AN OMNIDIRECTIONAL IMAGING SYSTEM FOR THE REVERSE ENGINEERING OF INDUSTRIAL FACILITIES

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ABSTRACT:

Digital photogrammetry continues to evolve from specialist applications such as topographic mapping and is rapidly emerging as a highly accessible method for capturing geometric data. A range of general-purpose softcopy photogrammetric systems are now widely available to end users who are thus able to exploit images captured from an increasing number of high-resolution non-metric digital cameras. In parallel with these developments an increasing diversity of range-imaging systems are being developed to facilitate the rapid acquisition of geometric data. To date these devices do not offer the resolution, portability or speed afforded by digital cameras, however this paper anticipates the development of hybrid range and intensity imaging systems. Through the extension of such systems to facilitate the acquisition of omnidirectional imagery the paper seeks to demonstrate the utility of such data in the rapid documentation of complex objects. The paper will demonstrate the development and exploitation of omnidirectional digital photogrammetry and range imaging systems to enable the creation and exploitation of massive image databases of large industrial objects such as process-plants, offshore oil platforms or power stations. Furthermore the paper will demonstrate the extent to which computer vision based analyses of such databases can, in turn, permit precise yet cost-effective documentation of a wide range of industrial facilities.

1. INTRODUCTION - MOTIVATIONS FOR AS-BUILT MODELLING OF INDUSTRIAL PLANT

Industrial facilities are often very dynamic environments in which new or improved equipment items are constantly being incorporated in order to improve efficiency, increase safety or reduce emissions. Costs associated with loss-of-production during planned maintenance are invariably very important to plant owner-operators and thus it is vital that any refurbishment is carefully planned to minimise unanticipated expenditure or loss of production revenue. It is essential that during such operations there is a 'first-time-fit' of new equipment with the existing structures and that such installations are 'clash-free' i.e. they do not physically conflict with new or existing plant items.
Plant design or modification is now routinely planned using 3D Computer Aided Design tools that enable the creation of a coherent 3D plant database in which the various design disciplines can share both geometric and attribute data relating to their specialisations. It has been suggested that maintaining such CAD models throughout the life of the plant would result in significant downstream benefits to facility managers who would be able to maintain the database to reflect the current operating status of the plant. Unfortunately design models are only rarely maintained after commissioning of the plant and often only drawings derived from the plant database are archived. This is, in part, due to the cost of upgrading design models to their true As-Built status. Frequently it is not possible to predict prior to commissioning which areas of a plant are likely to require the very detailed dimensioning to support subsequent modifications and, in most cases, a full three-dimensional survey of a facility is prohibitively expensive. Thus in many cases local As-Built surveys are undertaken for each plant modification in order to accurately document the interfaces between new and exiting plant. Informed by more than ten years commercial activity in this sector the authors believe that the deployment of appropriate omni-directional imaging systems enables the cost effective acquisition of massive image achives that document the as-built status of very complex industrial environments.
Thus a number of strategies have been developed to exploit these archives to facilitate the creation of As-Built CAD models with the principle objectives of:

- Reverse engineering CAD models of existing structures;
- Exploiting these models to ensure first-time fit, clash free, of new equipment; and hence
- Reduction of time spent on site

2. IMAGE-BASED AS-BUILT REPRESENTATIONS OF INDUSTRIAL ENVIRONMENTS

Complete automation of the transformation of either primary or secondary survey data into CAD based representation a has long been a goal of a large community of engineers, mathematicians and computer scientists. However, the size and complexity of the geometric models required to fully document dense, complex process plant environments poses real challenges to the Photogrammetric and Computer Vision communities seeking to automate scene description from image data.

In the mid 1990's several authors (e.g. Debevec, 1996) questioned whether there were classes of applications that might benefit from an alternative of Imaged Based Rendering (IBR) approach to scene representation. This activities were directed towards the rendering of interactive views of an object directly from image data bypassing, or at least minimising, the requirement for any geometric model of the scene. (Figure 1).

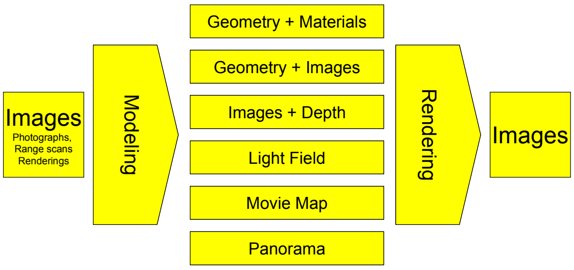

Figure 1. Image based rendering – from images to images, after Debevec, 1999.

