An embedded metrology system for aerospace applications

Dr. Tim Clarke and Dr. Xinchi Wang
Optical Metrology Centre, Dept. Electrical, Electronic, and Information Engineering,
City University, Northampton Square, London, EC1V 0HB.

Tel/Fax: +44 171 477 8127
Email: t.a.clarke@city.ac.uk
Web: www.city.ac.uk/omc

Abstract

As the move from craft-based aerospace manufacture to technology-based manufacture gathers pace measurement system assisted manufacturing will become common. Often these processes will require reliable, high accuracy position information of at least two objects at the same time. Photogrammetry is an ideal technique for such applications given that many points on an object can be measured at a single instant and this process can be repeated many times per second. As a result humans, actuators or robots can accurately place components or drill holes. This paper describes a photogrammetry system using a number of Digital Signal Processor based intelligent cameras and photogrammetric algorithms to provide real-time measurements integrated within a jigless assembly process.

1. Introduction

A fundamental task that is regularly and repeatedly performed in the aerospace industry is alignment of one object (for instance a drill, or a component) with respect to another. A number of schemes might be used to assist in these procedures such as: part-to-part assembly, a jig, eyesight and human skill, or actuators and measuring instruments. As manufacturing processes are refined or automated, measurement systems are playing a greater role.

There are many measuring methods suitable small volume ($1m^3$) tasks such as checking manufacturing processes, however, in the large volume arena ($1\text{-}10m^3$) there are fewer techniques available and the laser tracker, theodolite systems, portable articulated CMM arms and photogrammetry are key techniques. Each technique will be chosen for its particular merits, for instance: theodolites may be used if already available and the cost of a laser tracker cannot be justified; a laser tracker may be chosen where its relatively high cost can be justified by its performance characteristics, a photogrammetry system may be used where the ability to monitor the relative position of many points is needed, and the portable CMM arm may find applications where cost is an issue and the performance of the laser tracker is not required. Issues such as training and familiarity with the technique will also play a part in the decision making process.

One area where there is even less choice in the selection of a measurement system occurs when the relative position of two objects must be measured simultaneously. In this case all of the other techniques except photogrammetry are not practical to use. Photogrammetry is able to provide direct measurement of both component locations instantaneously and repeatedly. This functionality is highly desirable for a wide variety of applications and may see photogrammetry become a "black box" component as opposed to a "black art" as it is sometimes rightly described.

2. Jigless aeronautical manufacture

"Jigless assembly is about the transfer of tooling functions into component design and manufacturing processes" (Fowler, 1998). Part-to-part assembly is one method that is suitable for certain components where the added effort to manufacture holes or features accurately is justified. This paper is about the other aspect of the quotation - the transfer of tooling functions into manufacturing processes. The assembly of the leading edge of a wing is a structure that can be examined to assess the feasibility of jigless assembly. A measurement assisted jigless manufacturing procedure is illustrated in the following sequence of diagrams (figure 1).

Figure 1. The robot picks up a component (e.g. track rib) and delivers it to approximately the correct location where it is then guided into position by the measurement system

Drilling operations may be considered in the same context. An illustration of a robot controlled drilling operation is outlined in figure 2.

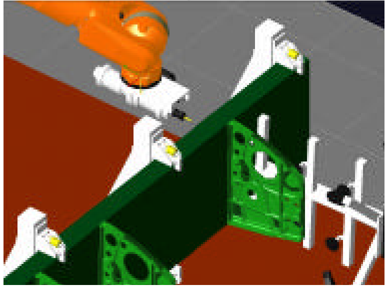

Figure 2. Robotic drilling

These figures illustrate the assembly process with a standard commercial robot of the type that might be installed in automotive industry. Such a robot is not a rigid or accurate enough for this application if used on its own. In addition the actual position of the spar may not be where it is expected to be. However, the robot is capable of fine movement and, in the case of the component positioning, a rib can be picked up by such a robot and brought into approximately the correct location. The measurement system can then used to guide the component into the desired location by using the photogrammetry system in the position control feedback loop. Drilling operations can be conducted in the same manner.

3. Measurement requirements

The general scheme describing the operation of a photogrammetric system is illustrated in figure 3.

