3D-NET - the development of a new real-time photogrammetric system.

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ABSTRACT

There are three essential requirements for real-time 3-D measurement using targeted points: fast 2-D image processing; a fast solution to the correspondence problem; and fast computation of 3-D co-ordinates. This paper brings together research work to produce such solutions and considers other work which has appeared during the project duration.

Keywords: real-time, networked cameras, intelligent cameras, 3-D measurement, target, photogrammetry.

1. INTRODUCTION

Close range photogrammetric methods have matured gradually but progress has been interspersed with significant step improvements in performance or functionality. Instances of this phenomena would be the development of the bundle adjustment, self calibration with models for lens distortion which included decentering distortion, and plumb line lens calibration. These techniques all gave tangible improvements, and all happened because of the availability of the computer and the inherent resolution available in film. More recently significant steps forward in functionality started with the use of Vidicon sensors and primitive frame-grabbers and matured with the introduction of the CCD sensor. Both frame-grabber and sensor have subsequently improved significantly. Further functionality for the close range photogrammetrist has been added by the return to portable cameras. In the future, developments of smart sensors may one day allow the sensor to be intelligent passing on information from its surface in parallel and at high speed. It appears that the time has now come for real-time photogrammetric systems to use intelligent cameras. There is usually a moment when an idea's time has come. Once the idea has been accepted it becomes difficult to imagine that it was not obvious to all concerned before this point. Examples from history would be the Copernican revolution or the theory of evolution. Today it is becoming obvious that cameras should have data processing capabilities and should be able to communicate using network technology. This paper concerns some research which may contribute to this goal. A programme to develop a network communicating and image data processing camera for real-time 3-D measurement system began in 1994. Some initial work was published (Pushpakumara, 1995; Gooch, et al., 1996; Clarke, et al., 1996; Pushpakumara et al., 1996). This paper brings the strands of this work together for the first time and puts them in context, these are:

(i) Real time 2-D image processing. Analysis of the difficulty of achieving true real-time photogrammetry at a reasonable cost led to several conclusions. Images contain a considerable quantity of information which has to be processed before target images can be extracted. The larger the sensor, the more information to be manipulated. Transportation of such quantities of information from camera to processor and its subsequent processing at one location by one processor has been a significant bottleneck. To address this problem a hybrid solution has been developed. First the image is pre-processed by hardware such that only information above a particular threshold is stored. This operation alone accounts for more than 90% of the processing in a typical system. The resulting information, is then processed to ascertain whether it meets size and shape criteria before being used to compute the location of the targets on the fly. The development of this feature extracting hardware is described along with a Digital Signal Processor system and interfacing methods. These components may be described as an intelligent camera.

(ii) Real-time communication using networked cameras. The next aspect to be considered was the passing of information from the intelligent cameras for further processing. The data rate was now at a level which enabled a standard technology to be used and the common Ethernet was selected as offering the means of connecting many cameras together and passing co-ordinate information to the next stage. The development of the networked cameras system is described in section 3 along with the methods used to ensure real-time operation.

(iii) Real time correspondence. Correspondence between targets and computing the 3-D co-ordinates of the targeted object. Consideration of this problem is given in more detail in Ariyawansa and Clarke (1997).

(iv) Least squares estimation. Finally, the problem of computing a 3-D co-ordinates of many parameters in real time is considered. A method of adjusting has been developed called a separated least squares estimation method which has been found to have many of the desirable characteristics required for a real-time system. The way in which this method operates and results of tests are given in section 5.

The resulting system has been called *3D-Net*. The objectives of the *3D-Net* project are as follows:

Real-time 3-D measurement.....................Up to 500 targets in 1/25 sec
Minimum latency..2/25 sec
Flexible architecture...............................2 to n cameras per cell, m cells
Low cost..........................Hardware cost < £1000/module excl. cameras
Future proof ....Not tied to a single camera or camera manufacturer
Scaleable .... Any resolution camera
High accuracy.................. Same result as traditional bundle adjustment
Operation................................. Simple - Photogrammetrist not required
Easy setting up..................................Rule based set up with CAD tools
Automated ....Fully automatic operation from switch on
Redundant ....Failure of cameras is permitted
Robust................................Self checking for blunders on several levels
Continuous operation........................…Cameras can be adjusted on-line

2. ANALYSIS OF COMMERCIAL SYSTEMS

2.1 Introduction

It may be argued that commercial developments will render academic developments unnecessary, that commercial work will either be ahead or behind academic work, but will always get to the same point in the end. Commercial work is driven by the imperatives of demand and profit. Academic work can sometimes be more objective or provide more fundamental insights than commercial work. Certainly academic work is generally published in detail. Two opposing observations are possible. First, some commercial companies appear to operate without any need to collaborate with academics. Second, other companies appear to originate from academic research or personnel, and some products are a direct result of academic work. The following analysis of cameras and 3-D measuring systems puts the academic research described in this paper into the context of commercial work.