Representation	Movement	Geometry	Lighting
Geometry + Materials	Continuous	Global	Dynamic
Geometry + Images	Continuous	Global	Fixed
Images + Depth	Continuous	Local	Fixed
Light Fields	Continuous	None	Fixed
Movie Map	Discrete	None	Fixed
Panorama	None	None	Fixed

Table 1. A classification of of image based rendering strategies. Adapted from Debevec, (1999).

Much of this activity, was stimulated by innovative work implemented by Apple in there QuickTime VR implementation of environment maps (Chen, 1995) configured as either inward looking 'Object Movies' or outward looking Panoramic Images that can be linked together via 'hot spots'. A major limitation of panorama based implementations is that the choice of viewpoints is limited to the projective centres of the input images and thus it is not possible to roam at will in, or around the scene. Whilst several light field rendering strategies have been proposed that allow interpolation between discrete samples of the full Plenoptic light field (c.f. Levoy & Hanrahan 1996, McMillan & Bishop 1995) clearly, in the absence of any geometrical description, the more densely images acquired the greater the sense of realism that is achievable by such techniques. In some circumstances it is possible to acquire very dense stereo panoramic intensity images of an environment that are sufficient to give a real sense of location and place (e.g. Shum and He, 1999).

Ideally we would wish to exploit panoramic range images to complement image archives to extend and enhance the current state-of-the art. In order to achieve this we require a compact panoramic range-imaging sensor.
Ideally this sensor would be capable of:

- flexible deployment as detailed in section 1.
- delivery of a calibrated gigapixel panoramic colour image
- accurate (better than +/- 2mm) ranging associated with each pixel
- capturing a panorama sufficiently quickly (less than 2 minutes) that the sensor can be deployed throughout the facility at spacings less than those in current HAZMAP deployments (i.e. less than 1m centres in X,Y and Z).

The authors remain convinced that such a sensor will be developed in the next 2-5 years, however in the absence of such a we show how such data may be included into an existing omni-directional image based rendering systems to deliver enhanced performance in as-built modelling.

3. OMNIDIRECTIONAL IMAGING TECHNIQUES FOR IMAGE-BASED RENDERING AND MODELLING

Many applications would benefit from a high resolution wide area image coverage to facilitate the cration of panoramic image archives and consequently a number of imaging configurations have been developed. (summarised in the table below). As can be seen from the table none of these configurations totally satisfy the conflicting requirements of high resolution, high speed and very wide angle coverage at a 'reasonable' cost.

Sensor Configuration	Wide FOV	High Resolution	Dynamic imaging	Geometric Stability	Typical cost	Example
Single camera with fish-eye lens	M	M	L	H	M	
Single camera with catadioptric Lens	H	L	H	M	L	
Camera on Pan/Tilt Unit	H	M	L	M	M	
Rotating line scan camera	H	H	L	H	H	
Multiple camera array	H	M	M	H	H	

Table 2. Categorisation of omnidirectional imaging systems

In our application we require very high resolution images captured within a robust geometrical framework. This led to the development of a a Video-theodolite based omnidirectional imaging system.
Images are acquired using a robotic video-theodolite system based upon a Spectra Precision motorised theodolite. A camera module attached to the theodolite enables the acquisition of either monochrome or colour images via a IEEE 1394, firewire, connection to thecontrolling PC. Each image is 'tagged' with the azimuth and altitude angle of the theodolite at the time of capture. The theodolite is driven in scan pattern enabling a panoramic mosaic of up to 150 individual images to be captured at each theodolite location (or station).

Calibration of the camera with respect to the telescope axis is done on site using the method proposed by Huang (Huang & Harley, 1990) and with the adjustment of these observations being undertaken as a conventional bundle adjustment. New camera technologies allow less than 40 images to captured at the same resolution as the older cameras, thereby reducing the time and costs of such surveys.

Once a station has been captured a single panoramic image is automatically generated from the image mosaic through a back projection from image space to a cylinder with a predefined radius in object space. This projection uses the interior and exterior orientation parameters from the bundle adjustment, rather than correlation based stitching more commonly found in other packages, since this is both more robust and yields results in the absence of well defined image texture.

