VISION-BASED DIMENSIONAL INSPECTION OF FREEWAY BRIDGE BLOCKS

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ABSTRACT

It is nowadays common for elevated roads (mostly freeways) in Japan to be constructed of steel. The construction process employed is similar to that in bridge building where hollow box sections of about 2-3m width and height, and up to 20m in length, here called 'bridge blocks', are prefabricated and literally bolted together. Each block is attached to its adjoining sections via a hundred or more bolts, and correct alignment is therefore critical to ensure a sufficiently accurate fit-up operation. This paper discusses the development of a digital close-range photogrammetric procedure for the accurate dimensional inspection and verification of bridge blocks. The inspection task is reasonably complex as it involves measurements of surface details, size, critical shape parameters and bolt hole positions. The latter of these are required to a relative positional accuracy of 0.1mm, and there is a need for the digital photogrammetric system to be very fast as the QC time budget for each manufactured block is only 30 minutes. General requirements to be met by the measurement system are described, and different sensor system configurations (off-line, real-time, a combination of both) and targeting strategies are discussed. The results of an experimental measurement, which demonstrated the operational feasibility and accuracy of digital photogrammetric techniques for bridge block inspection, are also reported.

1. INTRODUCTION

Elevated freeways built of steel rather than reinforced concrete are becoming an increasingly common sight in Japan. The same is also true to some extent for road and rail bridges. The assembly of such structures using bolted-together prefabricated hollow box sections calls for very tight dimensional tolerances in the manufacturing process. Shown in Figure 1 is an example of such a hollow box section, or 'bridge block', employed in elevated freeway construction. This particular section is about 14m long, and 2m in width and height. Also shown in the figure are some 100 or more bolt holes by which sections are joined into place at the time of erection. It goes without saying that should these bolt holes not line up, either due to localised errors in hole position or through errors in the shape and size of the overall bridge block, then problems will be encountered in the final construction phase. The dimensional tolerances imposed are tight, being around 1mm for the overall dimensions of the block and 0.1mm for the relative positions of the bolt holes within the areas of a join.

The question of how to best perform a final dimensional quality control inspection of bridge blocks at the point of manufacture is the topic of this paper. Hollow box

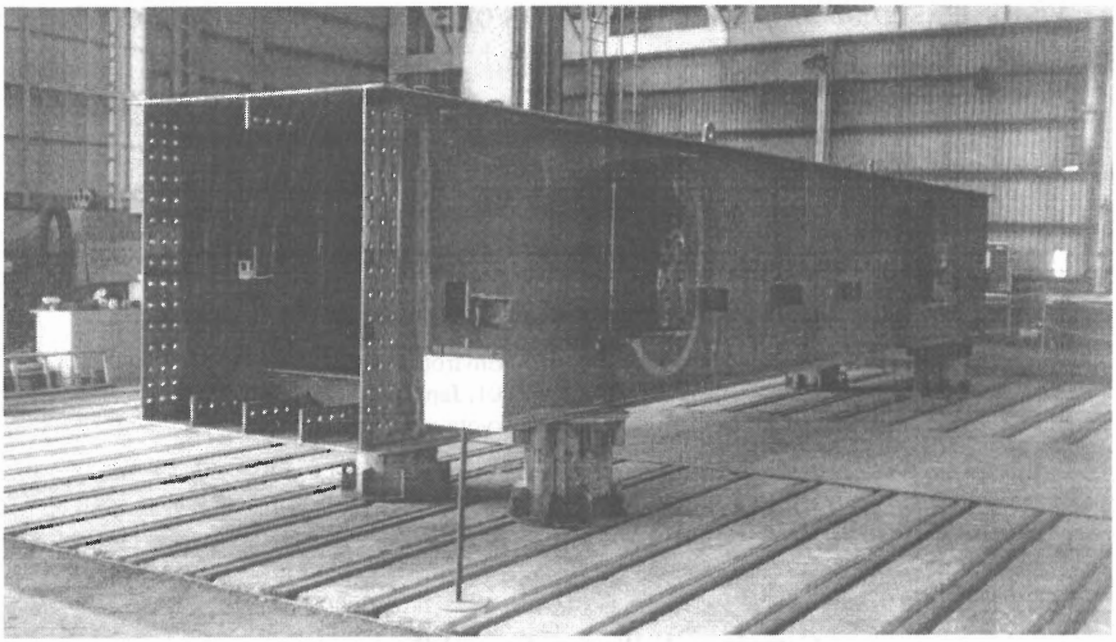

Figure 1: Sample hollow box section or 'bridge block'.

sections of the type shown in Figure 1 take about three days to weld together in an assembly-line environment, with inspection via optical techniques being used throughout the manufacturing process. This inspection concentrates more on alignment than on 3D shape characteristics, however, and the verification of the critical dimensions is left to a final inspection which has thus far principally involved measurement by a surveying total station. Yet this procedure is both labour intensive and slow, consuming considerably more time than the desired inspection period of 30 minutes. It also yields less dimensional data than is desired. In their ongoing endeavours to find a more efficient dimensional inspection technique, the maker of the bridge blocks, the Yokohama Engineering Works of Ishikawajima-Harima Heavy Industries Co. (IHI), turned to digital photogrammetry.