2.2 Intelligent camera developments

During the course of the project a number of camera products with internal processing and network communications came on the market. Each of these was developed for specific market requirements. MRT micros (Micros, 1996) produced a camera with an integrated PC (up to a 486) and digitiser (8 bit colour). The system communicates using an internal PCMCIA modem at up to 28.8 k baud, or by a RS232 serial port at up to 57.6 k baud. The system is aimed towards a range of applications such as surveillance or inspection where the camera would form a part of an OEM system. VE Technologies (VE, 1997) market at camera called VE-262 which has an Intel 486 SLC running at 50 MHz together with a DSP frame-grabber based on the Analog Devices 2105 running at 10 MHz. The sensor was 512x492 pixel interlaced sensor. The camera dimensions were 200x100x125 mm. Communications are via RS170, TTL or RS232. The DSP is able to apply various processes to a 512x512 pixel image, for instance, image subtraction takes 79 mSec, however, due to the frame-grabber style of operation the DSP will not be able to process targets in real-time. For the 10 MHz chip the threshold operation alone would take 512x512 operations which would take around 50 mSec to complete. Image Industries (Image, 1996) have produced the IM-C2 camera together with Checker 1 where the processor has been integrated into a single rugged package. A DSP is used for image processing and RS232 or RS422 serial ports used to output results. VLSI vision (VLSI, 1996) have produced the Imputer 1 and 2 with CMOS 256x256 pixel sensors. A Motorola 56002 is used it the imputer 2 operating at 20 MHz. A RS232 is used for communications.

2.3 Developments in 3-D measuring systems

A number of companies and some academic institutions have produced 3-D measurement systems. Rather than compare all of these systems a brief review of the characteristics that distinguish commercial systems from each other is now given.

Metronor (Metronor, 1997) has been working in the metrology field since the late 1970's. Their systems uses pre-calibrated cameras, LED markers and light pens. Two systems are produced for use with light pens a dual camera system (DCS) and a single camera system (SCS). Both of these systems use light pens which are LED illuminated. Because the geometry of the markers with respect to the pen is known a unique solution can be obtained for the location and orientation of the pen even with a single camera. As a result the pen becomes a probe and is used in a similar way to a CMM stylus. The pre-calibrated cameras are claimed to have a resolution of 0.01 of a pixel. An overall accuracy of 0.1 mm is claimed for a 5 x 5 x 2.5 metre volume. Processing is carried out centrally using VME based electronics. Metronor have applied their systems to many industrial clients in the aerospace and automotive areas.

OptoTrak (Optotrak, 1997) produces two systems the 3020 and the RH-2020. What makes these systems unusual is the use of linear CCD arrays. Such arrays can be 5000 pixels long and have read out rates as fast as 20 MHz, resulting in repeated measurement rates of the order of 4 kHz. The OptoTrak system uses infra-red light emitting diodes (LED's) which are switched on one at a time. Each linear camera's field of view is spread out in the direction perpendicular to the sensor length to extend the normally plane view to that of a pyramid. Each sensor is able to provide a one dimensional observation. By using a triplet of one dimensional image observations a unique intersection in the object space can be obtained providing X, Y, Z co-ordinates for each LED. Up to 256 markers can be used, 3,500 can be measured per second with a RMS. accuracy of around 0.1 mm. Data latency is 3 ms per target. OptoTrak have developed their systems for use in the harsh environment of Wind Tunnels and have applications in many areas such as medicine and aerospace.

Mapvision (Mapvision, 1997) has produced a system with the following characteristics: 2-15 cameras, accuracy 1:20,000 or better, image matching or target location in 0.4 sec / point / camera. What distinguishes this system from the previous ones is the use of grey scale feature matching alongside target matching. This can extremely useful when targets cannot be used and when features must be checked for integrity. The Mapvision system is sold through third party dealerships in some counties implying that the system has reached a mature stage.

Qualisys (Qualisys, 1997) have developed a motion capture system called ProReflex. The advantage that these systems appear to have is in the speed of image capture and analysis. The MCU 240 operates up to a maximum of 240 Hz and the MCU 1000 at 1000 Hz. In addition the camera units come with processing on board. Data is transferred by RS232 or RS422 standard ports. Up to 240 cameras can be connected together. The maximum number of markers that can be used in 10,000. The resolution is 1:50,000. These systems have been sold to a large number of medical users.

Leica (Leica, 1997), as well as acting as a representative for VSTARS systems developed by GSI, also sell a laser tracker called SMART. The SMART system uses a retro-reflective device and the fast two axis movement of a laser beam to measure the distance and angles between the system and the hand held reflector. In the most accurate mode an interferometer is used. The hand-held reflector is placed in a pre-defined home position at the beginning of a measurement cycle and then tracked to any position within the field of view of the device. Distance measurement is accurate to approximately 1 part in 1,000,000 and the angle encoders have a 0.7 arc second resolution. The latest device allows lower accuracy distance measurement without the problem of maintaining tracking.