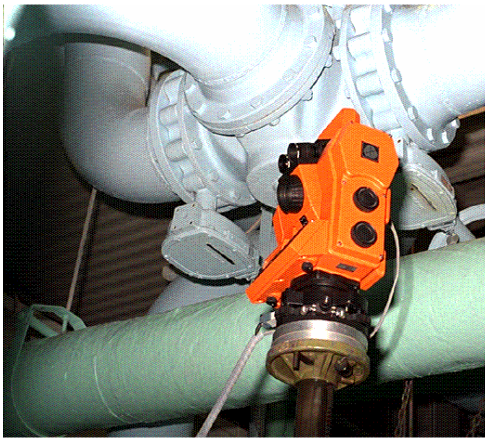

Figure 2. The Hazmap Videotheodolite

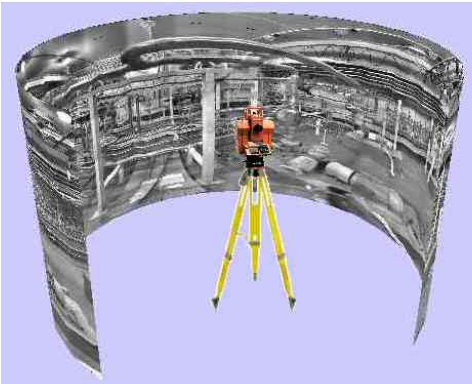

Figure 3. The Hazmap camera and a partial panorama generated from multiple image tiles.

The panoramic images, together with estimated station positions and orientations, form an immediate deliverable which can support qualitative assessment of plant condition through virtual walk-through technology. In the HAZMAP system a package called ViewPano has been developed to optimise such activities enables the recording and playback of paths through the model along with the superimposition of 2D and 3D models and animated textures .

In order to derive accurate positions and orientations for the camera locations it is necessary to measure homologous points for input to a photogrammetric bundle adjustment program. Using this method adjustments of dense networks of over 500 camera stations are now routinely undertaken yielding orientation parameters for over 30,000 individual image tiles. Analysis of the residuals from these highly redundant bundles indicate that the angular precision of the hybrid camera system is of the order of 20mgon and the precision of station locations are usually better that +/- 2mm. Once precise station parameters are available projects are available for accurate measurement of features through standard photogrammetric principles.

An image browser and measurement tool linked to the ViewPano panoramic browser supports multi-station measurement together with a geometric calculator function that enables the extraction of a wide range of dimensional data. The principle advantage of this tool is that it enables ad-hoc measurement to support engineering decision making and thus the package is intended to be used by plant engineers. Since such users often do not have extensive photogrammetric experience they must, therefore, be provided with sufficient guidance from the software and operating procedures to ensure that all data captured is 'fit for purpose'.

Figure 4. Typical panoramic image.

4. MEASUREMENT TECHNIQUES DEVELOPED FOR PHOTOGRAMMETRIC SEGMENTATION AND RECONSTRUCTION

A wide variety of measurement techniques have been developed. These build upon basic multi-station intersection of through the manual identification of homologous points. In order to facilitate efficient location of such points the user interface makes extensive use of epipolar line injection to reduce ambiguities in the identification of such points in images acquired from widely differing view points (figure 5).

4.1 Coupling photogrammetric point measurement to CAD modelling systems

Cost-effective photogrammetric modelling relies upon the rapid identification and measurement of key points on components. In order to achieve this it proved necessary to develop close linkage with target CAD modelling systems to enable the locating of complex objects drawn from a database of standard components by positioning datum points to identify location, orientation and scale. Such components range from simple geometric primitives such as cylinders and boxes to complex CSG based representations of equipment items such as pumps and valves. Through the development of an asynchronous file based communication strategy it proved possible to export measured points in a format that could be read by small applications (applets) written in the native macro or programming languages of major CAD systems. There applets could then drive complex operations within the CAD environment. An example of one such macro written in PML the Programmable Macro Language of the PDMS product is show in figure 6 and the dialog boxes below show typical PDMS dialogs to control the loose coupling of the Photogrammetric and CAD components of this modelling solution to enable the rapid placement of complex CAD entities drawn from a database of standard components.

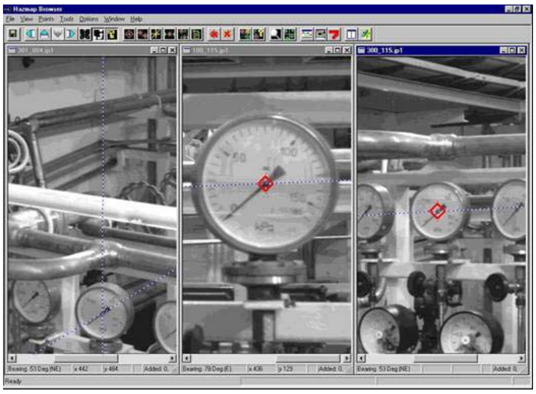

Figure 5. Epipolar line injection to aid identification of homologous points.