At first sight, digital close-range photogrammetry offers considerable potential for the bridge block inspection task. Modern vision metrology (VM) systems based on large-area CCD cameras with PC-based data processing are portable, accurate, flexible, fast and can be fully automated (e.g. Fraser, 1997). Moreover, the technology has been well proven as a dimensional inspection tool for large scale manufacturing (e.g. Beyer, 1995; Brown & Dold, 1995). Upon closer examination, however, it can be seen that the bridge block inspection does not lend itself well to a simple measurement solution. Points to be inspected comprise both readily targetable features such as bolt holes and join-points, and edge, corner and surface details which are not readily signalised with artificial targets. Moreover, the required measurement accuracies are non-homogenous, being modest (1mm) for the overall shape and size, and quite stringent (0.1mm) for bolt-hole centres.

In this paper we will discuss the possible scenarios for photogrammetric inspection of bridge blocks of the type shown in Figure 1, and describe a preliminary experiment which has been carried out to verify the utility and accuracy of the VM approach.

2. MEASUREMENT REQUIREMENTS AND INSPECTION APPROACHES

Stated in very general terms, the requirements of the dimensional inspection are straightforward: the 3D coordinates a hundred or so points, principally on the ends and sides of the bridge block, are required to be measured to one of two accuracy tolerances in a period of 30 minutes or less. Unfortunately, the 'measurement devil' is always in the detail. While much of the VM measurement of the overall dimensions and shape of the block can be achieved via 'standard' artificial targeting (e.g. stick-on retro-reflective targets), the same is not true of both the bolt holes and certain critical points on the structure. While an artificial targeting strategy is of course feasible, one can appreciate that, especially for the bolt holes, measurement without targets would be preferable. Fortunately, only about 10% of bolt holes, so-called pilot holes, need to be measured.

2.1 Off-Line VM

Both off-line and real-time VM system configurations could be employed for the inspection task, though accompanying the advantages of each are conspicuous disadvantages. In the case of a single-sensor off-line system a network of say 20 or so camera stations distributed around the block (assuming adequate clearance) would be sufficient to enable fast measurement of targeted feature points to an accuracy well exceeding the 1mm requirement. Indeed, if automatic measurement was adopted through the use of an exterior orientation (EO) device and coded targets, a time budget of even 15 minutes would be feasible. Unfortunately, when we consider the much higher accuracy sought for structural detail at the join surfaces (i.e. the ends and connection areas of the sides, both with pilot holes) a more involved imaging configuration coupled with specialised targeting is called for. The off-line single-sensor VM approach is then a less attractive though still feasible option when it comes to inspecting such detail.

2.2 Real-Time VM

Application of a two-camera, real-time VM measurement approach for the end and join areas of the bridge blocks has a lot of appeal. A special touch probe fitting could be employed to allow targetless measurement of bolt hole centres, whereas a normal probe could be used for detail described, for example, by the intersection of two scribe lines. The accuracy requirement of 0.1mm is also quite achievable in localised areas. The drawback of the real-time approach, however, comes with the requirement to measure the complete block structure, since this would necessitate a number of interconnected measurement set-ups around the bridge block – effectively a closed loop of sub-networks.

2.3 Combined Off-Line and Real-Time VM

In the foregoing paragraphs we have inferred that a stand-alone, real-time VM approach does not offer a feasible solution to the bridge block inspection problem, especially from the point of view of measurement time and complexity (the need for many sub-networks). Moreover, we have suggested that an off-line, single-sensor VM approach will only be optimal if the issue of specialised targeting is accommodated in a practical way, which is indeed quite feasible. There is, however, a further VM measurement option which combines the benefits of both the off-line and real-time approaches.