Newport (Newport, 1997) sells a number of systems based around a projector and two cameras whose optical axes are in a plane. The two cameras are convergent and the projector is mounted symmetrically between them. For a measurement volume of 380 x 230 x 280 mm a measurement accuracy of +/- 50 microns is claimed. In ten seconds a 3-D estimation if produced for each pixel in the image. By combining this dense data capturing system with a single camera (multiple exposure) 3-D system using sparse retro-reflective targets, the dense range maps are connected together. This hybrid approach has many advantages for certain applications such as reverse engineering in the automotive industry.

GSI (Geodetics, 1997) have produced what they call an “intelligent camera”. This system is based around the MegaPlus camera from Kodak with an industrial PC card (100 Mhz 486 DX4) mounted close to camera. A standard Ethernet is provided for communications. Cameras which can be used with this system are the Kodak MegaPlus 1.4, 1.6, 4.2, and 6.3, giving a sensor size from 1335x1035 to 3072x2048 pixels. Measurement speeds are claimed to be less than 1 second.

2.4 Conclusions

A significant event in multi-camera measurement over the past two years or so appears to be the development of a camera with on-board capabilities for processing images giving the consequent benefits of parallel processing. Camera based measurement systems developed by academics and commercial companies are now getting to a stage where they are a commodity item that can be sold in the same way as any other measurement system. Other complementary or competing techniques such as laser tracking are also becoming easier to use. The remainder of this paper describes an independent academic development of a system that contains many of the features of the best camera and 3-D measurement system developments.

3. THE DEVELOPMENT OF *3-D NET* HARDWARE

3.1 Overview

To overcome the bottlenecks in image processing and to provide the flexibility of a network solution a series of processes were implemented in electronic hardware. These processes are illustrated in figure 1.

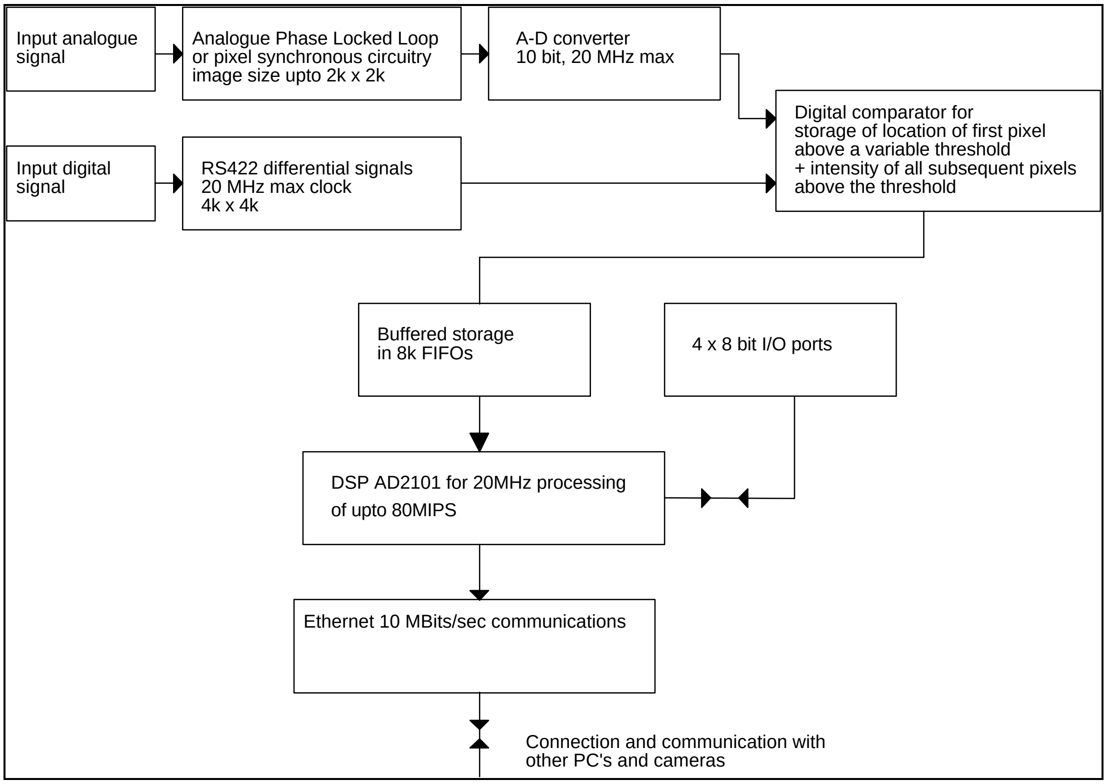


Figure 1. Functional block diagram of electronic operations

The diagram illustrates the approach to data processing. To enable the electronics to be used in a flexible manner the design was split into a number of modules. Each module was defined to be 90 mm in diameter and the system was named *DSP-90* as a result. Inter-board stack-through connectors were used to provide connections between the boards the EXP-BUS connector is 32 way and has four categories of connection ADDRESS (5), DATA (16), CONTROL (4), INTERFACE (6). A further PSU bus is provided with 12 connections of which six are available for other purposes, e.g. for powering sensors or cameras. Other connections are available between some of the boards via two pairs of 20 way connectors which are used for two fast 16 bit FIFO's, and four bi-directional and latchable 8 bit I/O ports.