Figure 6. Sample dialog box linking photogrammetric measurement system to CAD environment

4.2 Rapid identification of candidate images for measurement

A major overhead implicit in all photogrammetric measurement tasks is the selection of appropriate views of the object in order to make image observations that contribute to subsequent intersection. As we have noted access to linked panoramic images provides an accessible index to the measurement images. However in order to further improve techniques for semi-automatic identification alternate viewpoints a number of imaging searching strategies were developed. These all rely upon the definition of a 3D point in world space with subsequent searching of the image database for images which contain that point within their view frustum. These searching functions were authored so that they could be triggered either internally or externally through a macro interface and a variety of methods developed for the determination of the target 'hot spot' which include:

- Estimating a distance to an object observed on a single image;
- Intersection of a simple observation with a previously defined line or plane (commonly the ground plane);
- Internal or external specification of a 3D point coordinate.

As can be seen from figure 8 such techniques enable the user to focus attention on images that may 'see' the hot spot location. Clearly since we make no assumptions about occlusion of the target this can sometimes deliver inappropriate images, however as we will see later even a fairly low quality range image offers the potential to dramatically reduce the time for modelling by facilitating rapid recovery of candidate image pairs for intersection.

4.3 Measuring points that the observer cannot see

Interfacing the measurement system to advanced process plant based CAD modelling tools rapidly exposed conflicts between surface based measurements of features and the internal CSG based model representations. In many cases the datum points that define CAD entities are buried deep within the object and therefore nor visible to the photogrammetric operator. Even simple objects such as box like structures require a the definition of a transformation from the, visible, corners of the object to the centre of gravity which defines its origin in, for example, the PDMS system. Particular problems arise when measuring cylindrical or dish shapes items typical of such environments in which often have few surface markings suitable for intersection.

To address such problems simple techniques for tangent observations enable the rapid measurement of pipe centrelines – perhaps the most common feature type to be modelled. Such observations were based upon a 'rubber band' measurement technique in which an operator dragged and observation cursor across the image from one edge of an object to the opposite side – the image coordinate for the observation being recorded at the mid-point of this tangent measurement. From a subsequent camera stations further tangent observations can be made to facilitate the intersection of the centre of the feature. Whilst this approach facilitates rapid measurement where the position along a feature is clearly defined (for example at a weld or flange) it requires a slight modification for pipe-like featrures where the edges may be visible but there are no features to locate the position of a tangent observation along the pipe. In this case we can use the epipolar line corresponding to our first observation as a guideline for second, and subsequent, tangent observations by constraining our measurement to be along the epipolar line. In this situation the geometry of the camera stations is clearly critical – if the camera projection centres are co-planar with the pipe axis we reach a failure case. Thus for a horizontal pipe centreline we require a vertical separation of camera stations to ensure that the epipolar lines cut the pipe orthogonally

Given initial estimates for edge locations and orientation there is clearly scope for some degree of image-processing assistance to aid precise alignment of the components with features in the image archive. Initial research in this area focussed on the automated alignment of cylindrical components to tangent planes derived from edgels that correspond to an initial estimate of location and orientation of manually located cylinders (Jones et.al.1996). Within the HAZMAP research activity edgels were derived from relatively simple directional edge-filters that were oriented parallel to the initial cylinder estimate and the techniques proved to be relatively successful where strong un-occluded edges were visible in multiple views.

4.4 Superimposition of CAD models on image archives

Clearly overlay techniques offer the potential to refine the position of assemblies of components that have been approximately located – either by an operator of through superimposition of design models on as-built imagery as shown in figure 7.

Such techniques for the refinement of an initial model has been further demonstrated by researchers at the Delft University of Technology (c.f. Tangelder et.al. 2000, Earmes 2000) who use an interative solution to match model edges to image edgels.

In practice, whilst such applications do offer some degree of operator assistance their practical application proved to be constantly compromised by the relative sparsity of high quality, homologous edges in image archives of the environments we are seeking to model. In many, perhaps the majority, of cases the edge refinement technique was corrupted by specular reflections along the pipe or by occluding features – particularly in the very common situation where parallel pipe runs are packed together in pipe racks. Thus in practise only a very small minority of components benefited from automated refinement and the overhead of manual intervention in the myriad of failure cases required the development of alternative strategies.

