CCD or not CCD

D. R. Gordon
Civil Engineering Department
University of Canterbury
Christchurch, NEW ZEALAND
EMAIL: Gordon@civl.canterbury.ac.nz

ABSTRACT

An ongoing Biostereometric project aims to produce customised shoe-making lasts for people whose feet are too unusual to be fitted from normal (or abnormal) shoe stocks, or even to have shoes made from standard (or temporarily modified) lasts. This work requires some 30 to 50 points to define the total shape of such feet, and it is particularly important that irregular and unusually shaped feet are described in sufficient detail to ensure that the consequent last design and computer-controlled milling of individualised lasts are correct.

An overriding criteria of this programme has been to make the whole measurement and design process available to the bespoke shoe trade, and to ensure that lasts can be produced for a reasonable price. It is important that photogrammetrists and other (expensive) mensuration and design professionals are not required in the normal operation of producing such lasts.

This study compares the cost and efficacy of some methods of capturing this data. In particular it considers digital video pictures with automated and semi-automated data capture, as an alternative to conventional photography which is hand digitised on enlarged prints.

The comparisons will concentrate on cost effectiveness, accuracy, and on ease and reliability when used by non-technical non-photogrammetrists.

KEY WORDS: Photogrammetry, Close-Range, Biostereometrics, CCD, orthotic, shoes, feet

INTRODUCTION

I have reported elsewhere (Gordon, 1991) on my experience with a Christchurch made-to-measure footwear company, who estimate they decline some 10 enquiries a week from potential clients (from a total population in the Canterbury area of some 400,000 people) because their feet differed too much from the company's existing stock of lasts. The Last Footwear Company regularly make temporary modifications to their lasts for individual clients, usually by adding suitably shaped pieces of leather, but that there are limits to what they attempt in this regard.

Dr Ken Whybrew of the Mechanical Engineering Department in the Engineering School of the University of Canterbury, has joined me in a project to acquire dimensional data on a (misshapen) human foot and use the data (after due processing) to control a milling machine in producing a last from which a shoe can be made to fit that foot. The concept is not new (Duncan, et al 1974), and we are agreed that while neither the measuring nor the milling present insuperable problems, the data processing to link them will require more work.

My additional aim for this project is that the whole process should be available to, and operated by, the cobblers who make shoes for their clients. All of the numerical processing required for the data collection through to the production of the control data for the milling machine can be done on a personal computer of quite modest power and capacity. My aim is to have a turnkey process in which the problems in data acquisition, data processing, and the detailed instructions to the milling machine, are all solved in advance. In this way the cobbler simply goes through a prescribed process in data acquisition and processing, informing the computer as required about various choices left for the user (and their clients) to decide.

THE PROJECT

The mensuration section requires several facets

1 To capture the shape of the human foot. Clearly there is a high predictability about this, when probably 95% of the adult population's feet can be sufficiently(?) described by some 15 to 20 lengths ("size" and "half-size"), with two or perhaps three widths in each. This project is directed at the other 5% of the population, having sufficient variation

from these standard shapes and sizes to justify the cost and effort of custom-built shoe lasts and made-to-measure shoes. The mensuration task increases with the extent of this variation.

2 To determine this foot shape whilst it is subject to normal load. Even a cursory inspection will confirm that our feet change shape significantly as we stand up, and clearly it is this latter shape that is required for shoe-making. To measure feet in anything other than a standing position seems to me to be almost totally useless for this purpose.

3 The measurement must be done quickly. Standing is not a totally passive activity, even when we are standing still out feet have to move sufficiently for us to maintain our balance. My layman's estimate is that we should complete our measurements in less than one tenth of a second, so the best accuracy requires something very close to simultaneous determination of all points to be fixed.

4 In line with my aim of putting the whole process in the hands of the users, it is important that the most economical solution be found. This includes a reasonable balance between capital cost and the amount of time taken to measure and process the data.

My experiments so far have been on the assumption that photogrammetry would be the appropriate mensuration technique. The various traditional advantages of close-range photogrammetry for this sort of measuring work are still attractive. They include speed of capture, completeness, low costs for original photography, and the long-term stability of the stored record (the photograph itself). The requirement of a low-cost system has led me to plan on the manual digitising of (enlarged) photographs as in the Rollie and Wild-Leica systems. For reasons described elsewhere (Gordon 1991) I have chosen to concentrate on the use of mirrors to provide simultaneous multi-station exposures of the object. This approach is not new (Kratky, 1975; Keys, et al, 1975; Torlegaard, 1975) and offers a number of advantages. The mirrors automatically give simultaneous multistation exposures without any possibility of a partial failure in the synchronisation. A single flash unit can illuminate all the views, via the same mirrors that provide the multiple images. What is more it is quite easy to make the mirror system as robust as necessary. The layout of the mirrors was designed to provide at least 3 different views of each point. As can be seen from Figure 1, the view from each mirror is effectively a separate exposure from different 'camera' positions. As all the mirrors are vertical (or nearly so), each of these 'cameras' is tilted down from the horizontal by about the same amount as the real camera ≈15°.

