The Sydney Harbour Bridge High-Precision Terrestrial Laser Scanning Survey and 3D CADD Modelling

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ABSTRACT

Roads and Maritime Services is undertaking design and installation of new Arch Maintenance Units (AMUs) on the Sydney Harbour Bridge (SHB) structure. The key component of the project is precise design and installation of rails, on the eastern and western side of the SHB arch, for the AMUs to travel along. Terrestrial Laser Scanning (TLS) has been identified and implemented as the most suitable technique to provide the high-precision, 3-dimensional Computer-Aided Design and Drafting (CADD) model required for the AMU design, accurate manufacture and installation with minimum onsite modifications. Due to the unique location, safety aspects and high degree of relative accuracy required, this project involved developing and testing unique survey methodologies, utilising bespoke equipment and multiple laser scanners operating concurrently. Point cloud calibration and modelling took into account the continual movement of the bridge, constantly changing coordinate systems and customised modelling procedures to effectively model the iconic structure. This included precisely locating in excess of 41,000 rivets, brackets, hatches, portals, stairs, hand rails and services. To support further investigation of the structural behaviour of the SHB due to train loading, simultaneous monitoring surveys of the eastern and western arches were conducted to determine the relative horizontal and vertical movements at the top of the arch. Survey results assisted with understanding the actual movement patterns and magnitude. This paper presents an overview of the results, including aspects of the many challenges faced on the project, site constraints, safety considerations, design and selection of survey methodologies, customised survey equipment, personnel, data post-processing and modelling methodologies applied to deliver the data to Roads and Maritime G73 specification. Confidentiality and security of the information collected during this project were paramount. It is anticipated that a greater awareness and insight into the complexities of TLS and monitoring of structures will be gained from this paper.

KEYWORDS: *Terrestrial Laser Scanning, Sydney Harbour Bridge, monitoring, survey, high precision.*

1 INTRODUCTION

The Sydney Harbour Bridge (SHB) was designed in 1923 and constructed between 1923 and 1932 following decades of planning. Design and construction work were led by great visionary Civil Engineer, Dr John Job Crew Bradfield (1867-1943).

The SHB holds a significant place and value in the overall landscape of Sydney. It is one of Australia's most iconic heritage structures and a major rail and road arterial route for Sydney. The bridge now carries eight lanes of traffic, two rail lines, a dedicated cycleway and a pedestrian walkway. It supports the transit of an average of 204 heavy trains, more than 160,000 vehicles and 1,900 bikes every day. Since its introduction in 1998, the famous Bridge Climb also attracts hundreds of tourists from around the world to climb the bridge every day.

The maintenance of the SHB is an ongoing, programed task undertaken by Roads and Maritime Services (Roads and Maritime, 2007, 2017). The bridge is exposed to various atmospheric and environmental conditions that cause corrosion of the bridge steelwork and hence significant damage. Endless painting of bridge arches (and all steelwork in general) to protect the structure from corrosion presents a critical part of the maintenance work. In order to improve current maintenance processes, and painting in particular, Roads and Maritime is undertaking detail design, manufacturing and installation of a new mechanical access system to provide environmental and safety benefits. The key component of the project is the precise design and installation of rails on the eastern and western side of the SHB arch for the new Arch Maintenance Units (AMUs) to travel on. Two independent AMUs are proposed to be installed, one on the southern end and the other on the northern end of the bridge. These will travel independently over the arch. The AMUs are described in Figures 1 & 2.

A detail survey of the SHB structure to provide an accurate 3D Computer-Aided Design and Drafting (CADD) model for the AMU's design, manufacture and installation has been the main requirement of this project. The survey was divided into two parts, each with different tolerances required. Figure 3 describes the extent of each part. The relative tolerance required for area 1 (green) was ±3 mm and for area 2 (red) was ±50 mm.

The final 3D model needed to be produced in a file format compatible with Autodesk Inventor design software. Being a non-standard request and a critical point for the project realisation, this presented additional challenges for surveyors.

Terrestrial Laser Scanning (TLS) was recommended by Roads and Maritime as the most efficient methodology to capture the most detail information during field survey. However, it was uncertain if it could produce the final deliverables to the required tolerances. Roads and Maritime Surveying Section invited tenders from a select number of highly reputable Roads and Maritime Geospatial Survey Panel members to develop appropriate survey and processing methodologies to deliver the survey model to Roads and Maritime requirements. Jacobs Group (Australia) Pty Ltd was the successful tenderer and awarded the contract work in July 2017. To ensure the proposed field and processing methodologies would deliver the project requirements, Roads and Maritime required a small test area be completed and delivered first (see Figure 3).

This paper provides an overview of this unique project, including challenges faced, site constraints, safety considerations, design and selection of survey methodologies, customised survey equipment, personnel, data post-processing and modelling methodologies applied to deliver the data to a site-specific Roads and Maritime G73 Detail Survey specification. Confidentiality and security of the information collected during this project were paramount.

Figure 1: Visualisation of the Arch Maintenance Unit (AMU), rails and Bridge Maintenance Unit (BMU).

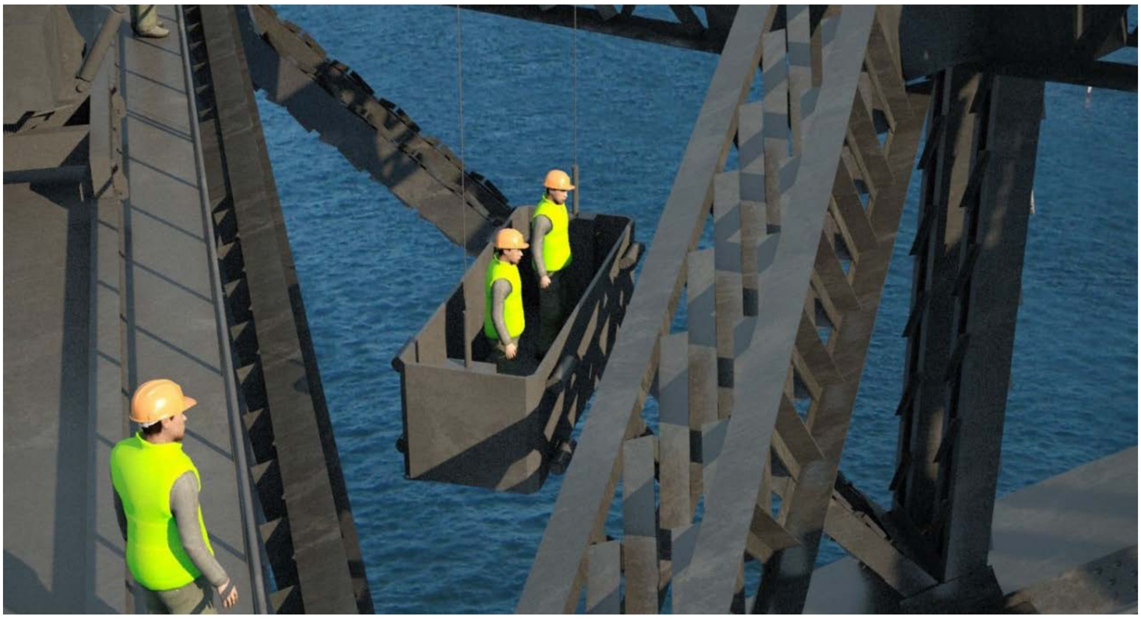


Figure 2: Visualisation of the BMU for difficult-to-access parts.

Figure 3: Areas of the bridge to be surveyed.

2 PROJECT CONSIDERATIONS AND LIMITATIONS

Technical and non-technical challenges associated with this project were overcome through innovation and sound project management involving considerable stakeholder consultation.

2.1 Information Security and Confidentiality

As the owner and operator of the SHB, Roads and Maritime has an obligation to protect the bridge from threats and restrict any information that could be used to plan or facilitate a breach or compromise of security for the bridge.

All those involved on the project were required to complete a Roads and Maritime Confidentiality Agreement that specified information that was to remain classified, including:

- Bridge plans and technical drawings that depict specific locations, measurements and materials of the bridge structures.
- Reports (including text, drawings and photographs) that identify or infer any vulnerability in the structure, bridge systems or maintenance regime.
- Photographs and video or film footage that reveal the assembly of major structural components that are otherwise hidden from public view.
- Any data relating to loading capacity or stress points on the bridge.
- Any details of bridge safety and security systems.

Guidance and assistance with this process was provided by the Critical Infrastructure and Security Resilience Branch within Roads and Maritime.

2.2 Technical Complexities

Technical complexities included:

- Developing and testing unique survey methodologies to deliver the data to the strict tolerances required.
- Programming and duration of surveys (control, detail and monitoring).
- Customised survey equipment.
- Number of highly skilled personnel.
- Survey network design.
- Calibration and control of point cloud data captured on a dynamic bridge structure.

- Customised modelling methodologies applied to deliver the data to Roads and Maritime G73 specification.
- Assurance that the final CADD model would be compatible with Autodesk Inventor design software.
- Large dataset analysis and presentation of the monitoring survey results.

2.3 Non-Technical Complexities

Non-technical complexities included:

- Project management.
- Collaboration and stakeholder consultation.
- Heritage considerations.
- Work Health and Safety (WHS).
- Bridge site access.
- Work around Bridge Climb operational hours.
- Obstructions at bridge walkways (e.g. current painting gantries, various equipment, Bridge Climb groups and temporary removal of steel mesh).
- Weather conditions.

3 ROADS AND MARITIME SURVEY REQUIREMENTS

3.1 Detail Survey and CADD Modelling: Area 1 and Area 2

An accurate 3D CADD model of the SHB arches was required to enable the design, manufacturing and installation of two AMUs and rails for AMUs to travel on. TLS was identified as the most suitable survey technique to provide the high-precision 3D CADD model required.

The survey specifications needed to comply with the Roads and Maritime Quality Assurance (QA) Specification, G73 Detail Survey. The survey area was broken into two parts, as described below.

3.1.1 Area 1

Detail survey and modelling of the inner third of the SHB top surface chord, along both the eastern and western side of the SHB, had to be performed to a relative tolerance of ±3 mm (Figure 4). This was later extended to include the inner two thirds of the chord. This was to include accurate locations of rivets, plates and changes in angle at the node points.