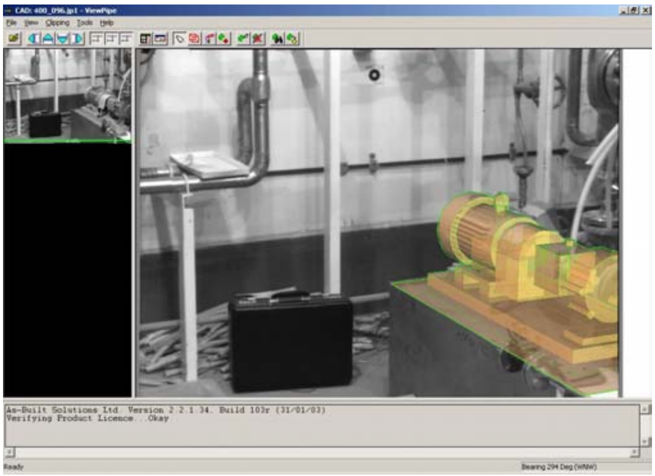

Figure 7. CAD model overlain on image archive

A further strategy enables the ‘rapid-routing’ of components that can be constrained to orthogonal directions aligned with either the site or local coordinate systems. Both of these techniques enable efficient, yet approximate, modelling with relatively few observations based on visual alignment of components with edges and other features against multiple images drawn from the image database.

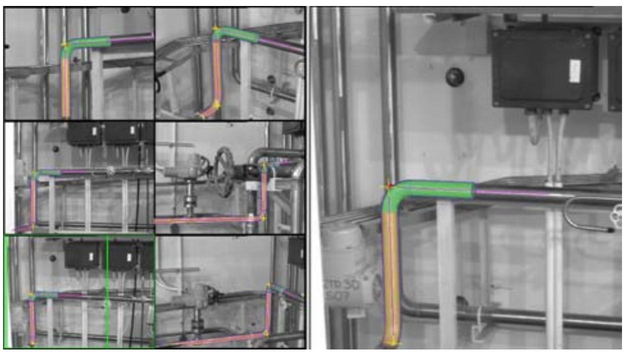

Figure 8. Construction of a piping component

5. QUALITATIVE VERSUS QUANTITATIVE ANALYSES OF PLANT CONDITION

It was rapidly found that in addition to the model construction or refinement measurement tasks that had been anticipated engineering end-users were also making extensive use of the archive to undertake qualitative assessments of plant condition and to inform early design decisions. In several instances circumstances relatively basic image inspection with very limited superimposition lead to some significant results including:

- images of a failed weld in a nuclear environment that indicated that a displaced unit had snagged a thermocouple housing – necessitating a modification to the robotic recovery strategy;
- images that clearly indicated that small bore piping that should have been installed with a slight fall to ensure self draining was, in fact, not parallel to other pipe runs and in fact run up rather than downhill;
- an ‘as-built’ model that contained equipment cabinets that had, in fact, never been commissioned and therefore were not present in the image archive;
- the overlay of a design model clearly showing that a structural member was of a significantly smaller diameter than had been used in a load-analysis based on the design data.

In each case there was little, or no, requirement for any environment modelling but each required rapid access to multiple views to confirm that these visual artefacts were not simply optical illusions.

However in a number of circumstances engineers started to extend their use of the image archive beyond the scope of what was originally envisaged. For example engineers began to use the rapid routing tools to design new piping installations using the image archive for ‘visual clash checking’ by subjective interpretation of the design layout when overlain on the image archive and viewed from a number of directions.

The development of such techniques clearly demonstrates the value of panoramic image archives as a cost effective, easy to use, tool for rapid plant verification and early stage design. However it is clear that access to range data associated with each image would provide access to enhanced visualisation and rigorous clash detection.

