Department of Spatial Sciences

Comparison of the Spatial Accuracy of Disparate 3D Laser Point Clouds in Large Scale 3D Modelling and Physical Reproduction Projects for Large Cultural Heritage Structures

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"This thesis is presented as part of the requirements for the award of the Degree of Master of Science (Surveying and Mapping) of the Curtin University of Technology"

December 2006
ABSTRACT

Cultural heritage features have historically been documented in two dimensions (2D) by painting, photography, and lithography, and more recently in three dimensions (3D) by photogrammetry and laser scanning. The latter has become very popular for both large and small scale cultural heritage documentation for the purposes of digital preservation, deformation studies, and modelling for replication. The emerging recording methodology by 3D laser scanning uses multiple instruments to capture details at multiple scales. However, rigorous procedures for integrating the data from the different data sources and quality assessment of the resulting product do not exist. Even in the academic domain the current procedures are ad hoc and several papers document the failed methodologies used on cultural heritage projects.

The objective of this research project has been to develop a sound framework for recording schemes for large-scale cultural heritage projects. The presented case study is the Ross Bridge recording project in Tasmania. Spanning the Macquarie River, this sandstone bridge is one of the premier heritage sites in Australia thanks to 186 intricate icons carved by convicts that decorate its arches. These are weathering rapidly and, without conservation, could be lost within 25 years.

This thesis will first present an overview of the multi-resolution data collection for the Ross Bridge project, with particular emphasis on the data capture methodologies and technologies used: the Leica HDS2500 and the Vivid 910 scanners. One of the reasons for the aforementioned failed projects was the lack of complete understanding of the error budgets of the scanners used. Therefore, the pertinent outcomes of full error and resolution analyses are described. Finally, results from registration of the multi-resolution dataset registration are presented, which will highlight the achievable outcomes and limitations of such a recording scheme.
ACKNOWLEDGEMENTS

This research project was carried out as part of a scholarship program for the Cooperative Research Centre for Spatial Information (CRCSI), in conjunction with Curtin University of Technology. I would like to thank the CRCSI for its support of this research. Special thanks go to Dr Derek Lichti who leads the CRC laser scanning research group, and the co-chair of the ISPRS terrestrial laser scanning working group as well as my supervisor for this project. Derek gave his time and knowledge freely for this research project, and his generosity enabled this project to be a success.

I would like also to thank Frank Giana, Geoff Mulcahy and Graeme Roberts from the Department of Infrastructure Energy and Resources (DIER) in Tasmania for their support, and for making the data for this project available, as the core data for the project was collected during one of their projects.

In particular I would like to thank Kwang-Ho Bae for the use of his registration software in this research project, as he made the software available in its infancy, and I believe that the results from his algorithm are exciting and I wish him well in the further development of it.

I would like to thank Dr Andrew Harwood for his inspiring directions to get this document into a coherent and readable form.

I would finally like to thank my wife Kate for her love and support through this project.
# TABLE OF CONTENTS

ABSTRACT ................................................................................................................................. i
ACKNOWLEDGEMENTS ........................................................................................................... ii
TABLE OF CONTENTS ........................................................................................................... iii
LIST OF FIGURES ................................................................................................................ vi
LIST OF TABLES .................................................................................................................... ix

1 Introduction ......................................................................................................................... 1
   1.1 History of the Ross Bridge ......................................................................................... 1
   1.2 The salient characteristics of the Ross Bridge .......................................................... 2
   1.3 Intention of the 3D scanning project for DIER ......................................................... 3
   1.4 Background of Cultural Heritage Scanning ............................................................. 5
   1.5 Aims of the project .................................................................................................. 5
   1.6 Approach ................................................................................................................ 7

2 Literature Review ................................................................................................................. 9
   2.1 Introduction ............................................................................................................... 9
   2.2 TLS suitability for the 3D modelling of cultural heritage features at multiple scales ................................................................. 10
      2.2.1 Accuracy of TLS for large scale cultural heritage features ......................... 10
      2.2.2 Precision Testing of the Cyrax 2500 ............................................................... 11
      2.2.3 Cultural Heritage recording methodology .................................................... 12
   2.3 Close range scanners for small scale cultural heritage recording ....................... 13
   2.4 Problems encountered when conducting close range laser scanning cultural heritage projects ................................................................. 14
      2.4.1 Project Study 1 – Statue of Hermes ................................................................. 14
   2.5 3D modelling from 3D laser scanned point clouds .............................................. 16
   2.6 Examples of projects containing multiple scanners operating at multiple scales ......................................................................................... 17
      2.6.1 Project Study 3 – Reshaping the Coliseum in Rome ....................................... 17
      2.6.2 Project Study 4 – Visualising Ancient Rome: 3D acquisition and modelling of a large plaster-of-Paris model of imperial Rome .......... 18
      2.6.3 Project study 5 – Sensor Fusion: Generating 3D by combining airborne and tripod mounted LIDAR data ......................................................... 19
   2.7 Point Cloud Registration ......................................................................................... 20
6.2 Scanned Accuracy for each icon ..............................................................70
6.3 Analysis of the different ICP algorithms for Icon 16 .........................71
   6.3.1 Analysis of surfaced point cloud for each algorithm ....................72
   6.3.2 Analysis of the deviations resulting from the Leica – Minolta registration .................................................................73
   6.3.3 Statistical analyses of the three registration algorithms ..............76
6.4 Analysis of the different ICP algorithms for Icon 37 .........................77
   6.4.1 Analysis of surfaced point cloud for each algorithm ....................77
   6.4.2 Analysis of the deviations resulting from the Leica – Minolta registration ........................................................................78
   6.4.3 Statistical analysis of the three registration algorithms ..........80
6.5 Analysis of the different ICP algorithms for Icon 78 .........................81
   6.5.1 Analysis of surfaced point cloud for each algorithm ....................81
   6.5.2 Analysis of the deviations resulting from the Leica – Minolta registration ........................................................................83
   6.5.3 Statistical analysis of the three registration algorithms ..........84
6.6 Summary of the results for the different algorithms over the three icons .86
7 Conclusions ................................................................................................88
8 REFERENCES ................................................................................................92
APPENDIX A - Leica HDS2500 and Minolta Vivid910 Laser Scanner Specifications ..............................................................................................................96
LIST OF FIGURES

Figure 1.1 Northern face of the Ross Bridge showing the carved icons around each arch ..........................................................................................................................2
Figure 1.2 Layout and Dimensions of the Ross Bridge in (a) plan view and (b) side elevation ..................................................................................................................3
Figure 1.3 Erosion of the icons over time. (a) Photograph of the “Arthur’s face icon” in 1970, and (b) its condition at the time of the survey ........................................4
Figure 2.1 Flow line for cultural heritage laser scanning projects (Bryan, et al, 2004) ......................................................................................................................................12
Figure 2.2 (a) Illustrates the effects of movement of the scanner, and (b) illustrates the effect of the subsurface scatter caused by the marble (Ionnidis et al, 2003) ..................................................................................................................................15
Figure 2.3 Reflections and refractive effects in non homogeneous semitransparent materials (like marble) (Ingensand et al, 2002).................................15
Figure 3.1 Time of Flight principle for TLS (Boehler et al 2002)........................24
Figure 3.2 Leica HDS2500 3D Laser Scanner .................................................................................................................................................................................................24
Figure 3.3 Scanning set-up locations with respect to the bridge .......................26
Figure 3.4 Entire bridge point cloud model from the northern face of the bridge ..................................................................................................................................28
Figure 3.5 (a) Photograph of the area scanned, (b) shows the difference in coverage over the icons from the 2-3mm and 10mm scans, and (c) a 2m wide cross section through the bridge ........................................................................29
Figure 3.6 Triangulation principle for close range scanners (Boehler et al 2002) ..................................................................................................................................28
Figure 3.7 Diagrammatic representation of the parameters for triangulation principal (Lichti, 2005a)....................................................................................................................30
Figure 3.8 Konica Minolta Vivid 910 Laser Scanner .................................................32
Figure 3.9 Photograph of the forklift mounted Minolta, scanning the icons ......33
Figure 3.10 Minolta fixed to the bi-axial rotation head mounted to the vertical arm ........................................................................................................................................34
Figure 3.11 (a) Photograph of the icon, (b) Initial scan data registration, and (c) NURBS 3D surface model .........................................................................................36
Figure 3.12  (a) Photograph of the cnc machine cutting the NURBS surface model from urial, and (b) 1:1 replicated model ..........................................................36
Figure 3.13  (a) Photograph of the icon and (b) Initial scan data registration........37
Figure 3.14  (a) 3D NURBS surface model and (b) 1:1 replicated model ..........37
Figure 4.1   Relationship between HDS2500 laser’s angle of incidence, range and the surface spot size .................................................................44
Figure 4.2   Relationship between HDS2500 laser’s angle of incidence, the surface spot size and the minimum point spacing ........................................45
Figure 4.3   Illustration of the creation of erroneous points due to the laser beam’s surface edge effects ........................................................................46
Figure 4.4   Comparison between the Leica HDS2500 scan data and the Minolta Vivid 910 data to highlight the edge effects present in the HDS2500 data ....47
Figure 4.5   Diagram illustrating the operation parameters of the Minolta Vivid 910 (Provided by Konica Minolta, 2006) .....................................................48
Figure 4.6   Demonstrates the effect of angle of incidence on the complex surface of Icon 78.................................................................49
Figure 4.7   Top view of the scanned rain as it appears as 3D data points in the scan data .........................................................................................50
Figure 4.8   (a) Scanned surface of the water and (b) the points collected from the reflections off the water .................................................................51
Figure 5.1   Distance measures between surfaces P and Q, (a) shows Q and P before T_k-1 is applied, (b) distance to the tangent plane of Q (Chen and Medioni, 1992) ........................................................................................................57
Figure 5.2   The differing neighbourhood sizes between the Leica and the Minolta point clouds .................................................................57
Figure 6.1   Photographs of each of the icons to be analysed from scanning set up locations: (a) icon 16; (b) icon 37; and (c) icon 78 ........................................69
Figure 6.2   Scanning set up locations with respect to the bridge ....................69
Figure 6.3   Photograph of the southern face of the Ross Bridge showing the position of icons 16, 37 and 78 .................................................................70
Figure 6.4   The surfaced models produced from the Leica HDS2500 data Icon 16 using the three registration techniques: (a) Cyclone; (b) Bae; and (c) Geomagic. (d) represents the Minolta data registered using Geomagic. ......................72
Figure 6.5  The zoomed in views of the surfaced models produced from the Leica HDS2500 data Icon 16 using the three registration techniques: (a) Cyclone; (b) Bae; and (c) Geomagic. (d) represents the Minolta data registered using Geomagic.................................................................73

Figure 6.6  The deviations between the surfaced Minolta data and the Leica point cloud, illustrated as normals to the surface showing the direction and magnitude of the deviations.................................................................74

Figure 6.7  Deviation differences between the three different registration software: (a) Cyclone; (b) Bae; and (c) Geomagic for the Leica surfaced point clouds and the Minolta data for Icon 16.............................................................75

Figure 6.8  Histogram of deviation difference (as a percentage) of the Leica data between the surfaced points produced by each registration software package and the Minolta data for Icon 16 using Geomagic.............................................................76

Figure 6.9  The surfaced models produced from the Leica HDS2500 data for icon 37 using the three registration techniques: (a) Cyclone; (b) Bae; (c) Geomagic; and (d) the Minolta data registered using Geomagic .............................................................78

Figure 6.10  Deviation differences between the registered Leica data and the Minolta data for Icon 37 with each figure representing the three different registration software: (a) Cyclone; (b) Bae; and (c) Geomagic.................................79

Figure 6.11  The deviation difference of the Leica data (as a percentage) between the surfaced points produced by each registration software and the Minolta data for Icon 37. .................................................................80

Figure 6.12  The surfaced models produced from the Leica HDS2500 data Icon 78 using the three registration techniques: (a) Cyclone; (b) Bae; and (c) Geomagic; and (d) is the Minolta data registered using Geomagic.............................................................82

Figure 6.13  Deviation differences between the Leica surfaced point clouds and the Minolta data for Icon 78 using the three different registration software: (a) Cyclone; (b) Bae; and (c) Geomagic.................................................................83

Figure 6.14  Deviation difference of the Leica data (as a percentage) between the surfaced points produced by each registration software and the Minolta data for Icon 78. 85
LIST OF TABLES

Table 3.1  Point cloud densities and detection confidence levels..........................26
Table 4.1  Summary of the Manufacturer’s specifications for the Leica HDS2500
          and the Minolta Vivid 910........................................................................39
Table 4.2  Instrument Error budget for both the Leica HDS2500 and the Minolta
          Vivid 910..................................................................................................54
Table 5.1  Typical Registration results from Cyclone point cloud registration ......61
Table 5.2  Error between the measured targets, and control points within the point
          cloud used in the global registration of the data........................................62
Table 5.3  Input data parameters for Kwang-Ho Bae’s program.......................65
Table 6.1  The range, angle of incidence, surface spot size and maximum
          achievable resolution for icons 16, 37 and 78 from scanning locations 1 and 270
Table 6.2  Summary of the deviations of the Minolta - Leica registration for each
          registration algorithm..............................................................................86
1 INTRODUCTION

This research has been conducted to develop a framework for recording disparate three dimensional (3D) laser point clouds for large scale 3D modelling and physical reproduction in large cultural heritage projects. The 3D laser scan datasets for this research were collected as part of a project for the Tasmanian Government Department of Infrastructure Energy and Resources (DIER) 3D laser scanning of the historic Ross Bridge and its carved icons.

This research solves an important problem in cultural heritage documentation because the majority of large scale cultural heritage features currently being conserved have surface features of different scales, requiring different equipment and different methodologies, and there has been little research in this area to date. In this research I will discuss the scanning methodologies used, analyse the datasets captured using each method, discuss the different registration algorithms used to combine the datasets, and compare and contrast the results from the different registration algorithms to determine the best data capture and registration methodology. An important aim of this research is that the results from this project will form the framework for future multi-scale cultural heritage scanning project in this field.

1.1 History of the Ross Bridge

The Ross Bridge over the Macquarie River on the former Hobart to Launceston Road was designed by the civil engineer and colonial architect John Lee Archer. The bridge was constructed by two convict stonemasons, Daniel Herbert and James Colebeck, with a gang of convict labour under the direction of Captain William Turner, the Commandant of the Ross township. Herbert created the unique ornamentation on the arches shown in Figure 1.1. Both stonemasons were emancipated on the completion of the bridge, which was officially opened by Lt Governor Arthur on 21 October 1836.

Initially designed to carry horse drawn wagons and coaches across the Macquarie River, the Ross Bridge is still an important part of the Tasmanian road network. While Ross is now bypassed by the Midlands Highway, the bridge still has heavy
vehicles, including tour buses and b-double trucks, travelling across it regularly. The longevity of the bridge, and its capacity to support vehicular traffic of a weight well in excess of 19th century transportation forms, demonstrates that the bridge was well designed and built (Greener and Laird 1971). As a major Tasmanian tourist attraction the bridge is one of the most visited sites in the state, with over a hundred and forty thousand visitors each year. A component in the road transport system of Tasmania, and a historically noteworthy tourist drawcard, the Ross Bridge is of continued significance to Tasmanian cultural and economic life.

![Figure 1.1 Northern face of the Ross Bridge showing the carved icons around each arch](image)

1.2 The salient characteristics of the Ross Bridge

The Ross Bridge was carved from local sandstone quarried near the site of the bridge. The construction of the bridge is a mortar-less “dry” free stone, where each stone was meticulously cut to fit. The three arches spanning the bridge have 186 carved icons on their outside faces. The carvings vary in size (approximately 1200mm high, 400mm wide and 500mm deep) and design (including images of numerous flora and fauna, Celtic Gods and Goddesses, and various colonial identities), and are shown in Figure 1.1.

The layout and dimensions of the bridge are illustrated in Figure 1.2. The dimensions shown for the bridge were taken from the Leica HDS2500 overall bridge scans, which will be described later.
1.3 Intention of the 3D scanning project for DIER

The Ross Bridge and its convict carved icons have undergone significant erosion over the last 170 years. The intentions of the scanning project for the DIER were to accurately model the entire bridge to an accuracy of 2-3mm, and individually model the bridge’s 186 icons to an accuracy of 0.5mm. This level of accuracy in detailing and documenting the salient characteristics of the bridge is a crucial component in the overall conservation strategy for the Ross Bridge.

The proposed uses for the 3D model of the whole bridge are temporal deformation analysis and as an accurate 3D model for conservation purposes. The 3D models of the icons are also to be used for temporal deformation analysis and conservation, and a select number were replicated using computer numerical control (CNC) technology. Both Fernandez-Martin et al (2005) and Abdelhafiz et al (2005) have
documented the extensive use of CNC technology and its associated methodologies in the recording and conservation of heritage structures.

Temporal deformation analysis is important to the future management of the bridge’s icons as they are exhibiting signs of rapid weathering. The Heritage Council of Tasmania argues that without an adequate conservation strategy the icons could be entirely lost within 25 years. Some of the effects of the erosion and decay process are illustrated in Figure 1.3. Figure 1.3(a) is a photograph of one of the icons taken in 1970, and Figure 1.3(b) is a photograph taken at the time of the survey, over the summer of 2004-2005.