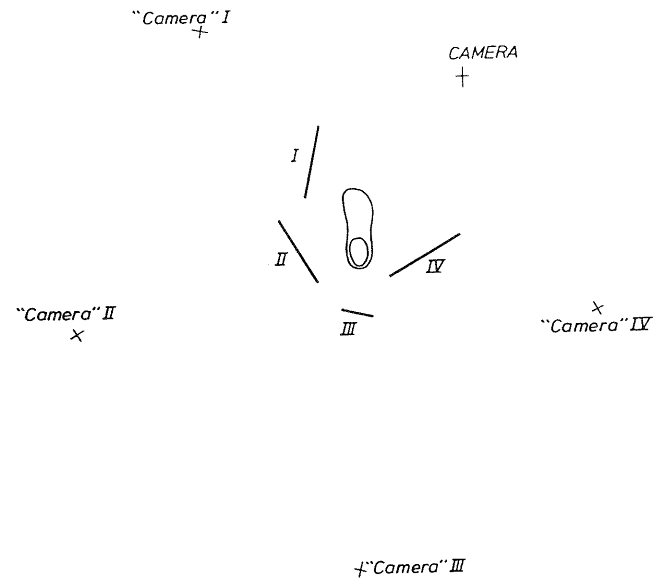

Figure 1. Planimetric layout of foot, camera station, 4 mirrors, and 4 psuedo camera stations

The determination of these 'camera' positions, and the positions of targets identified in two or more 'photographs', is classical close-range photogrammetry. While a number of solutions are possible (e.g. Granshaw, 1980), I have been using a bundle adjustment which is part of a suite called General Adjustment Programme (GAP) developed by Dr Jerry Clark at City University in London. I am pleased and grateful to have Dr Clark's permission and support.

Because of the divergent 'camera' angles involved, the possible targetting options led almost inevitably to spherical targets. Their prime advantage is that they remain regular and symmetric from every viewpoint. The most successful of these were some 3mm diameter dressmaking beads. Once mounted on a pin or cotton thread, and painted matt white, these proved to be the most satisfactory of all. While not perfectly spherical they presented a symmetrical image from all viewpoints, all with a common centre. The only retro-reflective targets I could find, or construct from reflective tape, were hard to find (let alone maeasure to) at the low angles of incidence they had in some of the views. The ideal target has a photographic image that presents an annulus around the measuring mark. Trinder (1971) advises that this annulus should be some 25 μm at photo scale where the optical enlargement is 10x, reducing to 15μm with clear high contrast images. With a 25μm measuring mark this implies a 75μm target, which scales up to 2.1mm for the most distance object point. All the targets I tried were larger than this optimum size, and this was exacerbated when their object distance were as much as 2.5x less than the maximum object distance. Most hand digitising tablets have a much larger solid and/or annulus marks, so these optimum target size sums will need to be done again once the final digitiser has been chosen.

	Average (mm)	Minimum - Maximum (mm)
σ_X	0.459	0.34 - 0.70
σ_Y	0.436	0.34 - 0.57
σ_Z	0.384	0.28 - 0.53
σ_{dist}	0.740	0.57 - 1.005

Table 1 Predicted accuracy of object point coordinates

The bundle adjustment (GAP) solved the unknown camera positions and object coordinates without difficulty. It also provided estimates of the accuracy of coordinate values for all other unknown object points. The average sigma values and their range for the 34 points in this test are shown in Table 1. The worst prediction for a distance error in a coordinate triplet was just 1.00mm, which is the arbitrary goal I had set myself for this work. The average predicted sigma value is 0.74mm. My initial estimates of the precision of conventional customised last-making techniques would be 1mm to 2mm, and that would apply to only 3 particular measurements.

the whole process may well be overtaken by cost effective direct raster scanning of the feet, possibly by applying rasterstereography through a mirror system similar to the one used in these trials.

ALTERNATIVES

There are alternative procedures for capturing the foot shape. There are a variety of structure light systems such as rasterstereography. These would not be ideal because one would need at least three such views to determine the shape of a foot, and they could not be simultaneous unless the three structured light arrays could be differentiated in some way. The cost of three exposure stations could possibly be avoided by the use of mirrors, but the differentiation problem becomes even more severe. I am aware of increasing activity in the direct raster scanning of distances to objects - a sort of close range Airborne Profile Recorder.

But the most rapid development in recent times has been in Charged Coupled Device (CCD) cameras, coupled with a 'frame grabber' in a computer to digitize the whole scene, and software to automatically identify and coordinate all targets within the scene (Shortiss 1988). There are cameras with a single line of CCDs that is mechanically scanned across the image plane, and there are the 'traditional' vidicon cameras that operate on an entirely different principle. I will be referring to CCD Array cameras in this paper, as it seems fairly clear that they are the type most amenable to photogrammetric processes. While generally worst in image quality they have a greater inherent stability across the format and with time than the alternatives.