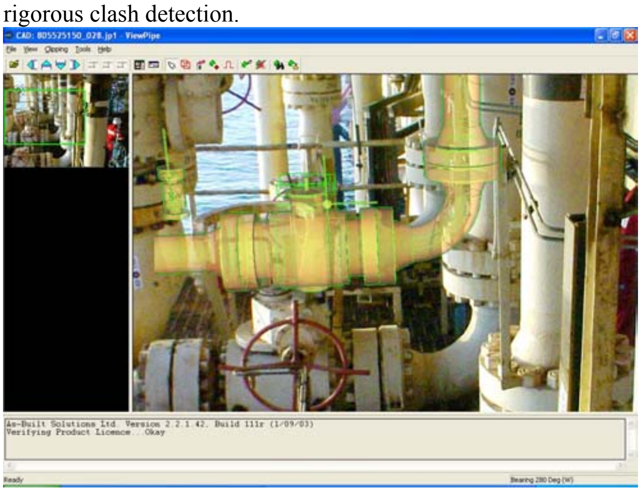

Figure 9. CAD entity superimposed on image to check conformity with design

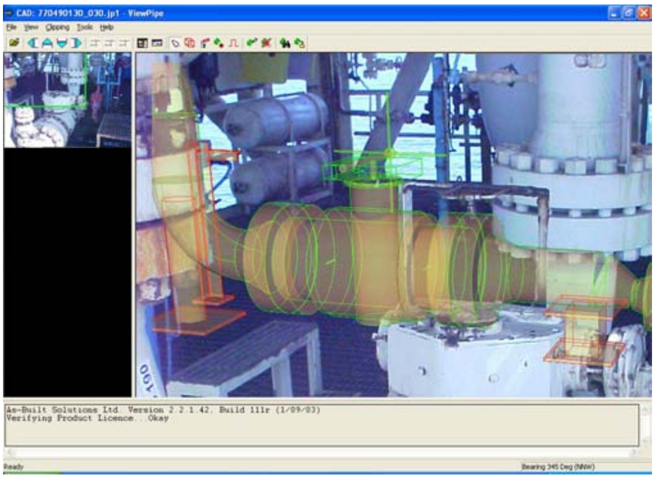

Figure 10. Early design of a new component – an initial check for possible clashing.

6. LINKING PANORAMIC PHOTOGRAMMETRY TO RANGE IMAGING VIA ACTIVE TRIANGULATION

The HAZMAP photogrammetric system have extended some of the concepts outlined in the earlier discussion into a robust commercial system for industrial measurement which has seen application in more than XXX projects in XXX countries and has created image archives with more than XXX images. In order to maximise the benefits arising from the accessibility of panorama based IBR techniques to a wide cross section of plant engineers whilst exploiting additional geometric data available from emerging range imaging systems a number of trials have been implemented using very compact short-range sensors.

6.1 Extension of the video-theodolite concept to include short-baseline active triangulation

Whilst the time of flight and phase based range-imaging systems are clearly suited to the measurement of large, regular structures their bulk and relatively long data acquisition times mean that they are less suited to the very cluttered settings of our target environments. However it was considered that there might be potential to deploy a low accuracy, very short baseline measurement solution that could augment the image data provided by the Hazmap system to give additional cues to an operator undertaking early stage design.

A proof of concept system was deployed that extended the theodolite based laser-diode pointing systems developed by Singh et.al. (1997). Here a video-theodolite was modified to carry an eccentrically mounted Lasiris laser-diode which could be fitted with a variety of lenses or diffraction gratings to project a very stable pattern of dot or lines. This led to a trial based upon a commercial implementation of a pan/tilt based active triangulation system. The Biris range imaging system which was initially developed by the National Research Council of Canada (NRC) (Blais et al, 1992) and has been adapted for use as a low-cost, highly portable measurement device suited to close-range applications from stand-off distances of the order of 0.3m (Beraldin et.al. 1998). This experiment sought to evaluate a modified Biris device that had been developed to work over ranges of up to 3m (El-Hakim et al, 1997).

Figure 11. The Long-range Biris device

The sensor is mounted on a Directed Perception pan/tilt device that enables full panoramic coverage from an image station through the projection and detection of a laser light stripe . The pan-tilt unit can be used to scan the 3-D laser profile around a 360° pan angle and a 110° tilt angle. The scanning parameters as well as the image resolution are computer controlled and therefore fully programmable. The very short baseline employed in the sensor (150mm) enables a robust and compact construction highly suited to this application at the expense of a relatively low precision .

6.2 Simulated and trial data sets

Since it was not possible to fully integrate the photogrammetric and range-imaging systems in the budget and timescale of this trial they were deployed separately and brought into a common coordinate framework through the measurement of a number of targeted control points. Figure 3 shows low resolution panoramas generated by the two systems. The partial Biris panorama is generated from four overlapping cylindrical strips each comprising 256 x 1024 pixels.