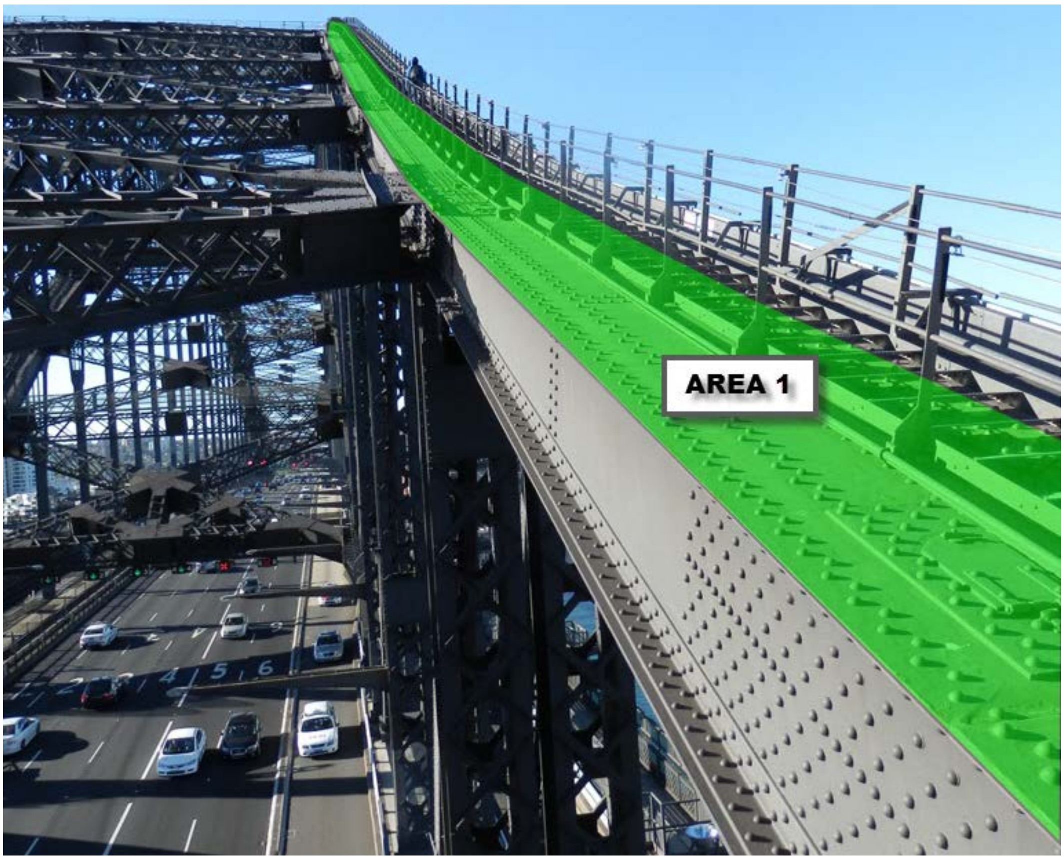


Figure 4: Nominated area 1 for detail survey and modelling (highlighted in green).

3.1.2 Area 2

Detail survey and modelling of the structure down to and including the lower chords had to be performed to a relative tolerance of ±50 mm. The level of detail was less than for area 1 and it was not required to model all the individual bridge elements in detail (Figure 5).

Figure 5: Nominated area 2 for detail survey and modelling (highlighted in red).

3.2 Detail Survey and CADD Modelling: Test Area

This project involved developing and testing unique survey and processing methodologies, utilising multiple laser scanners operating concurrently and the use of customised survey equipment. Significant investigation was required to deliver a 3D CADD model, compatible with Autodesk Inventor design software, which could be successfully used to design new AMUs and rails.

In order to ensure that field and processing survey methodologies were successful and that the deliverables complied with the specifications and tolerances required, a test area was nominated for detail survey and modelling. This test area needed to be completed and accepted in full by Roads and Maritime before proceeding with the survey of the whole project area. Combined top and lower arches, over the length of 20 m at the northern end of the SHB, were nominated as the test area (see Figure 3).

3.3 Survey Control Requirements

The project involved the establishment of suitable survey control network for all the survey activities. The control network was required to comply with class C as outlined in ICSM's Standards and Practices for Control Surveys (SP1), version1.7 (ICSM, 2007). Horizontal positions and levels of control marks were reduced to a plane coordinate system (approximating MGA56, i.e. MGA94 zone 56) and the AHD level (height) datum.

3.4 Monitoring Surveys

In 2015, Roads and Maritime investigated the structural behaviour of the western arch of the SHB due to train loading. This involved simultaneous monitoring surveys of three locations on the western arch (each end and top). Detailed analysis of the survey results determined the movement in the western arch caused by passing trains over the bridge. The largest movements were identified in the top of the arch. Details can be found in Roads and Maritime's 2016 Excellence in Surveying and Spatial Information (EISSI) Award Roads and Maritime nomination.

To better understand the relative horizontal and vertical movement of the two arches, additional simultaneous monitoring surveys of the top arches, on both the western and eastern sides, were required. Monitoring surveys were requested over 2 hours during the morning peak between 7 am and 9 am, when maximum train loading occurs, and over 2 hours well before dawn, when there were no trains on the bridge.

Continuous and simultaneous observations with two total stations of a minimum 1" angular accuracy and at 1-second time intervals were requested. Survey stations were located at ground level. Survey targets were Leica round prisms mounted to the SHB structure with custom-made steel brackets and installed by SHB riggers (Figures 6 & 7).

Monitoring survey results played a critical role in understanding the bridge dynamics and the selection of the most appropriate time window for the TLS survey. To minimise the impact of bridge movement and ensure the relative accuracy of the 3D model could be achieved, all laser scanning was undertaken at night and from approximately 12:30 am to 5 am, when there were no train movements over the bridge. The monitoring survey results also provided important information about relative movements that needed to be considered in the design of

the AMUs.

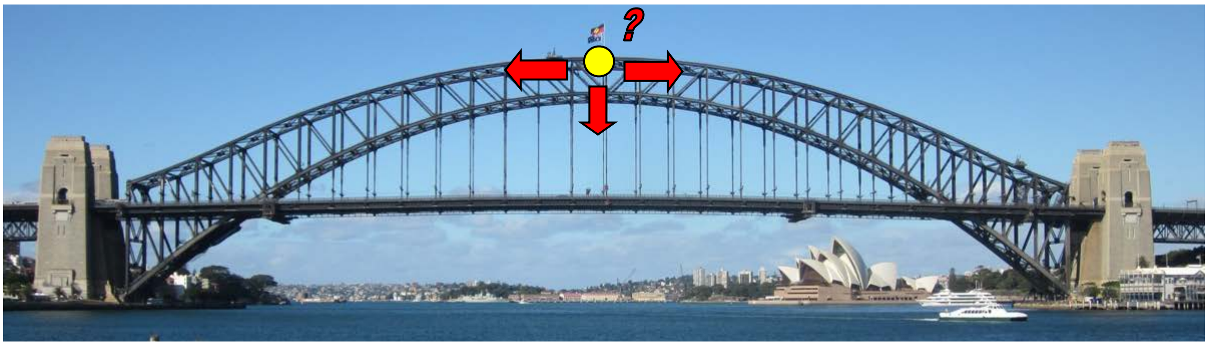


Figure 6: Prism locations on top of the bridge arch, western and eastern side.

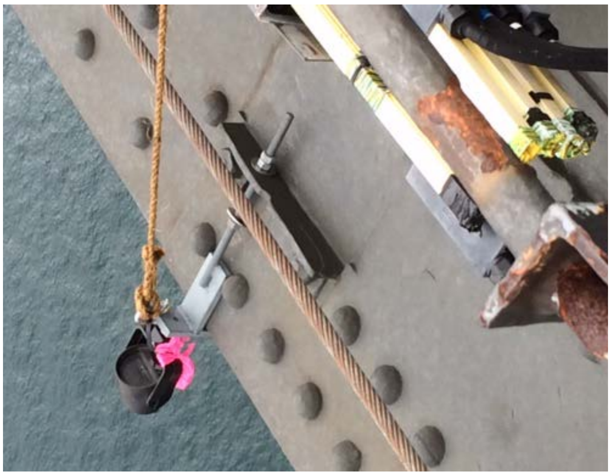


Figure 7: Typical monitoring target with custom-made mounting bracket.

3.5 Other Standard Requirements Unique to Roads and Maritime

As part of a standard Professional Services Contract (PSC) engagement process on Roads and Maritime projects and compliance with Roads and Maritime G73 Specification, Jacobs Group was required to submit evidence of the following hold-point documentation to the Roads and Maritime representative for approval:

- List of survey equipment to be used on this project and calibration records.
- List of surveyors to be working on this project and copies of their qualifications.
- Project QA plan.
- Documented methodology.
- Control survey network.
- Least squares adjustment output.
- Raw and processed survey data.
- Survey reports.
- Spreadsheets of results and graphs.

3.6 Environmental and Heritage Constrains

Compliance with environmental and heritage requirements was critical throughout this project. The SHB has outstanding national and state heritage significance. The bridge structure is protected by the Heritage Act (NSW) 1977 (2010) and its care and management

comply with specific conservation polices.

Heritage constraints for the survey work on this project required that there be no permanent marks or adverse impact on the SHB structure. Customised temporary brackets for survey equipment were designed to accommodate the heritage restrictions (Figure 8). Installation of the specially designed brackets on the steel structure required checking and approval by the SHB engineers.

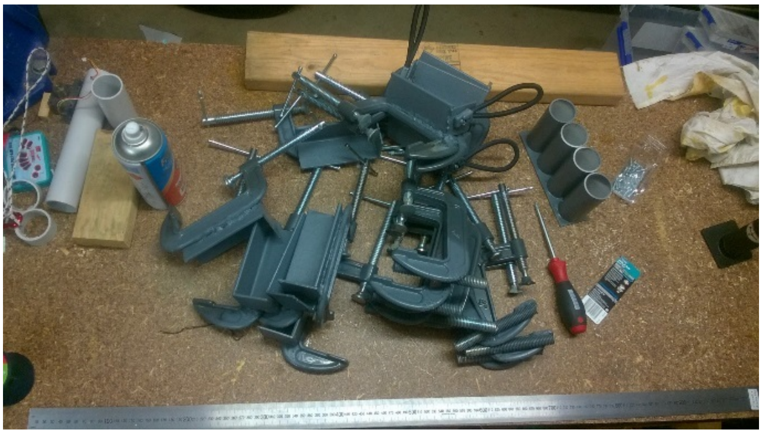


Figure 8: Array of customised mounting brackets.