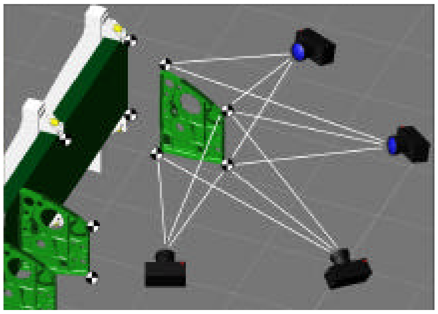

Figure 3. Photogrammetric measurement scheme

The application of photogrammetric techniques to jigless manufacturing requires:

- The measurement co-ordinate system to be in a known relationship with the robot or actuator co-ordinate system. This can be achieved by a number of means when initialising the system.
- The use of targets that are in a known relationship with the CAD model of the component(s) that is/are being measured
- The desired position of the component or the robot/actuator and the relevant tolerance information

In all of the processes errors accumulate such that the measurement system may have to measure more accurately than the nominal tolerance specification and the robot/actuator may need to be operated in a feedback loop. The disadvantages of photogrammetric systems are the need for targets that are applied to the object and clear lines of sight from two or more viewpoints. The advantages are that the 3-D co-ordinates of many targets can be determined at one time.

4. *3D-NET* measurement system

Cameras with on board processing are becoming increasingly common. These “intelligent cameras” are here to stay until intelligent sensors take over the functionality. The benefits are local processing, lower latencies, and lower bandwidth communications. The OMC system uses hardware image processing, a dedicated digital signal processor and Ethernet communications which are developed in-house (figure 4). The benefits are the computation of the 2-D locations of up to 170 target images in real-time (25 or 50 times per second) together with an extremely low latency from the time the image has finished being output by the camera (20 mSec for frame mode or a few microseconds for field mode).

Figure 4. Three intelligent camera processing systems

Solving correspondences in real-time can be time consuming. Several approaches are possible to avoid this with methods such as: back-projection, coded targets, or the epipolar and epiplanar methods. A real-time solution developed at City University recently uses rectification of target image co-ordinates to linearise the computational complexity and improve speed and predictability.

Estimation of 3-D parameters quickly and rigorously can be difficult. One of the approaches taken is to use a separated adjustment method that is capable of real-time 3-D measurement with the same result as a traditional bundle adjustment but with a far lower execution time.

Integration with CAD currently takes place by placing coded targets into close tolerance holes where the holes are in known locations with respect to the CAD model. Integration with the robot takes place using various least squares optimisation techniques to estimate the TCP of the robot.

5. Hardware testing of image processing

The *3D-NET* system is under development and various trials and tests are being conducted to assess its capability. This section describes a few of the tests that have been conducted to analyse the image processing capability of the OMC system.

5.1 Target image location precision tests

The variation in location of a stationary target will largely be due to electronic noise in the imaging formation and processing chain. This aspect can only be improved by better design, implementation, or better sensors. The location of a stationary target measured many times allows the estimation of target location precision. To check the target location accuracy of the DSP system, 500 measurements were made to a stationary target with the lighting and distance set up to obtain a bright image of a retro-reflective target. The result is illustrated in figure 5.

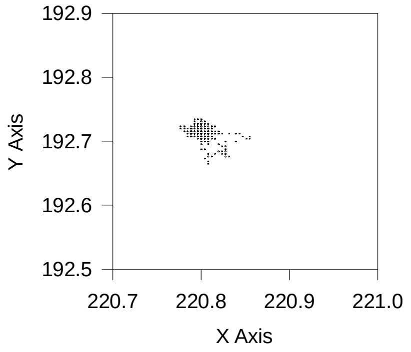

Figure 5. Target image location positions for a stationary target

In this figure, as the target is stationary, the quantization of the signal to 1/256 levels can be seen (this quantization is due to encoding the subpixel location in a single byte to minimise the data transferred and on the basis that the system cannot be expected to produce better results than 1/256 of a pixel). The standard deviation of the stationary signal is approximately 0.01 of a pixel in x and y (1/100 of a pixel). To illustrate this further the lighting and camera to target distances were altered to obtain various signal to noise ratios. The worst results would be expected in the x direction due to the additional effect of timing. The standard deviations of the x co-ordinate are given in table 1.

Target size and brightness	Small and dim	Small and bright	Large	Large and bright
Std dev (pixels)	0.0217	0.0178	0.0242	0.0131

Table 1. X direction subpixel location standard deviation

These tests illustrate a basic target location precision of the order of 1/50 to 1/100 of a pixel. This is a comparable result to that obtainable with a conventional frame-grabber.

5.2. Image accuracy measurements

A target was moved into known locations and the discrepancy between the known location and the measured location was determined. This type of test is very good at illustrating any systematic effects in the target location process. In the experiment a small linear stepper motor controlled stage was mounted approximately perpendicular to the camera’s optical axis. The stepper motor linear stage was mounted such that it was at approximately 45 degrees to the axes of the camera. The stepper motor was then used to drive the target at a constant speed while the 2-D locations (operating in field mode testing one field only) were computed and transferred to the PC and stored. The results are illustrated in figure 3.

