THE CONTROL OF A ROBOT END-EFFECTOR USING PHOTOGRAMMETRY

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KEY WORDS: Robotics, 3-D, Close range, Co-ordinate transformation, Six DOF

ABSTRACT

Most robots rely upon their rigidity to perform tasks. In the automotive industry the accuracy requirement for operations such as spot welding will be of the order of a millimetre. The aerospace industry provides a challenging environment to apply robotics in that the accuracy requirements are at least a factor of ten to twenty higher. Conventional robots are not capable of achieving this accuracy. However, combining a measurement system and a robot makes use of the ability of the robot to move precisely and overcomes the accuracy deficiencies. Photogrammetry provides a suitable method to measure the six degrees of freedom of many objects simultaneously. This paper describes work conducted at the Optical Metrology Centre, City University and Sowerby Research Centre, BAe Systems.

1. INTRODUCTION

Photogrammetry provides the unsual ability to simultaneously measure the six degrees of freedom of multiple objects at instant in time. This characteristic can be used in many ways, this paper considers how robotic systems might benefit. There are two alternative ways in which photogrammetric systems might be used: with the cameras viewing the robot's entire working volume (Beyer, 1999) or the only viewing the volume close to an end-effector (Clarke, 1999). Both schemes have advantages and disadvantages. In the former case a high relative accuracy is required but the robot position can be computed in a large area, while in the second case a lower relative accuracy may be acceptable but targets must be placed in known positions close to the task.

This paper describes the development of an end-effector based system that has been integrated with an industrial robot. The development of the physical and software components are considered. The physical aspects include: the image processing hardware, configuration of the cameras, lighting, coded targets, and location of the targets with respect to the CAD of the components. The software aspects concern the methods by which targets are identified, the 3-D estimation of the target locations, matching the targets to the CAD information of the components, and estimation of the robot tool centre point. The functionality of the system has been demonstrated for drilling and assembly operations showing that the scheme is feasible, the current status of the work is designed to assess the capability of such a system to operate within realistic tolerances.

2. IMAGE COLLECTION

The image collection process for this project can either take place via the usual frame-grabber approach or using the OMC-2D Net system (figure 1). This consists of a real-time hardware processor together with a Digital Signal Processor. This system has been described in other papers (e.g. Clarke et. al, 1997, Clarke et. al. 1998, Clarke & Wang, 1999) and is only summarised here.

Extensive testing of the DSP system has taken place and its performance has been shown to be the same as that of a conventional frame-grabber in terms of accuracy but with a very low latency and minimal requirements on the PC as 2-D target locations are passed to the PC via an Ethernet communication link.

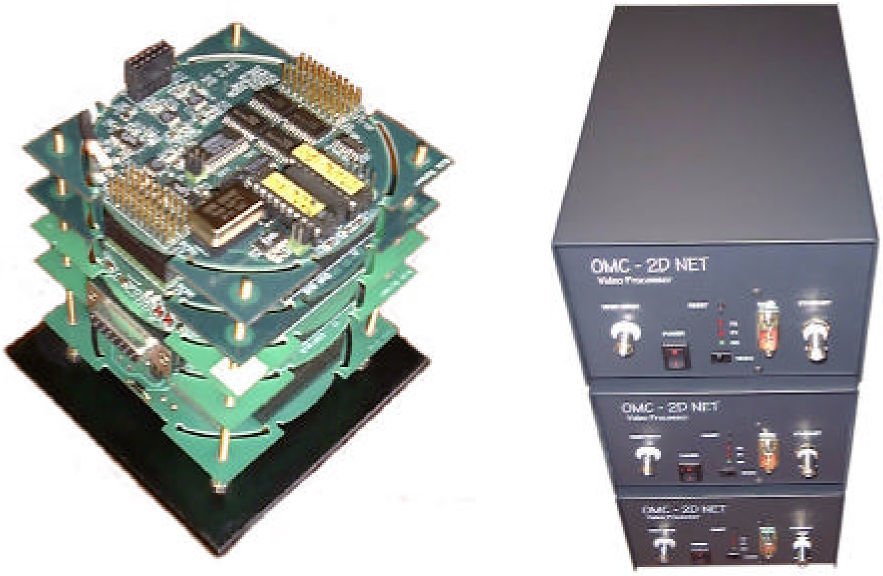

Figure 1. DSP electronics and cased systems

Some characteristics of the system are:

- Location precision: 1/70 of a pixel for 1000 measurement of stationary retro-reflective target
- Local precision - straight line fit to retro-reflective target moved over a straight line = 1/38 of a pixel
- Global precision, e.g. rms image residual from a bundle adjustment - between 1/30 and 1/50 of a pixel depending on configuration
- Resistance to image saturation - a few hours without failure
- Number of image processed without error - approx. 0.5 Million
- Warm up effects - approx. 1/16 of a pixel maximum variation in the x direction, stability after 15 minutes
- Number of targets processed in real-time - 170.