Shown in Figure 2 is a 'basic' 14 station convergent imaging configuration for an off-line survey of the shape

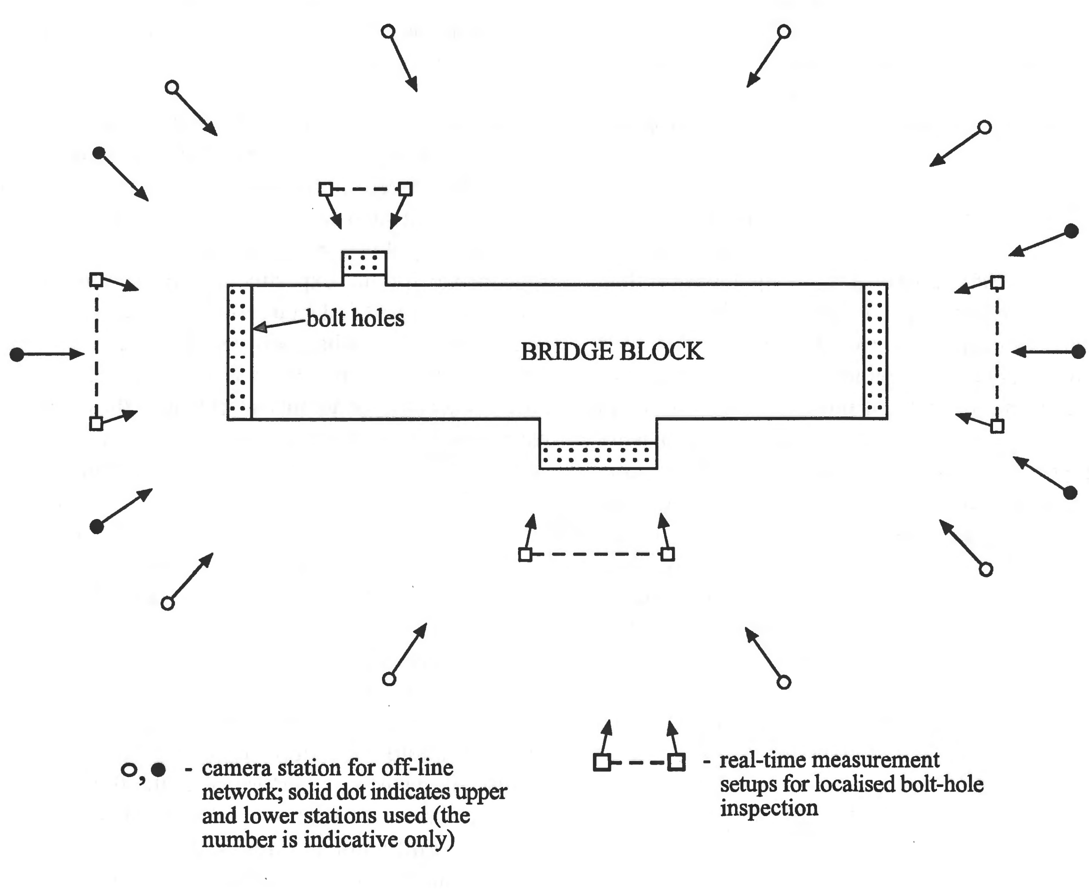

Figure 2: Indicative imaging geometry for a combined off-line and real-time VM inspection.

and dimensional characteristics of a bridge block. Very approximately, stand-off distances of between 5m and 10m are envisaged with the camera being a large-area CCD sensor (e.g. 1.5K x 1K, or 3K x 2K array) and the lens being in the vicinity of 20-30mm, depending on array size. This generates an average imaging scale of somewhere in the range of 1:300 to 1:400, which leads to an accuracy of triangulation (via self-calibrating bundle adjustment) in object space of about 0.1mm, under the assumption that image coordinates are measured to 3% of a pixel (say 0.3μm). Also illustrated in the figure are four two-camera, real-time measurement set-ups for the join areas at the ends and sides of the hollow box section. The exterior orientation of these measurement set-ups would be provided by targets previously measured in the off-line VM network. Indeed, this could be achieved automatically if coded targets where to be employed. Touch probe measurements would then be made, at an effective maximum rate of one every few seconds, to feature points such as pilot holes and scribe-line intersections.

The measurement scenario involving a combined off-line and real-time approach is very appealing from the point of view of flexibility. From the standpoint of time, the combined approach is clearly much faster than a solely real-time VM measurement solution of interconnected sub-networks, but it does not display conspicuous speed advantages when compared to the off-line approach. Indeed, if the time taken to apply targets is discounted, the combined approach will likely be slower than the off-line VM measurement, especially if a fully automated system is employed.