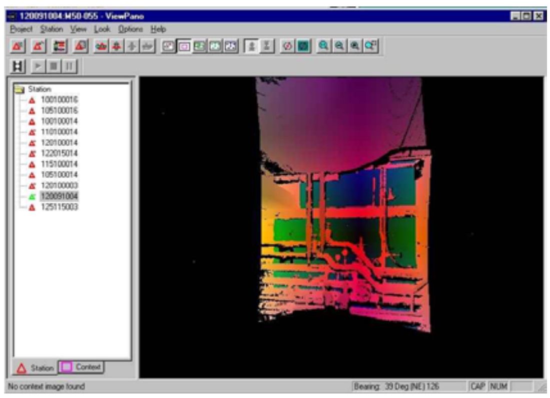

Figure 12. Biris range-image data in Hazmap browser

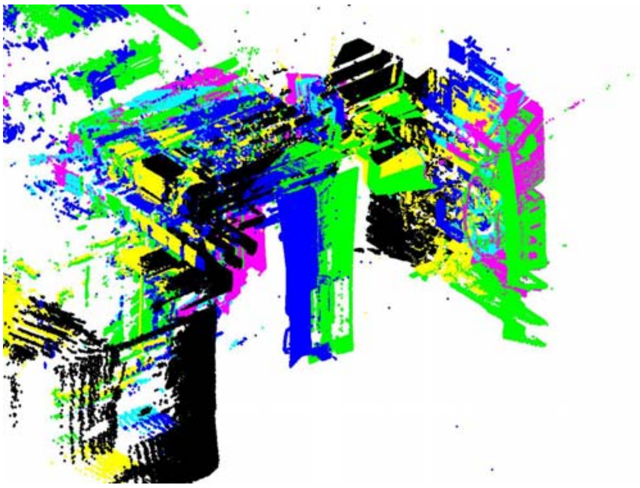

Figure 13. A point cloud generated by integrating Biris scans (each colour represents a different scan)

An increasing number of these laser scanning systems are capable of delivering such 'clouds' of XYZ coordinates. As with the digital photogrammetric systems a key factor in the success of such systems lies in the tools available for the consolidation of individual scans into a homogenous coordinate frameworks and the availability of sophisticated tools for rapid extraction of geometric entities appropriate to any 3D CAD model. Fortunately the problem of semi-automatic segmentation is more tractable for laser scanning data than in the case of digital photogrammetry and considerable progress has been made in the application of such techniques within commercial packages such as Cyra's Cyclone, Raindrop Geomagic's Wrap or Mensi's 3D Ipsos. Thus a in recent years a significant number of process plant modeling activities have been undertaken using such sensors (c.f. Sanders 2001, Amott et.al. 2000).

However due to the constraints on cost, size, weight and productivity mentioned previously we are presently unable to generate an equivalent density of data to that we can acquire using intensity imaging devices. Thus our analyses of range-data seek to extend and enhance the panoramic measurement interface described above. This is because we consider that an image-space based approach to measurement is likely to be more accessible to end-users whilst allowing qualitative interpretation of the fine detail accessible in the image data which is not currently present in range image point-clouds.

Thus we have implemented techniques that enable the import and display of range image data clouds enabling their display as either surfaces or as point-clouds. Access to such data enables:

- rapid setting of target hot-spots for image searching;
- clash analysis of design data against the point cloud;
- the deployment of best-fit strategies to refine object alignments.