3.2 Video feature extractor module (VFE-90)

The video processor board is a mixed-mode circuit, comprising both analogue and digital circuitry. Analogue circuitry is concerned with video conditioning, whilst digital circuitry is utilised for hardware processing of the digitised video signal, and for interfacing with the DSP-90 system.

A typical image of retro-reflective targets which has been obtained under optimum lighting conditions will consist of a number of bright peaks in the image which are similar to the Point Spread Function of the lens. A single level threshold will be sufficient to encompass the majority of grey levels associated with each target for minimum error target location using the squared intensity centroid method which has been extensively tested (Shortis, 1996). Under these circumstances the grey scale information necessary for each target amounts to around 25 pixels per target. Hence, for a 752x582 image containing 300 targets will only be using 25*300 / 438 k, i.e. less than 2% of the image. For a conventional system to recognise the target images will require an initial segmentation of the image which will require 438 k comparisons prior to the recognition and location stage. This operation represents a significant amount of processing which often has to be completed after the image has been converted and stored in image memory. The approach used in the VFE-90 module is to perform this operation in hardware. To achieve this one of the GPIO-90 ports is used to load a digital threshold level into a latch. The line-by-line video signal is A-D converted by a 10 bit Burr Brown converter and the output is compared with the threshold level. If this is the first edge encountered in the line the pixel location of this pixel is stored in a 16 bit word First In First Out (FIFO) buffer along with its intensity value. Any subsequent contiguous pixel intensity which is above the threshold is also stored. The same process is then repeated for all parts of the image that are above the threshold for that line. The next line is processed in the same manner. Prior to the beginning of each line a value of 0000 is stored in the FIFO denoting each line. For the case discussed the total storage required would be 582 + 300 * 25 FIFO = 8082 words. For interlaced imagery the odd-even field output of the synchronisation stripper is used to direct the data to one of two FIFOs one for odd lines and the other for the even lines. Each FIFO can be either 4 K or 8 K words. By performing the processing at the hardware level the data which requires processing is reduced considerably.

The VFE-90 board has been designed to be used with a variety of image formats. A voltage controlled crystal oscillator (VCXO) is used to enable high stability Phase Locked Loop synchronisation of CCIR or NTSC imagery. The pull in range for the VCXO is +/- 300 ppm. The pixel jitter for the circuit used is quoted as being less than 2 nsec. The counters are programmable via a GAL device and analogue imagery of up to 2k x 2k are possible. In addition there is a pixel clock input option as well as a line scan sensor option. The video processor board is built around a well specified video digitiser circuit. The ADC function is provided by a state of the art Burr-Brown 10 bit pipeline converter. This converter is driven by an amplifier configuration having a response up to 1GHz. This specification allows settling times to 10 bit accuracy to be achieved in around 15 nsec. Considering a typical CCIR camera, with pixel clock running at around 14 MHz, the corresponding period for each pixel is around 75 nsec. Hence the amplifier network is able to settle to the converter accuracy prior to the conversion

The modifications required to convert this board for use with digital cameras have been considered. Essentially all of the analogue circuitry would be unnecessary and the comparator circuit and subsequent circuitry would remain unchanged. The addition of RS-422 line drivers and some additional reprogramming of the GAL would be necessary to interface to a Kodak Megaplus camera for instance.

3.3 General purpose Input and Output module (GPIO-90)

The GPIO-90 module provides two functions only. IO ports and FIFO ports. Four IO ports are provided which can be read or write 8 bit data in latched or strobe mode. These ports can be used for a variety of purposes depending on how many are used for the main DSP-90 hardware. Options that currently exist are the operation of two DC Motors using a pulse-widthmodulation (PWM) controller which is part of the PWM-ENC-90 card. Obvious uses with *3-D NET* are pan and tilt mounts, synchronisation of flash lighting, and illumination of LED targets.

3.4 Digital signal processor module (DSP-90)

The DSP-90 module provides the processing power necessary to perform three essential operations. First the target images which are encoded and placed in FIFO's must be read and the target images re-assembled and checked for size and shape, second the centroid of the images must be computed, and third the resulting image co-ordinates must be communicated to another processor using the Ethernet communications module. Prior to recognition of the target images it is necessary to reset the FIFO's using the DSP and then read the subsequent data stream until the beginning of a new odd or even field.