3.7 WHS and Security

Compliance with Roads and Maritime SHB QA Specification G1 Job Specific Requirements was required for all workers at the site. G1 refers further to compliance with WHS documents and processes, including Roads and Maritime Specification G22 Work Health and Safety (Construction and Maintenance Work) and the SHB WHS Management Plan.

One of the main safety concerns when working on the SHB arches is objects falling from height onto the road or walkways and causing injury or damage. This issue had a significant impact on the survey activities as the team of surveyors carried a lot of survey equipment each night around the site. Each piece of equipment had to be secured by a lanyard to the structure at all times.

Jacobs was required to develop a site-specific Safe Work Method Statement (SWMS) and address all potential risks whilst on the SHB site. This document required approval by the Director Sydney Maintenance, Roads and Maritime. All nominated Jacobs field survey staff attended mandatory SHB site-specific inductions and fully complied with all Roads and Maritime requirements. Police criminal history checks for individual staff were also required to obtain SHB security clearance.

4 MEETING ROADS AND MARITIME CRITERIA AND JACOBS APPROACH

As outlined earlier, the project was broken into a series of tasks, including:

- Survey control: Primary control and scan control prisms.
- Monitoring of the top of the east and west arches (discussed above).
- A test area.
- Survey area 1: Top chord.

- Survey area 2: Mid-level laterals.
- CADD modelling: Feature extraction.

In the following sections, each of these tasks is discussed in detail.

4.1 Survey Control: Primary Control and Scan Control Prisms

A robust survey control network was crucial for undertaking the bridge monitoring portion of the project (Figure 9), and it was a fundamental requirement to achieve the high relative accuracy required for the scanning and subsequent modelling of the bridge structure.

A survey control traverse between existing Survey Control Information Management System (SCIMS) control marks, previous monitoring survey control marks and one new survey control mark was undertaken to provide a fully coordinated survey control network in a plane horizontal coordinate system (approximate MGA) and AHD datum meeting the specifications defined in the Roads and Maritime brief.

Jacobs undertook the control network observations with a 0.5” Leica TS30/60 total station and a Leica DNA03 digital level for height control. Not being feasible to undertake a reliable digital level run across the bridge, Jacobs used constrained centred bi-directional trigonometrical heighting to calculate the height differences across the harbour.

The coordination of the scanning control prisms was undertaken prior to the scanning work and consisted of firstly coordinating four high-accuracy 360 prisms, one on each of the four bridge pylons. SHB riggers installed the prisms using special mounting adapters specifically fabricated to allow attachment to the hand rails around the top of the pylons (Figure 10).

Interrogation of an existing Mobile Laser Scanning (MLS) point cloud, acquired by Jacobs from the deck of the bridge for an earlier project, showed that it would not always be possible to see the four 360 prisms installed on the pylons and that additional control prisms would be required on both the upper and lower chords of the arch (Figure 11).

All network control observations were adjusted in a minimally constrained ‘freenet’ adjustment and achieved class B for the prisms mounted on the top of each pylon. The traverse was constrained by adopting PM285 and SS175644, achieving order 2 (Figure 12). AHD values for PM285 and SS175645 were adopted for height. Trigonometrical heighting checks agreed within 0.005 m across the harbour. The survey coordinates were then converted to a plane datum (holding the MGA coordinates of PM285 fixed), providing a plane horizontal datum and AHD for height.

It was from this control network that the multiple image targets captured in each of the laser scans were coordinated. Targets were coordinated using resection techniques, taking into account atmospheric corrections throughout each night and adjusted using CompNet version 2.9 to provide the plane coordinates used for the registration of each scan.

Figure 9: Survey control network.

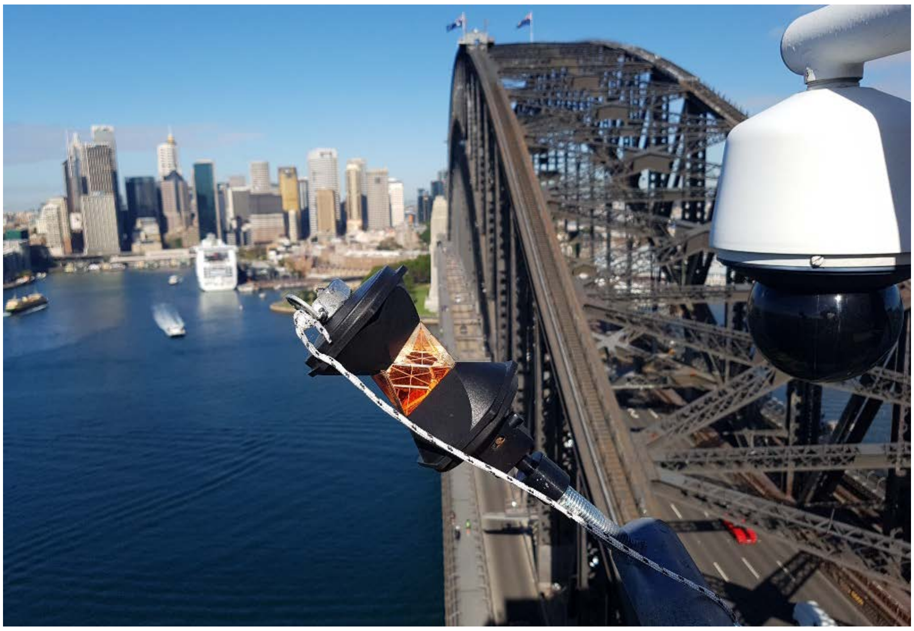


Figure 10: Typical 360 prism install at the pylons.

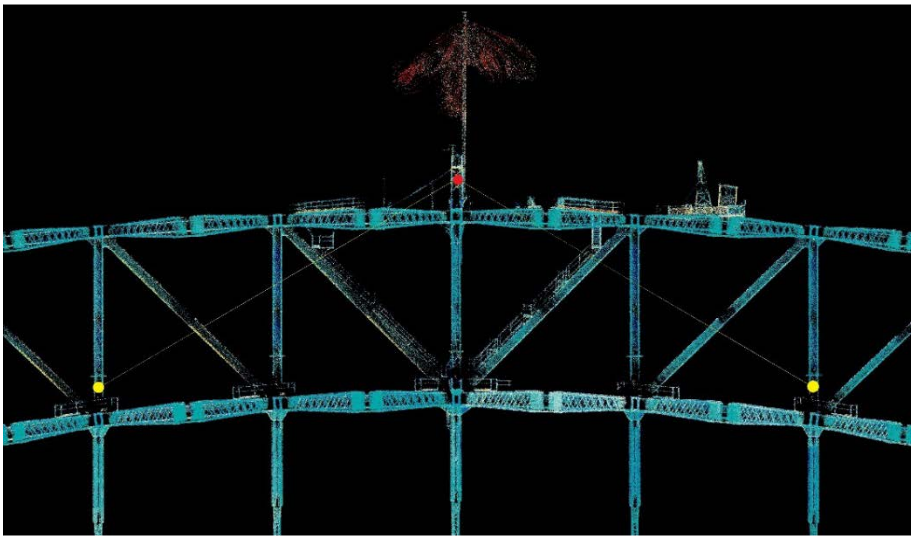


Figure 11: MLS point cloud and selection of lower chord prism locations.

Figure 12: Primary control mark.

4.2 Initial Proposed Methodology

The proposal phase of the project included extensive investigation by Jacobs into how the project could be carried out. The methodology proposed included using two Leica P40 laser scanners simultaneously, one on each side of the arch (within the walkway), with individual scans taken every 5 m over a length of 520 m. Four laser scan targets were to be placed on the outside edge of each walkway and coordinated, so that each scan registration was able to use up to eight targets (Figure 13).

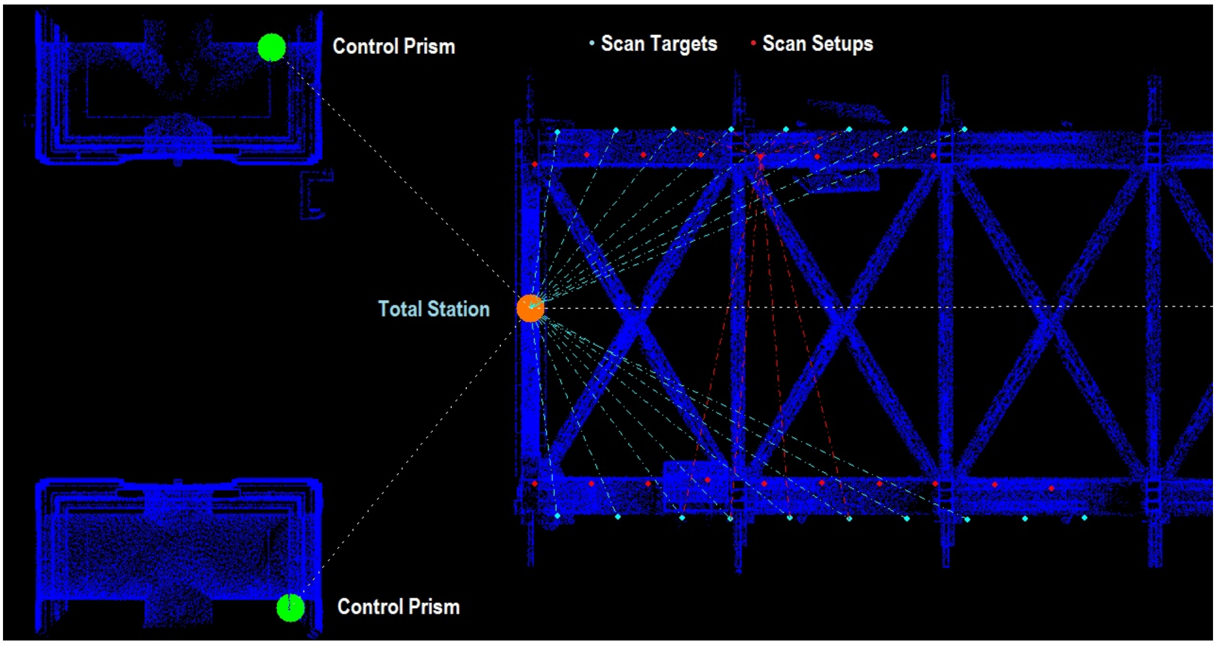


Figure 13: Indicative scan and target locations.