In terms of accuracy, the real-time measurement networks offer the potential of higher localised precision (say 1:50,000 or about 0.05mm over a 2.5m square area) than the basic 14 station off-line configuration illustrated in Figure 2. This advantage, however, could be lessened quite easily by enhancing the geometry of the off-line VM network, through the addition of more camera stations in the end areas, for example. A minimal time penalty would be incurred under the assumption of a fully automatic measurement. To appreciate the speed of automated VM operation, let us assume that the full network comprises about 150 targeted points. With an operation time of 15 minutes for an automated single-sensor VM system, an effective rate of measurement of one point every six seconds is approached.

At the present stage of the investigation into the applicability of VM for the dimensional inspection of freeway bridge blocks, we have not comprehensively analysed which is the better of the off-line or combined measurement approaches. This is because more than simple photogrammetric issues are involved (e.g. the practicability and economy of specialised targeting has yet to be evaluated in any detail). It is also conceivable that given the range of bridge block shapes (note the distinctions between Figures 1, 2 and 3), the off-line approach might be better suited to the more basic shapes (e.g. Figures 3), whereas the combined approach might prove optimal for complex block shapes (as indicated, for example, in Figure 2). The question of just how many pilot holes need to be inspected will also be a factor in choosing between the two measurement scenarios. The fewer the number of pilot holes, the more favourable the off-line approach becomes. Numbers as low as 20 pilot holes are under consideration.

3. EXPERIMENTAL TESTING

What has been achieved to date, beyond verification of the accuracy potential of off-line VM using test fields, is a successful experimental measurement of the 8m-long bridge block shown in Figure 3. An object point field comprising 126 targets was used to represent a routine dimensional inspection requirement, even though in an actual survey more edge features and bolt holes would be measured. The camera chosen for the experiment was an unmodified Kodak DCS460 still-video camera with a 20mm lens. The 'unmodified' aspect is important, since the measurement was performed in full recognition of the fact that the unstable interior orientation of the DCS460 would significantly degrade the accuracy as compared to that obtained using this model of camera with a stabilised CCD chip mounting. Such a 'luxury' was unfortunately not afforded in this case.

As can be seen from Figure 3, most of the retro-reflective targets, both stick-ons and especially machined targets for bolt holes, faced horizontally outwards. The network geometry indicated in Figure 2, in which all camera axes are basically horizontal, would thus have been quite appropriate for the experimental measurement had there not been 12 bolt-hole targets which faced vertically up and down. The white arrows in Figure 3 indicate two such targets, there being six at each end of the block. In order to accommodate measurement of these points, albeit with only 3 rays per point, three additional stations were added at each of the two end areas. With reference to Figure 2, at each of the six positions indicated by solid black dots both a 'high' (2.5m above floor level) and a 'low' (floor level) image were recorded. This brought the total number of images in the network to 20.

As has been mentioned, with automatic off-line VM operation modest changes in the number of images do not have a significant bearing on the data processing time. Thus, it could be safely assumed that the experiment could well have been performed in the time required with either 20 or 40 images had a fully automated process been adopted. Full automation was, however, not available in this instance, so in order to optimise the image mensuration and data processing time with the AUSTRALIS software system (Edmundson & Fraser, 1998) used in the experiment, the number of camera

