Applications of LiDAR for Productivity Improvement on Construction Projects: Case Studies from Active Sites

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Abstract -

The McKinsey Global Institute's digitisation index ranks construction amongst the least digitised sectors globally. This translates to a relatively slow rate of labour-productivity growth which, according to McKinsey, costs the global economy US$1.6 trillion per year. One area ripe for improvement is validation of final components on construction sites. This is a critical step in the quality assurance process, but also one that consumes significant resources when performed manually. Digitisation, using reality capture technology, can enable rapid component analysis through automation. However, traditional survey tools, which focus on individual points or fixed locations, tend to provide limited coverage, are difficult to operate and hard to interpret. More recently, developments in Light Detection and Ranging (LiDAR) has enabled rapid digital representation of geometry. The resulting point clouds can then be processed using modern computing techniques, including the proprietary BuiltView platform used here, to perform automatic checks that are faster and more accurate than manual measurement and achieve greater coverage than traditional surveying technologies. As the technology develops to become cheaper and more readily available, potential on-site applications should be fully explored. To improve the understanding of options, applications and productivity benefits, we present case studies performed on active construction sites in which an aspect of the built environment was scanned with LiDAR and the data analysed to estimate value accretion for the builder. In floor flatness analysis and site visualisation we demonstrate results that are prohibitively difficult to perform manually. In LiDAR-based precast scanning and formwork analysis we show promise for detecting defects before they cause delays and costs further down the value chain. We present the context and methodology for each case study, along with the benefits and difficulties encountered with LiDAR use. Finally, we calculate the approximate value added compared with traditional approaches to quantify the relative merit of point cloud data. Findings from our case studies suggest LiDAR has the potential to significantly improve construction productivity, quality of works, documentation and client engagement.

Keywords -

LiDAR; Construction; Productivity; Case studies

1 Introduction

Due to a variety of factors including underinvestment in digitisation and innovation, the construction industry is losing $1.6 trillion globally each year [1]. As project and site complexities increase, the industry can leverage technological advancements to increase productivity through automation and quality improvements. In this study, we focus on one such technology - Light Detection and Ranging, or LiDAR - and investigate its potential for adoption through the BuiltView platform to complete a variety of tasks on active sites. LiDAR, like that shown in Figure 1 is commonly used by surveyors to take accurate measurements of spaces, particularly where traditional manual measurement is prohibitively difficult or slow.

Figure 1. Survey grade tripod LiDAR scanning piles during excavation works.

Here we present case studies of five applications of LiDAR that were conducted to address issues site engineers were facing during a particular phase of construction, with a high-level overview of the technical approach taken in each case.

Our main objective for each case study is to estimate the potential for productivity, financial o r r isk management improvements provided by the LiDAR application.

2 Background

The construction industry is worth roughly US$10 trillion (2017), accounting for roughly 13% of world GDP. According to the McKinsey Global Institute [1], this number could grow by US$1.6 trillion if productivity enhancements, such as digitisation and advanced automation, were more widespread. These productivity improvements can come from a variety of sources, including additive manufacturing [2], increase prefabrication [3], or by automating progress monitoring [4, 5] inspection [6] or as-built modelling [7], to name a few.

One of the major issues facing construction is the cost of rework, defined as "activities in the field that have to be done more than once, or activities which remove work previously installed as part of the project" [8]. A 6-year study of nearly 20,000 rework events across 346 projects concluded that the mean yearly profit reduction was 28%[9]. As much as 52% of total cost growth is due to rework, which also increases schedule overrun by 22%[10, 8]. As such, any preventative methods to reduce rework, for instance by increasing quality checks [11, 12, 13], have the potential to drive considerable productivity improvements.

Technological advancements in laser scanning using Light Detection and Ranging (LiDAR) have enabled several notable high-accuracy inspection processes with the potential for automation, primarily focused on 3D model reconstruction and geometric quality inspection [12]. LiDAR produces an output commonly referred to as a "point cloud", which is a collection of thousands to millions of positions in 3D space representing solid matter and derived from high accuracy distance measurements from the sensor. A lot of work has gone into converting these point clouds into Building Information Models (BIMs) which are more common in the industry and easier to work with. This can take the form of generating as-built models of site [14, 15] or precast units [7], quickly generating models of existing structures for heritage, renovation or integration purposes [16], or updating progress through comparison with 4D BIM [4].