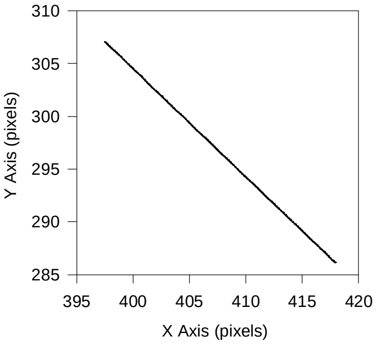

Figure 3. The movement of the target in the camera image.

While the plot illustrates a movement of around 20 pixels in x and y it is necessary to perform some analysis to draw any significant conclusions from these data. To do this a straight line may be fitted to the data and the residuals from that line can be noted to provide a statistical measure of the error. The results are illustrated in figure 4.

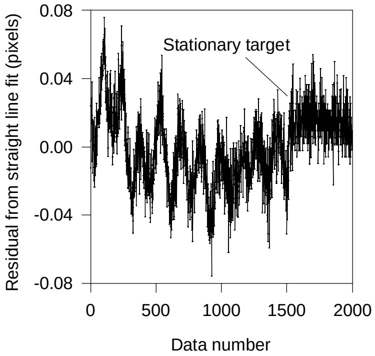

Figure 4. Residuals from the straight line fit

The results illustrated in figure 6 show a number of characteristics worthy of discussion:

- The moving and stationary parts of the data can clearly be identified.
- There are characteristic oscillations in the image data correspond to pixel boundaries.
- The local accuracy is extremely good being of the order of 0.02 pixels standard deviation for the whole data set

Other tests were conducted to assess the full image capabilities by: alternately moving a target in two orthogonal directions while collected target location data, moving diagonally across the image plane and by rotating a target through 360 degrees in the image plane. These tests were again able to show that the frame-grabber/DSP algorithm were capable of performing at around the level of a standard frame-grabber with no major vices.

5.3 Assessment by 3-D measurement tests

To determine the full capability of the system a 3-D artefact was measured to assess the accuracy of target locations over the whole image plane. A 16 mm lens and suitable lighting for the 70 or so targets retro-reflective targets on the 3-D testfield was used. The corners of the testfield had coded targets that allowed the orientation of the camera to be automatically computed. A total of 8 images were taken, four with the object rotated at one angle to the camera and another four with the equivalent of a camera roll of 90 degrees. After the initial resection, correspondence, and intersection procedure, a self-calibrating bundle adjustment program was used to compute both the 3-D co-ordinates of the targets and the camera interior parameters. The results of the calibration were as follows. The r.m.s. image residual from the 8 images was 1/27 of a pixel. A typical view of the residual vectors is illustrated in figure 5.

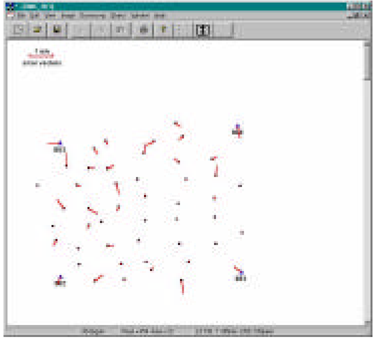

Figure 5. Image residuals from the calibration process

There appeared to be no major systematic effect in the image data. The result of 1/27 of a pixel was roughly in line with what is expected from these cameras with a potential maximum subpixel precision of around 1/40 of a pixel. A histogram of all of the image residual values is given in figure 6 which indicates an approximately normal distribution apart from a high percentage of values at or around zero.

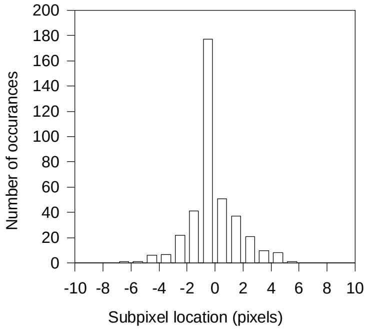

Figure 6. Histogram of image residuals

5.4. Conclusions

The DSP system appears to have equivalent image processing capabilities compared to a typical frame-grabber but is able to deliver 2-D co-ordinates to a 3-D processor continuously and with minimal latency. Other work is described in: Ariyawansa and Clarke, 1997; Pushpakumara, et al, 1996; Clarke et al, 1997; Clarke et al, 1998; Wang, & Clarke, 1996; Wang & Clarke, 1998.