The initial concept involved setting the laser scanners up on custom-made scanning platforms clamped onto the steel stair stringers. The scanning platforms were to be attached near a guidepost anchor to minimise any lateral movement. The scanners were to be set up on an adjustable mount built in a ‘T’ format that lies across the stairs from stringer to stringer with the third arm attached to an adjustable magnet to sit on the flat of the arch between the steps. The adjustable platform could accommodate the varying incline of the bridge chord that varies from approximately 26º to zero at the top (Figure 14).

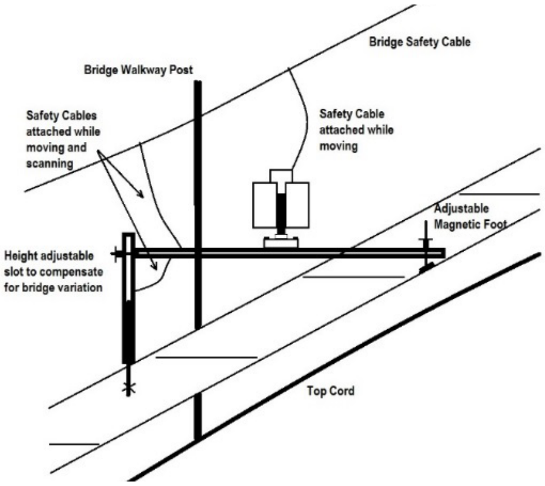


Figure 14: Proposed adjustable scan mount.

In addition to the 5 m scan locations, Jacobs had proposed to undertake a tripod-mounted scan approximately every 20 m along the walkway that would give a viewpoint from above the railing. The four laser scan targets on each side were composed of a G-clamp with welded 5/8th thread that the rotating laser scan targets screwed onto. Each target had a cable (lanyard) and carabiner that could be attached to the bridge walk safety cable while in place or attached to a carabiner on the workers belt while moving (Figure 15). The targets were attached to the upright guiderail poles running alongside the walkway, which are securely attached to the bridge chord and are the most solid structure available. The targets were to be located on the outside-edge guide posts at a distance of between 2.5 m and 5 m from each laser scanner.

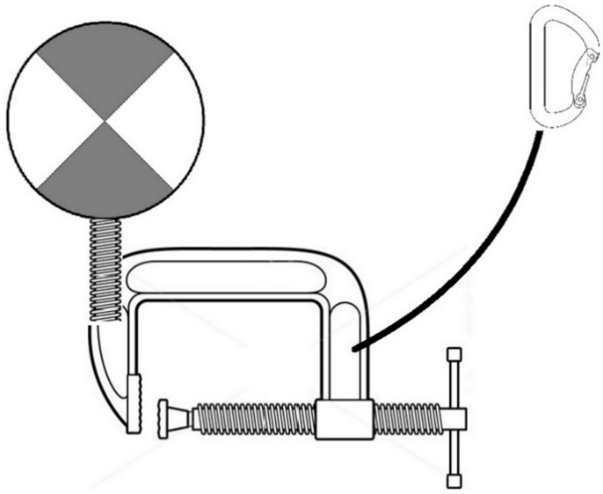


Figure 15: Proposed target attachment.

The total station setup locations were proposed to be on the cross walkways between the arches where they would have line of sight to coordinate each of the laser scan targets and be able to make check measurements between the arches from a single setup. Laser scan targets were be coordinated using a Leica TS15 1” instrument as a single set of four arcs, with the first and last observation arcs being to the control prisms. Atmospheric measurements were to be recorded and set within the instrument. Averaging limits of 5 mm would be in place within the sets of angles to alert the survey staff if any target measurements exceed these limits.

The methodology included a 5-person survey team, with one surveyor operating the total station and coordinating the laser scan targets, two surveyors to operate the two laser scanners and two surveyors moving the targets.

To assist with infilling data for both area 1 and area 2, it was proposed to undertake a series of laser scans on the lower level walkway in a similar fashion to the top level scans in order to capture additional detail not visible from the top or the road. This would equate to approximately another 20 scans on each side (Figure 16).

Figure 16: Lower chord scan positions.

4.3 Survey Area 2: Lower Arches

As discussed above, Jacobs was fortunate to have captured an MLS point cloud over the deck of the Sydney Harbour Bridge for the Roads and Maritime M1 Smart Motorway project. The existing cloud is highly detailed, with over 400 million points captured between the main bridge pylons (Figure 17). The existing point cloud had a relaxed accuracy of approximately ±100 mm, however Jacobs were able to improve this to well beyond the required ±50 mm and use this point cloud to model the additional detail required.

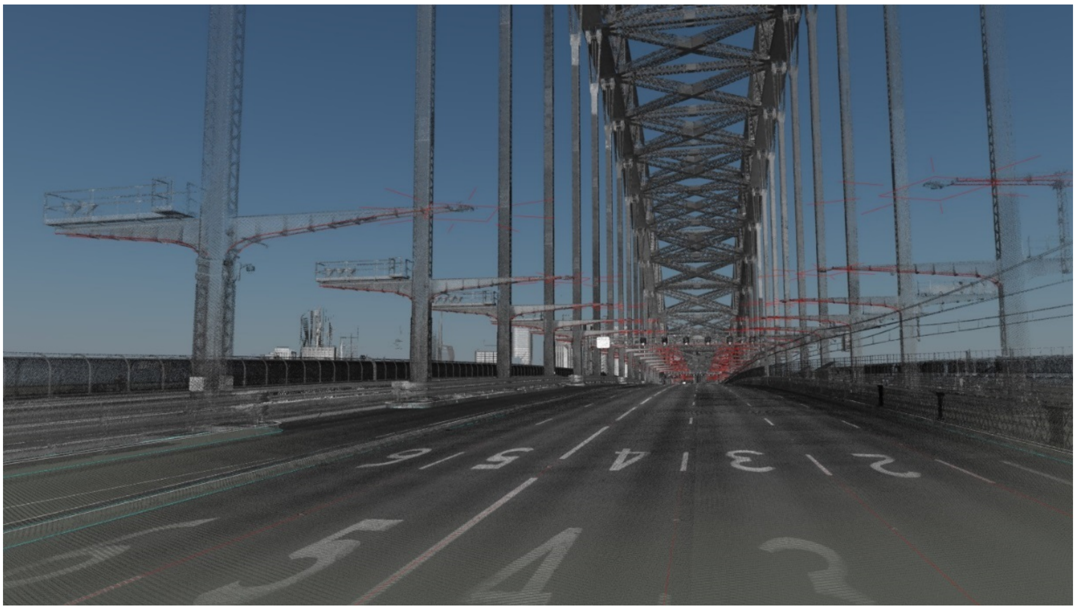


Figure 17: M1 Smart Motorway MLS.

4.4 Test Area

As required by Roads and Maritime, Jacobs undertook an initial pilot survey of the test area on the northern side of the bridge. The pilot survey involved a team of five surveyors, two Leica P40 scanners, one Leica TS60 total station, eight scan targets and dozens of mounting brackets and lanyards. The scanning included the first four spans of the bridge structure and was undertaken in a single night (Figure 18).

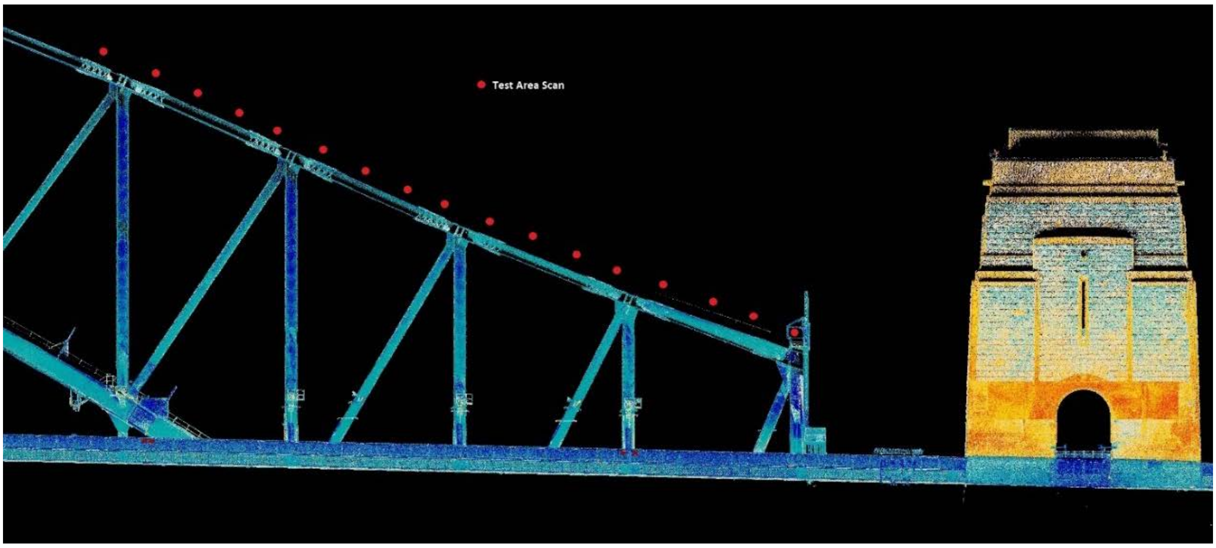


Figure 18: Test area scan locations.