Figure 1.3  Erosion of the icons over time. (a) Photograph of the “Arthur’s face icon” in 1970, and (b) its condition at the time of the survey

There is a noticeable amount of erosion in this time alone (1971-2005); note in particular the loss of Lt Governor Arthur’s nose. Erosion accelerated in the subsequent 15 years after the 1971 photograph was taken until a stabilising agent was used to treat the icons and slow the rate of decay. The data that was collected as part of this project will form a base line to test the effectiveness of that and subsequent attempts at stabilising and mitigating against erosion of the icons.
A major component of this project was the replication of the bridge’s icons. The production of very high accuracy replica models of the icons is important for:

- interpretation by conservators and the general public;
- physical enhancement modelling by experts to build the replicated icon from a high accuracy base to show how a repaired icon would appear and;
- to establish public confidence in the methodology to ascertain whether there was significant interest in replicating “repaired icons” for possible replacement of the ones on the bridge.

1.4 Background of Cultural Heritage Scanning

The act of documenting cultural heritage is primarily undertaken to accurately record the status and condition of important physical features. Historically this has been achieved in two dimensions through painting, photography and lithography, and more recently in three dimensions by photogrammetry and laser scanning (Bryan et al. 2004).

Terrestrial laser scanners (TLS) have been become very popular for large and small-scale cultural heritage architectural documentation (Boehler et al. 2003). Numerous authors (Ioannidis and Tsakiri 2003; Gordon et al. 2003; Guidi et al. 2004; Balzani et al., 2000; Ogelby 2004) have demonstrated TLS as a technology suited to digital recording for preservation, accurate studies of deformation, and 3D modelling for the replication of cultural heritage features. Three-dimensional laser scanning has become very popular due to its ability to collect a highly accurate and dense point-cloud of the target feature’s surface in near real time with less post processing when compared to other methods (Johansson, 2002).

1.5 Aims of the project

This research aims to define the best suited 3D laser scanning equipment and methodologies to model both large scale features (bridges and buildings) and small scale features (intricate rock carvings and statues) to use as a framework for further development in the field. This research is important since objects of many sizes occur in cultural heritage documentation, and no single scanner can be recommended for all tasks (Boehler and Marbs 2002).
A comprehensive study of a project’s accuracy requirements is required prior to selecting a scanner to record and model the relevant features (Bryan et al, 2003; Lichti, 2004). In conjunction with a cultural heritage project’s accuracy requirements, a comprehensive error budget for the scanners is necessary prior to the survey to ascertain whether they can meet the features output model requirements for use in recording, deformation, or replication (Lichti 2004; Gordon and Lichti 2002; Boehler et al 2003).

The aim of this research is to develop a framework for all large scale work of this nature in the future. The steps required to achieve this project’s goal are:

- Determine the error budgets of 3D laser scanners suited to undertaking high accuracy cultural heritage recording and to understand the limitations of the current methodology and resulting datasets.
- Determine the actual modelled resolution obtained when using these scanners on cultural heritage recording projects with respect to the impact of edge effects and different data collection incidence angles. Subsequently, to understand the effects of the different field methodologies and processing techniques and also to understand the level of detail that can be resolved.
- Perform a comprehensive comparison of the two disparate, multi-scale datasets with a view to quantifying differences between the two, to understand the error sources of each technique, and to enable a full assessment of the accuracy and resolution of each technique’s datasets.
- Determine the relationship between the acquisition technique and instrumentation error budgets, to make an equipment and methodological assessment for future cultural heritage projects.

The steps noted above constitute a definitive methodology that can provide solutions to some of the problems identified by the community of organisations and industries that utilise 3D laser scanning for cultural heritage documentation projects. Examples of these difficulties can be found in the work of El-Hakim et al (2004) and the scanning of in situ Australian Aboriginal rock art; Balzani et al (2000) and the documentation of large scale heritage structures, such as buildings, churches, and bridges; and Guidi et al (2004) and Ioannidis et al (2003) on both large scale features
and small scale cultural heritage artefacts held in museums, such as statues and skeletal remains.

This research project is also scientifically salient as the Ross Bridge has not previously been documented by any corresponding technology similar to the 3D scanning equipment utilised here. Additionally, while multi scale datasets have been collected in other cultural heritage projects, they have not been combined together in a homogenous dataset Balzani et al (2000). It is anticipated that the methodology that forms part of this research will be used as a reference guide by industry for future work in the field of cultural heritage conservation. This methodology is of added relevance considering that the Australian Cooperative Research Centre (CRC) for Spatial Information has noted the importance of finding solutions to the myriad problems relating to the combination of multi scale datasets, as evidenced by the dedication of substantial research aid (in the form of grants and facility support) to related projects by several industry consortium members.

1.6 Approach

As stated earlier, collection of the 3D laser scan datasets for this research was part of a project for the DIER that involved 3D laser scanning the historic convict built Ross Bridge in Tasmania. DIER has made this dataset available for analysis and manipulation for this research program.

In Chapter 2 a comprehensive literature review is undertaken so as to analyse the existing research in the field and to develop an understanding of the current status of 3D laser scanning and cultural heritage recording. This literature review demonstrated that there exists a significant lack in the field regarding the methodological and technical descriptions for combining the data from multiple instruments at multiple scales, and this strengthens the need for this research to develop the methodology for future projects.

Chapter 3 outlines the field capture of the 3D laser scan data of the Ross Bridge conducted using the Leica 2500 Terrestrial Laser Scanner (TLS) scanning the bridge to a spatial accuracy of 2 - 3mm. This chapter also discuss the scanning of the 186
icons on the exterior of the bridge that was conducted using the Minolta Vivid 910 close range 3D laser scanner scanning the icons to a spatial accuracy of 0.2 - 0.5mm.

The determination of the error budgets attributed to each technique was the next important step in the research and this is discussed in Chapter 4. This chapter determines the spatial accuracy of the final combined dataset. This is one of the most critical components of the research project as it sets the accuracy levels for all the research analysis to be conducted subsequently. The error budgets of each scanner is determined by modelling each of the inherent accuracy limitations (laser range accuracy, angular accuracy and laser beamwidth) of the respective instruments in order to develop a surface model accuracy error budget (Lichti 2004; Boehler et al, 2003; Tucker 2002; Schulz and Ingensand 2004a).

Chapter 5 details the next step in the research project, which involved an analysis of the effects produced by using different registration algorithms to process the collected data so as to obtain a fully aligned model. The discussion of the final modelled surface accuracy is focussed on the point cloud data overlap, data density and gradients/roughness of the point clouds least squares accuracy constraints of the point cloud registration algorithm used. The properties (point cloud collection density, collection accuracy, and the modelled surface accuracy) of each of the disparate datasets are also the determining factors in the accuracy of the final combined datasets’ modelled surface.

Chapter 6 discusses the registration of the Leica bridge data using three different registration algorithms where the point cloud is registered, and a volumetric difference analysis between the Leica HDS2500 data and the Minolta Vivid 910 data is conducted. Analyses of the use of different registration algorithm parameters and their effect on the two datasets is statistically analysed to determine the influencing parameters, such as incidence angle and edge location.

Chapter 7 discusses the analysis of the research to enable the accurate determination of the relationship between 3D laser scanning acquisition techniques of both TLS and close range scanning surveys, and the instrumentation error budgets for future cultural heritage recording and replication projects.
2 LITERATURE REVIEW

2.1 Introduction

Terrestrial Laser Scanners (TLS) have become very popular for large and small scale cultural heritage architectural documentation (Boehler et al 2003), and for the purposes of recording for digital preservation, deformation studies, and 3D modelling for replication of the cultural heritage features.

This review aims to define the best suited 3D laser scanning equipment and methodologies to model both large scale features (bridges and buildings) and small scale features (intricate rock carvings and statues) to use as a framework for the research project. This research is important since objects of many sizes occur in cultural heritage documentation, and no single scanner can be recommended for all tasks (Boehler and Marbs 2002).

This review considers some of the methodologies adopted for the 3D modelling of multi-scaled architectural features that have been proposed in the literature, to make correlations between the size and intricacies of the heritage features, and the suitability of the scanners selected with respect to the subsequent 3D models produced.

The investigations into the accuracies of TLS by Ingensand et al (2003), Boehler et al (2003); Gordon et al (2003); Johanasson (2002); Gordon and Lichti (2002) and (Lichti and Licht 2006) have detailed comparisons between the different scanning manufacturers and their stated and measured point data accuracies, and their respective point cloud resolutions. In many cases, the measured accuracies of the TLS when compared to the stated accuracies provided by the manufacturers are significantly better (Gordon et al, 2004), and in some cases they are worse (Lichti, 2004);(Lichti and Franke 2005).

In conjunction with the investigations into the accuracies of the different TLS in cultural heritage recording, other papers have documented their findings in actual cultural heritage modelling projects. Both large scale projects (Balzani et al 2000); (Bryan et al 2004);(Pfeifer 2001) and small scale projects (Balzani et al 2000);
(Tsakiri et al, 2003); (Trinks et al, 2005); (Guidi et al, 2005), have detailed a set of successful and unsuccessful methodologies.

Finally, the significant research into the different ICP algorithms used in the registration of terrestrial laser scanning data will be identified, as the nature of the registration of 3D datasets will be fully analysed in the thesis.

2. 2 TLS suitability for the 3D modelling of cultural heritage features at multiple scales

The TLS’s used for large scale cultural heritage recording are predominately time of flight (TOF) scanners. The principle of these types of scanners being that a laser pulse is sent to the object and the distance between transmitter and the reflecting surface is computed from the travel time between the signal transmission and reception (Boehler and Marbs, 2002).

The main advantage of TLS’s as compared to close range photogrammetry is the availability of near real time 3D coordinates for irregular surfaces (Boehler et al, 2003). This capability may result in TLS’s replacing other conventional surveying practices (Tucker, 2002). Although in many cases TLS have been used in conjunction with photogrammetry as a DTM base for rendering, in conjunction with this photogrammetry has also been used to control the TLS data (Fabio, 2003).

2.2.1 Accuracy of TLS for large scale cultural heritage features


Every point cloud produced by a laser scanner contains a considerable number of points that show gross errors Boehler et al (2003). With this knowledge Boehler et al (2003) developed a comprehensive test program and subsequently tested as many scanners as possible to ascertain their accuracy.

Tests conducted on the TLS’s by Boehler et al (2003) and Lichti and Licht (2006) were designed to model each scanner’s characteristics in response to tests for angular
accuracy, range accuracy, scan resolution, edge effects, surface reflectivity response, and environmental conditions.

2.2.2 Precision Testing of the Cyrax 2500

The results of this study illustrated that the Cyrax 2500 (now the Leica HDS2500) had the greatest accuracy and resolution of all the scanners tested, and it was consequently well suited for the requirements of large scale cultural heritage projects.

Schulz and Ingensand (2004b) found when testing the range of the Cyrax 2500 that a repeatable accuracy comparison of 1mm to observations taken with an HP interferometer was achievable, which dramatically exceeds the stated accuracy of 6mm from the manufacturer.

Tucker (2002) produced two tests to observe the errors in the peripheries of the field of view and errors in different range observations of the scanner. The field of view observations returned better than the manufacturers specifications of +/-6mm, with results of 1.1mm, while the range testing results proved inconclusive (but still within the manufacturer’s specifications) due to uncertainties in the testing methodology.

Gordon et al (2003) illustrated when conducting testing on the Cyrax 2500 (and the Riegl LMS – Z210) for the use of TLS’s in precision measurement of structural deformation, that the mean RMS of the residuals from the least squares adjustments were +/-0.6mm for the Cyrax 2500 and +/- 5.3mm for the Riegl LMS – Z210. In using the scanner to model deflection, the mean RMS of the differences (compared to photogrammetry) was +/- 0.22mm, which represents a factor of improvement (in precision) of 27 times the stated single point precision for the Cyrax 2500.

Lichti (2004) provided a new measure of TLS point cloud resolution in his study of the spatial resolution of several TLS’s, and decoupled the range and angular resolution from the spatial resolution. Lichti (2004) gives a guide to determining the resolution of the acquired point cloud by saying that the maximum achievable resolution is obtained only when the sampling interval is 55% of the beamwidth.
2.2.3 Cultural Heritage recording methodology

Bryan, et al, (2004) presented a process for the development of TLS standards in cultural heritage projects to facilitate capture and delivery for the future. They have described a typical project flow line (in Figure 2.1) for a heritage recording TLS survey, and although this methodology is intuitive to most surveyors, it does document the procedure so that important steps that cannot be overlooked.

In 3D laser scanning, point density and measurement precision are directly linked. Without a high density, point measurement features cannot be accurately described, and subsequently without accurate measurements, the features cannot be accurately located (Bryan et al, 2004). Equation 2.1 is proposed by Bryan et al (2004) because it allows the appropriateness of the chosen density to be addressed:

\[ Q = 1 - \left( \frac{m}{s} \right) \]  
Equation 2.1

Where: Q is the quality of the data; m is the point density on the object; and s is the minimum feature size using this formula. By using this formula, a value can be obtained to indicate the likelihood of a particular feature being detectable.
The example given by Bryan et al (2004) is that a point density of 5mm on a feature 10mm in size would give a value of 0.5 or 50% confidence that the feature would be visible. This equation leads to very high point densities being required in order that the features can be detected in the scan data. It is also very important to note that just having sufficient point density to detect a feature in the data is usually not sufficient to successfully model an irregular feature entirely from the point cloud.

Bryan et al (2004) goes on to state that although possible using close range photogrammetry, terrestrial scanning is clearly unsuited to recording very small features, and it serves to further emphasise the fundamental role of TLS in large scale surface scanning projects. Lichti (2004) determined that though the measurement density may be set high using a TLS, the resulting resolution recorded in the point cloud when recording small complex features is still basically determine by the beam width of the TLS on the feature.

Boehler et al (2002) states that if irregular surfaces have to be modelled (usually by a mesh representation), noisy point clouds can be a nuisance in processing, especially when the presence of edges does not allow for smoothing operations. Therefore, the scanning must be carried out with the most accurate scanner available for the size and range of the particular object. This is a very important point as it further emphasises the use of a correct scanner for the scale of the feature being modelled in line with the accuracy and testing recommendations.

2.3 Close range scanners for small scale cultural heritage recording

Close range scanners are predominately triangulation scanners. They consist of a transmitting device sending a laser beam at a defined incrementally changing angle from one end of a mechanical component onto the object and a CCD camera at the other end of this base that detects the laser spot (or line) on the object (Boehler 2002).

To model small scale features in cultural heritage recording you must use a scanner with a very small beam width, and one that is capable of very small point spacing. Unlike all TLS’s, close range scanners operate in this range (Guidi et al 2005), and
this is required to maintain the required precision when modelling small scale features.

Close range laser scanners generally have a range between 0.5m – 2m with an accuracy between 0.001mm – 0.02mm (Marbs, 2002). Typical applications being for quality control, reverse engineering, and rapid prototyping of small objects. Close range scanners have been used for cultural heritage documentation with varying degrees of success. This variability has primarily been due to methodological problems rather than issues to do with the instrumentation itself.

Data management can be a considerable issue with close range laser scanners as datasets can become very large (measured in Gigabytes), and segmenting the data into workable sizes is the only way to conduct further data processing (Marbs 2002 and Ionnidis et al 2003).

2. 4 Problems encountered when conducting close range laser scanning cultural heritage projects

To illustrate some of the issues with undertaking close range scanning on cultural heritage projects, two project studies have been summarised to highlight problem sources for future work.

2.4.1 Project Study 1 – Statue of Hermes

Ionnidis et al (2003) documents a large close range cultural scanning project that was undertaken to scan the statue of Hermes in Greece. The Hermes statue is dated to 343 BC and is from Parian marble. The height of the statue is 2.13m and it is 0.84m wide.

The statue was scanned with the Minolta Vi900 to an accuracy of 0.25mm from a range of approximately 1m from the statue. The scanner was tripod mounted, and set up on a scaffold to enable the close range scanner to scan the entire statue’s surface.

This produced one of the first set of problems for the project: that any movement of the scanner or the scaffolding whilst scanning, produced a rippling effect in the data, and subsequently propagated onto the modelled surface of the statue, as shown in Figure 2.2(a).
The second major problem encountered in the project was subsurface scattering and refraction of the laser through the surface of the marble (Ionnidis et al, 2003) as shown in Figure 2.2(b). Ingensand et al (2002) also corroborate these findings that marble exhibits two important properties of translucency and non-homogeneity. A diagram of this effect can be seen in Figure 2.3 below (Ingensand et al 2002).

The final output from this project was the production of a triangulated mesh surface, which unlike other surfaces (i.e. NURBS), is not as useful for future restoration work, and the final surface was deemed to be flawed, due to the problems associated with the scanning that it was unusable for its originally designed purpose. This
project would have been better performed using a different solution to the use of scaffolding, such as a motorised arm mounted on a moveable base (as was used for the Ross Bridge Laser Scanning Project). In conjunction with the vibration mitigation a very fine totally removable powdered coating (0.001mm thick) could have been applied to the statue to negate the effects of subsurface scattering inherent when scanning marble.

2.4.1.1 Project Study 2 – Scanning the Pharaoh Pepi 1

In the scanning of the Pharaoh Pepi 1 Heinz (2002) documents that the accuracy of the digital model produced using the Mensi S25 (Triangulation scanner, point accuracy 0.6 – 2mm) was not capable of producing the manufacturer’s stated accuracy for the surface.

Heinz (2002) goes on to state that the software used for the processing was not sufficiently powerful to process all the data being collected, and the final digital model produced was not accurate enough for reconstruction of the sculpture. Although he states that a replicable model was not a project objective, if it was required another scanner with a higher accuracy (like the Vivid 910) using different techniques should be used to produce the required accuracy of the modelled surface.

2.5 3D modelling from 3D laser scanned point clouds

Large 3D point clouds, although detailed, are not useable datasets for most engineers and architects. To make this data usable for these end users, the reconstruction of precise surfaces from these large point clouds is required.