Another common use for point clouds is high-fidelity quality inspection. In some cases, this involves directly measuring particular built elements like railway power lines [6] or concrete rebar positions [13]. Another case is floor flatness measurement, typically performed using manual straightedge methods which can be automated with tripod-based LiDAR or aerial scanning [17]. Laser scanning is capable of great accuracy, with some scanners detecting 1mm flatness defects from 20m away [18].

Recent advances in algorithm development have enabled a trend towards mobile LiDAR, which enables rapid surveying, whether handheld [16, 14], vehicle-mounted [6] or aerial [19, 20]. With handheld LiDAR, for example, a single operator can scan entire floors of buildings in a few minutes using a backpack-sized device. Similar scanning using static (tripod mounted) equipment can take hours. The downside however, is mobile LiDAR lacks the accuracy of static sensors. The need for programmatic stitching, and a proclivity towards cheaper laser scanners, means handheld sensors typically achieve 5-30mm accuracy, depending on the object being scanned [14]. Despite this impediment, mobile LiDAR has several site applications due to its ease of use. For example, colourised mobile LiDAR enables rapid detailed capture of site conditions which can be used for communication or documentation purposes [21].

Our study employed a combination of mobile and static LiDAR, while also varying static LiDAR between high density (1M points per scan) and low density (1K points per scan) capture.

2.1 Sites

This study was undertaken on a number of active construction sites operated by Laing O'Rourke in various stages of development which have different contexts and priorities.

Project 1 was a newly developed Health Precinct consisting of an 8-story building. The building comprised mainly teaching and learning areas including lecture theatres, labs, hospital simulation studios, X-Ray and CT rooms and other work spaces.

Project 2 was a 10 story building composed mainly of engineering laboratories. This was further complicated by revitalisation and integration with an existing engineering building which was still largely operational for classes and research.

Project 3, located in Western Australia's Pilbara region, required replacement of 7 active railway bridges with precast concrete culverts. The project complexities included high desert temperatures over 40°C and short time windows to replace each bridge to ensure the rail line remained operational.

Finally, Project 4 was not a construction site but rather a Design for Manufacture and Assembly (DfMA) facility in London, England, operated by Laing O'Rourke which produces high-volume and bespoke components for sites around the country. For quality assurance purposes, laser scanning is used to validate precast components and formwork. However, technical constraints limit the rate at which such analyses can be performed, so automation can add significant value.

3 Methodology

In this section we provide an overview of our five case studies, the data capture and method used, and processed data visualisations.

Throughout these case studies, we utilise the BuiltView platform for data capture and processing. BuiltView is a software platform developed in house which comprises robust data handling methods and innovative point cloud handling tools. The technical details of this platform are out of scope for this report.

3.1 Precast verification

As described in Section 2.1, Project 3 involved assembling a railway bridge using large precast concrete culverts. Due to the site conditions and time constraints, there was interest in verification of the culverts before attempting assembly. Of particular interest were any twists in the uprights which would affect the fit of adjoining culverts.

To enable the analysis, site engineers scanned two precast culverts using static LiDAR, compiling scans from multiple directions into one point cloud shown in Figure 2. The point clouds were then split into individual culverts and registered to their respective design models by performing optimised alignment using the Iterative Closest Point (ICP) algorithm.