4.5 Lessons Learned, Issues Encountered and Revised Scanning Methodology

After scanning the test area, there was a scope change to increase the scan coverage of the upper chord from the inner third up to the inner two thirds. This required a revised approach as it was now a requirement to survey a significant number of rivets located underneath the steps on the walkway.

The following is a summary of the revised methodology required to either meet the change in scope, or to address shortcomings of the initial proposed methodology:

- As the scope now required full survey data below the steps on the walkways, the scan distance was changed from every 5 m down to every 3.75 m or approximately every second walkway pole.
- Jacobs had developed platforms to mount the P40 scanners that securely attached to the step treads and stringers (Figure 19). However, it became apparent after the test that the platforms were cumbersome and time-intensive to set up and, more critically, there were shadow areas in the resultant cloud as the scanner was not positioned high enough to see over the stair stringers into the inner half of the chords.
- After the test, the scanning platforms were abandoned in favour of tripods. The extra height of the tripod yielded better point cloud coverage. Two feet of the tripods were held by G-clamp brackets to the base of hand rail uprights, the remaining foot was held by a magnet (Figure 20). Tripod setups were more likely to be affected by wind, so scanning was only undertaken in light winds.
- Upon processing and registering the point cloud from this first night, it became apparent that the targets furthest away from each scanner exhibited poor orientation towards the far scanner. Whilst the initial methodology was to scan concurrently to minimise any relative movement (east/west) between the chords, it was necessary to scan on one side first with all targets orientated towards the active scanner, then reorientate the targets and carry out the second scan (Figure 21). Typically there were only 20-30 seconds between the first scanner finishing and the opposite scanner starting. This resulted in a minor increase in scanning time.

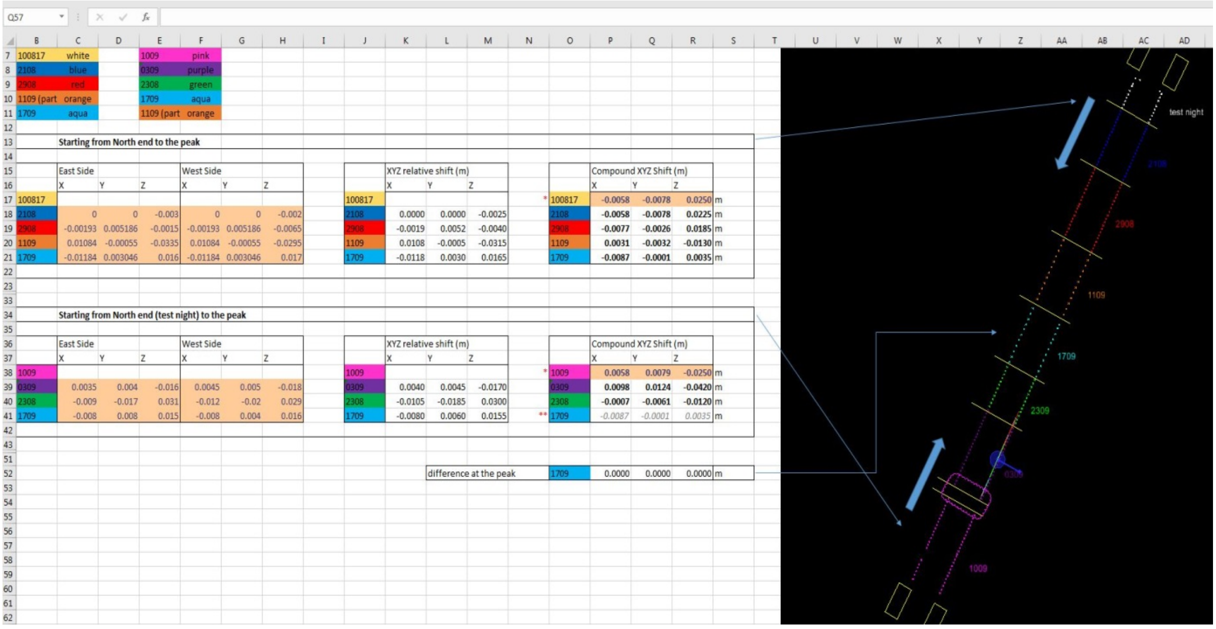
Figure 19: Trial adjustable scan platform.

Figure 20: Tripod leg attachment.

Figure 21: Scan target attachment.

- Total station location: The position of the total station used to coordinate the laser scan targets and take the QQ measurements between the chords, was initially proposed to be located centrally on the transverse walkways to allow a clear view of all scan targets. This was not possible on the north end as this position is not accessible. The other walkways were found to be unstable. To address this, the total station was positioned on the chords either uphill or downhill from the scan locations and did require several re-setups during each night. This had a small impact on the scan rates and also the capture of QQ points. As per the initial plan, the total station was coordinated by resection using visible pylon prisms, additional prisms placed on the bridge and survey control marks on the ground.
- Due to the amount of survey equipment necessary to take onto the bridge each night, all equipment (with the exception of laser scanners and total station) were stored in a locker room within the pylons overnight.
- Each night, equipment was taken onto the bridge and set up prior to the last scheduled train. Scanning was undertaken between approximately 12:30 am and 4:30 am while no trains were running.

- Walkway covering: Walkways at the top of the bridge have no steps installed and are instead covered with steel or fiberglass mesh and carpet to eliminate slips and provide safe walking of bridge climbers. These covers can only be temporarily removed overnight between Bridge Climb tours. After the initial scope was extended to cover the inner two thirds of the chord, the grated walkway covering at the top of the bridge became an issue as it significantly obstructs the rivets and structure below. Capture of these rivets will require the removal of steel or fibreglass mesh with carpet at a later stage and has been excluded from the current scanning/modelling scope until a feasible system for the capture can be developed.
- Painting equipment, scaffolding and existing AMUs: The existing AMUs and equipment related to painting caused minor obstructions to the laser scanning. This was addressed as much as possible on site. However, one of the existing AMUs was unable to be moved and has resulted in some data shadows. Some additional scanning may be required to capture the missing bridge detail – this could possibly be done when the walkway scanning is undertaken.
- Survey QQ points: Poor lighting and difficult access meant that it was not possible to accurately measure to the outside of the chord. As an alternative, check measurements were taken between the top centre of rivets on each side of the bridge and these coordinates used to evaluate the absolute and relative accuracy of the laser point cloud. Reflectorless observations proved to be problematic, due to insufficient light, so a mini-prism was used to measure to the top of the rivets.
- Bridge contraction and nightly adjustment: After several nights of laser scanning had been completed, it was discovered that there was a noticeable movement of the bridge structure over the course of each night due to the contraction of the steel. In short, this equated to a mostly vertical shift of up to 15 mm in the position of the bridge structure at the start of the night compared to the end of the night. This had some effect of the correctness of QQ shots taken if the observation time differed significantly to when the scanning was undertaken. The main impact was on the relative position of each consecutive night's scans. When fixing each end of the bridge and connecting each consecutive night's scans, it resulted in an approximately 60-70 mm height difference at the flag poles at the top of the arch. After consultation with Roads and Maritime, this was addressed by adjusting each night's absolute position slightly (Figure 22).
- During each night, there were often unscheduled train movements across the bridge. This required suspending operations until the train had passed. We understand that these movements were as a result of Sydney Trains repositioning empty trains around their network. These train movements had a small but noticeable impact on the laser scan rate.
- The southern pylon king post lift was not working for a portion of the project. This required the team to carry equipment across the bridge on some occasions. This also had an effect on the order that the scanning was undertaken in.
- Truck movements were found to have a noticeable effect on the bridge, with larger trucks causing the deck and structure to 'bounce' slightly. While these movements are unavoidable, we believe they had a small effect on the laser scan registrations, with the largest error vectors generally being in the Z direction.



100817	white	1009	pink
2108	blue	0309	purple
2908	red	2308	green
1109 (part	orange	1709	aqua
1709	aqua	1109 (part	orange

Starting from North end to the peak

	East Side			West Side				XYZ relative shift (m)				Compound XYZ Shift (m)			
	X	Y	Z	X	Y	Z		X	Y	Z		X	Y	Z	
100817							100817				* 100817	-0.0058	-0.0078	0.0250	m
2108	0	0	-0.003	0	0	-0.002	2108	0.0000	0.0000	-0.0025	2108	-0.0058	-0.0078	0.0225	m
2908	-0.00193	0.005186	-0.0015	-0.00193	0.005186	-0.0065	2908	-0.0019	0.0052	-0.0040	2908	-0.0077	-0.0026	0.0185	m
1109	0.01084	-0.00055	-0.0335	0.01084	-0.00055	-0.0295	1109	0.0108	-0.0005	-0.0315	1109	0.0031	-0.0032	-0.0130	m
1709	-0.01184	0.003046	0.016	-0.01184	0.003046	0.017	1709	-0.0118	0.0030	0.0165	1709	-0.0087	-0.0001	0.0035	m

Starting from North end (test night) to the peak

	East Side			West Side				XYZ relative shift (m)				Compound XYZ Shift (m)			
	X	Y	Z	X	Y	Z		X	Y	Z		X	Y	Z	
1009							1009				* 1009	0.0058	0.0079	-0.0250	m
0309	0.0035	0.004	-0.016	0.0045	0.005	-0.018	0309	0.0040	0.0045	-0.0170	0309	0.0098	0.0124	-0.0420	m
2308	-0.009	-0.017	0.031	-0.012	-0.02	0.029	2308	-0.0105	-0.0185	0.0300	2308	-0.0007	-0.0061	-0.0120	m
1709	-0.008	0.008	0.015	-0.008	0.004	0.016	1709	-0.0080	0.0060	0.0155	** 1709	-0.0087	-0.0001	0.0035	m

difference at the peak	1709	0.0000	0.0000	0.0000	m

Figure 22: Night vertical shifts.

5 DATA EXTRACTION AND MODELLING

Jacobs utilised Microstation Topodot software to undertake the 3D modelling exercise. Modelling was required of the following bridge elements:

- Arch edges.
- Changes in angle.
- Existing rail connection.
- Plate locations.
- Rivet locations.
- Hanger posts.
- Stringers.
- Hand rails.
- Cross-girders.
- Cable trays/conduits.
- Laterals.
- Other infrastructure.