Many methods have been developed and documented (Remendino, 2003) to create a regular and continuous (triangular) mesh representation from a point cloud. These surfaces tend to have very large file sizes and are effectively a collection of non overlapping faces joined along their edges (joining points) (Remendino, 2003).

Spline surfaces are a piecewise polynomial function that can have a locally very simple form but at the same time be globally flexible and smooth. A class of these parametric curves and surfaces is the Non-Uniform Rational B-Splines (NURBS) surfaces. The NURBS surfaces created usually need some refinements to correct
imperfections, or errors in the surface. The operations required are often undertaken manually, by fixing polygonal boundaries, adjusting vertices, and removal of spikes generated by erroneous points.

The refined NURBS surface can be used for digital restoration, rendering, visualisation or computer numerical control (CNC) replication. This is because the surface is easily manipulated and accurately modelled and, in the case of CNC replication accurate tool paths can be assigned, as was done on the Ross Bridge project.

2.6 Examples of projects containing multiple scanners operating at multiple scales

2.6.1 Project Study 3 – Reshaping the Coliseum in Rome

Balzani et al (2000) conducted a 3D laser scanning project at the Coliseum in Rome. The data collection was seen in two projects, where the first section was a large scale scanning project utilising the Cyrax 2400 (the precursor to the Cyrax 2500, and now the HDS2500) to scan large architectural features to an accuracy of +/- 2mm with a 20mm sample spacing. The second project was to scan an engraved frieze and other small architectural features using the Minolta Vivid 700 (the precursor to the 900, 910 and now the 9i) to an accuracy of 1mm with a 1.25mm (x,y) and 0.61mm (z) sample spacing.

Once the data had been collected, to reduce the data size and surface, the collected point clouds were converted to NURBS (Non Uniform Rational B-Spline) surfaces from the Cyrax 2400 masonry data (Balzani et al 2000). This made for better computation performance when manipulating the data for those surfaces requiring structural restoration work.

The NURBS surface produced a highly satisfactory solution which resulted in a 4mb file for a large section of the Cyrax scan data without a loss of any of the geometric accuracy for the required architectural applications. The close range scan data produced using the Minolta scanner was used as a basis for rendering colour images taken with a camera, and subsequently the two were aligned and the images were overlaid on the geometry using an affine transformation.
The creation of high accuracy NURBS surfaces enables the modelled surface to be manipulated easily, due to the file size and the characteristics of the surface and this is why it is used for restoration/modelling projects, as well as being used for visualisations and rendering of 3D models (colour image overlaying).

One of the aspects of this project was that the two different scale models were not combined and compared as part of the project. The combination of multi scale data will become one of the cornerstones of cultural heritage 3D recording, and this will be one of the focuses of my research.

2.6.2 Project Study 4 – Visualising Ancient Rome: 3D acquisition and modelling of a large plaster-of-Paris model of imperial Rome

Guidi et al (2005) conducted a project to scan a large (16m x 17m) model of imperial Rome using a combination of advanced industrial metrology laser radar and the Minolta Vivid 910 close range scanner. The model of ancient Rome was built at 1:250 scale, is an incredibly intricate model made from plaster, and took 3 decades to make in a collaboration between model makers and surveyors in Rome.

This scanning project had some extremely tight environmental constraints that meant the scanning team could not place any equipment over the model. As normal close range laser scanners have an operational range of 1-2 metres a different methodology was required.

The equipment selected to undertake the majority of the scanning on the project was the Leica Geosystems LR200 laser radar. This is a time of flight (TOF) scanner, but it operates on a completely different principle to pulse propagation (used in all other TOF scanners, like the Cyrax). The principle is known as Coherent Frequency Modulated Continuous Wave radar (FM CW) and it has an operational range of up to 24m. One of the unique factors of this industrial scanner is that it dynamically refocuses the laser beam to a point size below 1mm to maintain the required resolution.
The Minolta Vivid 910 scanner was used to scan and integrate part of the 3D model of ancient Rome that could not be acquired by the LR200 (primarily the edges) due to obstructions to its view. These additional features on the model were scanned to a resolution of 0.5mm. The resolution of the Minolta data was coherent to that collected by the LR200, so the Minolta data could be merged with the Leica data without a loss of accuracy in the overall model which made the choice of the Minolta scanner very important.

The Vivid 910 data was aligned with the LR200 data using an ICP algorithm implemented in the 3D scanning processing software Polyworks. The final mesh of the project is still undergoing a massive modelling and digitising phase, and Guidi et al (2005) state that it has been made a lot easier due to the quality of the data produced by both scanners.

The methodology used for the Ross Bridge project was determined in a proactive way, by analysing the modelled surface accuracy requirements, and subsequently selecting the suitable accuracy instrumentation to meet those requirements.

2.6.3 Project study 5 – Sensor Fusion: Generating 3D by combining airborne and tripod mounted LIDAR data

Iavarone and Vagners (2003) conducted a combined Airborne Laser Scanning (ALS) and TLS 3D modelling project of the Toronto City Hall, in Canada, to create a full 3D model of the building and the surrounding area.

The ALS data was collected using an ALTM 2050 ALS (that collects 50,000 points per second), at an altitude of 850m with a resulting ground point density of 60cm with a point accuracy of 10cm. As this project’s area was only a section of the total ALS flying program, the area took only 10 seconds to acquire the site’s 500,000 points. As the ALS data is collected and georeferenced using the onboard differential GPS system, all the data provided was within a UTM datum.

The Optech ILRIS-3D TLS was used to collect data to fill in the vertical surfaces of the City Hall that were not scanned as part of the ALS survey (i.e. the sides of the building). All the required TLS data was collected in 12 scans with a surface spacing
ranging from 29 to 74mm, with each TLS scan having sufficient overlap for alignment and data completeness. All the TLS scans were registered prior to the alignment of the TLS and ALS datasets.

The alignment of the TLS data onto the georeferenced ALS data was done using the laser scan data processing software Polyworks by picking common features in both models and conducting an ICP registration with the global registration alignment of the two datasets having an RMS discrepancy value of 0.014m. The overall accuracy of the final model is set to the accuracy of the ALS data, thus degrading the global accuracy of the overall dataset. This problem has been investigated further as part of this research project, and will be discussed in Chapter 6.

This is an interesting project, as it integrates two disparate datasets into one continuous model for a large scale 3D modelling project. The same principles can be applied to using any multi scale datasets with the consideration that the global accuracy of the resulting amalgamated dataset being determined by the least accurate model.

2.7 Point Cloud Registration

In conjunction with the examination of the different terrestrial laser scanners, and the critical nature the selection of the correct scanner has on a project, the selection of the registration software and the registration algorithm used can have an as important role in determining the final modelled surface accuracy.

The registration of 3D point cloud data was first developed by Horn (1987), where he developed the closed form solution to register two point datasets together using corresponding points. This was further developed by Besl and Mackay (1992) who created the Iterative Closest Point (ICP) algorithm, and this has become the basis for all current registration software available today. Numerous other variations of the ICP have been developed, including Chen and Medioni (1992), Gruen and Akca (2004) and Bae and Lichti (2004).
A full discussion and analysis of the different ICP algorithms will be presented in Chapter 5, and the effects of applying the different ICP algorithms on the same dataset will be analysed in Chapter 6.

2.8 Summary

This review of the current research on laser scanning has covered the uses of a range of Terrestrial Laser Scanners, Close Range Scanners, Industrial Metrological Scanners and Airborne Laser Scanners being used for cultural heritage projects (or ones with similar accuracy and modelled surface requirements). The common thread amongst all the projects reviewed has been that the project’s accuracy requirements have guided the choice of the best suited scanner for the project.

Both Iavarone and Vagners (2003) and Guidi et al (2005) have discussed the issues arising from using multiple range/scale 3D laser scanners on a project, with the global accuracy of the resulting modelled feature being that produced by the least accurate scanner. As shown by Lichti (2004) and Boehler (2002) the resolution of the resulting point cloud model produced by a laser scanning survey is not just determined by the measurement density, the angular/range accuracy, and beam diameter of the laser, but by a combination of all these factors.

A comprehensive study of a project’s feature model accuracy requirements (Bryan et al, 2004) is required prior to the selection of a scanner to record/model the feature. In conjunction with cultural heritage project’s accuracy requirements, a comprehensive error budget for the scanners is required prior to the commencement of the survey to ascertain whether they can meet the features output model requirements for use in cultural heritage recording, deformation, modelling, or feature replication.

The research projects discussed as part of this review have shown some of the advantages and disadvantages of their selected instrumentation and methodologies, and suggested that future directions in this field will be determined from the lessons learned from these research projects. The project of scanning the multi scale features at the coliseum in Rome (Balzani et al 2000) documents the use of a close range scanner and a TLS to model large scale structures and small scale carvings. (Balzani
et al, 2000) did not, however, combine the two datasets to produce a single model, and this will be one of the focuses of my research project.

The dominant direction for industry research into cultural heritage 3D laser scanning has been the use of multiple 3D laser scanners to collect cultural heritage structures/features with detail at multiple scales and this project aims to further develop research in this field.
3 FIELD DATA COLLECTION

The 3D laser scanning data collection of the entire bridge and the icons will be discussed separately, as they were both undertaken using different scanners, with different accuracies and in different conditions at different times.

3.1 Overall Bridge Scanning

The intention of the overall bridge scanning project for DIER was to collect a seamless model of the outside surfaces for use as a baseline 3D model for a temporal 3D deformation analysis of the bridge as a whole structure. This would enable the analysis of all the elements of the structure individually, and could be used as a basis for the conservation of the bridge.

The overall bridge scanning project was conducted to enable the client to have a full 3D model of the coverage of the outside of the bridge to a point accuracy of 2 – 3mm with 10mm point spacing, and 2 – 3mm point spacing over the icons. These data are to be used as a baseline record for the conservation model for the overall stability and integrity of the bridge, and it is to be used for deformation analysis in the future. As the bridge is still part of the Tasmanian road network, and has heavy vehicles including b-double trucks across regularly every day, the data collected as part of this project may act as part of traffic management into the future.

The field capture of the 3D laser scan data of the whole Ross Bridge structure was conducted in September 2004 using the time of flight (TOF) Leica HDS2500 TLS. The principle of the TOF scanners is that a laser pulse is sent to the object and the distance between transmitter and the reflecting surface is computed from the travel time between the signal transmission and reception (Boehler and Marbs 2002). This is illustrated in Figure 3.1.

The Cartesian coordinates from the TOF laser scanners \((x,y,z)\) are derived from the scanner’s observables: range \((s)\), horizontal angle \((\theta)\) and vertical angle \((\alpha)\). The relationship between the observables \((s,\theta,\alpha)\) and the scanner-centric Cartesian coordinates \((x,y,z)\) is given in Equation 3.1 (Gordon and Lichti, 2004).
\[ \vec{v} = \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} s \cdot \cos(\alpha) \cdot \cos(\theta) \\ s \cdot \cos(\alpha) \cdot \sin(\theta) \\ s \cdot \sin(\alpha) \end{pmatrix} \quad \text{Equation 3.1} \]

Figure 3.1 Time of Flight principle for TLS (Boehler et al 2003)

3.1.1 3D Laser Scanning Data Capture

This section describes the capture methodology and equipment used in the scanning of the entire bridge structure. The Leica HDS2500 (shown in Figure 3.2) has an observation field of view (FOV) of 40° × 40° and a laser spot size of 6mm at a range ≤ 50m, with a maximum operational range of 100m. The Leica HSD2500 uses a Class 3R laser which was designed for use in the open environment, and is not affected by natural ambient light. The Leica HSD2500 equipment specifications were sourced from the Leica website (Leica, 2006) and are included in Appendix A.

Figure 3.2 Leica HDS2500 3D Laser Scanner
The Leica HDS2500 can observe a maximum of 1,000,000 data points per scan and this coupled with the 40°×40° FOV, dictates that the amount of target surface coverage possible per scan will be limited by the desired object point density (Boehler, et al 2003; Lichti, 2004).

3.1.2 Scanning Methodology

As the required point density for the project was 10mm coverage over the entire structure of the bridge, and 2-3mm over the icons, the overall bridge scans were conducted first, and then the 2-3mm icon scans were registered to the overall bridge model. The point density required on the surface of the bridge and the icons was based on a simple formula (Equation 3.2) derived by Bryan et al (2004) (previously described in Chapter 2) with respect to the final modelled surface accuracy requirements. The simple formula is:

\[ Q=1-\left(\frac{m}{s}\right) \]  
Equation 3.2

Where \( Q \) is the quality (or resolution) of the data, \( m \) is the point density (in mm) on the object, and \( s \) is the minimum feature (in mm) size using this formula. Using this formula, a resolution value can be obtained to indicate whether a particular feature is detectable.

This equation leads to very high point densities being required in order that the features can be detected in scan data. Although possible using close range scanning, terrestrial laser scanning is clearly unsuited to recording very small features and it serves to further emphasise the fundamental role of laser scanning in surface measurement (Bryan, et al 2004).

The required scanning point densities and their detection confidence levels (\( Q \)) for the project are detailed in Table 3.1. This table demonstrates that the Minolta Vivid 910 scanning ability is critically important to the project’s methodology.
### Table 3.1: Point cloud densities and detection confidence levels

<table>
<thead>
<tr>
<th>Scanner</th>
<th>Area to be scanned</th>
<th>(m) Point Density</th>
<th>(s) Feature Size</th>
<th>(Q) Detection Confidence Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leica HDS2500</td>
<td>Whole Bridge</td>
<td>10mm</td>
<td>20-50mm</td>
<td>50% - 80%</td>
</tr>
<tr>
<td>Leica HDS2500</td>
<td>Icons</td>
<td>2-3mm</td>
<td>2mm</td>
<td>0%</td>
</tr>
<tr>
<td>Minolta Vivid910</td>
<td>Icons</td>
<td>0.1-0.5mm</td>
<td>2mm</td>
<td>75% - 95%</td>
</tr>
</tbody>
</table>

#### 3.1.2.1 Scanning the whole bridge to create the 10mm model

Due to the limited observation FOV, the limited view of the bridge from each station due to obstruction, and limited access (as the scanner could not be set up in the Macquarie River), the scanning of the Bridge was undertaken from 8 separate locations on both sides of the river. The locations of each of the scanning stations with respect to the bridge are illustrated in Figure 3.3.

Due to the depth of the icons and bridge abutments ($\leq 0.5m$), shadows were created in the data collected from each side of the river, and these were filled when the models from the opposing side of the river were registered together. The data from each of the locations were registered together using a combination of target based registration and point cloud based registration using Leica’s Cyclone 5.3 software. Full analysis of the registration results are presented in Chapter 4.

![Figure 3.3: Scanning set-up locations with respect to the bridge](image-url)
3.1.2.2 Field requirements for the registration of the whole bridge scan point clouds

Due to the $40^\circ \times 40^\circ$ FOV restriction of the Leica HDS2500 it was necessary to take 3 or 4 scans of each face of the bridge from each scanning location to produce a continuous model and maintain the 10mm point density required. It is important to note that the next evolution of Leica Scanners, the Leica HDS3000, has the ability to scan $360^\circ$ horizontally and $270^\circ$ vertically, which would have meant that only one scan would be required from each side of the river, rather than over twenty.

3.1.2.3 Target Registration

The target-based registration technique was used to register the overall bridge scans, the point clouds of each face of the bridge and the road surface together to form the final overall point cloud of the bridge. This was possible as there was insufficient overlap of the point clouds of each face of the bridge and the road to conduct an overall point cloud registration.

A minimum of four targets per 10mm scan were required by the Cyclone software. Where it was not possible to place sufficient targets in each FOV, a combination of target and point cloud registration was undertaken. Each of the scanning targets was located using a Leica TC1203 total station, thus coordinating each of the targets and providing an independent check of the whole bridge model. There were 15 targets within the model that had been coordinated by total station. Undertaking a further point cloud registration, after using the target registration as an initial alignment (and checking the redundancies), provided an independent check to the point cloud registration.

3.1.2.4 Control Traverse

The scanned target registration was used to coordinate the survey onto the Australian Map Grid by locating each target and existing ground control marks using the total station. The target-based registration was conducted using Cyclone 3.2 software and the residuals from target registrations were all within 2-4 mm.

Each of the scanning targets was located from at least two stations using the Leica TC1203 reflectorless theodolite, which was used to conduct a fully-constrained control traverse. Local $3^{rd}$ Order State Permanent Marks (SPM) (global accuracy of
near the bridge were also surveyed, and this brought the 3D laser scanning survey onto the Australian Map Grid 66 (AMG 66; as there were no GDA94 coordinates available for the state control marks located at the time of the survey).

The control traverse closed to an accuracy of 2mm and this was adjusted out using a least-squares adjustment in the survey software Terramodel, and each of the scanning control marks was coordinated to an accuracy of +/-2mm (x,y,z) (checked by multiple measurements of each target).

3.1.3 Scanning the icons to an point spacing of 2-3mm

Due to the $40^\circ \times 40^\circ$ scanning FOV restriction of the Leica HDS2500 it was necessary to take scans of significantly smaller areas when scanning to obtain the 2-3mm coverage over the icons (approximately 2m x 2m). The purpose of this scanning was to produce a surface model of the icons to register the sub-millimetre scans onto. Due to the very large file sizes of the sub-millimetre scans this was deemed impractical for the project, but the data are there ready for when the computing power becomes available.

3.1.4 Overall Bridge Scanning Project Deliverables

The overall bridge scanning deliverable to the client was the entire registered bridge point cloud, Figure 3.4 illustrates the entire bridge point cloud model, and Figure 3.5 shows the coverage over the icons.