3. TARGET IDENTIFICATION

The unique identification of targets in each image is a necessary prerequisite for calculation of the six degrees of freedom of objects. To achieve this reliably two approaches are used. The first is the use of coded targets. A number of these targets are placed on the object to be measured such that any other targets on the object can be computed using their projection onto the image planes of the cameras and matching with the image locations of the target images. Subsequent to this initial start up procedure, correspondence in maintained by tracking.

The coded targets have been rigorously tested and have been shown to be highly resistant to variations in scale, orientation, position, illumination, and occlusion. In addition the targets can also be picked out of noisy images.

4. PHYSICAL DESIGN

An example task chosen for investigation is the positioning of a wing leading edge rib with respect to a spar. A three or four camera system would be preferred from the point of view of redundancy, however, the physical constraints of the application are such that this arrangement would be too bulky. A stereo configuration was chosen as a good compromise for this application. The physical arrangement of the system takes into account the trade-off between accuracy in the X and Y direction and the Z axis. The arrangement prefers to compromise the Z accuracy in favour of the beneficial effect of a compact system that will be able to view targets at a wider range of angles of orientation.

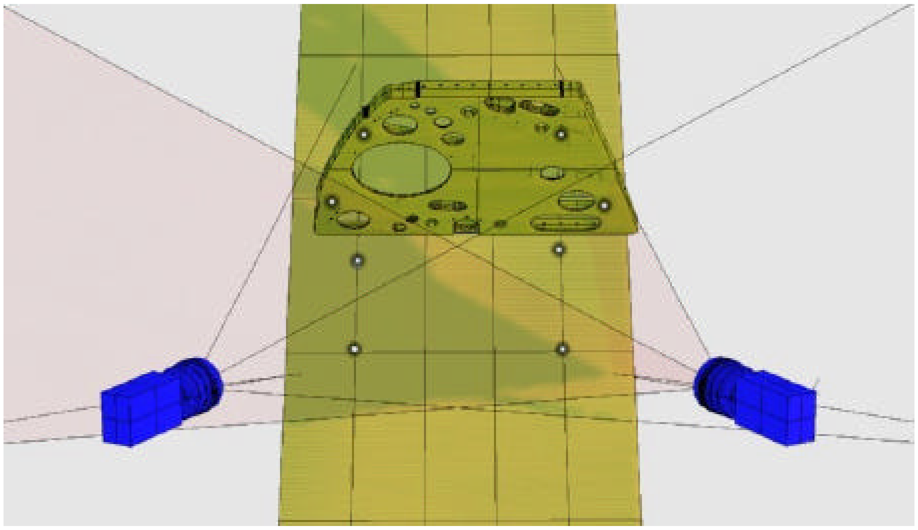

Figure 2. Configuration of measurement system with respect to rib and spar.

5. 3-D ESTIMATION

To set the system up two steps are required. In the first the cameras are calibrated and in the second the relative orientation of the cameras is estimated. To calibrate the cameras a 3-D calibration artifact is used. The artifact consists of a number of posts mounted on a metal base. The design of the artifact is such that when viewed from an angle the minimum number of targets are occluded by the posts. The artifact has a significant element of 3-D to enable the highest possible accuracy in the determination of the relative orientation of the cameras.