The modelling involved extensive consultation with both Roads and Maritime and Design Company engaged and has gone through a significant number of modifications and variations. This section summarises the issues encountered and how they were addressed.

The initial proposal was to model the structures as a series of vectors as a wireframe. However, it became apparent that the design package Autodesk Inventor could not effectively use a wireframe and so modelling as complex 3D solids was required. Unlike a wireframe, where the edges can be vectorised relatively quickly, this significantly complicated the modelling process, effectively increasing the modelling time by approximately 25-30%.

It was requested that Jacobs model all rivets within the scope area as a 3D dome. This was a significant endeavour as there were approximately 40,000 rivets to be modelled. These were

modelled initially as a 2D circle placed perpendicular to each major bridge plate, which was then draped onto the surface of the plate to create the base of the dome and provide the axis/rotation for the dome (Figure 23).

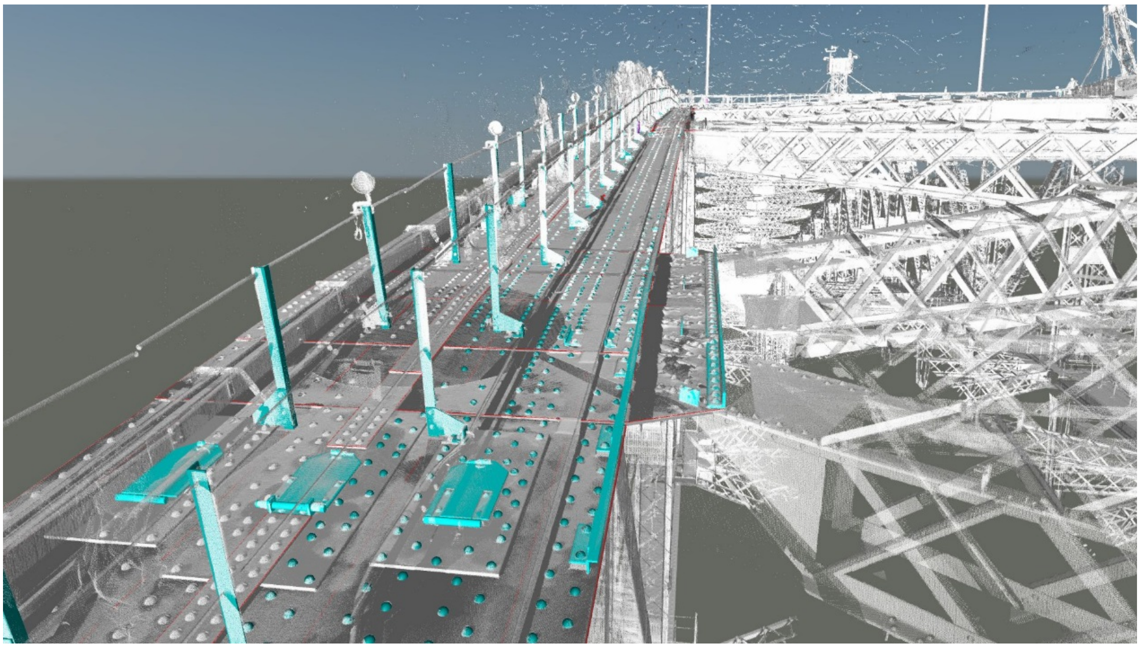


Figure 23: Solids modelling over point cloud.

There was an amount of shadowing from obstructions, particularly from the walkway step treads. If there was not enough cloud to accurately model the rivet, then an approximation was made as a best fit and moved to a secondary layer tagged with an uncertainty. The modelling and placement of rivets included development of a script to help automate the process.

Together with the additional modelling across the chord, there was a request to model one cross walkway in high detail (other elements/structures in this area were only modelled in low detail to ±50 mm), with the intention of highlighting what features and obstructions the new AMUs may have to navigate as they make their way up the bridge (Figure 24).

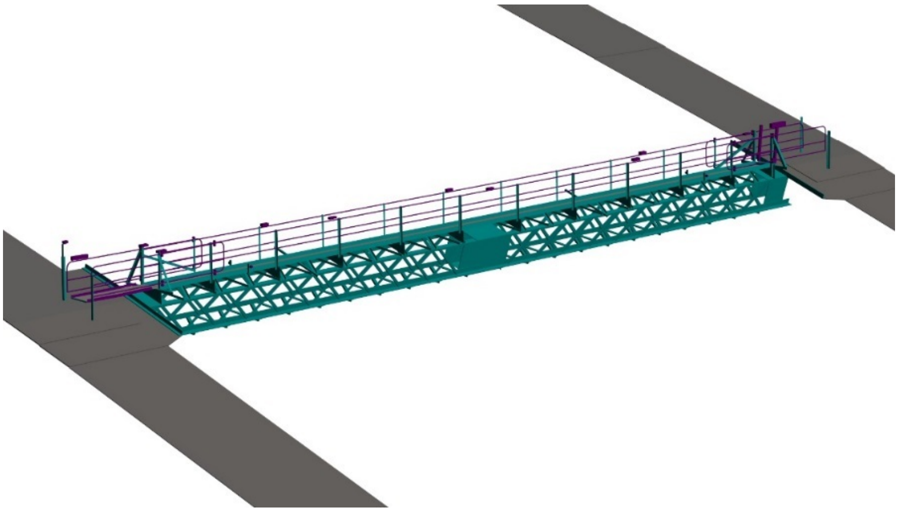


Figure 24: Detailed modelling of connecting walkway.

Element deformation: As the project progressed, it became evident that the bridge was far from uniform; in fact it showed a series of deformed and warped elements. This meant that the original methods of modelling that had a level of generalisation did not meet the accuracy requirements for the modelling, a much higher level of sampling was required than originally planned. In addition, it was requested that objects modelled be independently positioned and orientated, and a significant number of unique features were modelled. It was also noted that many of the edges in many of the plates were difficult to distinguish as their edges had been filled in, possibly to limit water pooling and further corrosion.

Coordinates: Jacobs modelled the bridge in plane (approximate MGA) coordinates as required by the project brief. The number of significant digits in the coordinates caused difficulties importing the model and displaying correctly in Inventor. It was found that Inventor could not display complex 3D surfaces in real-world coordinates. Despite spending many days trialling different formats and coordinate options for an import solution into Inventor, it was necessary to shift the model back to a 0,0,0 origin.

Data format: The original proposal intended to provide the extracted model in a DWG format. However, this did not import correctly into the design package (Inventor), despite being an Autodesk product. This required significant trial and error, and in conjunction with the coordinate issue there were issues with certain objects (e.g. complex 3D solids and extrusions) not converting with errors or not converting at all.

Additional data sources: Jacobs spent significant time investigating the existing plans to obtain a more complete understanding of the bridge elements than what was visible from the cloud only. This allowed more accurate interpretation of structure elements to be modelled than could be observed from the cloud alone and helped provide a more complete and accurate model.

Modelling of survey area 2 was simpler and required a lower accuracy, providing just the shapes of the main beams and excluding small lateral beams, with the intention of modelling to only show structures, which could potentially impede the clearance of the AMU or the painting module that will be deployed.

6 RESULTS

6.1 Monitoring Survey and Results

6.1.1 Monitoring Survey: Night

Relative horizontal and vertical movements were presented as differences from the initial observation recorded (XYZ) at time 00:35:53, along the bridge alignment and with *positive* directions for offset X-East, chainage Y-North and height Z-Up. Monitoring survey results and individual observations were presented in Excel spreadsheet tables and graphs.

The survey results indicate the magnitude of the movements is generally consistent and stable in both survey targets, at the western and eastern top arches. No significant changes in horizontal position and level were identified in both monitoring targets for the duration of the survey, except at one event at time 02:02:30. Times and descriptions of train passes were not recorded during this survey. It has been assumed that the sudden movement in both observed

targets for a short time was caused by an irregular train passing over the bridge. This event has caused a change of more than 10 mm in offset, chainage and level in the western target and a drop of more than 10 mm in offset only in the eastern target.

The survey results further indicate changes in the western and eastern top arches at the same time (Tables 1 & 2). It should be noted that the observations during the train event from 2:02:26 to 2:02:37 were excluded from the dataset.

Table 1: Western top arch movements (night).

Top Arch West	**Range** **From [mm]**	 **To [mm]**	**Average** **[mm]**
Offset X	-6	13	4
Chainage Y	-6	7	-1
Height Z	-13	10	-7

Table 2: Eastern top arch movements (night).

Top Arch East	**Range** **From [mm]**	 **To [mm]**	**Average** **[mm]**
Offset X	-6	8	0
Chainage Y	-5	5	0
Height Z	-9	8	-3

Analysis of the night-monitoring survey results indicates:

- Eastern top arch target being more stable than western top arch target. More noise was detected in the 3D position of the western top arch.
- Progressive drop in level in the *western* top arch target by the end of the survey to around 10 mm progressive increase in leaning towards the western direction to around 5 mm, and unchanged chainage.
- No significant change in the *eastern* top arch target, except a slight progressive drop in level to around 5 mm by the end of the survey.
- Maximum changes in 3D position identified in the eastern top arch have not been recorded during the train event, they have occurred at different times. These changes may have been caused by heavy trucks crossing the bridge. Details of road traffic were not recorded during survey.

6.1.2 Monitoring Survey: Day

Relative horizontal and vertical movements were presented as differences from the initial observation recorded (XYZ) at time 06:55:45, along the bridge alignment and with *positive* directions for offset X-East, chainage Y-North and height Z-Up.

Times and descriptions of train passes were not recorded during this survey. The relative movements of the two prisms correlate with the movement of trains over the bridge. The magnitude of the movements is generally consistent and repeatable.

The survey results indicate changes in western and eastern top arches at the same time (Tables 3 & 4).

Table 3: Western top arch movements (day).

Top Arch West	Range From [mm]	Range To [mm]	Average [mm]
Offset X	-31	9	1
Chainage Y	-13	13	0
Height Z	-40	6	-2

Table 4: Eastern top arch movements (day).