Figure 3.4 Entire bridge point cloud model from the northern face of the bridge
Figure 3.5  (a) Photograph of the area scanned, (b) shows the difference in coverage over the icons from the 2-3mm and 10mm scans, and (c) a 2m wide cross section through the bridge.

3.2 Very high resolution scanning of the icons on the bridge

The scanning of the 186 icons on the exterior of the bridge was conducted over three periods: September 2004, February 2005, and June, July and August of 2005. The reasons for the delays in data acquisition were weather, equipment and personnel difficulties experienced whilst scanning.

As the required point density for the very high resolution scanning of the icons was 0.5mm, at the time of the survey in 2004 only the close range triangulation scanners could achieve the required accuracy given the bridge’s physical and environmental constraints. The very high resolution scanning was conducted using the Minolta Vivid 910 as it was deemed to be the best suited laser scanner for the project (Balzani et al 2000; Bryan et al 2004). The data collected is an important dataset as it is the largest very high resolution 3D laser scanning survey of its kind undertaken in Australia.
3.2.1 3D Laser Scanning Data Capture

Laser triangulation used by the Minolta Vivid 910 is an active stereoscopic technique where the distance of the object is computed by means of a directional light source and a video camera. A projected laser beam is deflected from a mirror onto the scanning object. The object scatters the light, which is then collected by a video camera located at a known baseline distance from the laser. Using trigonometry, the 3D spatial (XYZ) coordinates of a surface point are calculated (Equations 2.3, 2.4 and 2.5). The CCD camera’s 2D array captures the surface profile’s image and digitizes all data points along the laser line.

The Minolta Vivid 910 (specifications provided in Appendix A) is an active triangulation scanner. A projected plane of laser light is swept across the field of view by a mirror rotated by a precise galvanometer. The laser light is reflected from the surface of the scanned object, and each line is observed by a single frame, captured by the charge coupled device (CCD) camera the operation is shown in Figure 3.6. The contour of the surface is derived from the shape of the image of the reflected scan line. The entire area is captured and the surface shape is converted to a lattice of over 300,000 points (Konica Minolta, 2005).

The Cartesian coordinates \((X_p, Y_p, Z_p)\) from the active triangulation laser scanners are derived from the observables; the inclination of the projected plane of light (\(\theta_p\)), and the \((x_p, y_p)\) location in the focal plane, and the instrument’s constants; the fixed base length between the laser source and the CCD, (B), and the principle distance of the photographic lens (c). The physical layout of each of the parameters with respect to the laser, mirror, and CCD is shown in Figure 3.6.

Figure 3.6  Triangulation principle for close range scanners (Boehler et al 2003)
to the scanner, the object, and the focal plane array are illustrated in Figure 3.7 (Lichti, 2005a).

The relationships among the observables \((\theta_p, x_p, y_p)\) and instrument constants \((B, c)\) and the scanner-centric Cartesian coordinates \((X, Y, Z)\) are given in Equation 3.3, 3.4, and 3.5 (Lichti, 2005a), and for a full derivation for each of the equations see Jalkio et al (1985) and Lin and Chi (1983)

\[
Y_p = \frac{B \sqrt{x_p^2 + c^2}}{y_p + \sqrt{x_p^2 + c^2}} \tan \theta_p \tag{Equation 3.3}
\]

\[
Z_p = \frac{cB}{y_p + \sqrt{x_p^2 + c^2}} \tan \theta_p \tag{Equation 3.4}
\]

\[
X_p = \frac{x_p B}{y_p + \sqrt{x_p^2 + c^2}} \tan \theta_p \tag{Equation 3.5}
\]
3.2.1.1 Manufacturer’s Specifications

The Minolta Vivid 910 (Figure 3.8) has an observational range of 0.6 - 2.5m with accuracy of 0.5mm using the mid lens (which is one of the three lenses available) mounted on the scanner, and it measures 640 x 480 points per scan, (Konica Minolta, 2004).

![Konica Minolta Vivid 910 Laser Scanner](image)

Figure 3.8 Konica Minolta Vivid 910 Laser Scanner

The Minolta Vivid 910’s Class 2 Laser operates in the visible light spectrum and cannot be used in outdoors due to interference from the sun’s natural ambient light. This problem has been previously overcome by other researchers by setting up a tent over the scanning area (Trinks et al, 2005). However, as the icons were suspended on the outside face of the bridge and no physical contact was allowed with the bridge in case of damage, the scanning of the icons was conducted at night.

3.2.1.2 Scanning Methodology

Due to the range limitations (0.6m – 2.5m) of the Minolta 910, the field collection methodology had to be adapted to get the scanner close enough to the bridge (without making any contact with it), scanning without any ambient light interference and still meeting the accuracy requirements of the project. The feasibility of mounting scaffolding on the outside of the bridge was considered, but it was deemed to be too prone to movement by either the river or the wind. As the scanner would be directly set up on the scaffolding, it was seen as too great of a risk
to the project, given the problems of a similar nature encountered by Ionidis et al (2003) using a Minolta Vivid 910 scanner mounted on a tripod set up on a scaffold scanning a marble statue.

To meet all the project’s requirements, the scanner was fixed to a motorised mount on the end of a large extendable arm, which was mounted on a Hubtex sideways-moving forklift. Figure 3.9 shows the setup for the scanning operation on the forklift, and the location and orientation of the scanner with respect to the operator. This was one of the major technical difficulties to be overcome by the project as without being able to physically see what the scanner was scanning it would be impossible to efficiently scan the icons on the face of the bridge. To overcome the lack of line-of-sight between the operator and the scanner a small video camera was mounted on the face of the scanner and a live video link was set up and connected to a control screen observable on the forklift (see Figures 3.9 and 3.10).

![Figure 3.9 Photograph of the forklift mounted Minolta, scanning the icons](image)

This enabled the scanner to be driven across the face of the bridge and be raised and lowered by a vertical arm (mounted on a custom-built aluminium rack) to position the scanner in front of the icon to be scanned. Then, using the motorised bi-axial rotational scanner mount attached to the end of the arm, the scanner was rotated so
the observation angle of the scanner was perpendicular to the area to be scanned. The scanner was manoeuvred using the fork lift, vertical arm and bi-axial rotational motorised scanner mount to fully scan each icon to obtain the required coverage and point density.

Figure 3.10  Minolta fixed to the bi-axial rotation head mounted to the vertical arm

The controls for the location and orientation of the scanner, and the scanning software (Geomagic) to drive the scanner, were housed in a Dual AMD computer workstation mounted within the forklift. This was done to ensure the operator had full control of the field acquisition to ensure that sufficient coverage and point density were maintained. Dual monitors for the two functions were mounted on the outside of the forklift (as it was too tight inside) and this enabled the operator to independently manoeuvre the scanner and scan each location quickly. The scanning computer mounted on the forklift was connected to an additional much larger computer (2Gb RAM, 1 Terabyte of Hard disc) via a 20m cable, and this was set up on the bridge to store and backup the incoming scan data, and start the registration processing.

Each of the icons had all its scanned point clouds registered on-site (using Geomagic) within minutes of collection to ensure that sufficient coverage was being maintained, and where required, to instruct the operator in the fork lift to re-scan some areas of a shadow or low coverage. The most important function of the onsite processing was to ensure that all the necessary data were collected whilst on site, as the mobilisation cost of the forklift and other scanning equipment was a considerable
component of the project’s overall budget. Subsequent re-visits to the site to collect missing or in-fill areas of insufficient data would have been prohibitively expensive.

Another reason for completing the onsite registration was to simplify the project’s data flow. The very large volumes of data being collected (10 gigabytes per night) would have been extremely difficult to register after the initial collection due to the small areas scanned at each time, and the large volumes of complex data with 30% – 40% overlap. Further re-registration, cleaning, surfacing and modelling of all the data collected was conducted in the office environment after the field collection was complete, and this was a much quicker process to undertake as all the initial registration and orientation had already taken place.

3.3 Icon Reproduction

The high resolution scanning of the Ross Bridge’s 186 carved icons was conducted to enable the client to have a full 3D model of each of the icons on faces of the bridge to a point accuracy of 0.5mm, with 0.5mm point spacing. This was to produce an accurate record of the current state of the icons, and to subsequently use the data for conservation, repair, replication and erosion analysis.

Two of the bridge’s icons were replicated using a high density synthetic polymer called urial using a 4-axis CNC machine to an accuracy of ±1mm of the modelled surface, shown in Figure 3.11. The CNC replication process for the “Arthur’s face” icon is demonstrated in Figure 3.12.

At the time of the carving of the first two icons, the CNC machines required the modelled surface from which the cutting would be based to be a NURBS surface. NURBS surfaces are a type of surface model that is very accurate in the creation of smooth surfaces. Solids and individual surfaces can be made up of NURBS surfaces. CAD / CAM (CNC replication) applications are NURBS based because of their capability to produce very precise and accurate surface models (Piegl and Tiller 1997).
Figure 3.11  (a) Photograph of the icon, (b) Initial scan data registration, and (c) NURBS 3D surface model

Figure 3.12  (a) Photograph of the cnc machine cutting the NURBS surface model from urial, and (b) 1:1 replicated model

It was determined that after the replication of the first two icons and comparing the NURBS/STL surfaces in Geomagic, that the NURBS surface was reducing the complexity or “smoothing” the data, and consequently making it less like the true surface that the project had worked so hard to collect (where STL surfaces are raw unstructured triangulated mesh surfaces with connecting vertices between points). The comparison between the NURBS surfaces and the triangulated mesh STL surface will be discussed in Chapter 5.
Figures 3.13 and 3.14 demonstrate the evolution of the replicated icons; from its location in-situ on the bridge 3.13 (a), the initial registered 3D scan data (prior to any data cleaning) in 3.13 (b), final 3D model in STL format ready for cnc replication 3.14(a), and the cnc model replicated in the synthetic polymer model urial 3.14(b).

Figure 3.13  (a) Photograph of the icon and (b) Initial scan data registration

Figure 3.14  (a) 3D NURBS surface model and (b) 1:1 replicated model
3.4 Summary

The field data collection methodology for both the overall bridge scanning and the scanning of the icons was determined by the resolution and accuracy requirements of the feature surface, and purpose for which the resulting dataset was to be used.

The overall bridge scanning methodology was tailored to the requirements of the client to have a continuous model over the bridge’s surface to an accuracy of 2-3mm, and using the equation produced by Byran et al (2004), the surface scan density was determined. The accuracy of the surface model also determined that the Leica HDS2500 3D laser scanner would be best suited to scanning the bridge. The accuracy and feature resolution requirements for the icons also determined the selection of scanner and methodology used for this component of the project.

The methodological assessment detailed in this chapter ensured that the client was going to receive the surface model to the stated accuracy, and that the data could be used for the desired purposestated at the commencement of the project.
4 ERROR BUDGET ANALYSIS

Each of the scanning methodologies used for this project have sources of error due to the limitations of the equipment used, the application of the equipment, and environmental factors associated with working in the field in Ross, in Northern Tasmania, both during the day and night. All of these sources of error will affect both the precision and accuracy of the scanned point cloud. This chapter will discuss these effects.

4.1 Manufacturer’s Specifications

The manufacturer’s specifications for each of the scanners have already been discussed, but it is worth presenting the relevant information here as it will be re-addressed in this section. A summary of the relevant specifications are detailed in Table 4.1 for both the Leica HDS2500 and Minolta Vivid 910 (full specifications are given in Appendix A).

Table 4.1 Summary of the Manufacturer’s specifications for the Leica HDS2500 and the Minolta Vivid 910

<table>
<thead>
<tr>
<th></th>
<th>Leica HDS 2500</th>
<th>Minolta Vivid 910</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measuring Method</td>
<td>Time of Flight (TOF), Pulsed method</td>
<td>Triangulation, Light Blocked Method</td>
</tr>
<tr>
<td>Range</td>
<td>Up to 100m</td>
<td>0.6 to 2.5m</td>
</tr>
<tr>
<td>Accuracy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Point Accuracy</td>
<td>±6mm @ 1.5-50m, 1σ</td>
<td>±0.29mm Stand dev. of XYZ axes</td>
</tr>
<tr>
<td>Distance</td>
<td>±4mm, 1σ</td>
<td>Co-ordinate Range for the Minolta Scanner:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>x: ±0.22mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>y: ±0.16mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>z: ±0.10mm</td>
</tr>
<tr>
<td>Angle</td>
<td>±60 µrad 1σ (Horiz. (θ) &amp; Vert. (α))</td>
<td></td>
</tr>
<tr>
<td>Spot Size</td>
<td>&lt;6mm 0-50m (up to 100m)</td>
<td></td>
</tr>
<tr>
<td>Scan Density (Vertical/Horiz.)</td>
<td>0.25mm min. pt to pt spacing at 50m</td>
<td></td>
</tr>
<tr>
<td>Max. Number of points per scan</td>
<td>1,000,000</td>
<td>307,200</td>
</tr>
<tr>
<td>Environmental</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating Temp</td>
<td>0° to 40° C</td>
<td>10° to 40° C</td>
</tr>
<tr>
<td>Laser</td>
<td>Class 3R (Green)</td>
<td>Class 2 (Red)</td>
</tr>
<tr>
<td>Lighting</td>
<td>Fully operational between bright sunlight and complete darkness</td>
<td>Office environment (500lx or less) Not operational in full sunlight</td>
</tr>
<tr>
<td>Operating Software</td>
<td>Cyclone (scan)</td>
<td>Geomagic</td>
</tr>
<tr>
<td>Processing Software</td>
<td>Cyclone (register/model)</td>
<td>Geomagic</td>
</tr>
</tbody>
</table>
4.2 Instrument Error Analysis

There are a number of instrumental factors that affect scanner performance and the accuracy and precision of the resulting data produced. This section will discuss these factors and analyse their affects on the final dataset.

4.2.1 Leica HDS2500

4.2.1.1 Range accuracy

The range from the HDS2500 to the target is computed using the pulse time of flight (TOF) method. Between the outgoing and returning signal TOF scanners show about the same accuracy for any range (Boehler et al 2003).

When testing the range of the Leica HDS2500, Ingensand and Schulz (2004) demonstrated a repeatable accuracy of ±1mm when compared to observations taken with an HP interferometer, which dramatically exceeds the HDS2500 stated accuracy from the manufacturer (±4mm, 1σ). Johansson (2002) also found the range precision to be ±2mm, which again is better than Leica’s specifications.

Gordon et al (2003) illustrated when conducting testing on the Leica HDS2500 for the use of TLS’s in precision measurement of structural deformation that the mean RMS of the residuals from the least squares adjustments was ±0.6mm when compared to a modelled surface. In using the scanner to model deflection, the mean RMS of the differences (compared to photogrammetry) was ±0.22mm, which represents a factor of improvement (in precision) of 27 times over the stated single point precision for the Leica HDS2500.

The range for the overall bridge scanning was between 10 to 50m, which is within the operating range of the Leica HDS2500 scanner. As discussed in the literature review, studies have illustrated that the Leica HDS2500 has the greatest accuracy and resolution of all the TOF scanners tested, and it was well suited for the requirements of large scale cultural heritage projects.
4.2.1.2 Angular Accuracy of the Leica HDS2500

In addition to the scanner’s range accuracy, the 3D accuracy is also influenced by the angular pointing of the beam. Boehler et al (2003) conducted tests on the Leica HDS2500 (formerly the Cyrax 2500) for both the range and angular accuracy, and showed that the manufacturers specifications of ±60 µrad 1σ are acceptable, as they achieved ± (50 – 80) µrad.

Schultz and Ingensand (2004) tested the angular accuracy of the Zoller+Frohlich Imager 5003, and Lichti and Franke (2005) also researched the angular accuracy and self calibration of the iQsun 880 3D laser scanner. The results produced by Schultz and Ingensand and Lichti and Franke modelling the angular errors (errors in the horizontal and trunnion axis, etc) are scanner hardware manufacturer specific and do not aid this research. But Lichti and Franke present a measurement methodology to determine the range and angular accuracy of any laser scanner for the purposes of calibration, and this would be a worthwhile investigation for future research.

Given that the range for the overall bridge scanning was between 10 to 50m, the angular accuracy specifications of ±60 µrad translate into accuracies orthogonal to the range of the scanner of ±0.6mm to ±3mm.

4.2.2 Minolta Vivid 910

4.2.2.1 Range accuracy

Triangulation scanners solve the range determination in a triangle formed by the instrument’s laser signal deflector, the reflection point on the object’s surface and projection centre of the camera, mounted a certain distance from the deflector (Boehler et al 2003). The camera is used to determine the direction of the returning signal. In contrast to the TOF scanners, the accuracy of the ranges acquired with the square of the distance between the scanner and the object (Boehler and Marbs, 2002).

Lichti (2004) conducted a report on the repeatability testing of a Vivid 910 laser scanner by scanning an array of table tennis balls. This test enabled a good indication of the precision of the Vivid 910, but not accuracy as the diameters of the table tennis balls were unknown. The study produced an overall RMS of parameter differences of
repeat scans of ±0.007mm in x, ±0.004 in y, ±0.008 in z, which far exceeds the manufacturer’s specifications.

4.2.2.2 Angular accuracy

Setan and Ibrahim (2004) calculated the angular accuracy and resolution of the Minolta Vivid 910 scanner’s different lenses (or resolution as stated) for the mid lens (which was used on the bridge) to be 0.068mm (0.0016”). When testing the Vivid 910 by scanning a 45mm cylinder, they found the difference when comparing the scanned modelled surface and the known diameter cylinder was a difference of 0.836mm. This figure seems excessively large, and may be due to edge effects produced when scanning, and limited data cleaning prior to modelling.