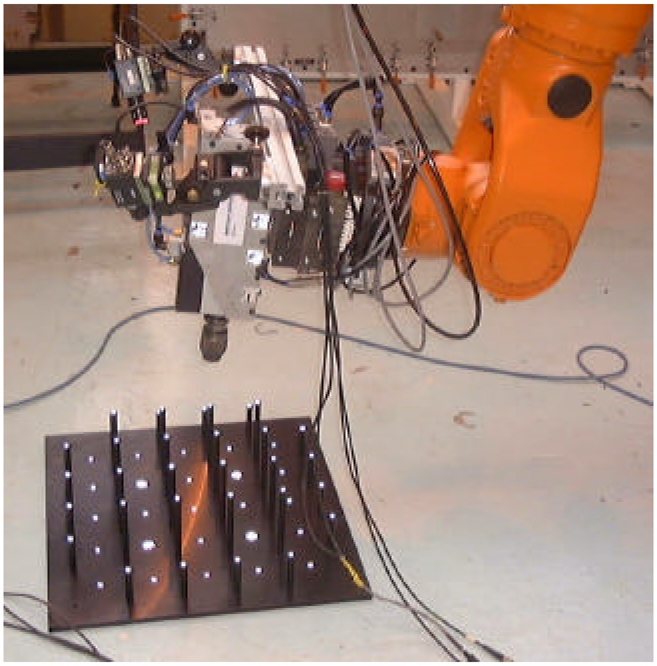

Figure 3. The calibration and relative orientation artifact being used to calibrate the cameras

The calibration process normally involves making the robot rotate the measurement head to observe pairs of images of the artifact from four different directions followed by a four further images with the equivalent of a camera roll of 90 degrees. Typical image residuals for the small format cameras used are typically 1/30 of a pixel. The 3-D estimates of the targets are stored and then used to compute the relative orientation of the cameras. 3-D estimation is then by direct intersection. The small format cameras are used to develop the system and will be replaced by higher resolution sensors at a later stage.

6. 6DOF ESTIMATION

The assembly operation that this project is investigating involves the computation of the six parameters describing the position and orientation of the rib and spar. The general arrangement is illustrated in figure 4.

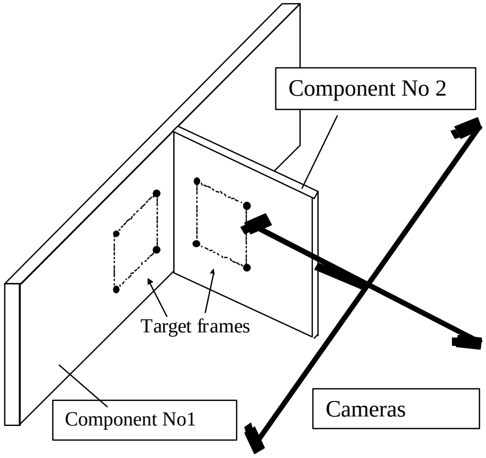

Figure 4. Assembly configuration

The process can be split into two steps: Step 1. Determine object to camera transformation relationship T_{otc} using a target datum interface (TDI) on spar as illustrated in figure 5 and Step 2. Determine rib movement parameters in the robot co-ordinate system as illustrated in figure 6.

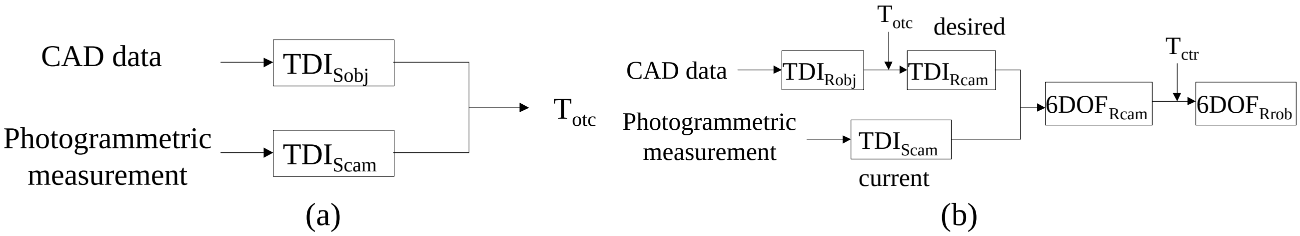

Figure 5. Co-ordinate transformation relationships

7. TOOL CENTRE POINT ESTIMATION

The previous step allowed the relative orientation of the rib and spar to be estimated with respect to the desired assembly position. The next step is to determine how the command the robot move in it's co-ordinate systems. A procedure of moving the robot end-effector into a number of positions while measuring a number of stationary points has been devised to enable the TCP of the robot to be estimated (figure 6).

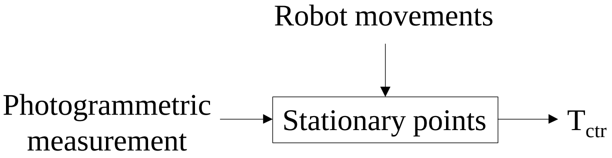

Figure 6. Estimation of the relationship between camera system and robot tool centre point

The accuracy of this process may be a critical error source but a feedback loop should be used to avoid this problem.

8. PRACTICAL REALISATION

Two versions of the system will have been developed by the end of the project. In the first system the functionality was demonstrated using a KUKA robot at Sowerby Research Centre (figure 7). In the second system, which is currently under development, a Staubli Puma robot will be used to assess the capability.