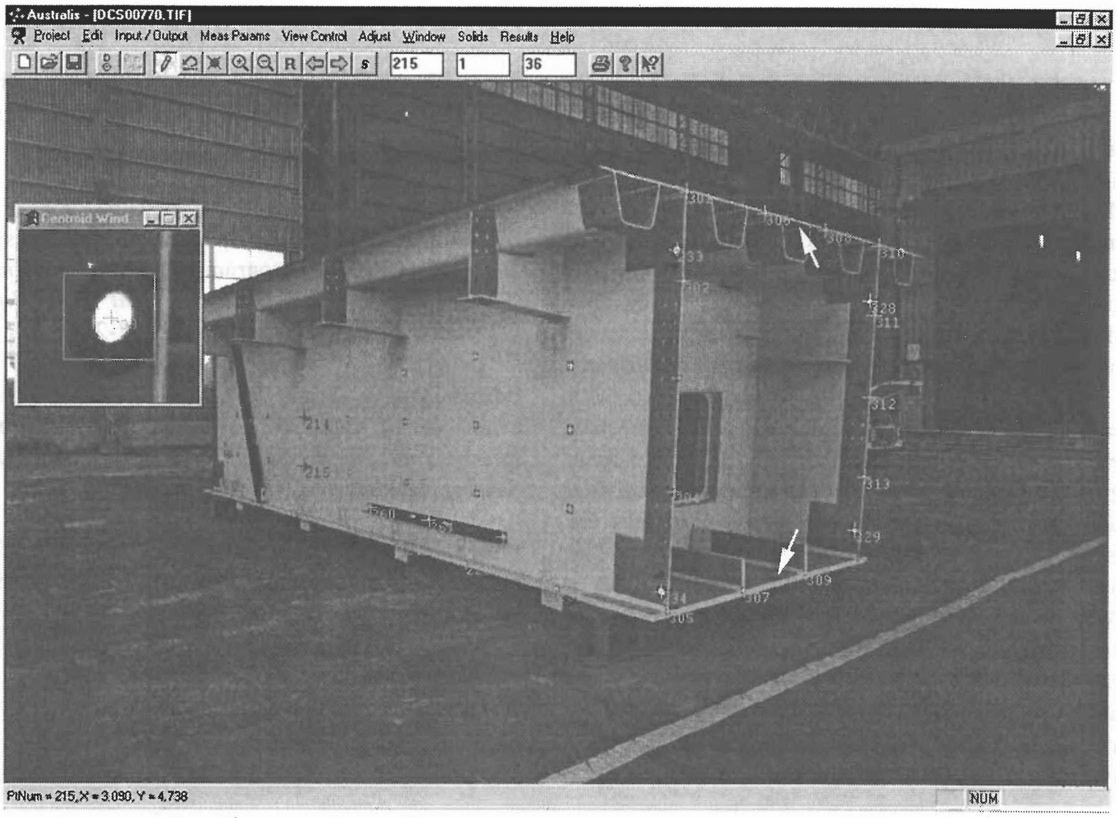

Figure 3: Bridge block used in test inspection, shown in the AUSTRALIS image measurement environment.

stations was confined to twenty. The aim remained to try to achieve a complete measurement in close to the desired time allocation of 30 minutes.

The only redundant object space control information available was scale bar data, which facilitated post-checking of distance measurements. Preliminary XYZ coordinate values (obtainable from CAD) were provided which facilitated rapid image mensuration through resection driveback. This preliminary coordinate information also effectively defined the datum of the free-network bundle adjustment (via inner constraints) employed in AUSTRALIS.

As regards time, the images were acquired in about 10 minutes, and it was possible to measure the complete network using AUSTRALIS in a further 25 minutes. This indicated that the desired inspection duration of 30 minutes would certainly be achievable with an automatic off-line system such as the V-STARS/M system from Leica/Geodetic Services, Inc. (Brown & Dold, 1995) since the time budget was almost met with the AUSTRALIS system. Again under the assumption of full automation, with say 10-15 minutes for the off-line measurement, the combined approach could possibly yield the desired measurement times but only in instances where the localised real-time networks could be restricted to few in number (e.g. 2 or 3).

As far as accuracy was concerned, the DCS460 behaved as predicted, namely producing an RMS value of image coordinate residuals of 0.6 μm, whereas with a stable interior orientation a figure closer to 0.25 μm would be expected given the good quality of the imagery and targets. This then effectively degraded the 0.1mm accuracy anticipated for object point triangulation to close to 0.2mm. Given the influence of the unstable interior orientation, however, we were reluctant to subject the network to too much scrutiny as far as accuracy was concerned. Suffice it to say that the accuracy was acceptable but not optimal. Distance discrepancies on two scale bars were in the order of 0.05mm, though it was apparent that some localised distortions in the network of greater than 0.5 mm were also present. The accuracy potential of a DCS420/AUSTRALIS combination had been verified in earlier experiments at IHI which had utilised calibrated test fields, and which had yielded relative accuracies to better than 1:100,000. The focus of the reported test measurement was thus placed on evaluating overall operational aspects against the requirements set down by the engineers at IHI. In this context the experiment was judged to be successful.

4. OUTLOOK

At this writing the investigation of the applicability of digital close-range photogrammetry for the dimensional inspection of freeway bridge blocks at IHI is continuing. The findings to date have confirmed the applicability of the VM approach in general, and particularly highlighted the benefits (and shortcomings) of both the off-line approach and a strategy which combines both off-line and real-time measurement. It is our view that in the next stage of the investigation an evaluation of the specialised targeting requirements needs to be more comprehensively carried out. The outcome of this work, coupled with consideration of the number of pilot holes to be inspected, will then provide information which will have quite some bearing on the decision as to whether to adopt an off-line VM measurement strategy, or one which combines the benefits of off-line and real-time measurement. The combined scenario can of course be achieved with a single VM system. The adoption of the combined, multi-camera approach over the single-sensor, off-line procedure does at the present time have significant cost implications so there is an understandable preference by IHI for a single-sensor solution if one can be achieved that meets all operational requirements.

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