4.3 Data Resolution Analysis

The term “resolution” describes the ability to detect small objects or object parts in the point cloud. Technically, two different laser scanner specifications contribute to this ability, the smallest possible increment of angle between two successive points and the size of the laser spot itself on the object (Boehler et al, 2003). The effect of the angle of incidence from the scanner to the target for each technique, and the subsequent effect of the surface spot size of the laser will be discussed individually initially, and the consequences for the registration of the two models will be investigated in the qualitative error budget section of the chapter.

Even when well focused, the laser spot on the object will have a finite size. But when the laser spot hits an object edge, only part of it will be reflected there, the rest may be reflected from the adjacent surface behind the edge, or not at all (when no further object is present within the operational range of the scanner). Both TOF scanners and triangulation scanners produce a variety of artefacts in the vicinity of the edges, and they are usually to be found on the ray from the laser deflection point to the edge point, behind the edges away from the scanner, (or in front for phase based scanners) (Boehler, et al 2003).
4.3.1 Leica HDS2500

4.3.1.1 The data effect of the angle of incidence and laser spot size

Though the main surface of the bridge is relatively flat, the angle of incidence over the icons varies dramatically, and this in turn produces most of the observational errors in conjunction with edge effects and the spot size.

It is worth noting that the angle of incidence on the flat surface of the outside face of the bridge is between 34° – 64° on the northern side of the bridge, which translates into a “smearing” of the laser spot size from its 6mm diameter to a surface spot size of 7 – 14mm. The surface spot size was calculated using Equation 4.1:

\[ d_1 = \frac{d_2}{\cos \theta} \]  

Equation 4.1

Where; \( d_1 \) is surface spot diameter size; \( d_2 \) is transmitted spot diameter size; and \( \theta \) is the angle of incidence. As stated, the angles of incidence on the flat faces of the bridge are measurable as the azimuth of the bridge is known from the point cloud, and the origin of the scanner is known. But the effect of the “smearing” of the spot size will affect the flat surfaces less than the complex surfaces.

Figure 4.1 illustrates the relationship between the spot size and the angle of incidence of the laser onto the flat surfaces of the bridge (this sample is taken from scanning location 3 on the north eastern side of the bridge), where the spot size ranges from 7mm to 14mm, which is significantly different to the emitted radius of 6mm.
Figure 4.1  Relationship between HDS2500 laser’s angle of incidence, range and the surface spot size

This is due to the fact that the return signal is the superposition of all reflections within the spot. When the scanner is normal to the feature surface, the surface spot size of the laser will be the same as that projected by the scanner, and it will subsequently produce the correct range measurement. But on an irregular surface (such as the icons), where the angle from scanner to surface varies from the normal, there is a difference between the projected spot size and the surface spot size. This variation in the surface spot size of the laser affects the scanner’s range calculation.

Lichti (2004) provided a new measure of TLS point cloud resolution in his study of the spatial resolution of several TLSs, and decoupled the range and angular resolution from the spatial resolution. He goes on to give a guide to determining the resolution of the acquired point cloud by saying that when the sampling interval is 55% of the beamwidth, the beamwidth equals the resolution of the resulting point cloud.

Figure 4.2 illustrates that the maximum achievable resolution of the final resulting Leica HDS2500 point cloud for the flat surfaces of the bridge when the surface point cloud density is between 4mm and 8mm. The bridge was scanned at a point cloud density of 10mm, which is at a lower density than the maximum achievable resolution, and therefore the resolution of the model will be lower than the beamwidth.
The resolution of the surface is at a considerably lower level for the complex surfaces of the icons, due to the icon’s irregular angle of incidence and varying surface spot size, and therefore the maximum achievable resolution for the icons is going to be higher than the collection density of 2-3mm. A full analysis of the resolution of the modelled surface over the icons will be discussed in detail in Chapter 6.

![Relationship between Angle of Incidence, Spot Size and the Minimum Point Spacing](image)

Figure 4.2 Relationship between HDS2500 laser’s angle of incidence, the surface spot size and the minimum point spacing

4.3.1.2 Erroneous point errors associated with edge effects

The largest errors associated with the scanning of the faces of the bridge are to be found on the irregular surfaces of the icons, as they are significantly more detailed than the main sandstone faces of the bridge. The erroneous points in the dataset are exacerbated by the observed angle of incidence, the difference between the spot size and the level of detail of the surface of the icons.

When the projected laser “clips” the edge of a feature on the surface of the icons being scanned the range calculation to the observed location is affected and it creates the measured point location between the clipped edge and the reflecting surface behind (for TOF scanners). This artefact is illustrated in Figure 4.3.
Figure 4.3 Illustration of the creation of erroneous points due to the laser beam’s surface edge effects

Figure 4.4 shows the Leica HDS2500 data over icon 78 (which is the centre icon on the south eastern arch), which has been registered onto the Minolta Vivid 910 data. The different colours of the points represent distances from the Minolta surface to the Leica point data. In this instance the Minolta point cloud surface can be considered a “true” surface when compared to the Leica data as it is an order of magnitude more accurate, so any errors associated with the data will be inconsequential when compared to the Leica data.

The areas highlighted in red in Figure 4.4 represent erroneous points that have been produced from scan points that have partially clipped the edge of the icon, while the rest of the laser spot hits the area behind the edge on the face of the stone under the lion’s mouth.

The right hand side of the icon was scanned from a range of 44m and at an angle of incidence to the bridge of 53°, whereas the left hand side was scanned from a range of 27m and an angle of incidence to the bridge of 43°. But it is noticeable that the angle of incidence to the face of the lion is 14°, and this may account for the error differentials of 1mm or better on the left hand side of the lion. The effect of the angle of incidence and spot size will be discussed in greater detail in Chapter 6.
4.3.2 Minolta Vivid 910

4.3.2.1 The effects of the angle of incidence and laser size

As the Vivid 910 uses a plane of light, not a single point (or spot) of light as does the Leica HDS2500, the same error effects related to angle of incidence and spot size are more difficult to quantify. Figure 4.5, provided by Konica Minolta, illustrates the operational parameters of the Vivid 910 scanner and demonstrates the relationship between the range and beam width of the scanner.

Based on the available Vivid 910 specifications and the information provided by Konica Minolta, the CCD chip used by the scanner is “1/3inch” (physical dimensions of the chip are 4.8mm x 3.6mm), where the CCD array has a maximum resolution in fine mode of 307,000 pixels.

Figure 3.5 illustrates that the surface coverage in fine mode is 111mm x 83mm. Therefore, for every 1mm$^2$ on the surface of the feature being scanned there are 33.3pixels$^2$ on the CCD array, therefore the maximum resolution of the scanner will be 0.173mm for every pixel.
The effects of the angle of incidence and the laser beam width will be less using the Minolta, as each of the Vivid 910 scans are of a much smaller area than that collected with the Leica, and unlike the Leica scans, the majority of the Minolta scans were observed perpendicular to the surface of the icons.

4.3.2.2 The erroneous point errors produced by edge effects

As with the errors associated with the angle of incidence and spot size of the laser, the Minolta Vivid 910 scanner will have significantly fewer errors associated with edge effects as the scanner collects data over much smaller areas in each scan, with a spot size similar to the level of detail of the icons.

Figure 4.6 is taken from the raw scans registered in Geomagic and it highlights differences between overlaying scans. This illustrates the effect of angle of incidence and subsequently the edge effects on the scans taken by the Minolta Vivid 910 on the complex surfaces of the larger icons on the face of the bridge.
Figure 4.6 Demonstrates the effect of angle of incidence on the complex surface of Icon 78

The errors due to the angle of incidence and its effect on the edges of the surfaces in the data are in the order of 0 to 0.7mm. One of the key reasons why these errors are observable in the data is due to the multi scan overlap of several different scans over the same area. They were removed by “cleaning” each of the individual scans prior to producing the final dataset.

4.4 Qualitative Environmental Effects

As the scanning of the whole of the Ross Bridge and its icons were undertaken in the open environment, the scanners were operating in the ambient temperature of the air when the scanning took place. The conditions for scanning the bridge and the icons were very different, as the overall bridge scans were undertaken during daylight hours, between 7.00 am and 6.00pm, in the week starting the 20th of September 2004. The icons’ scans were undertaken at night over three periods in September 2004, February 2005, and June to August 2005.

4.4.1 Qualitative Environmental effects whilst using the Leica HDS2500

When the overall bridge scanning was undertaken at Ross, the laser scanner operated within the normal operating temperature range as described in the manufacturer’s specifications. The only difference to normal operating conditions was when it rained lightly at some of the scanning locations.
4.4.1.1 Temperature

Rueger (1990) states that the error associated with the difference in the temperature affects the refractive index (and hence the range) by 1ppm for every 1°C outside the specified operating temperature. For the ranges over which the scanning was conducted (10m – 50m), the effect is between ±0.01mm to ±0.05mm for every 1°C outside the specified operating temperature, with a maximum temperature differential of 10°C (or 0.5mm), which is negligible in the context of the project.

4.4.1.2 Rain

The rain did not physically affect the scanner, but it did mean that during the course of scanning that section of the bridge, rain caused a sufficient amount of backscatter, thereby resulting in erroneous points. The rain appears in the point cloud dataset as 3D data points in space between the bridge and the scanner (Figure 4.7).

The main difference between the bridge surface data and the rain data points is that the latter have an intensity of between 0.38 and 0.4 which is lower than the points on the bridge, which are between 0.45 and 0.51 (where the full range of intensities for the point cloud is 0.38 – 0.69). This difference in intensity could be used to clean the data, and this function is available in Leica processing software Cyclone, but was not used in this project.

![Figure 4.7 Top view of the scanned rain as it appears as 3D data points in the scan data](image)

Face of the Bridge

Rain data Points
The scanning of the rain did not perceivably affect the point cloud density on the bridge, but it did require the rain to be “cleaned” from the data. Once the rain got heavier than light drizzle, the scan was stopped, the equipment covered, and the survey was postponed until the rain stopped.

4.4.1.3 Water reflections of the point cloud data

As with the rain there was no affect to the scanner or its results scanning the bridge due to reflections of the water whilst scanning, but there were some unexpected results produced. The water acted as a backscattering surface when it was disturbed by the wind (see Figure 4.8(a)), and as a mirror when there was no wind and the water was perfectly still (see Figure 4.8(b)).

The red/orange points of the water data and the reflected data in Figure 4.8 represent 3D point data of lower intensity, and the yellow/green of the bridge data is higher intensity data.

Figure 4.8  (a) Scanned surface of the water and (b) the points collected from the reflections off the water
The reflection of the bridge in the data is a mirror image of the bridge being scanned at that time, and the point azimuth has remained the same onto the water, but the range observation has been reflected off the surface of the water onto the bridge with the same angular observation, thus giving a false distance and the data is vertically mirrored.

As with the rain-affected point cloud, the main difference between the bridge surface data and the reflected data is that the rain points have an intensity of between 0.38 and 0.4 which is lower than the points on the bridge, which are between 0.45 and 0.51.

The scanning of the water’s surface did not perceivably affect the point cloud density on the bridge, but it did require the reflections and water’s surface to be “cleaned” from the data, and as with the rain data the difference in intensity could be used to clean the data, and this function is available in Leica processing software Cyclone, but was not used in this project.

4.4.2 Qualitative Environmental effects whilst using the Minolta Vivid 910

As the Minolta Vivid 910 scanner operates in the visible light spectrum, interference from the ambient light during the day time meant that the scanning of the icons on the bridge was undertaken at night. Undertaking the scanning at night brought a range of both positive and negative environmental effects to the project.

4.4.2.1 Wind

Wind became one of the most disruptive elements to the scanning of the icons. Over a period of a week the scanning team were on standby due to just wind interference alone. As the scanning of the icons on the faces of the bridge was undertaken at night, the wind that normally comes blowing down the valley during the day was considerably less. This ensured that there was no vibration of the equipment due to wind. When it was windy during the scanning (over 5km/hr), the effects could be observed by scanning the same location twice and comparing the data, and if there were any vibrations due to wind, the scanning was halted until the wind died down.
4.4.2.2 Temperature

The temperature whilst scanning the icons on the bridge at night varied between 10 and -10° Celsius, and whilst this was outside the operational range of the scanner (as shown in Table 1), there was no evidence that it physically affected the operation of the scanner.

One reason for the equipment’s ability to function outside of its specified temperature range has been suggested by Boehler et al (2003). They state that the temperature inside the scanner may be far above the temperature of the surrounding atmosphere due to internal heating of the mechanism within the scanner. Though their research was leaning toward the effects of heat in the upper range limit 50° C of the scanner’s specifications, the implications of their research are still valid as an explanation for the Vivid 910’s successful operation in these conditions.

4.4.2.3 Fog

On some of the colder nights scanning the icons on the bridge, there was a very thick covering of fog in the valley. This in turn blocked out the sun when it rose in the morning, and the team were able to scan for several hours after the normal conclusion to scanning. But, on several occasions the fog was so thick that the laser was unable to penetrate through it, and this meant that the scanning had to cease until the fog had lifted sufficiently to continue. Several days over the course of the project were lost due to fog obscuring the icons from scanning.
4.5 Summary of the error budgets for both scanners.

As discussed in this chapter, each of the instruments, their related methodologies and working environments have errors associated with them. Table 4.3 summarises the overall error budget for both the scanners.

Table 4.2 Instrument Error budget for both the Leica HDS2500 and the Minolta Vivid 910

<table>
<thead>
<tr>
<th></th>
<th>Leica HDS2500</th>
<th>Minolta Vivid 910</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range accuracy</td>
<td>±4mm (*)</td>
<td>±0.011mm (**) ±0.10 (^)</td>
</tr>
<tr>
<td>Angular Accuracy</td>
<td>±0.6mm to ±3mm (*)</td>
<td>±0.173mm (^)</td>
</tr>
<tr>
<td>Orthogonal to Range</td>
<td></td>
<td>(±0.22,±0.16)(x,y) (^)</td>
</tr>
<tr>
<td>Maximum Achievable Surface Resolution</td>
<td>±4mm to ±8mm (**)</td>
<td></td>
</tr>
</tbody>
</table>

Note: (*) denotes that the values were taken from the Leica Specifications

(^) denotes that the values were taken/calculated from the Minolta Specifications

(**) denotes that the values were calculated from Lichti (2004)

In conjunction with the range and angular accuracies stated in Table 3.3 there are significant errors associated with the effect of the angle of incidence and spot size and their associated erroneous data at the edges of the features being scanned. These are significant sources of error within both datasets, and if these are not cleaned from the data they can propagate errors through the final dataset by affect the point cloud data registration. A full analysis of the different registration algorithms used in the project will be presented in Chapter 5.
5 DATA EVALUATION OF THE SCAN DATA AND THE ICP ALGORITHMS AND METHODOLOGIES USED

The registration of the laser scan data collected using the Leica HDS2500 and the Minolta Vivid 910 was conducted initially using two different software packages, Leica Cyclone 5.3 and Geomagic 8. A part of this research program was to compare the results of different software packages. The Leica data was registered using Cyclone, Geomagic, and an automated registration package written by Curtin PhD graduate Kwang-Ho Bae. All three software packages will be analysed as part of this chapter, and differences in their final registrations will be compared and contrasted.

5.1 Background of point cloud registration

In the field of photogrammetry and 3D laser scanning the registration of two datasets is a 3D spatial transformation problem to align two sets of data points together. This is done by using point to point, and point to surface based algorithms to minimise the sum of the distances between points in corresponding datasets. The transformation of two Cartesian coordinate systems can be thought of as a result of a rigid body motion, and can be decomposed into a rotation and a translation (Horn, 1987). There has been a vast amount of research and numerous variants of the iterative closest point (ICP) registration algorithm, but the ones discussed in this chapter have relevance to the ICPs used in this research project.

Horn (1987) first suggested the use of a closed form least squares solution to provide a single step solution using measurements of corresponding points in two coordinate systems. In Horn’s model the solution is based on quaternions to represent the rotations between the two datasets. Quaternions can be thought of as a unit vector with a rotation at the centroid. The translation is the difference between the centroid of the master dataset, and the scaled and rotated dataset. It is important to note that Horn’s model relies on exact point to point correspondence to determine the translations and rotations.

The rotation from the centroid can be represented as the unit quaternion and is represented as:

\[ \dot{q} = q_0 + q_1 i + q_2 j + q_3 k = q_0 + \bar{q} \]  \hspace{1cm} \text{Equation 5.1}
The unit quaternion can also be expressed in terms of angle and axis as:

\[
q = \cos\left(\frac{\theta}{2}\right) + \sin\left(\frac{\theta}{2}\right)n_1 i + \sin\left(\frac{\theta}{2}\right)n_2 j + \sin\left(\frac{\theta}{2}\right)n_3 k \\
\]

Equation 5.2

\[
n_1^2 + n_2^2 + n_3^2 = 1 \\
\]

Equation 5.3

Figure 5.1 illustrates the rotation, (θ) around the vector (\(\vec{r}'\)) from the origin (O) to the transformed point (\(P'\)). The quaternion can therefore be expressed as:

\[
\vec{r}' = M\vec{r} \\
\]

Equation 5.4

Where, M is the quaternion rotation matrix.

The rigid body transformation is represented as:

\[
\vec{r}' = M\vec{r} + \vec{t} \\
\]

Equation 5.5

Where, (\(\vec{t}\)) is the translation vector and (M) is the rotation matrix.