Top Arch East	Range From [mm]	Range To [mm]	Average [mm]
Offset X	-46	7	-6
Chainage Y	-10	15	0
Height Z	-6	24	5

Analysis of the day-monitoring survey results reveals:

- 64 'spikes' indicating change from the nominal position in both western and eastern top arch targets for the duration of the survey (over 132 minutes). These changes have been caused by single or multiple trains passing the bridge in each direction.
- There is a typical shape and magnitude of 3D movement in western and eastern top arch targets at the *same time*, as shown in Figures 25 & 26 (sample data shown are simultaneous observations taken at 1-second interval and over 70 seconds, from 6:57:58 to 6:59:08).

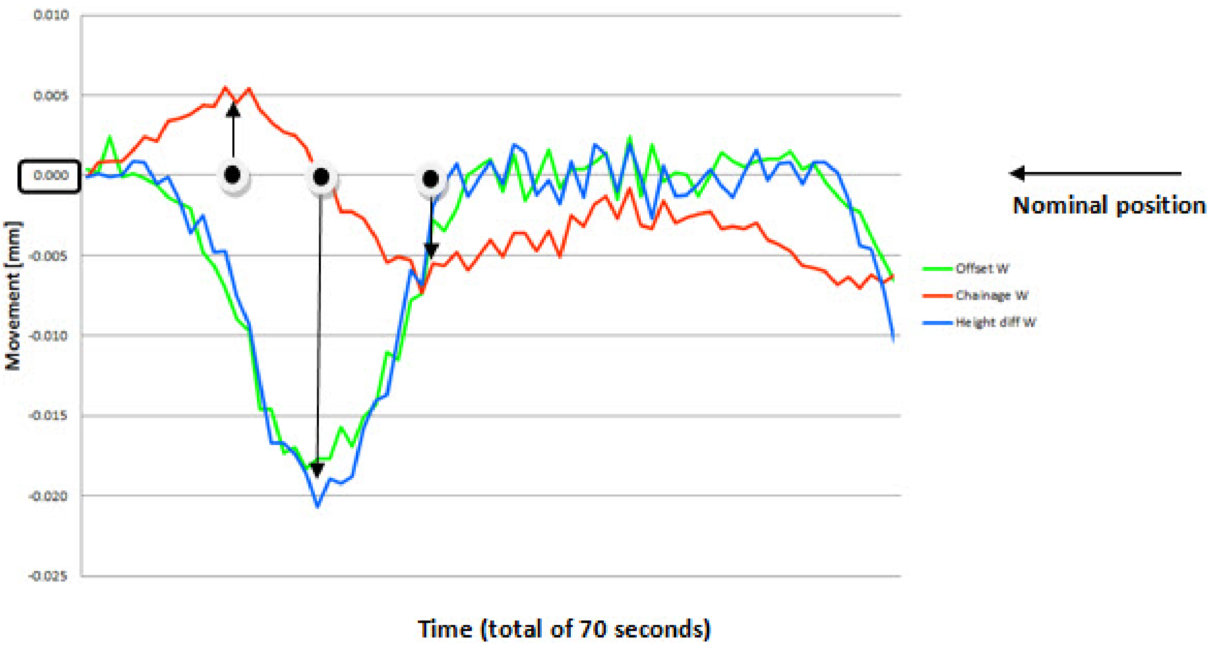


Figure 25: Typical 3D movement at SHB west top arch (observations at 1-second interval).

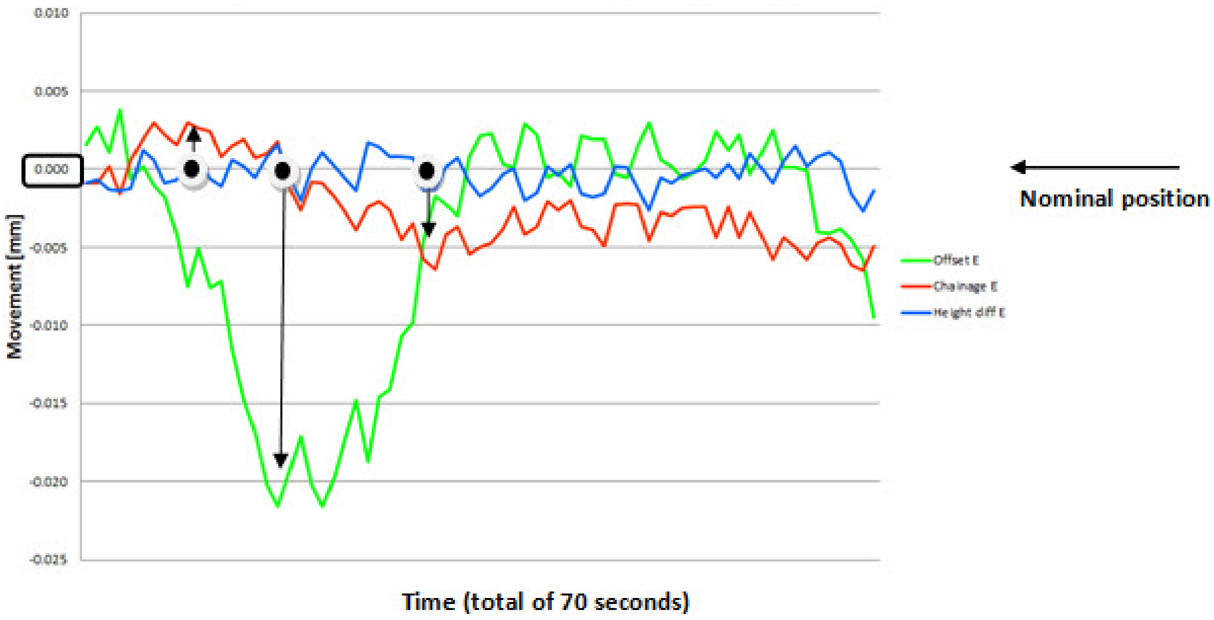


Figure 26: Typical 3D movement at SHB east top arch (observations at 1-second interval).

Generally, when trains reach the centre of the bridge, the western top arch leans towards the west and drops in level at a similar magnitude. Changes in chainage (up and then down) indicate that the western top of the arch moves in the northern direction and then the same distance in the southern direction, before it returns to its nominal position.

At the same time, the eastern top arch leans towards the west for a similar distance as the western top arch. The chainage follows the same shape of movements as the western top arch but for smaller distances. The levels are mostly unchanged.

Other general observations include:

- As of around 7:50 am, the *eastern* top arch gradually *rises in level* for up to 20 mm and stays *up* until the end of the survey, not returning to nominal zero.
- As of around 8:20 am, the *eastern* top arch moves in a *westerly* direction for up to 20 mm and stays in that position until the end of the survey.
- As of around 8:45 am, the *eastern* top arch moves in a *northerly* direction for up to 5 mm and stays in that position until the end of the survey.
- As of around 7:50 am, the *western* top arch moves slightly in an *easterly* direction but returns to its nominal position after around 25 minutes. As of 8:45 am, it moves in an *easterly* direction for up to 5 mm and stays in that position until the end of the survey.
- Chainages and levels of the *western* top arch generally return to their nominal positions after the train passes.
- An observation recorded by the Jacobs survey team is that truck movements had a noticeable effect on the bridge, with larger trucks causing the deck and structure to ‘bounce’ slightly. The largest impact would generally be in the Z-Up direction.

An analysis of relative differences between the eastern and western prisms are shown in Table 5, indicating the range and average values. Graphical representations can be found in Figures 27 & 28.

Table 5: Relative differences in east-west direction.

Relative Diff (east-west)	Range From [mm]	Range To [mm]	Average [mm]
Offset X	-25	7	-6
Chainage Y	-5	13	0
Height Z	-7	43	7

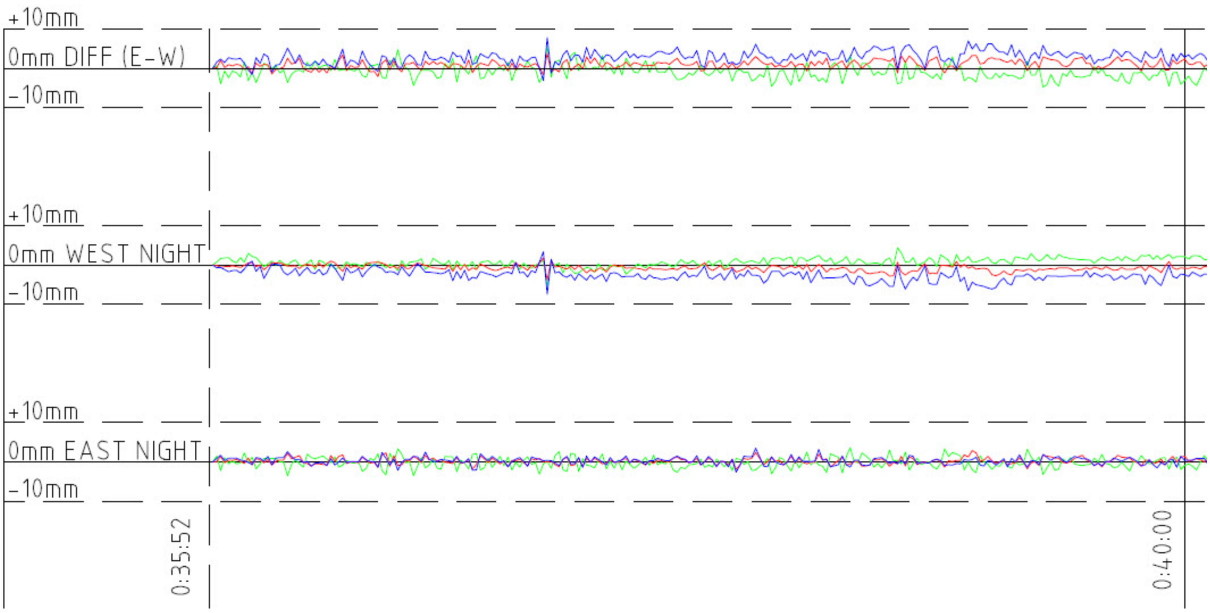


Figure 27: Sample graphical presentation of relative movements at night over an 8-minute interval, including legend.