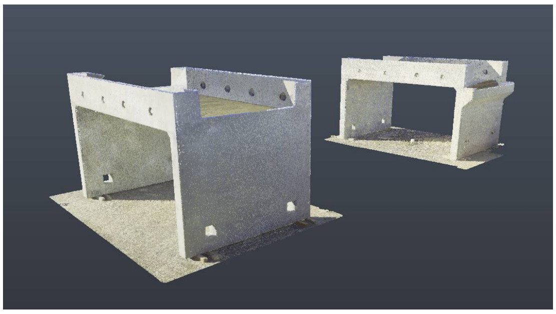


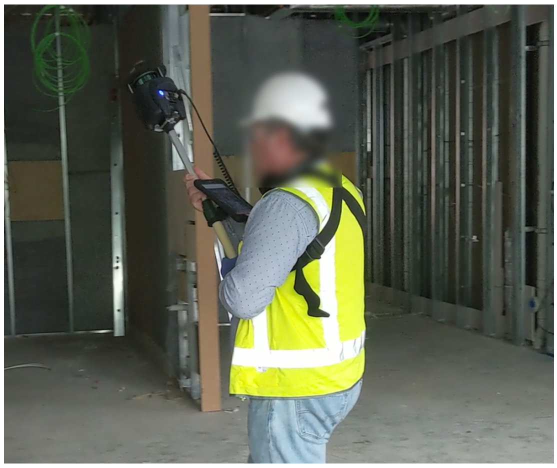
Figure 2. Point cloud scans of precast culverts at Project 3. The culverts are approximately 4m tall.

After the scan was aligned with the design model, a pointwise distance metric was computed by finding the distance between each point in the scan and the nearest point on the model. This metric allowed identification of specific points that were significantly deviated from design, in addition to geometric differences like scale and twist. For improved understanding, we displayed this information as a heatmap by projecting the distance metric of each point on a colour scale from blue to red.

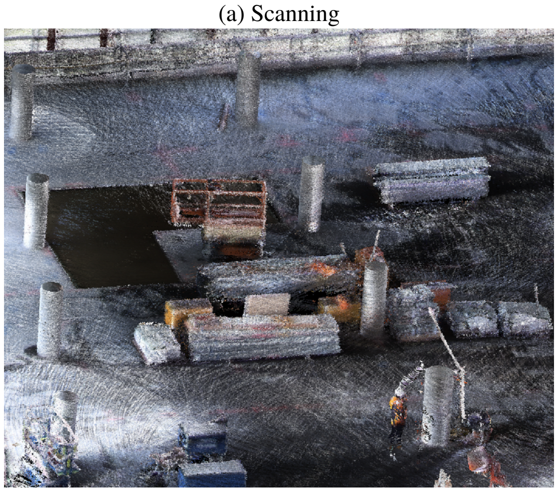
3.2 Floor flatness

At Project 1, site engineers requested an analysis of floor flatness on several levels of the building. Due to changeover of subcontractors, a short timeframe was required, as any defects discovered after several weeks would cause program delays. Consequently, manual checking was infeasible, and LiDAR was trialled as a potential solution.

In previous collaborations with Project 1, we found static LiDAR scanning prohibitively slow. This was primarily due to increased processing (registration) time, caused by internal walls that limited the visibility from individual locations. Knowing this, we opted to use a handheld mobile LiDAR for this capture - a Paracosm PX-80, shown in Figure 3 - that enabled rapid scanning of the building.



(a) Scanning



(b) Raw scan output

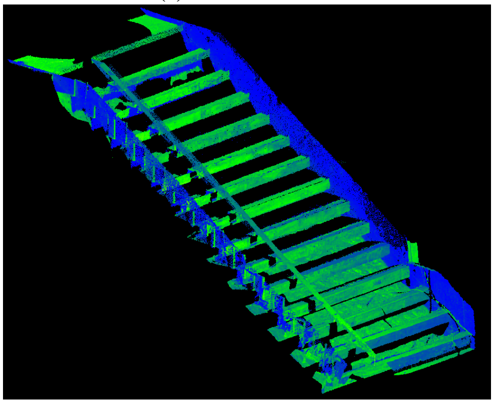
Figure 3. Capture process and output from Paracosm PX-80 handheld LiDAR scan.

When processing the data, we considered registering the point cloud to the BIM to compare points with their exact location on the ground plane. However, this approach would demonstrate global deviation (the entire slab being slightly too low or high), when the desired insight for flooring compliance was relative deviation. Therefore, we extracted the points representing the ground from the raw point cloud data and computed a best-fit plane. We then computed the point-to-plane distance from each point to this best fit plane and displayed this data using a heat map visualisation.