Target recognition. (Pushpakumara et al, 1996) The image data are read by the DSP and the location of each section of image stored in a memory buffer. A line-by-line algorithm correctly associates the strips of image data by keeping track of the numbers of up going and down going edges for each line. Particular care is taken of two cases where images either split or merge. Following this step the target images are then stored in memory where they are recognised as targets by using several easily calculated measures such as area, perimeter, maximum extents, or peak to threshold ratio.

Target location. The method of moments is used to compute the location of the centroid of the target image. This is an operation that the DSP is particularly suitable for, as it is capable of single cycle multiply and accumulate operations. The location of the targets along with a measure of its quality is then stored. At the end of the image it is possible that the target image co-ordinates will have been computed before the next set of image data is sent to the FIFO. This will depend on the number of objects that require processing. Because, each field is placed into its own FIFO it is also possible to use the field images resulting in a 50 Hz repeat rate as opposed to 25 for full frame images. The images will be half the resolution in the y direction.

Communication. The target information, quality measures, and a frame ID number are either kept until the location data is requested by a processor, or continually sent to a selected processor using the ENET-90 module. The DSP has several means of communication available. Serial port, parallel port (using the GPIO board) or Ethernet. The Serial port can either operate in a synchronous mode or by using a small plug in module communicate over a RS232 link to a PC. Similarly the parallel port can be used in a number of ways and in one configuration can communicate with a PC using its parallel port. Communication using the parallel or serial port is necessary for debugging programs or downloading programs. A Microsoft Windows program can be used to upload memory for diagnostic purposes or download programs. The DSP has two LED indicators which are used to indicate successful downloading of programs and program operation. Once a particular task has been programmed an EPROM can be programmed such that when the DSP-90 processor is switched on or reset it will run the program in the EPROM.

3.5 Ethernet communications module (ENET-90)

The Ethernet communications module uses the NE2000 chipset which is almost a de facto standard for 10 Mbits/second Ethernet. The module requires a packet driver in the same way that a PC does. The packet driver senses when data arrives and interrupts the DSP-90 processor so that the data can be collected. When a packet is required to be sent to another Ethernet address the DSP-90 sends the data to the ENET-90 board in the correct manner and initiates the sending process.

3.6 Power supply unit module (PSU-90)

In many applications it is necessary to mount the instrument many metres from a power supply sometimes in an electrically noisy environment. To ensure that the DSP-90 system and any other ancillary equipment can have a clean power supply a PSU-90 module is provided. This module uses up to three DC-DC converters to allow a wide band input signal (9-18 Volts, or 18-36 Volts) to produce the voltage levels required. The inputs are protected from over and under voltage. CCD cameras, lasers, and motors can be driven from the same supply if necessary.

3.7 Conclusion

A set of modules have been produced for the specific purpose of providing in a flexible and relatively cost effective manner distributed processing for a 3-D measurement system. The hardware is illustrated in figure 2.

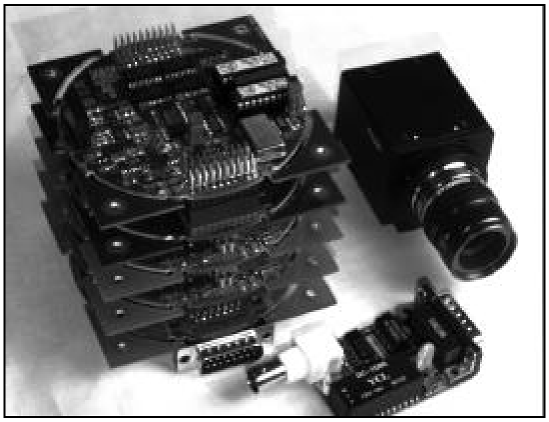


Figure 2. ***3D-NET*** **hardware for a single camera node**

The advantages of this system are: real-time operation; flexible configuration of cameras; dynamic change to the configuration is possible; the system may be put to a number of uses; and information from the system is available on a standard communications network.

4. CORRESPONDENCE

The correspondence solution devised for the *3D-Net* system is at an early stage of development. Some initial work is described in Ariyawansa et al. (1997) where the ground-work for a correspondence solution which is predictable and reliable is discussed. One of the key elements that is expected to be highly useful is tracking. If the measurement process operates fast enough for target images to be observed with movement distances smaller than their dimensions there is a high chance that they can be tracked successfully. A tracked target that has been successfully corresponded will retain its correspondence. As a large proportion of targets can fit into this situation at any moment in time it is expected that the computational effort will be significantly reduced. Tracking is a task that the DSP may undertake. Several modes may be possible such as location averaging, differential position reporting, or target tagging. Location averaging will have beneficial effects on the precision of location due to the random image noise perturbing the true position of the image centroid. This process would operate on the reported location estimates rather than attempt to refine the target images which would require significantly more storage space. Differential position reporting would be used to reduce in the quantity of information that it is necessary to transmit. For small movements it would only be necessary to sent the target ID and the amount that it has moved by. Target tagging would use a bit in the target data to indicate that the target had been tracked. The use of the DSP in the correspondence solution through tracking will benefit the whole measurement process in that the processing will be distributed between n processors and relieve subsequent processors of unnecessary work.

