	-0.1009	0.2510
P10	-3777.6372	1444.3238	480.1845	0.3840	-0.0384	-0.0786	0.3938
P1	-16878.1670	-43.8772	271.5929	0.0225	0.4660	0.2540	0.5312
P2	-16926.8448	-57.5180	-1284.6590	-0.0120	0.5658	0.2069	0.6025

Figure 40, Best fit of the re-measured points to the corresponding points from the original data.

The results show that the new measurements are within 1 mm of the original measurements. This appears to confirm the validity of the original data.

6 Conclusions

The objective of this work was to provide the ViewNet project with measurements of so-called reference features (door frames, windows *etc*), within the Merchant Venture Building at the University of Bristol. These reference features are required to provide scale and for calibration of the VSLAM system.

To achieve this, a permanent network or fixed reference points (magnetic drift nests) has been established within and around the building. This network has been used to facilitate a laser tracker survey of features in the building within a consistent coordinate frame. The coordinates of these reference features have been established with an uncertainty of around 2 mm.

The reference points were also surveyed in the GPS coordinate frame by specialist from the Ordinance Survey. An attempt has been made to transform the laser tracker measurements onto the GPS coordinate frame, so that the VSLAM system can be located into the global coordinate frame. However, an inconsistency in the OS data has prevented the satisfactory fitting of the two data sets.