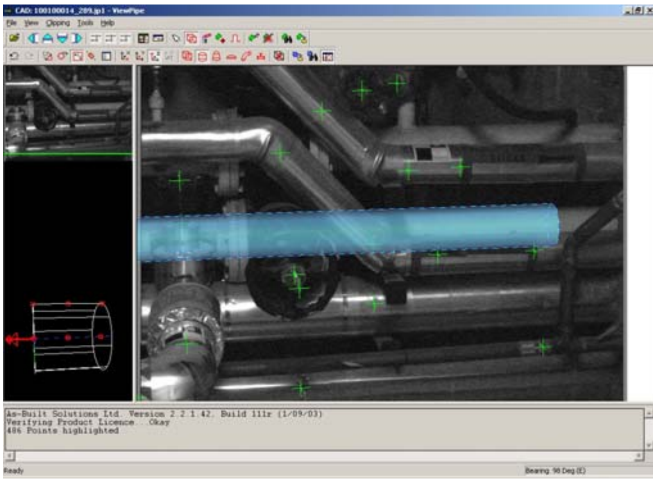

Figure 14a. Design pipe superimposed on image archive

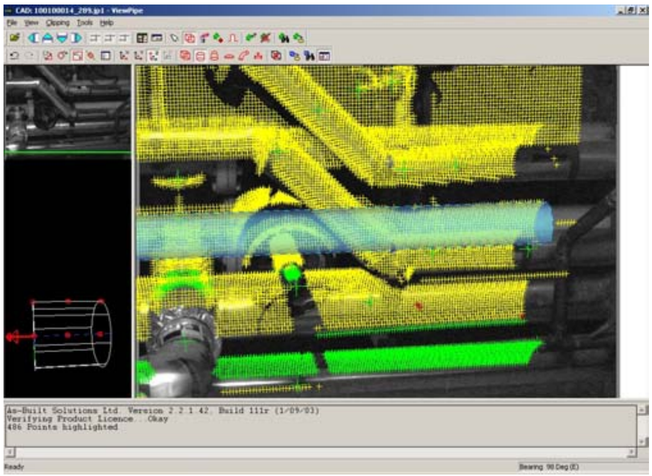

Figure 14b. Range image loaded

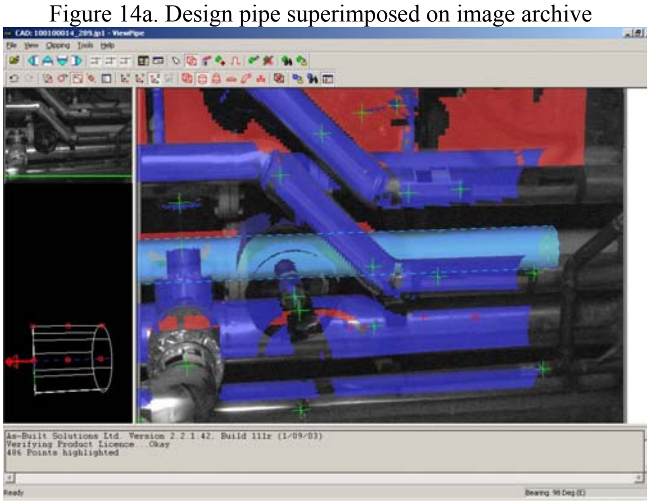

Figure 14c. 'Shrink wrap' surface fitted to range data

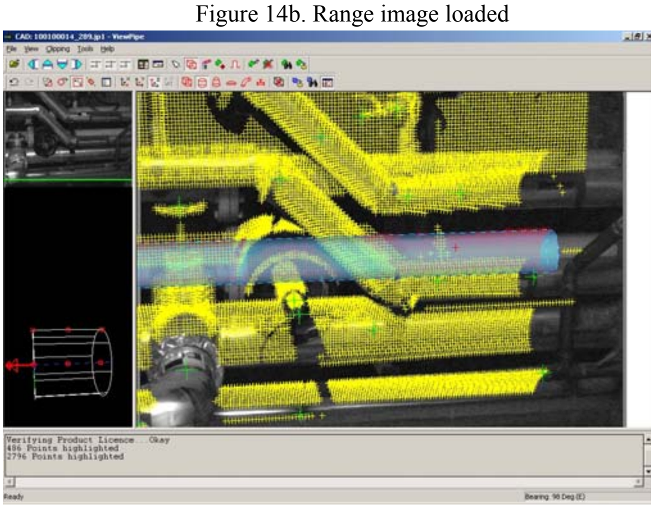

Figure 14d. Points within +/- 10mm of design selected for least-

squares refinement of position

7. CONCLUSIONS

The utility of image databases describing plant assets is now widely accepted within the process industries. As improvements in the speed, resolution and cost of digital sensors drive down the costs of acquiring such archives their application is likely to expand dramatically. However there still appears to be much further research required before we are able to routinely extract appropriate geometrical descriptions from such databases without human intervention.

Future prospects for the convergence of photogrammetric and range-imaging techniques may well lead to a new generation of sensors that combine the accessibility of high quality intensity images with the undoubted benefits of having a depth value for every pixel and thus facilitate a much greater degree of automation.

To date few systems are capable of acquiring a high quality intensity image that is co-registered with a range image over a wide field of view. Arguably an optimal sensor for these environments would comprise a high resolution (Gigapixel) 360 degree range imaging device capable of delivering high precision (< 1mm) range (X,Y,Z) and intensity (R,G,B) images. At the time of writing such devices would appear to be still one or two years away. However it is already clear that debates of the merits of Laser Scanning versus Photogrammetry are likely to increasingly sterile and that the immanent convergence of these competing systems is likely to afford real benefits to end users.

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