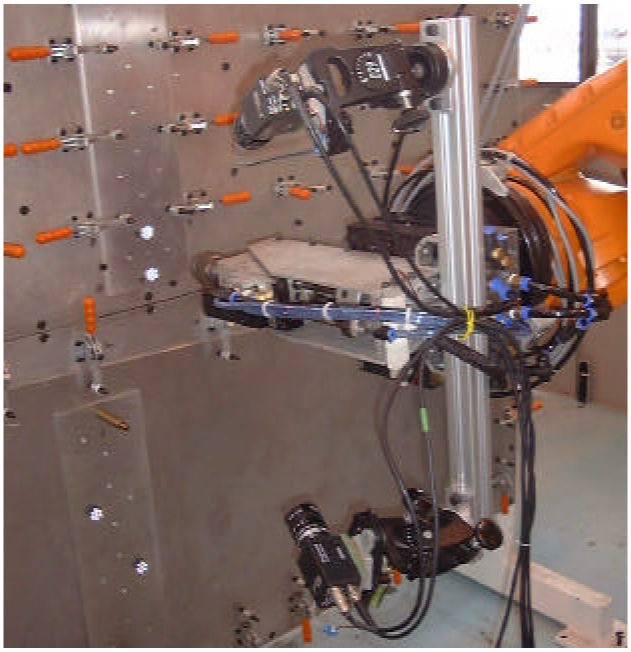

Figure 7. Drilling trials

9. VERIFICATION OF PERFORMANCE

The performance of the system is in the process of being tested. There are four aspects to this work: (a) Target error estimation using simulation to predict the error map for the system which varies considerably throughout the measurement volume. (b) Error propagation from targets through to the component tolerances. (c) Direct testing using known rotations and translations to compare measured to reference. (d) Direct testing using a length artifact (figure 8 & 9). The work being conducted for this last section is part of a wider program of research to develop a consistent method for photogrammetric systems and Laser Trackers based upon the ISO 10360-2 standard.

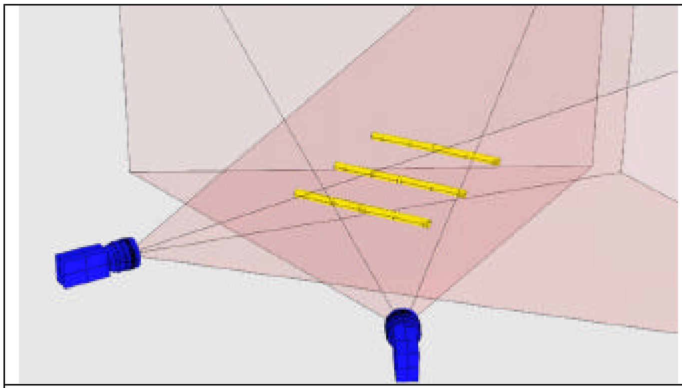

Figure 8. Three length artifact measurement location aligned with the x axis

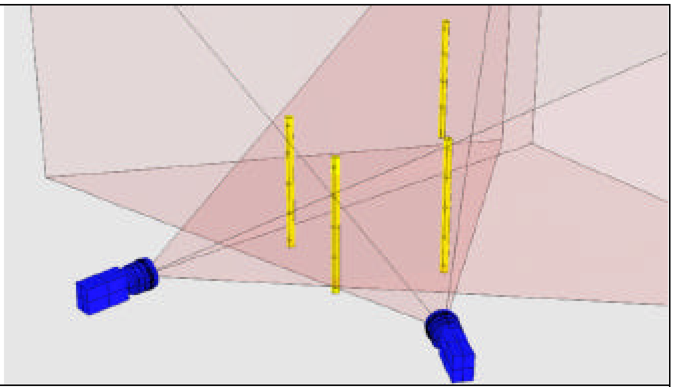

Figure 9. Four length artifact measurement locations aligned with the y axis.

10. FUTURE WORK

The work described in this paper is now reaching the stage where it will be rigorously tested and analysed. By pulling together all elements from image processing to 6DOF calculations it is expected that verifiable performance will be obtained. Whether this system capability together with the advantages and disadvantages of the methodology are appropriate for it to be applied to the application for which it is has been developed is not ultimately important. It is expected, however, that by being able to demonstrate capability rigorously in one instance it will be possible to apply the techniques in other applications.

11. ACKNOWLEDGEMENTS

The assistance of personnel from 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.

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