6. Assembly and drilling

The development of a system of jigless assembly or drilling is about more than the measurement system itself. The manufacture and integration of all of the components required to perform these operations has been undertaken with the objective of first demonstrating the functionality of a measurement assisted system followed by quantitative work to assess its capability. In the process many alternative configurations, algorithms, and methodologies will be considered and tried. This section briefly describes some of the early work to demonstrate the basic functionality in a project with British Aerospace.

6.1 Drilling functionality

To develop the drilling functionality a number of separate areas required development. For instance, the calibration of the cameras, initialisation of the stereo system, estimation of the drill body with respect to the camera co-ordinate system, and the estimation of the camera co-ordinate system with respect to the robot co-ordinate system. Some of the early development work is illustrated in the following figures that show a drill and a targeted component

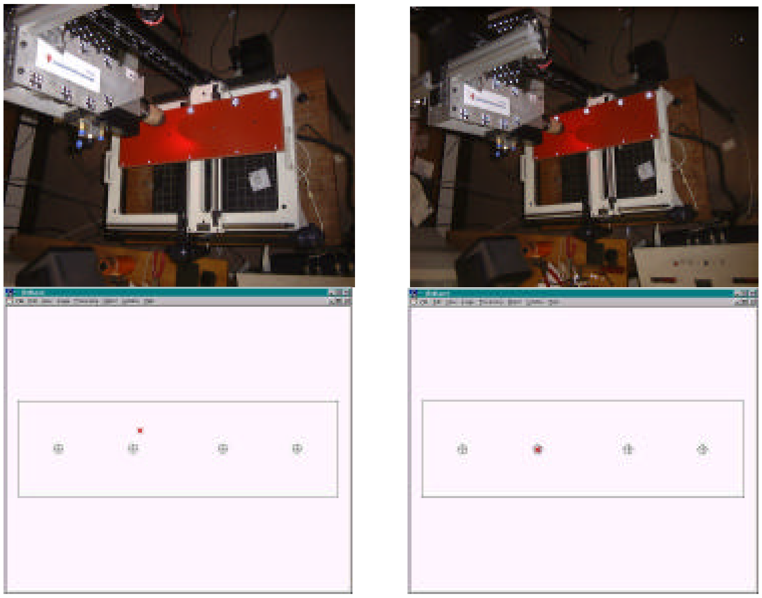

Figure 7. The measured location of the drill before and after movement to the desired location as dictated by the measurement system

Subsequent work involved drilling holes with a Kuka robot under the control of the measurement system. The functionality was deemed to be a success but further work is being undertaken to improve the ease of use, reliability and robustness, and accuracy.

6.2 Assembly

The demonstration of assembly used an end effector with suction cups to hold a track rib that was to be assembled to a spar. The scheme is illustrated in figure 8.

Figure 8. The Kuka robot and assembly end-effector

Targets were attached to the spar and using an initialisation process to establish the various co-ordinate transformations, the rib was successfully moved into the desired position using the information from the measurement system. Further work is required to improve procedures and accuracy.

7. Conclusions

A system for jigless assembly and drilling has been discussed. In particular one of the components of a real-time version has been tested and the results indicate that a high accuracy real-time capability is feasible. The use of a photogrammetric measurement system integrated in the manufacturing process for drilling and assembly operations has been demonstrated and further work is underway to improve the functionality and capability further.

8. Acknowledgements

The assistance of Richard Gooch of BAe’s Sowerby Research Centre is gratefully acknowledged in the joint work on jigless assembly under the BRITE-EURAM project ref. CT-95-0092 and the EPSRC JAM project reference GR/ L89310.

9. References

Ariyawansa, D.D.A.P, and Clarke, T.A. 1997. High-speed correspondence for object recognition and tracking. SPIE Vol 3174, Videometrics V, pp. 70-79.

Pushpakumara, D.D.A. Gooch, R.M &Clarke, T.A., 1996, Real time image processing and data communication for a 3-D measurement system. 15th National Information Technology Conference, Computer Society of Sri Lanka. pp. 1-9.

Clarke, T. A. Gooch, R. M. Ariyawansa, D. D. A. P. Wang, X., 1997. *3D-NET* - the development of a new real-time photogrammetric system. Videometrics V, SPIE Vol 3174. pp. 222-233.

Clarke, T.A., Li, L, & Wang, X., 1998. 3D-Net - a new real-time photogrammetric system. ISPRS Vol. XXXII, Part 5, pp. 29 - 34.

K. Fowler, Private communication, 1998.

Wang, X. & Clarke, T.A. 1996. An algorithm for real-time 3-D measurement. ISPRS Vol 31. Part B5. pp. 587-592.

Wang, X & Clarke, T.A. 1998. Separate adjustment of close range photogrammetric measurements. ISPRS Vol. XXXII, Part 5, pp. 177-184.