Horn’s algorithm was extended by Besl and McKay (1992) who developed the (ICP) algorithm which is used where exact point to point correspondence does not exist. Given an adequate set of initial rotations and translations for a particular class of objects with a certain level of “shape complexity”, one can globally minimise the mean square distance metric for all six degrees of freedom (Besl and McKay, 1992). It uses Horn’s quaternion-parameterisation, and requires good a-priori orientation estimates so that transforming the dataset by at least one initial registration will place the point set into the correct equivalence.

Besl and McKay’s algorithm registers the data surface P, with \(N_p\) points, to the model surface X with \(N_x\) geometric primitives (points, lines and surfaces) by minimising the sum of the squared registration errors, and both datasets are reduced to their centroids.

\[
\sum_{i=1}^{P} (\vec{r}'_i - M\vec{r}_i)^T (\vec{r}'_i - M\vec{r}_i) \\
\]

Equation 5.6
To undertake the ICP, a-priori transformation parameters need to be applied to P, and for each point in P, the ICP finds the closest point in X, regardless of the representation of X.

Chen and Medioni (1992) have suggested an alternative technique to Besl and McKay’s point to point correspondence, which involves minimising the distance from point to surface. It also minimises the sum of the squares of a point to a surface. This algorithm is generally faster than the ICP, and as with ICP it still relies on an initial assumption that the transformation parameters are known.

Chen and Medioni’s registration algorithm assumes that where there are two surfaces P and Q, and an initial transformation $T_0$ is applied to P. This is illustrated in Figure 5.2, and Chen and Medioni’s registration algorithm is presented in Equation 5.7.

![Figure 5.1](image)

Figure 5.1 Distance measures between surfaces P and Q, (a) shows Q and P before $T^{k-1}$ is applied, (b) distance to the tangent plane of Q (Chen and Medioni, 1992)
where:

- $e^k$ is the difference between the two surfaces
- $ToT^{k-1} = T^k$ is the transformation
- $S_i^k = \{ [p_{ij}^k \bullet (q_j^k - s) = 0] \}$ is the tangent plane to $Q$ at $q_j^k$
- $n_{ij}^k$ is the normal to the surface $Q$ at $q_j^k$
- $q_j^k = (T^{k-1}l_i) \cap Q$ is the intersection point of $Q$ with line $T^{k-1}l_i$
- $l_i = \{ a[p_i - a] \times n_{pi} = 0 \}$ is the normal line to $P$ at $p_i$
- $p_i \in P$ is a point on $P$
- $d_n$ is the signed distance from a point to a plane

(• and × stand for scalar and cross products respectively)

The iterative closest compatible point (ICCP) algorithm has been proposed to reduce the search space of the ICP algorithm (Godin et al 1994; Godin and Boulanger 1995; Godin et al 2001). In the ICCP algorithm the distance minimisation is performed only between pairs of points considered compatible on the basis of their viewpoint invariant attributes, such as colour/intensity, curvature (Gruen and Akca, 2004).

Least squares 3D surface matching (Gruen and Akca, 2004) is a generalisation of the least squares 2D image matching concept as it can handle any kind of 3D surface, and as a non-linear estimation model it requires good approximations of the unknowns (Guarnieri et al 2004).

Arun et al’s (1987) registration method uses the singular value decomposition (SVD) to compute the optimal registration parameters in the presence of point correspondences. This method is a closed form solution for a 3D similarity transformation between two point sets, which reduces the unknown translation parameters by shifting all the points to the centre of gravity, calculate the unknown rotation matrix, and finally calculate the transformation parameters (Gruen and Acka 2004).
Bae and Lichti (2004) proposed a new method based on geometric primitives and neighbourhood search, where the change in geometric curvature and approximate normal vector of the surface formed by a point and its neighbourhood are used to determine the possible correspondence of point clouds. This method is the source behind Kwang-Ho Bae’s program that was used to register the point clouds, and will be discussed further in this chapter.

5.2 ICP algorithms used to register the Leica and Minolta data

As discussed previously, the scanning of the Ross Bridge was a two stage project where the overall bridge was scanned using the Leica HDS2500, and the bridge’s carved icons were scanned using the Minolta Vivid 910. These two scanners produced two disparate datasets, and both were initially processed using two different 3D software packages. The Leica HDS2500 data was collected and registered using Leica Cyclone 5.3 and the Minolta Vivid910 data was processed using Raindrop Geomagic 8. In conjunction with Cyclone and Geomagic, another software algorithm written by Dr Kwang Ho Bae was used to register some common data together to compare results with the other software systems. This section will discuss the different ICP algorithms used within Cyclone and Geomagic (where the information has been made available by the manufacturers), and discuss the differences in the registration results from each.

5.2.1 Leica Cyclone 5.3

The point cloud registration algorithm used by Cyclone appears to be a variant of Besl and McKay’s ICP by its requirement for an initial alignment, and its use of quaternions in the registration process (as is shown in the registration section of Chapter 3). Leica was contacted to provide information on their ICP algorithm, and the broad response from them was that it was an ICP using quaternions. Any further information regarding their registration algorithm was considered proprietary and not for public release.

The registration method for the point cloud scan data was conducted in a two stage process that involved point cloud registration and target registration. The registration process and methodology will be discussed separately in this chapter.
5.2.1.1 Leica Cyclone point cloud registration

To register two point clouds together, a minimum of three “matching” points (Cyclone calls them “Cloud Constraints”) in each of the scans needs to be identified to give Cyclone a starting point for the registration. The more matching points that are located, the fewer number of iterations required, and the greater the possibility that the software will converge to the correct alignment. It is important to note that a good distribution of matching points is required (as in a standard 6 parameter rigid body transformation in photogrammetry). The distribution of the control points is required to be evenly spaced across the overlapping area between the two scans and they cannot be collinear. If these requirements are not met, the registration can converge to an incorrect alignment.

The number of iterations can be varied, and the number and configuration of the matching points can be altered in Cyclone if the registration continues to converge to the wrong alignment. The alignment and the registration residuals can be checked prior to adding the current registration to the larger model “on the fly” to ensure that the registration is successful.

When registering the individual point clouds there was a maximum registration resolution of an RMS discrepancy of 6mm achieved by the Cyclone software when registering either the overall bridge scans or the higher resolution scans of the icons. Guarnieri et al (2004) also found the maximum achievable point registration RMS value was 6mm from Leica HDS2500 data using Cyclone, and the authors are unsure whether this is the maximum alignment inbuilt into the software.

5.2.1.2 Registration results for the Leica HDS2500 data

The Leica HDS2500 data was registered using the cyclone software by both point cloud registration and target registration. The point cloud registration was undertaken to register each of the individual scans of the bridge together as it was impossible to place targets on the faces of the bridge without obscuring the features that were being scanned. The target based registration was used to conduct the global registration of the point cloud onto AMG66, to connect sections of the bridge that had insufficient overlap for point cloud registration, and to provide an independent check of the point
cloud registrations by measuring each of the targets using a Leica TC1203 total station.

5.2.1.2.1 Point cloud based registration

As there were over 50 scans of the bridge registered using point cloud registration it is not possible to display the overall registration alignment values, but the alignment values from a typical scan of a section of the bridge (which is of the north western arch scanned from both sides of the river) are presented below in Table 5.1.

Table 5.1 Typical Registration results from Cyclone point cloud registration

<table>
<thead>
<tr>
<th>Overall alignment</th>
<th>0.007 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overlap Point Count</td>
<td>838633</td>
</tr>
<tr>
<td>Overlap Error Statistics (m)</td>
<td>RMS:0.007</td>
</tr>
<tr>
<td>Translation (m)</td>
<td>x:-54.305°</td>
</tr>
<tr>
<td>Rotation angle-axis parameters</td>
<td>-0.0800</td>
</tr>
<tr>
<td>Rotation about the axis</td>
<td>79°48’00”</td>
</tr>
</tbody>
</table>

5.2.1.2.2 Target based registration

The target based registration was used as a check of the point cloud registration results and for the global registration of the bridge onto the AMG66. The results are presented in Table 5.2 and the mean error lengths for all the measured control points are 0.010 m.

Table 5.2 demonstrates that the overall registration result comparison between the point cloud and the control points measured using the TC1203 total station is within the expected range of ±10mm, with some outliers up to 15mm. The difference in the overall registration results and the control points can be attributed to errors propagating into the registration from observational errors (for example due to edge effects), and this became an error in the translation of the point cloud data on to AMG66.
Table 5.2  Error between the measured targets, and control points within the point cloud used in the global registration of the data

<table>
<thead>
<tr>
<th>Control Point Name</th>
<th>Error Vector Length (m)</th>
<th>Error Vector (m) (x,y,z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>104</td>
<td>0.007</td>
<td>(0.003, -0.004, 0.005)</td>
</tr>
<tr>
<td>103</td>
<td>0.015</td>
<td>(0.010, 0.010, -0.007)</td>
</tr>
<tr>
<td>107</td>
<td>0.003</td>
<td>(0.002, 0.001, 0.001)</td>
</tr>
<tr>
<td>106</td>
<td>0.013</td>
<td>(0.007, 0.006, 0.009)</td>
</tr>
<tr>
<td>146</td>
<td>0.006</td>
<td>(0.003, 0.000, 0.005)</td>
</tr>
<tr>
<td>147</td>
<td>0.004</td>
<td>(0.004, -0.001, 0.002)</td>
</tr>
<tr>
<td>148</td>
<td>0.005</td>
<td>(0.001, 0.004, -0.003)</td>
</tr>
<tr>
<td>141</td>
<td>0.014</td>
<td>(-0.012, 0.003, -0.005)</td>
</tr>
<tr>
<td>142</td>
<td>0.009</td>
<td>(-0.007, -0.003, -0.004)</td>
</tr>
<tr>
<td>129</td>
<td>0.015</td>
<td>(0.011, -0.007, -0.007)</td>
</tr>
<tr>
<td>131</td>
<td>0.014</td>
<td>(0.010, -0.006, -0.007)</td>
</tr>
<tr>
<td>119</td>
<td>0.011</td>
<td>(-0.009, 0.000, 0.006)</td>
</tr>
<tr>
<td>117</td>
<td>0.014</td>
<td>(-0.014, 0.000, -0.002)</td>
</tr>
<tr>
<td>118</td>
<td>0.011</td>
<td>(-0.009, -0.003, 0.006)</td>
</tr>
</tbody>
</table>

The overall translation from the scanner control space to AMG was: (x,y,z,) (540516.229, 5346718.002, 179.179) in metres; and the angle axis rotation values: (0.3481, -0.6817, -0.6435); and the angle of the rotation about the axis is 143°31’37”.

5.2.2 Raindrop Geomagic Studio 7

Raindrop Geomagic were contacted by the author to describe their registration algorithm so it could be analysed as part of this research. The response from Geomagic was that their ICP algorithm was proprietary, and they did not wish to divulge any information regarding it. As a consequence, the analysis in Chapter 5 is based on the results comparisons between the three algorithms used.
5.2.3 Bae’s Iterative Closest Point (ICP) point cloud registration program

Bae’s ICP algorithm is not a highly polished program like the other two from the major software manufacturers as it has been prepared as part of a PHD thesis and not under years of commercial development. The program requires extensive preparation in the DOS command line prior to commencement, but it functions well and it was extremely fortunate to have Bae available to customise his program for the purposes of this research.

Bae’s ICP uses quaternions to perform the transformation between the two datasets. It is different to the others used in this research project, as it does not require an initial alignment to orientate the scan data, but instead finds matching points on the basis of curvature matching. The only initial alignment to the ICP is provided by calculating the centroids of each of the two point clouds prior to the initial alignment. Bae modified his program for the purposes of this research to enable the registration of both Leica to Leica, and Leica to Minolta data. This provides the basis for a good comparison to the other two software packages.

5.2.3.1 Preparation of the input parameters into Bae’s program

Bae’s ICP program requires a specific set of input parameters to conduct the registration, and parameters chosen were based on experience and trial and error. If the neighbourhood search parameters were too large, the registration would not converge (i.e. oscillate). If they were too small, the time required for each iteration would be too long, and time out. The required input parameters for the ICP program were:

- K_neighbourhood: number of points surrounding each registration point to be used by the ICP algorithm
- Threshold_for_distance: maximum translation distance for each iteration
- Threshold_for_angle: maximum quaternion angle rotation for each iteration
- Maximum_iteration: total number of iterations for the program to run
- Threshold_for_alignment_error: the minimum alignment error acceptable
- Data1: the master point cloud (the point cloud that will remain unmoved by the ICP)
- Data2: the slave point cloud (the point cloud to be translated and rotated)
The point cloud format for Leica HDS2500 and the Minolta Vivid 910 data had to be converted from their native file formats to a consistent universal format that Bae’s program could interpret. The .xyz text file format was selected as it is a standard ASCII data file format that is universally acceptable by all software packages.

5.2.3.2 Bae’s ICP program principles

Bae’s ICP is documented in Bae and Lichti (2004). The ICP in Bae’s program firstly calculates the centroid of each point cloud to provide an initial alignment to the two datasets. It then calculates a subset of the whole dataset by sampling a percentage (10% was used) for the ICP alignment. This was done to speed up the alignment process by reducing the data sizes.

The next step is to calculate the normal vectors for each of the data subsets where the normal vector of a point is estimated by one of the eigenvectors of the 3x3 real, positive-definite covariance matrix for a point and its neighbourhood (Bae and Lichti, 2004). The covariance of a point and its $k$ neighbouring points, $COV(p_i)$, is expressed by Bae and Lichti (2004) as:

$$COV(p_i) = (p_i - p_{cent\text{neighbour}[j=1-k,p_i]})^T(p_i - p_{cent\text{neighbour}[j=1-k,p_i]})$$  \hspace{1cm} \text{Equation 5.8}

Where; $p_{cent\text{neighbour}[j=1-k,p_i]}$ is the centroid of $p_i$ and its $k$ neighbouring points. The eigenvector of the minimum eigenvalue is the approximate normal vector of the surface formed by $p_i$ and its $k$ neighbouring points (Bae and Lichti, 2004).

The next step is to determine the geometric curvature $M_{\text{curv}}(p_i)$ of a point by estimating the normal vectors of the point, and its neighbourhood as shown in Equation 5.9.

$$M_{\text{curv}}(p_i) = \frac{1}{k} \sum_{j=1}^{k} \left\| n_{p_j} - n_{\text{neighbour}(j,p_i)} \right\|$$  \hspace{1cm} \text{Equation 5.9}

Where $n_{p_i}$ and $n_{\text{neighbour}(j,p_i)}$ are the normal vectors of $p_i$ and its $j$th neighbourhood.

The change of geometric curvature estimation is required to calculate and model the curvature $M_{\text{curv}}(p_i)$ of each data subset, and is expressed in Equation 5.10.
By selecting the initial parameters for the translation and rotation for the ICP algorithm, it determines the corresponding points from each data subset based on areas of high curvature.

The next step is to run the ICP algorithm based on a select number of neighbouring points (neighbourhood size of 10 points were used here) from each dataset and repeat a set number of iterations of the ICP algorithm (20 used here) and the success of the registration is determined if each of the datasets converge to the specified alignment error threshold.

5.2.3.3 Registration steps used for both the Leica and Minolta datasets

As discussed earlier, Bae’s program was used to register both the Leica HDS2500 / Leica HDS2500 point clouds and the Leica HDS2500 / Minolta Vivid910 point clouds. The parameters used for these registrations will be presented in the next section.

5.2.3.3.1 Leica HDS2500 / Leica HDS2500 registration

Bae’s program was used to register each individual Leica point cloud for an individual 2-3mm scan of an icon from the bridge together. The parameters presented in Table 5.1 were selected through experimentation when running the program, and knowledge of the specifications of each of the datasets.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>K_neighbourhood</td>
<td>10 points</td>
</tr>
<tr>
<td>Threshold_for_distance</td>
<td>0.1m</td>
</tr>
<tr>
<td>Threshold_for_angle</td>
<td>10°</td>
</tr>
<tr>
<td>Maximum_iteration</td>
<td>20</td>
</tr>
<tr>
<td>Threshold_for_alignment_error</td>
<td>0.001m</td>
</tr>
</tbody>
</table>

Once each registration was completed, another dataset was registered on to the newly registered point cloud until all the Leica data for each icon was combined.
5.2.3.3.2 Minolta Vivid 910 / Leica HDS2500 registration

Bae’s program was customised further to register the now-registered Leica point clouds onto the Minolta point cloud. The same input parameters (Table 5.3) were used and the registration algorithm was the same. However, this program scaled the Minolta dataset from millimetres to metres, and calculated the corresponding centroids of each dataset, as they were not aligned prior to this registration (unlike the Leica data that had been aligned to an accuracy of ± 6mm).

5.2.3.4 Registration considerations when running Bae’s program

Due to the order of magnitude difference in the point density between the 2 datasets (Minolta 0.0003m and Leica 0.003m) sub-sampling of the Minolta dataset was performed (10% of the original point cloud density was used). The sub-sampling of the data was required because the curvature analysis on Leica data would be 10% less detailed than the Minolta dataset and yield very different results given the same neighbourhood size.

Also, due to the effect of the subset sampling density, the radius of each neighbourhood of points calculated for Minolta was 10% of the Leica data due to the point density, and this meant that for each Leica control point neighbourhood there was 10 Minolta points at the centre. This is illustrated in Figure 5.2.

The effect of the difference in point density will mean that the Minolta data neighbourhood will act as a single point in the ICP registration of the two datasets. To resolve this, the number of Minolta data points in the neighbourhood was increased to ten times the size that of the Leica dataset to obtain an equivalent size for the ICP.