5. LEAST SQUARES ESTIMATION

5.1 Theory

The estimation of 3-D co-ordinates is a time consuming activity. Approaches such as the DLT have the benefits of speed but the results are not as accurate as simultaneous least squares estimation processes which are slow. Research at City University by Wang (Wang and Clarke, 1996) has attempted to provide the merits of both methods without the demerits. This resulting method is called a separate least squares estimation (SepLSE) method as distinct from a simultaneous (SimLSE) or sequential (SeqLSE) least squares estimation method. The unknown parameters are divided into groups and adjusted separately. In photogrammetry, the unknown parameters are naturally divided into: the co-ordinates of the object points and the camera parameters. Based on the collinearity equations the functional model, after linearisation, may be expressed as

$$A_1\Delta x_1 + A_2\Delta x_2 = b$$

where x_1 denotes the co-ordinates of the object points and x_2 the camera parameters. A_1 and A_2 are the corresponding design matrices. The principle of the separate adjustment is to treat the unknown parameters x_1 and x_2 separately. When estimating the object points, the camera parameters are considered to be constants. $\Delta x_2 = 0$, therefore the observation equations for estimating the co-ordinates of the object points are

$$A_1\Delta x_1 = b$$

By the criteria of least squares, the corrections to the 3-D co-ordinates are estimated by

$$\Delta x_1 = (A_1^t W_l A_1)^{-1} A_1^t W_l b = A_{11}^{-1} A_1^t W_l b$$

Since A_{11} is a block diagonal matrix, the inverse of A_{11} can be calculated by inverting a series of 3×3 matrices. The computation time required is directly proportional to the number of the object points and the maximum memory requirement is for 3×3 elements. When adjusting the camera parameters, the co-ordinates of the object points are considered to be constants. $\Delta x_1 = 0$, therefore the observation equations for estimating the camera parameters are

$$A_2\Delta x_2 = b$$

By the criteria of least squares, the corrections of the camera parameters are estimated by

$$\Delta x_2 = (A_2^t W_l A_2)^{-1} A_2^t W_l b = A_{22}^{-1} A_2^t W_l b$$

where A_{22} is a block diagonal matrix. The inverse of A_{22} is calculated by inverting a series of 6×6 matrices. The computation time required is directly proportional to the number of cameras and the maximum memory requirement is for 6×6 elements.

5.2 Speed assessment

The SepLSE process is iterated between two steps until a stopping criteria is met. During this process the camera parameters and the 3-D co-ordinates are refined. To assess the speed of this method some 3-D co-ordinates were generated and image locations formed using an arbitrary numbers of cameras and targets. Noise was added to each target image locations and a fixed number of iterations was performed using a standard SimLSE program (developed at City University) and the SepLSE method. For the SepLSE method the computation time was, as expected, a linear function of the numbers of cameras, targets, and iterations. The computation time for a Sun Sparc Classic was found to be 215 µs per ($C \cdot T \cdot I$), where C = number of cameras, T = number of targets, and I = number of iterations. For a 120 MHz Pentium the coefficient was found to be 42 µs. It should also be noted that main storage requirement is for the 2-D and 3-D co-ordinates of the input and output respectively. A comparison with a SimLSE program developed at City University for a 4 camera network was performed and the results illustrated in table 1.

Number of Targets	***SimLSE (GAP)***	***SepLSE***
50	11	0.4
100	66	0.9
200	521	1.7
400	3967	3.4

Table 1. Comparison between the SimLSE and SepLSE methods (Sun Sparc Classic)

Table 1 shows that the SepLSE method is superior to the SimLSE method. However, the results from each LSE process are equivalent. This is because, even though the parameters are separated in the SepLSE method, the solution is based upon the identical functional model and minimisation of the least squares estimation process is based on the same target function.

The algorithm converges to the same sum of squares of the residuals on the image plane. This has been tested in many simulations and practical experiments. This result must be considered to be of some significance. A disadvantage of this method is that the the full covariance matrix (which is a by product of the SimLSE process) is not provided directly but can be obtained when required. It should be noted that optimised LSE programs such as Bingo (1996) or CAP (1996) are likely to be more efficient both in terms of memory usage and speed.