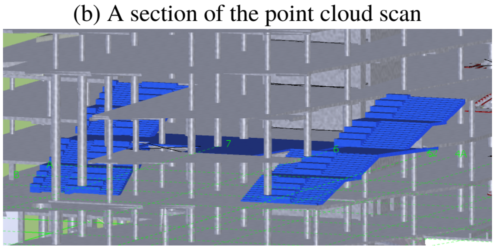
3.3 Formwork

Prevention is always preferable to reparation on site, as rework is costly in both time and money. With this being the case, we investigated the possibility of validating concrete pours at the formwork stage rather than after the pour as in the other case studies. Also taking place on Project 1, this case related to a set of multilevel staircases undergoing rework due to an error in the original design. Due to this context, we had an opportunity to scan the formwork of the stairs before the pour, and compare it to a correct BIM as well as an incorrect BIM to investigate preventative analysis.

(a) Scanner on site



(b) A section of the point cloud scan



(c) Building Information Model

Figure 4. Context of staircase formwork at Project 1. Four sensor locations captured using a Leica BLK360 were registered to generate a scan which was then compared to the BIM shown.

We scanned the formwork using a Leica BLK360 static LiDAR as shown in Figure 4. Since a static LiDAR was used, occlusion was a significant concern so we scanned the formwork at several positions along the staircase and then registered the scans using common points. We then aligned the completed scan to the BIM, using the inner faces of the formwork to align to the outer faces of the concrete model. This process was repeated for the correct and incorrect model, at which point computing the shortest distance metric allowed us to analyse the formwork scan to determine if it was correctly built.

3.4 Reinforcement scanning

Correct placement of rebar in concrete is critical to the long-term survival of the construction project. Inspecting the size, number and spacing of rebar can be difficult and time-consuming. Enabling easier inspections is of particular interest at Project 4's manufacturing facility, where components are prepared for use on construction sites. Furthermore, there is value and interest in having detailed information about the internal structure of a slab for future works including penetrations and proof of completion to specifications in the case of disputes.

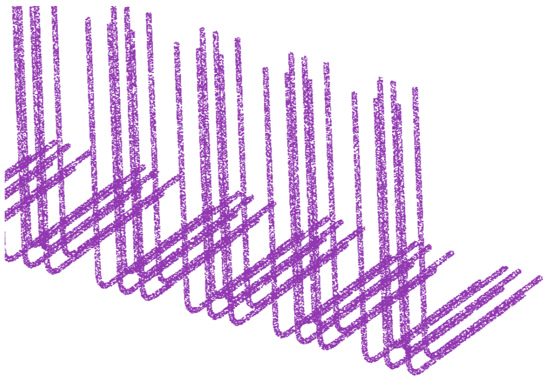


Figure 5. LiDAR scan of rebar at Project 4

By scanning the reinforcement before the concrete is poured, the structure can be inspected digitally using the point cloud and future works can be performed using a 3D map of the internal structure of the component. Rebar is difficult to scan with LiDAR due to the reflective properties of the steel, so the scanner used by Project 4 is a low-density high-accuracy scanner which captures point clouds in the order of thousands of points rather than millions. An example of this scan is shown in Figure 5.

Our primary aims in this case were identifying bars by diameter and detecting relative spacing between bars. To achieve both aims, we perform cylinder fitting on the point clouds. This generates a collection of 3D shapes from which the diameter and spacing can be derived.

3.5 Visualisation and Documentation

Documentation and communication between parties involved can be difficult, particularly between agents in different industries. Project 4 faced challenges in this domain communicating a planning error with the client relating to shared access to a teaching lab which was intended to be used while construction was being undertaken. The issue faced was caused by a design element whose size dictated an overlap into the teaching space which would cause logistical issues, but communicating and proving this using 2D resources proved difficult. By using LiDAR to capture the contested space in 3D, dimensions and clashes could be made more visible and easier to communicate.

Again, we used the Leica BLK360 static LiDAR to create a highly detailed colourised scan of the space. Use of this LiDAR also allowed capture of panoramic photography during scanning which could also be used for visualisation. Due to the cluttered nature of the scene caused by internal walls and furniture, many scans were required to generate a clear and complete scan of the area. All individual scans were then registered together using shared points and vision targets to create a cohesive scan, which was then further registered to the building model to allow the scan and model to be overlaid to demonstrate any clashes.

4 Results

4.1 Precast verification

We validated precast components on Project 3 using nearest-point heatmap analysis, comparing the point cloud scans as built to the design model. An example of the result for this analysis is shown in Figure 6.