![Figure 5.2](image)

The differing neighbourhood sizes between the Leica and the Minolta point clouds
5.2.3.5 Bae’s program output files

There are a variety of outputs from Bae’s ICP program and as with every other aspect of using the program they have been customised to meet the project’s requirements. Each of the individual Leica and Minolta point clouds are output as translated and rotated point clouds from the alignment of the slave dataset onto master dataset and this is combined to form the registered point cloud dataset.

There are also metadata files for each aspect of the registration consisting of:

- a file for the resulting parameters from each iteration of the registration \((x,y,z,ω,φ,κ)\);
- a file containing the registration error for each iteration;
- a file containing the signed distance from the each of the subset (high curvature control points) from the point to the corresponding surface; and
- a log file illustrating the parameters derived from each iteration, making clear whether the registration has converged, or not.

This metadata was used as the primary comparison to the other registration algorithms.

5.3 Summary of the ICP Algorithms Discussed

In this chapter the background and the mathematics of the ICP registration algorithms have been discussed to demonstrate a range of different ICP variations, and the history of the development of the ICP has been outlined. Unfortunately, for purposes of this research the two commercial software packages used were unable to provide any information about their ICP algorithms due to the proprietary nature of the information, and this has made the analysis of the ICP algorithms for each package difficult. The third package, developed by Bae, has provided a full description of his program’s methodology and the ICP algorithm, which has made analysing his program possible. A comprehensive analysis of the results obtained from all three registration algorithms discussed in this chapter will be presented in Chapter 6.
6 DATA COMPARISONS

As discussed in Chapter 5, the registration of the Leica HDS2500 3D point clouds was undertaken by using three different software packages with three different ICP algorithms, with only Bae’s being adequately defined. All three packages operate using different input and operating parameters and, most importantly, these result in three different registration solutions.

In this chapter the attributes of the registered 3D Point cloud model will be analysed individually. Then the deviations resulting from the Leica – Minolta registration will be analysed. Statistical analyses of all the techniques will be conducted to compare and contrast the results. For this analysis, the Minolta dataset will be considered a “perfect” representation of the actual surface of any icon as this dataset is an order of magnitude higher resolution than the Leica data. Thus any deviations between the Leica data and the Minolta data will be assumed to be errors in the Leica data.

A full comparison of the registration parameters for each algorithm was not possible as the information was not readily accessible from each software package, and requests to the manufacturers were not able to be met. This did not, however inhibit the project’s development at any stage, or detract from the findings of the research conducted.

6.1 Selection of the icons to be analysed

As part of the Ross Bridge scanning project, 186 icons on the bridge were scanned, but for the purposes of this research project three were selected to be processed using the three different software packages. The registration results for the three icons will be discussed and compared in this chapter. They will adequately display the effects of the different scanning locations, their associated errors (discussed in Chapter 3), and resulting differences encountered using the different ICP algorithms.

The three icons to be analysed were selected for their different characteristics: position on the bridge with respect to the scanning location; orientation and shape; and the depth and complexity of the icons. Figure 6.1 shows a photograph of each icon.
It is important to note that the photographs shown in Figure 6.1 were taken from the Leica scanning locations (shown in Figure 3.3), so the observable surface coverage for each is demonstrated in each image. Photographs (a) and (b) were taken from scanning location 1, and (c) from location 2. Another key selection criterion for the icons to be analysed was that they were all on the same side of the Bridge (southern face), so that the same scanning location was used for each of the icons, and this enabled a consistency to the calculations for the range and angle of incidence.

Figure 6.2 shows the location of each of the icons on each arch of the southern face.

Figure 6.1 Photographs of each of the icons to be analysed from scanning set up locations: (a) icon 16; (b) icon 37; and (c) icon 78.

Figure 6.2 Photograph of the southern face of the Ross Bridge showing the position of icons 16, 37 and 78.
The distribution of the icons was chosen so that there was one icon on each of the arches, and that they were significantly different to each other to illustrate the different effects of angle of incidence and range, and to analyse the errors produced in the point cloud data.

6.2 Scanned Accuracy for each icon

The angle of incidence and range for each of the icons from each of the scanning location is presented in Table 6.1. This table shows the effects of the angle of incidence on the spot size for each icon from each scanning location, and the maximum achievable resolution as described by Lichti (2004).

<table>
<thead>
<tr>
<th>Icon 16</th>
<th>Icon 37</th>
<th>Icon 78</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range from (1) (m)</td>
<td>27.77</td>
<td>32.15</td>
</tr>
<tr>
<td>Range from (2) (m)</td>
<td>47.14</td>
<td>39.58</td>
</tr>
<tr>
<td>Angle of incidence to (1)</td>
<td>22°20'</td>
<td>36°15'</td>
</tr>
<tr>
<td>Angle of incidence to (2)</td>
<td>64°50'</td>
<td>58°35'</td>
</tr>
<tr>
<td>Surface Spot Size from (1) (mm)</td>
<td>6.5</td>
<td>7.4</td>
</tr>
<tr>
<td>Lichti’s Max. Achievable Res. (mm) from (1)</td>
<td>3.6</td>
<td>4.1</td>
</tr>
<tr>
<td>Surface Spot Size from (2) (mm)</td>
<td>14.1</td>
<td>11.5</td>
</tr>
<tr>
<td>Lichti’s Max. Achievable Res. (mm) from (2)</td>
<td>7.7</td>
<td>6.3</td>
</tr>
</tbody>
</table>

The surface spot size and Lichti’s maximum achievable resolution values for each of the icons are an important guide to the visual and statistical analysis discussed in this chapter, as they will be viewed as the maximum achievable resolution of the scan data prior to registration by each of the different algorithms. It is important to note that the angle of incidence values shown in Table 6.1 are for the overall surface of each of the icons, as each of the icons’ surfaces are complex and the actual angle of incidence will vary across the surface of each.

6.3 Analysis of the different ICP algorithms for Icon 16

Icon 16 will be discussed first as it has the middle level of depth and complexity of the three icons being analysed. The scanning of icon 16 was undertaken from
locations on both sides of the Macquarie River (locations 1 and 2 in Figure 6.2), and the range and angle of incidence from each station are shown in Table 6.1.

In conjunction with the registered Leica HDS2500 data shown in Figure 6.4 the registered Minolta Vivid 910 scan data is shown to illustrate the difference in the resolution of the two scanning methodologies and to present the surface to which each of the datasets will be compared. Once each of the registration algorithms had aligned the individual scans, the final dataset was loaded into Geomagic to be surfaced (as shown in Figure 6.3) for display. The data was surfaced using the same parameters for each dataset to ensure there was no bias in the presentation of each of the registered point cloud datasets.

Each of the surfaced datasets presented in Figure 6.3 have different characteristics that demonstrate the attributes of the registration algorithms used to register the same scans of icon 16 together to form the final dataset. The main purpose for loading each of the final datasets into Geomagic was to register each dataset to the Minolta Vivid 910 data to analyse the differences between each of the registration algorithms by comparing the deviations between for each algorithms final registered point cloud to the Minolta Vivid910 data.

In Figure 6.3 (a), (b) and (c) the holes in the data are areas of poor coverage in the surfaced model, and each of them has a red border around them. The larger holes are seen as gaps in the data (clearly seen in (b) and (c)), but the smaller holes are just visible as red spots on the surface, and there are a large number across the surface of (a).
6.1 Analysis of surfaced point cloud for each algorithm

Visual analysis of the surfaced model produced from the Cyclone registration of the individual point clouds shown in Figure 6.3(a), shows that this model is the “roughest” of any of the algorithms (when compared to the Minolta data in 6.3(d)), and it also has the least number of “large holes” in the surfaced model.

Figure 6.3(b) is the Bae registration model, and has more holes, but has less roughness, and it is visually the closest to the surface to the Minolta data. The Geomagic registration model Figure 6.3(c), and this is the “smoothest” model and
has similar levels of detail to the Bae model, but it has a less textured surface, and possibly less detail than the other models. The roughness of the surface is further illustrated in Figure 6.4, where each of the results has been zoomed in to highlight the roughness of each surface, and it clearly shows the roughness difference associated with each of the individual algorithms.

![Figure 6.4 The zoomed in views of the surfaced models produced from the Leica HDS2500 data Icon 16 using the three registration techniques: (a) Cyclone; (b) Bae; and (c) Geomagic. (d) represents the Minolta data registered using Geomagic.](image)

6.3.2 Analysis of the deviations resulting from the Leica – Minolta registration

Figure 6.5 illustrates the calculation of the surface normal between the Leica point cloud, and the surface Minolta. The Leica and Minolta models registered in Figure 6.6 show the results of the registrations, the deviations between the registered Leica point cloud and the Minolta surfaced model for each technique.

![Figure 6.5 The deviations between the surfaced Minolta data and the Leica point cloud, illustrated as normals to the surface showing the direction and magnitude of the deviations](image)
As the complexity of each side of icon 16 is basically the same and the adjoining icons are identical, there should be no bias to the data due to icon shape or errors produced by edge effects from the neighbouring icons, or if there is a bias it will be symmetrical. The registration of the data from the different algorithms onto the Minolta data by Geomagic appears to be unbiased by the erroneous data within each model. This is demonstrated as there is a relatively even distribution of green colour (±1mm range) across the surface (except in the areas of red erroneous point cloud data). This assumption has been made as there does not appear to be areas of the negative deviation with corresponding positive deviation on either the top/bottom or left/right, which is what would indicate a tilted or biased registration due to erroneous data or a bad registration.

![Figure 6.6 Deviation differences between the three different registration software: (a) Cyclone; (b) Bae; and (c) Geomagic for the Leica surfaced point clouds and the Minolta data for Icon 16.](image)

The right hand side each of model is the eastern side of the icon and it is closest to scanning location 1, and this presents lower deviations to the Minolta data, due to its shorter range, lower angle of incidence and smaller resulting surface spot size. The left hand side has higher deviations and is a result of the longer range, greater angle of incidence (which could be causing positive (red) edge effects from the adjoining icon) and a greater surface spot size.
The greatest deviations are in the Cyclone registered model in Figure 6.6(a). They exist predominately on the western side of the icon, and are not present in the other models. This could be caused by a possible misaligned registration of one of the individual scans due to erroneous points caused by surface edge effects present in the data (as discussed in Chapter 4) that is biasing the cyclone’s registration algorithm, and consequently misaligning the model. But, if the large deviations were due primarily to erroneous data within an individual point cloud, the deviation would appear as deviations for each registration algorithm.

Bae’s model in Figure 6.6(b) appears to have the best alignment (as it has the most -1 to +1mm “green” coverage of the models, and it still has greater areas of high erroneous data than the Geomagic model. The Geomagic registration in Figure 6.6(c) has a greater homogeneity of colour than the other models, and yet a greater amount of finely distributed yellow (positive 1 to 2mm deviation) which implies an over “smoothing” of the data by possibly trying to incorporate erroneous data into the registration rather than ignoring it.

6.3.3 Statistical analyses of the three registration algorithms

The visual results of the three registration algorithms from Cyclone, Bae and Geomagic presented in Figure 6.6 suggest that the most “accurate” registration is either Bae or Geomagic, with Cyclone least accurate. The histogram of deviations produced by Geomagic is presented as a percentage of the data verses the deviation from the Minolta model to the registered Leica data for icon 16.
Figure 6.7 clearly shows that the registered Leica data produced by Bae’s algorithm has the highest correspondence to the Minolta surface model of the three datasets, with 57.6% alignment of the points within ±1mm, 40.2% for Cyclone and 27.2% for Geomagic. A further more important comparison shows 94.2% alignment to within ±3mm, with 79.8% for Cyclone and 69.5% for Geomagic. A summary of all this information is shown in Table 6.2.

All three histograms are centred at zero, suggesting that no large biases exist. Bae’s method and Cyclone share similar shapes, whereas Geomagic is more dispersed. These differences are backed up by the results observed in Figures 6.3(c) and 6.6(c), where the Geomagic data appeared to be smoother than Bae’s model.

The difference between the registration of Bae’s model and Cyclone’s is in the positive deviation “tail” that mirrors Bae’s curve, but is 1.5 – 2% higher as the deviations get above 3mm. This also matches to the findings in Figure 6.6 where the models had a similar distribution, apart from the western side of the icon where there is an area of misaligned data.

The maximum achievable resolution for icon 16 based on results presented in Table 6.1 shows that when scanning icon 16, the Leica HDS2500 can achieve a maximum surface resolution of 3.6 to 7.7mm. The raw scan data is more accurate than the
stated resolution, as the surface resolution (correspondence to the Minolta surface) has been exceeded in Bae’s registered dataset (94.2% within ±3mm).

6.4 Analysis of the different ICP algorithms for Icon 37

The next icon to be discussed is icon 37, and it has the least level of depth and complexity of the three icons being analysed. In contrast to icon 16, the ranges shown in Table 6.1 demonstrates that the range from the scanner to the icon 37 is nearly the same, and angle of incidence is less disparate, which makes the surface spot size difference between each scanning location smaller. Due to these factors and its lower level of complexity it should produce less edge effects, and this should produce less a less error biased model.

6.4.1 Analysis of surfaced point cloud for each algorithm

Icon 37 had five Leica HDS2500 scans over its surface, and these scans were registered using the same three different registration algorithms as icon 16. Each of the surfaced datasets for icon 37 are presented in Figure 6.8, and as with icon 16 they all have different characteristics that demonstrate the different attributes of the registration algorithms.

![Figure 6.8](image)

*(a) (b) (c) (d)*

Figure 6.8 The surfaced models produced from the Leica HDS2500 data for icon 37 using the three registration techniques: (a) Cyclone; (b) Bae; (c) Geomagic; and (d) the Minolta data registered using Geomagic
Visual analysis of the surfaced model for each registration algorithm’s point clouds are shown in Figure 6.9. The surface characteristics of each algorithm are very similar to the results for icon 16. Figure 6.8(a) displays the “roughest” surface of any of the techniques (the same as for icon 16). Figure 6.8(b) is the Bae registration model, and has more holes, but has less roughness, and as with icon 16 appears to be the closest to the surface shown in the Minolta data. Figure 6.8(c) is the Geomagic registration model, and this is the “smoothest” model and has similar detail to the Bae model, but it has a less textured surface, and is less detailed.

6.4.2 Analysis of the deviations resulting from the Leica – Minolta registration

The Leica and Minolta models registered in Figure 6.9 visually present the deviations of the Leica point cloud from the Minolta surfaced model for each algorithm. As with icon 16, the complexity of each side of icon 37 is basically the same so there is no bias to the data.

Figure 6.9 Deviation differences between the registered Leica data and the Minolta data for Icon 37 with each figure representing the three different registration software: (a) Cyclone; (b) Bae; and (c) Geomagic
The Cyclone registration shown in Figure 6.9(a) appears to have more large positive (red) deviations around the edges of the “swirls”, which are due to edge effects, than the other algorithms. Bae’s registration in Figure 6.9(b) has less red and generally more green (-1mm to 1mm). But the biggest difference is with the Geomagic registration in Figure 6.9(c) where the majority of the positive red (and negative blue) deviations are a green/yellow (positive 1 – 3mm deviations).

These results are similar to those for icon 16, but the smoothing of the data in the Geomagic registration is more noticeable in the deviation differences for icon 37. A reason for the smoothing of the Geomagic registration could be due to the lack of complexity and depth of the surface, and it is possible that Geomagic had less unique points to use to differentiate for registration control points for this icon. It is also possible that Geomagic is more susceptible to this source of error than the other algorithms.

6.4.3 Statistical analysis of the three registration algorithms

The visual results of the three registration algorithms from Cyclone, Bae and Geomagic presented in Figure 6.9 suggest that the best aligned registration is either Bae’s or Geomagic, with Cyclone least accurate. This is the same result as for icon 16. However, visual inspection of the icons can be misleading, and the statistics reveal that these assumptions may be incorrect.

Figure 6.10 shows the histograms of deviations for the three algorithms, as a percentage of the data verses the deviation from the Minolta model to the registered Leica data for icon 37. As with icon 16 it shows registered Leica data produced by Bae’s algorithm has the best fit to the Minolta surface model of the three datasets. Figure 6.11 illustrates that Bae’s algorithm registers 51.7% of the data within a deviation of ±1mm compared to 37.1% for Cyclone and 25.8% for Geomagic. A further more important comparison shows Bae’s algorithm aligns 93.7% of the data to within ±3mm, with 83.3% for Cyclone and 68.4% for Geomagic.
In Figure 6.10 the curves for Geomagic and Cyclone appear positively skewed, and unlike the curves for icon 16, the Cyclone deviation curve mirrors Bae’s curve in the negative deviations and Geomagic for the positive deviations. The skew is due to the large positive differences between the two models (shown in red in Figure 6.9).

As with icon 16, the Geomagic curve is significantly flatter than the other two, and this follows with the observations made of Figure 6.9(c) where the data appeared to be “smoothed”, with the large positive and negative deviation being merged into the registered model.

The maximum achievable resolution for icon 37 based on results presented in Table 6.1, show that the Leica HDS2500 can achieve a maximum surface resolution of 4.1 to 6.3mm. The raw scan data is more accurate than the stated resolution, as the surface resolution (correspondence to the Minolta surface) has been exceeded in Bae’s registered dataset (93.7% within ±3mm).

6.5 Analysis of the different ICP algorithms for Icon 78
The last icon to be discussed is icon 78, and it has the highest level of depth and complexity of the three icons being analysed. Table 6.1 demonstrates that the range from the scanner to the icon 78 is nearly the same as for icon 16, and angle of
incidence is basically the same from either scanning location, which makes the surface spot size difference between each scanning location the smallest, and thus producing the most consistent model of those being analysed.