A technique which has often been used to provide fast 3-D co-ordinate computation is resection followed by intersection where the DLT model Abdel-Aziz and Karara (1971) may be used. This method could be the fastest means of computing 3-D co-ordinates but the accuracy will not be as good as either of the two methods previously compared because: typically the camera exterior orientations are calculated using a small number of control points; the degrees of freedom are fewer than for the SepLSE and SimLSE methods; and, due to the re-arrangement of the functional model, the minimisation of the LSE process is no longer the sum of squares of the residuals in the image plane. Hence, this method takes less numerical computational effort than one iteration of the SepLSE method and the results (which will be less accurate) are not as rigorously obtained.

5.3 Simulation of a continuous measurement process

To test the SepLSE algorithm for real-time measurement processes a number of 3-D co-ordinates were produced and projected onto the image planes of eight cameras placed in four locations such that the convergent angle between opposing cameras was 90 degrees. One set of four cameras was rotated through 90 degrees. Random noise with a Gaussian distribution was added to the image co-ordinates. Twelve sets of 3-D data were created with a 2 mm linear movement between each set and a new set of random noise was generated and added to the target locations. The results of twelve sets of ten iterations of the SepLSE algorithm are illustrated in figure 3 and 4 for the maximum adjustment of the 3-D co-ordinates and the standard deviation of the 3-D co-ordinates respectively.

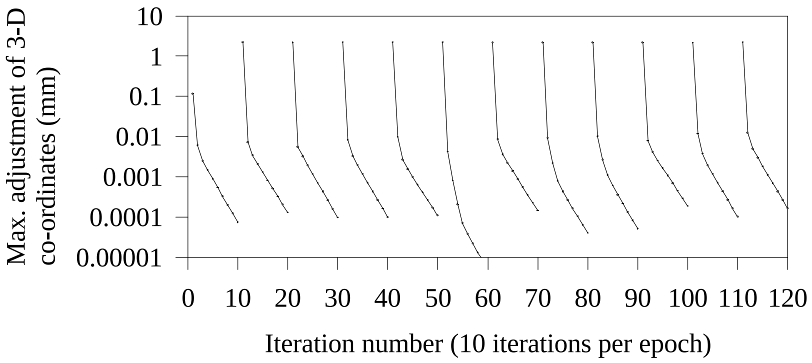


Figure 3. Graph of maximum adjustments for the 12 sets plotted for each iteration (note Log y axis)

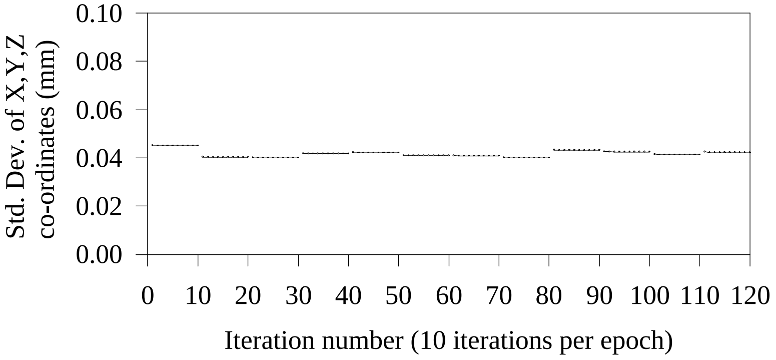
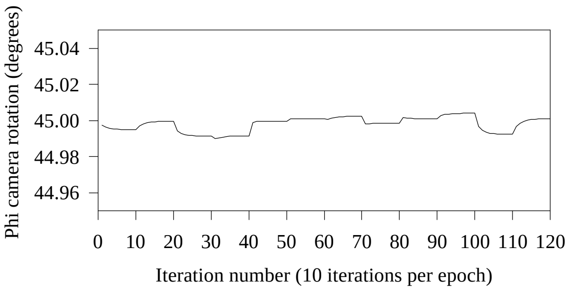
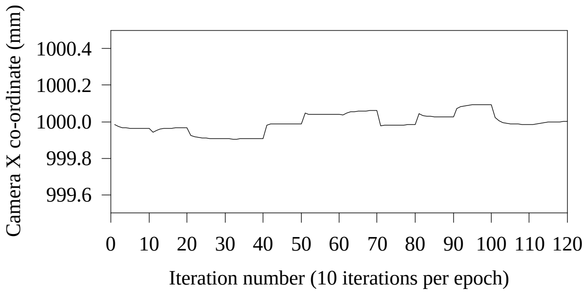


Figure 4. Graph of the standard deviation of the X,Y,Z co-ordinates for each iteration

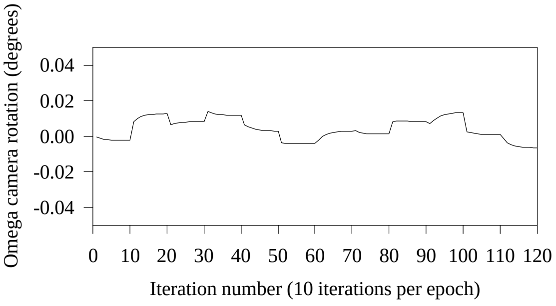
Figure 3 illustrate that after the first iteration which required a 2 mm adjustment, the maximum change of the co-ordinates rapidly approaches zero. Figure 4 illustrates that, for this set of data, the post priori standard deviation of the object space estimates of the 3-D co-ordinates were almost static after the first iteration of each set. Furthermore, the largest difference occurred between sets where differences in the random noise probably resulted in marginally differing standard deviations of the object space co-ordinates.