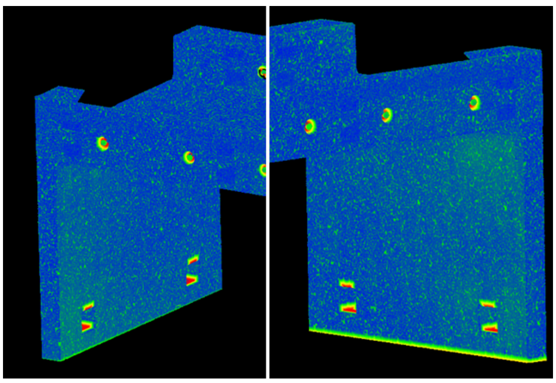


Figure 6. Heatmap analysis of Project 3's precast culverts. Colour scale represents distance from each point to the design model, from blue at 0mm to red at 100mm.

In general, the distances measured are blue, implying little difference between the scan and the model. However, the green gradients towards particular corners of the culvert imply a subtle twist in the uprights which are designed to be planar, which was a very useful insight for the site team as it is a difficult thing to measure manually but could cause gaps between installed culverts which could have flow-on effects. The other features of note were the interfacing holes at the bottom of the uprights. The red points around these reveal that they are not in the correct location, rather they are approximately 11cm out of place vertically.

There is good potential here for process improvements here, specifically in the area of risk mitigation. The LiDAR scan can analyse the entire culvert at once, and potential catch geometrical deformations that a human inspector would not notice. Project 3 required many of these culverts to be cast, so early detection of any issues would prevent inordinate amounts of rework.

4.2 Floor flatness

Our results for floor flatness analysis are similarly presented in heatmap form, though the distances in this case are computed as normal distance to an artificial plane. The results for one floor are shown in Figure 7. Around the starting position of the scan, circular "ridges" in the point cloud can be seen which likely are artefacts caused by the initialisation procedure of the mobile sensor and can be safely ignored. The rest of the scan shows minor variations in the height of the floor, where green points are level with the computed best-fit plane, blue points are lower and red points are higher. The pattern of points shows areas which are of concern, in particular near the edges of the scan where some areas demonstrate a rapid shift from green to red. Besides gradient changes, the other area of interest is local inconsistencies which could cause problems for flooring, and small red and blue areas can be seen in the scan which also merit manual inspection.

Another consideration here is that the operator was able to scan 5 floors in only a few hours, despite significant internal occlusions.

As mentioned, the floor flatness inspection at Project 1 took place before a changeover of subcontractors. Typically, the surveyors used have a turnaround time of approximately 2 weeks, which would delay the identification of faults until after the relevant workforce had vacated the site. These sorts of delays to rectification works can easily cause cost increases of 5 to 10 times, due to the additional logistics of bringing back subcontractors to perform the works. Rapid detection of issues would enable the project to keep the relevant workforce in place and siginificantly reduce the cost of rectification.

4.3 Formwork

Analysis of the Project 1 formwork is a slightly different case, since the object of interest is the concrete

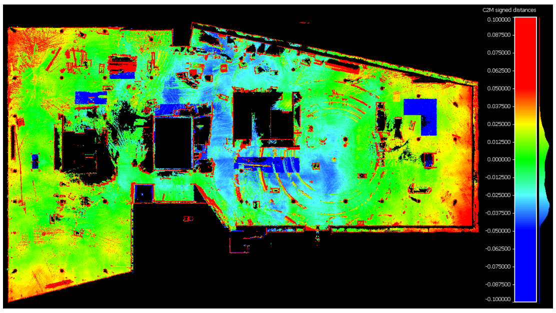


Figure 7. Point-to-plane distance heatmap analysis for the floor slab of a single level of Project 1.

pour which does not yet exist, so the analysis has to be of the shapes surrounding it. As mentioned earlier, we performed a heatmap analysis after aligning the inner faces of the formwork structure with the outer faces of the correct and incorrect building models, then compared the results. This comparison can be seen in Figure 8.

The result for the incorrect model demonstrates some notable characteristics. Several steps are mostly blue and green, representing the part of the scan which has aligned best to the model. However, further along the scan the shortest distances get higher, with significantly more orange and red points visible.