6.5.1 Analysis of surfaced point cloud for each algorithm

Icon 78 had four Leica HDS2500 scans over its surface, and these scans were registered using the same three different registration algorithms as icons 16 and 37. Each of the surfaced datasets for icon 78 are presented in Figure 6.11, and as with icons 16 and 37 they have different characteristics that demonstrate the attributes of the registration algorithms.

The visual analysis of the surface model produced from each registration algorithm’s point clouds shown in Figure 6.11 presents the surface characteristics of each algorithm, and they have similar characteristics in some areas, and are different to those found for icons 16 and 37 in others. Bae’s algorithm model shown in Figure 6.11(b) has the roughest surface, and the greatest number of holes in the surface of the three, but as with the visual analysis of icons 16 and 37 it has the surface closest to the Minolta surface. Figure 6.11(c) is the Geomagic registration model, and this is the “smoothest” model and has similar detail to the Bae model, but it has a less textured surface.

The holes in the model are shown with red around the edge of the hole, and the predominate cause of the holes in this model are due to the edge effects when scanning the complex surface. This is especially evident under the mouth of the lion and on the right hand side which was scanned from further away.
Figure 6.11 The surfaced models produced from the Leica HDS2500 data Icon 78 using the three registration techniques: (a) Cyclone; (b) Bae; and (c) Geomagic; and (d) is the Minolta data registered using Geomagic.

6.5.2 Analysis of the deviations resulting from the Leica – Minolta registration

The Leica and Minolta models registered in Figure 6.12 display the results of the registration, and deviations from the Minolta surfaced model to the Leica point cloud for each technique. Unlike icons 16 and 37, the complexity of the right hand side of icon 78 is greater, but there does not appear to be any bias in the registration of the Leica onto the Minolta data as a result.
Figure 6.12  Deviation differences between the Leica surfaced point clouds and the Minolta data for Icon 78 using the three different registration software: (a) Cyclone; (b) Bae; and (c) Geomagic

Unlike the deviation difference comparisons for icons 16 and 37 there is a significant difference between the data scanned from either side of the river. As stated earlier, the right hand (eastern side) of the icon shown in Figure 6.12 was scanned from a range of 43.323m, the mane of the lion has both positive and negative deviations, and this is due to the 11mm spot size on this complex and undulating area. In conjunction with the errors associated with the complexity of the mane, there are also large edge effects on both sides of the lion produced from glancing shots from the neighbouring icons onto the sides of icon 78.

The main source of erroneous data for the icon 78 data is located under the mouth of the lion, where the large area of positive deviations are present and are attributable to edge effects from the outer edge of the mane on the eastern side when scanned from location 1 on the eastern shore of the Macquarie River. These erroneous data points are caused by scan points that have clipped the edge of the mane on the right hand side and the range of the point is approximately half way between the edge of the mane and the face of the stone under the chin.

Bae’s algorithm appears to have dealt with this erroneous data better than the other two algorithms, as the majority of the surface area outside of the eastern mane and
the area under the mouth appears to be green (± 1mm), and it appears to have ignored the erroneous data in the overall registration of the scans. This is not the case for Cyclone in Figure 6.12(b), which appears to have more negative blue (-1mm to -3mm) area’s across its surface, and this is possibly due its algorithm compensating for the large area of erroneous positive deviation data under the mouth. The Cyclone algorithm deviations shown in Figure 6.12(a) are also greater than the other two in both the positive and negative directions. Figure 6.12(c) shows that Geomagic has dealt with this area of erroneous data the worst, by what appears to be compensating for the erroneous positive deviation data, by producing a negative bias in the registration, with the majority of the surface blue (negative 2-3mm).

6.5.3 Statistical analysis of the three registration algorithms

The visual results of the three registration algorithms from Cyclone, Bae and Geomagic presented in Figure 6.12 suggest that the most “accurate” registration is again either Bae’s or Cyclone, with Geomagic least accurate, which is different to the results for icons 16 and 37.

Figure 6.13 presents the histograms of the three algorithms as a percentage of the data verses the deviation from the Minolta model to the registered Leica data for icon 78. As with icons 16 and 37 it shows the registered Leica data produced by Bae’s algorithm has the highest correspondence to the Minolta surface model of the three datasets. In Figure 6.13 Bae’s algorithm registers 56.5% of the data within a deviation of ±1mm compared to 43.0% for Cyclone and 27.5% for Geomagic. A further more important comparison shows Bae’s algorithm registers 91.1% of the data to within ±3mm, with 84.2% for Cyclone and 72.2% for Geomagic.
Figure 6.13  Deviation difference of the Leica data (as a percentage) between the surfaced points produced by each registration software and the Minolta data for Icon 78.

The curves for Geomagic and Cyclone appear positively “skewed” in Figure 6.13, which is the same as the curves for icon 37, and the Cyclone curve mirrors Bae’s curve in the negative deviations and Geomagic for the positive deviations. As with icons 16 and 37, the Geomagic curve is significantly flatter than the other two, and this follows with the observations of Figure 6.12(c). Geomagic’s data appeared to be biased by the large amount of erroneous positive deviations, with the large erroneous positive deviation being merged into the registered model, and thus creating a flattening of the curve. Bae’s curve is also skewed, but to a much lesser extent and this is due to the erroneous positive data, and is consequently less biased.

The maximum achievable resolution for icon 78 based on results presented in Table 6.1 show that the Leica HDS2500 can achieve a maximum surface resolution of 5.5 to 5.4mm. The raw Leica scan data is more accurate than the stated resolution, as the surface resolution (correspondence to the Minolta surface) has been exceeded in Bae’s registered dataset (91.1% within ±3mm).
6.6 Summary of the results for the different algorithms over the three icons

Each of the three icons presented in this chapter have different physical attributes, and were observed from different ranges and angles of incidence. These differences enabled a comprehensive assessment of the performance of the three registration algorithms.

Table 6.2 presents the registration results for each of the icons. Interestingly the results for each algorithm are relatively consistent for each of the different icons. This consistency of results is contrary to what was expected, as the different ranges, angles of incidence, physical shape and complexity, appears not to affect the registration algorithms ability to register the data.

Table 6.2 Summary of the deviations of the Minolta - Leica registration for each registration algorithm

<table>
<thead>
<tr>
<th>Registration Algorithm</th>
<th>Icon 16</th>
<th>Icon 37</th>
<th>Icon 78</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geomagic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deviation ± 1mm</td>
<td>27.2%</td>
<td>25.8%</td>
<td>27.5%</td>
</tr>
<tr>
<td>Deviation ± 3mm</td>
<td>69.5%</td>
<td>68.4%</td>
<td>72.2%</td>
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<tr>
<td>95% confidence level value</td>
<td>5.8mm</td>
<td>6.0mm</td>
<td>6.2mm</td>
</tr>
<tr>
<td>Cyclone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deviation ± 1mm</td>
<td>40.2%</td>
<td>37.1%</td>
<td>43.0%</td>
</tr>
<tr>
<td>Deviation ± 3mm</td>
<td>79.8%</td>
<td>83.3%</td>
<td>84.2%</td>
</tr>
<tr>
<td>95% confidence level value</td>
<td>8.4mm</td>
<td>4.7mm</td>
<td>5.7mm</td>
</tr>
<tr>
<td>Bae</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deviation ± 1mm</td>
<td>57.6%</td>
<td>51.7%</td>
<td>56.5%</td>
</tr>
<tr>
<td>Deviation ± 3mm</td>
<td>94.2%</td>
<td>93.7%</td>
<td>91.1%</td>
</tr>
<tr>
<td>95% confidence level value</td>
<td>3.4mm</td>
<td>3.4mm</td>
<td>4.4mm</td>
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<tr>
<td>Lichti (2004) Average Max. Achievable Resolution</td>
<td>5.6mm</td>
<td>5.2mm</td>
<td>5.5mm</td>
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</table>
The visual analysis of the colour deviation maps, though good at highlighting the location of erroneous data within the model, can be misleading, and the statistics (shown in the histograms) must be used in conjunction with the plots when analysing the results of the registrations to determine the overall registration alignment accuracy.

Bae’s registration algorithm demonstrates that the maximum achievable resolution for the Leica HDS 2500 is actually greater than the values put forward by Lichti (2004), as the 95% confidence level of the Bae registered point cloud was consistently less than Lichti’s maximum achievable resolution values. Bae’s method is able to achieve accuracy greater than that of the Leica point cloud, and this is not unusual as sub-sample or sub-pixel resolution is routinely achieved in photogrammetry.

The 95% confidence level value is a good indication of how the registration algorithms deal with erroneous data, as the lower the value the less the algorithm has distributed these erroneous data deviations throughout the registration. Bae’s algorithm consistently registers the datasets more accurately than Cyclone or Geomagic, and this might be due to Bae’s algorithms ability to ignore (or at the least not use) the erroneous data when selecting control points for the ICP algorithm to use.

Bae’s (2006) method of automatically registering two point clouds works by selecting areas of large changes in curvature in each point cloud dataset which are used as registration control points. The selection of areas of large changes in curvature as control points for each dataset is a possible reason for the success of the algorithm over the other two. This success is because the areas of high curvature are likely to be surface edges, or corners within the datasets, and subsequently the algorithms is less likely to be affected by edge effects and the angle of incidence of the scanner, which the other two algorithms may, if they select control point areas that can possibly contain this erroneous data.
7 CONCLUSIONS

This final chapter summarises the results from the areas of research undertaken in each chapter, draws conclusions from the research findings, and makes recommendations for utilising future recording schemes in large cultural heritage conservation projects. This research has established a viable and novel methodology for combining the different scales (using different ICP algorithms) when recording multi-scale large cultural heritage features.

As part of this methodology, it was determined that an initial understanding of the error budgets and the relationship between the instrument’s error budget and the associated acquisition technique particular to each instrument. Once the error budgets for each instrument were compiled from the specifications (and discussions with the manufacturers), the actual maximum resolution for each instrument was determined using the methodology stated by Lichti (2004). The maximum achievable resolution value for the Leica HDS2500, calculated from the specifications, was 3.3mm, and the calculated maximum surface resolution for the bridge was between 4mm and 8mm due to the differing surface spot sizes.

The error sources of each acquisition technique were analysed to ascertain for the effects of the range, angle of incidence, and the resulting edge effects had on the final datasets, and though this test was not repeated on the same surface from a full set of different ranges and angles of incidence it provides a sufficient set for this project. The calculation of the maximum achievable resolution values provided a basis for the determination of the actual surface resolution. This was achieved by incorporating the range, and the angle of incidence from selected icons on the bridge to the scanning locations to calculate the actual surface spot size of the laser. The surface spot size values enabled the determination of the expected modelled surface accuracy (which was lower than the values in the specifications) for each technique, and were the basis for the maximum modelled surface accuracy comparisons for different ICP registration algorithms.

Three different registration software packages (Cyclone, Geomagic and Kwang-Ho Bae’s ICP) were discussed and analysed in Chapter 5, to ascertain what differences,
if any, would occur in the registration of the same data using each of them. To assess the effects of the errors associated with each registration algorithm, three icons were selected on the southern face of the bridge. The icons were selected on the basis that they had different ranges and angles of incidence from the scanning locations, and that they were all physically different sizes. Additionally of the icons surfaces were of differing complexity. This was done to highlight any errors associated with the different ICP algorithms.

The Leica point cloud data for each icon was then registered using each of the three different ICP algorithms, and then registered on the Minolta data to show the deviation differences between the two registered datasets. The data from each technique was analysed visually (to locate the sources of error) and statistically to determine which ICP performed better for each icon. It is important that the statistical analysis is conducted in conjunction with the visual analysis as the visual interpretation on its own can give misleading results.

The results from the comparisons between the registered Leica data and the Minolta data were unexpected as the deviation differences from each algorithm were considerably different. The results for the performance of each ICP are presented in Table 6.2 in Chapter 6, and shows that Bae’s algorithm had the greatest correlation to the Minolta surface, then Cyclone, and then Geomagic.

The results for each of the algorithms were even more surprising as Bae’s algorithm consistently achieved a resolution greater than the expected maximum achievable surface resolution calculated, by up to 40%. The differences in results between each of the algorithms highlights that the modelled surface accuracy of the final dataset has as much to do with the acquisition technique as the ICP algorithm used to register the scans together.

Bae’s registration algorithm was able to produce a modelled surface accuracy greater than that of the Leica point cloud, and though this is not unusual, as sub-sample or sub-pixel resolution is routinely achieved in photogrammetry, it raises the need for a new determination of a point clouds modelled surface accuracy.
As discussed in Chapter 6, Bae’s ICP algorithm uses areas of high curvature to select control points for the registration of two point clouds. In selecting these points for the ICP registration, it appears to ignore areas where errors are more likely to be located. This assumes that each of the areas of high curvature are edges within the data, and as edge effects are the greatest source of error within point cloud datasets, it is unlikely that erroneous data will be located at these points.

The greatest limiting factor in the pre-registration accuracy of the 3D point clouds of the Ross Bridge was the effect of the angle of incidence on the surface spot size, and the erroneous data points that were produced from the increase in spot size. The subsequent pre-registration precision of the point cloud is 4mm to 8mm, and this makes the results produced by Bae’s algorithm more important.

The results from this research highlight the need for comprehensive error budget analysis prior to the commencement of any project. Any assessment of a project’s error sources will need to address:

- the instrumentation to be used;
- site metrics and acquisition methodology; and
- the type of ICP algorithm in the software package used to register the collected individual point clouds data together.

In the case of large cultural heritage projects, the size of the smallest detailed feature on the structure being scanned will be used to determine whether the detail on the surface can be reliably modelled, taking into consideration the maximum achievable accuracy of the scanner selected. In conjunction with the scanners surface resolution values, the ICP algorithm in the registration software used will determine how the accuracy of the scanner’s acquired point cloud translates into the accuracy of the modelled surface produced.

In conclusion, this research project has produced a proven methodology for 3D laser scanning surveys for large cultural heritage scanning projects. This methodology provides a guiding base line for future scanning projects in both the field of cultural heritage conservation, and potentially other 3D laser scanning surveys that have similar demands of bringing together multiple scale datasets from various instruments into the one 3D model.
8 REFERENCES

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Godin and Boulanger 1995

Godin 2001


Heinz (2002)


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APPENDIX A - LEICA HDS2500 AND MINOLTA VIVID910 LASER SCANNER SPECIFICATIONS
Who gives you a World Class 3-D Scanner with LASER accuracy, One-button camera simplicity and an amazingly low price?

KONICA MINOLTA, that's who

The essentials of imaging
Theory of Operation

Basic Principle

The VIVID 960 uses LASER triangulation. This object is scanned by a sheet of light coming from the VIVID square aperture. The plane of light is swept across the field of view by a mirror, rotated by a precisely geared motor. This LASER light is reflected from the surface of the scanned object. Each scan line is obtained by a single scan, captured by the CCD camera. The contour of the surface is derived from the shape of the image of each reflected laser line. The entire area is captured in 3.5 seconds (6.5 seconds in FAS model), and the surface shape is converted to a list of over 500,000 vertices (intersected points). VIVID gives you more than a point cloud; each polygon-mesh is created with all connectivity information retained, thereby eliminating geometric ambiguities and improving detail capture. A brilliant (print-quality) color image is captured at the same time by the same CCD. Unlike other scanners, the VIVID has no parallax error; its "spoil-off".

High Accuracy Measurement

A high-accuracy scanner and a high-accuracy calibration facility unit to be used for claiming 9.0 data have been developed for the VIVID 960. The 9.0 reference chart applicable to the national standards has also been established to utilize the technology and algorithm that enable various accuracy measurement.

Specifications

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<tr>
<td>Required Memory</td>
<td>3.0GB (FAS mode), 4.0GB (FAS mode)</td>
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<td>Required Storage</td>
<td>4.0GB (FAS mode), 6.0GB (FAS mode)</td>
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<td>Required CPU</td>
<td>2.0GHz (FAS mode), 3.0GHz (FAS mode)</td>
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<td>Required System</td>
<td>Windows 7, Windows 8, Linux (FAS mode)</td>
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<td>Required Network</td>
<td>100BASE-TX (FAS mode), 1000BASE-T (FAS mode)</td>
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<tr>
<td>Required Port</td>
<td>100BASE-TX (FAS mode), 1000BASE-T (FAS mode)</td>
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<tr>
<td>Required Interface</td>
<td>USB 2.0 (FAS mode), USB 3.0 (FAS mode)</td>
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<td>Required Power</td>
<td>60W (FAS mode), 90W (FAS mode)</td>
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<td>Required Ambient Light</td>
<td>500 Lux (FAS mode), 500 Lux (FAS mode)</td>
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<td>Required Environment</td>
<td>10°C to 30°C (FAS mode), 10°C to 30°C (FAS mode)</td>
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<tr>
<td>Required Humidity</td>
<td>40% to 80% (FAS mode), 40% to 80% (FAS mode)</td>
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<td>Required Noise</td>
<td>60dB (FAS mode), 60dB (FAS mode)</td>
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<td>Required Safety</td>
<td>UL60950-1 (FAS mode), UL60950-1 (FAS mode)</td>
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<td>Required Certification</td>
<td>CE, C-Tick, FCC, CB (FAS mode), CB (FAS mode)</td>
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</table>

System Block Diagram

[Diagram of the system block diagram showing various components and connections, including an enclosure, a printer, a computer, and other peripherals.]

SAFETY PRECAUTIONS

- Never look at the laser beam directly.
- Do not expose the sensor to wet or extreme temperatures.
- Only use the equipment as described in this manual.

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