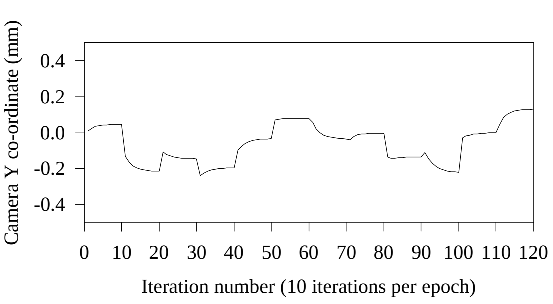
(a)



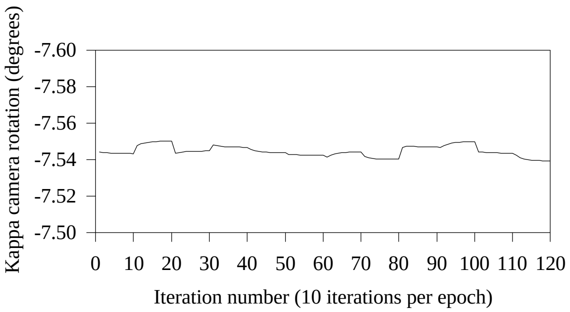
(a)



(b)

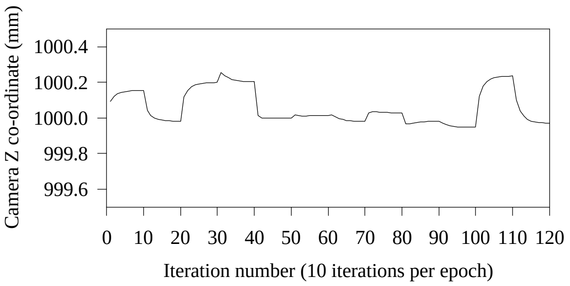


(b)



(c)

Figure 5(a-c) Camera rotation parameters



(c)

Figure 6(a-c) Camera position parameters

Figures 5 and 6 illustrate the stability of the camera parameters during the continuous SepLSE process. It can be observed that the camera parameters are not influenced by the change in the 3-D co-ordinate positions of the object points during movement but appear to change because of the differences in the random errors which are introduced which may have a slight bias due to the relatively small numbers involved.

6. OPERATION OF THE *3D-NET* SYSTEM

The operation of the *3-D NET* system has been tested using four cameras and a EPIX frame grabber. The algorithm used in the DSP was used to compute 2-D target locations in each image. These target images were checked for size and shape and sent to another processor using an Ethernet connection. This processor computed the correspondences and 3-D co-ordinates of targets using the SepLSE method. The resulting target locations were then displayed on the screen of the computer. Initialisation of the system was achieved using computer controlled LED targets to identify control points. Continuous measurement was achieved with a rate of measurement of about five seconds per set of camera images. The *3-D NET* hardware requires some software to be written before it can be tested. Other investigations have begun into object recognition and control of robots within the measurement volume. It is hoped that the system will be assembled and tested in the near future.

7. CONCLUSIONS

The development of a new real-time 3-D measurement system has been reported. This system is new in that all of the elements for the work have been developed in-house and with regard to the first and last essential elements of a real-time system, fast 2-D co-ordinates and a fast 3-D algorithm, the solutions described have elements which are unique and particularly useful in this context. With regard to the correspondence element of the work the solution is likely to make use of the best of others research and make full use of object oriented and tracking approaches to perform this element in real-time. In addition the proposed system has the highly desirable linear features of a real-time system. Each element, from image acquisition to 3-D co-ordinates computation takes a linearly increasing time dependent on the number of cameras and targets used. It is expected from simulation and practical testing that between 100 and 300 targets can be measured at a frame rate of 40 ms and with a maximum latency of around two frame periods. The latency will be proportional to the number of targets. If more targets are required to be measured it will be necessary to drop image frame data.

This paper has summarised the main features of the research and development of a real-time 3-D measuring system and reported the current state of progress. All of the elements which make up the *3D-Net* system have been tested and perform as expected. The system is capable of most of the objectives of a real-time system stated in the introduction. Further work is required to put all of the elements together and to perform system testing.

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