The result for the correct model, however, is far more uniform, with most steps an even blend of blue and green. In this context, the green points represent the sections of formwork which are not close to the final concrete product, while the blue points represent the faces which will directly contact the concrete.

Comparing the two, it is easy to distinguish a correct model from an incorrect model when measured against the as-built formwork, implying the possibility of a method to assess the correctness of formwork prior to the pour and enabling pre-emptive rectification works.

This could potentially reduce costly rework. In particular, this case involved a demolishing and reconstructing a four-story concrete staircase due to design errors. The rework required to complete this took several weeks, increasing both budget and schedule blowout. Through formwork assessment, many situations like this can be avoided.

4.4 Reinforcement scanning

Due to the difficulty in scanning steel rebar and the low-density scanner used, the cylinder fitting must be able to distinguish between individual bars in the point cloud. Figure 9 shows a section of the rebar scan with each point assigned a unique colour according to the cylinder to which it was fit.

The resulting colours demonstrate that the analysis is able to correctly distinguish between the bars using cylinder fitting. The derived cylinders also have specific geometric properties which can be used to analyse the rebar as needed. Firstly, each cylinder has a diameter, which is important during inspection since certain numbers of bars need to be installed to fulfil design specifications. Furthermore, since the cylinders are roughly parallel, the distance between them can be derived, which is another important consideration for as-built verification.

Errors in reinforcement and a lack of asbuilt information can significantly affect project risk, from increased danger during slab penetrations to short- or long-term deterioration of structural components. At Project 4, one engineer with expensive LiDAR equipment is able to inspect 5-10 elements before casting per day on the manufacturing line, which is approximately 10% of the project throughput. By automating the data processing and limiting manual activities to data capture, this productivity can be easily improved by 2 to 5 times, enabling a much higher coverage rate and significantly reducing risk.

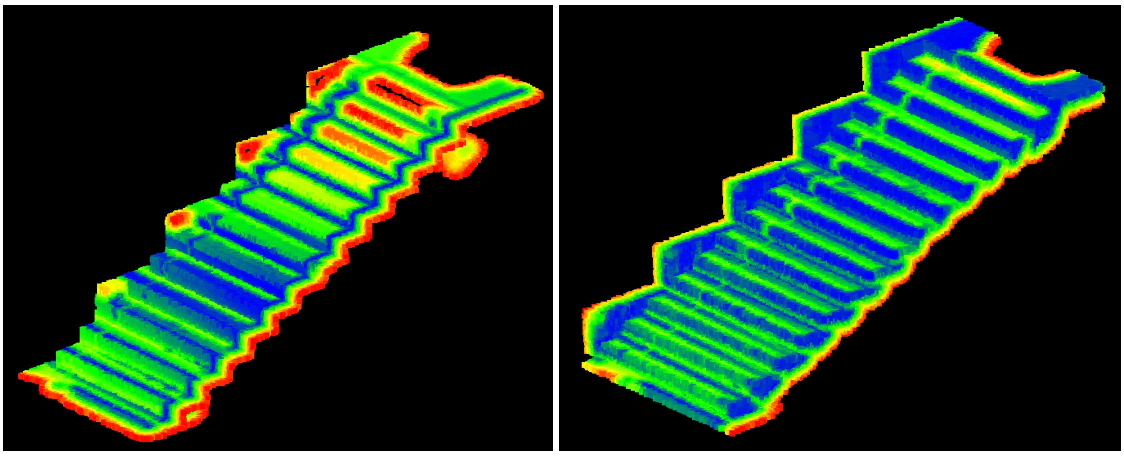
4.5 Visualisation and Documentation

A high-density visualisation of the contested space on Project 2 was completed using colourised LiDAR scans. A snapshot of the results is presented in Figure 10.

The visualisation allowed for better communication with the client since two dimensional plans can be harder to understand for people outside construction, and furthermore the scan is correctly scaled such that the building model can be overlaid to illustrate conflicts. Improvements in communications can have signficant effects on productivity and avoiding rework by ensuring a cohesive understanding of the works to be undertaken. In this case specifically, the improved ability to convey information ensured that the project did not impact, and was not impacted by, client operations in the same space. This avoided damaging relationships with stakeholders as well as preventing rework due to a misunderstanding.