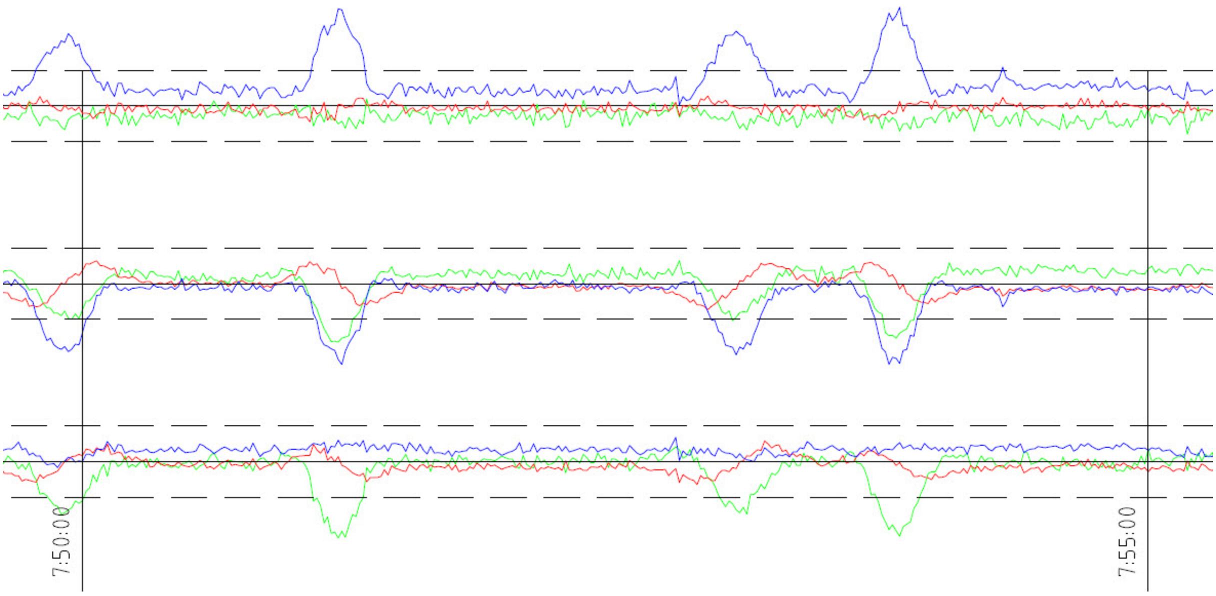


Figure 28: Sample graphical presentation of relative movements during the day survey over a 5-minutes interval.

6.2 Scan Results

Due to limitations of the total station setups and the movement of the bridge throughout the night, the most accurate and reliable source of QA for relative accuracy were the laser

scanning registration reports. These reports show the error vectors between the position calculated for each scan target in each separate scan and the target location calculated from the reflectorless total station measurements. This provided an excellent comparison to multiple targets that were taken at the same time as the laser scanning, which compensated for the bridge movement due to temperature and also localised movement from vehicles on the bridge.

Results indicate that it was more reliable to measure reflectorless to the centre of the scan target than it was to take a mini-prism shot to the rivet heads. So while the rivets are a valuable, fully independent check on the scan accuracy, the registration results themselves more correctly show the relative accuracy between scans and provide independence through redundancy. It should be noted, as mentioned earlier, that it was very difficult to see and measure to the inside chord flange. Furthermore, it was not physically possible to reach out and measure the chord-flange edge with the mini-prism as it was outside arm's reach.

With each scan having the same eight targets as the opposite scan and six overlapping targets as each adjacent scan, this provided a large number of constraints and points for comparison. The point cloud adjustment software, Cyclone, created a best-fit position using all of these constraints to give the scans an absolute position fix. The registration report compares these position coordinates for every scan.

Each registration report has hundreds of constraints, as summarised below (some targets were occasionally excluded, generally due to distance or obstruction):

- Night 1: Mean absolute error: for enabled constraints = 0.003 m (615 constraints).
- Night 2: Mean absolute error: for enabled constraints = 0.002 m (931 constraints).
- Night 4: Mean absolute error: for enabled constraints = 0.002 m (804 constraints).
- Night 5: Mean absolute error: for enabled constraints = 0.003 m (1,251 constraints).
- Night 6: Mean absolute error: for enabled constraints = 0.003 m (1,181 constraints).
- Night 7: Mean absolute error: for enabled constraints = 0.002 m (1,479 constraints).
- Night 8: Mean absolute error: for enabled constraints = 0.003 m (674 constraints).
- Night 9: Mean absolute error: for enabled constraints = 0.002 m (491 constraints).
- Night 10: Mean absolute error: for enabled constraints = 0.002 m (201 constraints) (lower chord ±50 mm requirement).
- Night 3/4: Mean absolute error for enabled constraints = 0.003 m (747 constraints), for disabled constraints = 0.010 m (80 constraints).

While the laser scan registration provides an excellent metric of the relative scan accuracy, independent total station readings were also taken to provide a check on the absolute accuracy and additional checks on the relative scan positions. Due to the low lighting, it was not feasible to take reliable reflectorless shots to the inside edge of the chord beam and it was also not generally possible to have total station setups on both sides of the bridge within a single night to capture inter-chord measurements.

Due to these factors, QA shots were taken to the top of the rivets using a mini-prism, which was then compared to the comparable point within the registered point cloud (Figure 29). For the inter-chord comparisons, the distance in the point cloud between rivets at approximately the same position on each side of the bridge was compared to the total station measurements. In order to check the height more accurately, extra shots were taken to the face of the chord.

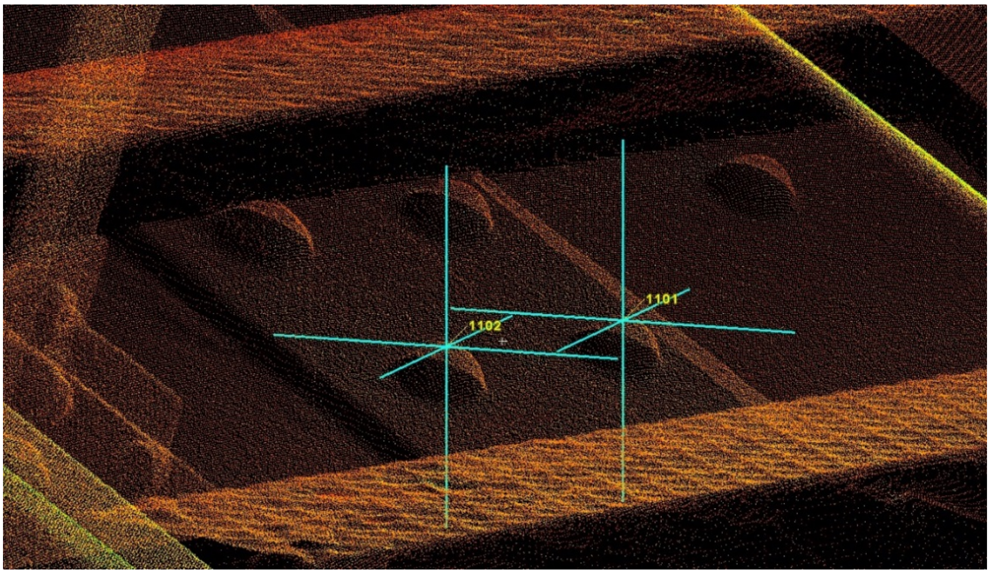


Figure 29: QA – Rivet location.

The results show that the scanning meets the 3 mm (1 sigma) relative requirements for the project (Figure 30).

		INTER-CHORD DISTANCE CHECKS - RIVET TO RIVET										
DIST CTRL						DIST CLOUD						Δ dist
334585.1	6252995	70.669				334555.2	6253002	73.214				
334555.2	6253002	73.21		30.8349		334585.1	6252995	70.6696		30.8336		-0.001
334574.7	6252974	79.668				334548	6252987	79.6716				
334548	6252987	79.669		29.877		334574.7	6252974	79.6703		29.8769		-0.001
334542.2	6252976	85.402				334542.2	6252976	85.401				
334568.2	6252961	85.861		29.676		334568.2	6252961	85.8634		29.6748		-0.001
334531.9	6252955	95.642				334531.9	6252955	95.644				
334558.9	6252943	95.096		29.624		334558.9	6252943	95.0996		29.6244		0.000
334472.8	6252835	131.043				334472.8	6252835	131.044				
334501.4	6252827	130.477		29.809		334501.4	6252827	130.4792		29.8078		-0.001
334425.3	6252742	129.702				334425.3	6252742	129.7007				
334453	6252731	129.975		29.817		334453	6252731	129.9767		29.8174		0.001
334419.8	6252731	127.836				334419.8	6252731	127.8329				
334447.4	6252718	127.909		30.290		334447.4	6252718	127.9082		30.2898		-0.001
334411.1	6252713	124.232				334411.1	6252713	124.2276				
334438.6	6252701	124.455		30.169		334438.6	6252701	124.4524		30.1680		-0.001
334343.8	6252579	70.132				334343.8	6252579	70.1335				
334369.1	6252563	69.189		29.704		334369	6252563	69.1916		29.7039		0.000

Figure 30: Inter-chord distance checks.

7 CONCLUDING REMARKS

Roads and Maritime has engaged with a private-industry specialist partner to deliver this challenging project. Working in collaboration with Roads and Maritime, a set of procedures were established fulfilling the requirements of the G73 Specification, which may be applied to future projects.

The high-precision 3D CADD model produced as part of this project will enable design, manufacture and installation of two AMUs at the Sydney Harbour Bridge. This will increase

the efficiency and provide safety benefits for Roads and Maritime when undertaking routine maintenance activities on the bridge.

The high-precision 3D CADD model may also be used for other asset maintenance activities, including development of a Building Information Model (BIM), logging completed and planned activities. The accurate and comprehensive point cloud data captured for this project may be used for further investigation of bridge attributes as required in the future.

The ability to use this dataset as a source for future 'data mining' should be emphasised, recognising that data captured now may later be used for data extraction of additional features as required by Roads and Maritime and other stakeholders, i.e. 'capture once, use many times'.

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DISCLAIMER

The views, opinions, considerations and conclusions expressed in this paper are strictly those of the authors and do not necessarily reflect the views of Roads and Maritime Services.

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