5 Discussion and Future Work

The case studies presented here represented just a few use cases for LiDAR on construction sites. Even with the scanning infrastructure used here, many more applications could be implemented. For example, the floor scans of Project 1 were used for floor flatness analysis, but the data captured also included construction equipment which could be used to infer utilisation, service installations which could update progress, and incomplete elements which could be analysed for impending clashes. The adoption of scanning as a frequent operation in the industry would enable more value-add propositions in this vein, though several considerations are involved.



(a) Incorrect BIM (b) Correct BIM

Figure 8. Heatmaps for the same point cloud compared to two different versions of the BIM. The first version was revised due to stair spacing and the scanned formwork was built to the specifications of the second.

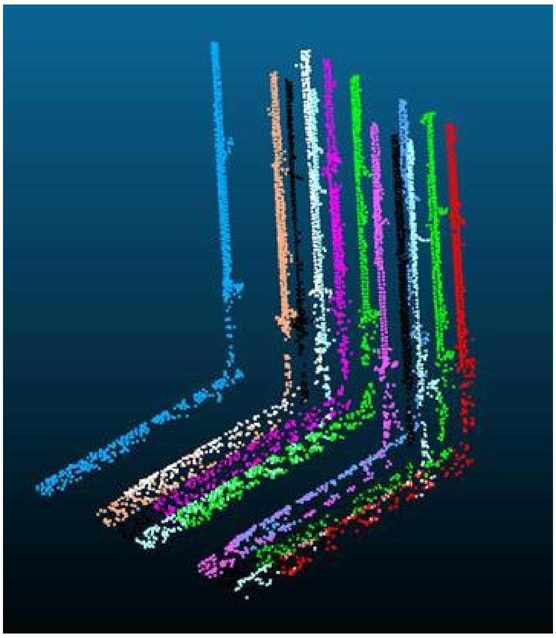


Figure 9. Analysis of rebar using LiDAR scans. Each bar has been identified as separate using cylinder fitting.

Static LiDAR is currently used commonly in surveying but requires significant processing and trained operators. Furthermore, scanning can take a long time when features like internal walls are involved and causing occlusions. The rise of mobile LiDAR enable scanning of large-scale infrastructure projects (using vehicle-mounted scanners), scanning of difficult-to-reach areas (using aerial LiDAR) and rapid scanning for applications requiring frequent updates (using handheld LiDAR). Many handheld sensors are also very simple to use, requiring minimal training or processing time. However, the accuracy of mobile LiDAR is not as good as that of static scanners, due to error introduced by motion. Because of this, the application of the different technologies depends on tolerance requirements and liability. Operations like progress updates, communication and visualisation can easily be performed using mobile scanners, while small-tolerance deviation analysis requires more accurate static ones.

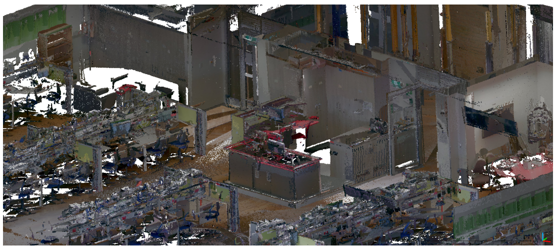


Figure 10: Snapshot of visualisation of contested space at Project 2

A major advantage of the processes presented here is the potential for significant automation. If sensors can be operated autonomously, as is already the case with certain aerial or robotic scanners[20], certain aspects of processing may also be automated. This can enable high quality inspection and verification works with far less human intervention and allow the industry to operate with more confidence than it currently does with less effort.

There is also a push in the construction industry for greater progressive documentation of the build. Such documentation can be helpful for future works on completed sites, and also reduce difficulties during conflict resolution. LiDAR is a powerful way to capture this data, since the results are relatively simple to collate and analyse and contain high quality measurements of all surfaces. Whereas traditional point-and-line survey can verify locations of key components, LiDAR measures the entire visible area, so defects or deformations are more likely to be discovered early.

6 Conclusion

In this study we have presented several applications of LiDAR on active construction sites to provide value using relatively simple algorithmic techniques and user-friendly outputs. As the technology develops and becomes more usable and affordable, we hope to see widespread adoption to help the industry close the digitisation and productivity gap which is currently in evidence.

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