Cameras, frame grabbers and simple image processing software for 512x512 pixel arrays are now readily available, although still more expensive than 70mm film cameras. Because of the high proportion of the device(s) that is solid state digital electronics we can expect these CCD systems to become much cheaper than film cameras. This will probably also be the case for 1024x1024 pixel, 2048x2048 pixel and 4096x4096 pixel array systems which are all now commercially available, although obviously over a much longer time period. These larger array sizes will also require more power and memory capacity of their host computer. The accompanying software is also likely to be more powerful (and expensive), but not necessarily in ways that will benefit this sort of application. There are already a range of reports on the use of CCD devices (Wong & Ho, 1986),on their calibration(Curry & Baumrind 1986, Shortiss 1988 and Fryer & Mason 1989), self calibration (Shortiss 1991), and software techniques techniques for improving the accuracy of automated pointing (Trinder 1989).

Frobin et al (Frobin & Hierholzen, 1988) report on the direct digitisation of structured light profiles from CCD array images (automated rasterstereography?). I have already discussed the difficulties inherent in applying rasterstereography to this project, and they remain in this automated approach except for the possibility that with enough fast memory three separate views might be captured in the 100 msec time frame I have mentioned. Even with the use of mirrors this would also require some way of switching rather quickly between separate structured lighting arrays.

However it is clearly possible to use a CCD array device, either instead of a film camera, or as a scanner of a conventionally taken photograph. It seems important to identify the parameters of when that might be the appropriate choice

MERITS OF CCD ARRAY SYSTEMS

A clear and abiding advantage of the CCD array cameras is that they facilitate the automatic acquisition of target coordinates. Provided the image processing system can identify the targets from predictable image characteristics and/or from predictable image locations, the user is not required to do the measuring work. This gives rise to some significant benefits for CCD cameras.

1 The target coordinates are acquired very much faster. Whereas a photograph would not be available for checking or observation for a day or more,

a fully automatic target coordinating system would be completed in a matter of minutes. In terms of dealing with clients this is almost 'real-time', and it would certainly be acceptable to have a client wait for internal consistency checks on the acquired targets, and to take another image if required.

2 The target coordinates would be acquired much more cheaply. In addition to the cost of film, processing, and printing, the traditional approach would take some 2 hours to observe with sufficient care.

3 The CCD approach has the potential to be a much more predictable and reliable provider of target coordinates. To achieve this one would need to obtain comprehensive calibration data on the camera/lens combination, and to have a particularly consistent targetting system. Under these conditions one could be very confidant of achieving predictable precisions of target coordinates - not necessarily the same over the whole format. Precision variations are usually less of a problem for adjustment than unpredictable (i.e. unknown) changes in precision.

As mentioned earlier in this paper, the cost of electronic componentry tends to reduce at a significant and steady rate. This is true for CCD cameras, and especially true for frame grabbers, image processing software, and corresponding computer hardware and software. These savings are partially offset by increasing power and facilities being offered at all levels (CCD array size, frame grabber capacity, sensitvity, and speed, image processing capability, and computer speed and memory capacity). So we can identify another advantage for CCD cameras;

4 Reducing cost, from an intially high figure. It is inevitable that 512x512 pixel systems will eventually be cheaper than 70mm film cameras. Because the latter will always require highly skilled manufacture and assembly their cost will remain relatively static whereas all levels of CCD array systems can be expected to become cheaper in real terms.

We should note that where the CCD camera is used to scan conventional photography the advantages are limited to numbers 2 and 3. Because a conventional film camera and photographic processing are involved in the observing procedure the turnaround time and the cost of the system will be worse (or hardly better) than a straight photographic system.

5 Depending on the array size required, a CCD array camera would be much less bulky than a 70mm film camera. If this is pleasing to the shoemakers and their clients it is a consideration. However the system requires the inclusion of a computer to capture the digital (digitised?) image, which rather tips the 'bulk' issue in the opposite direction unless the computer is located and controlled remotely.

DE-MERITS OF CCD ARRAY SYSTEMS

1 For the time being CCD array systems have demonstrably lower image resolution than (say) most 70mm film cameras. While this has clear implications for stereoscopic observations, it will not always matter directly in the acquisition of target coordinates. Shortiss (1991) has reported target coordinate accuracies of 0.03 to 0.07 pixels for small CCD array cameras, which is well within the requirements of this project. The limitations could come with target images of low contrast, so system design, especially illumination and contrast of targets, will require special attention.

2 However Trinder's work (Trinder, 1989) indicate that in order to achieve the sort of positional accuracies quoted above the target diameters should not be less than 5 pixels. Beneath that level the accuracy of the pointing drops off very quickly. Now if one were to require targets to have an image diameter of 5 pixels and a minimum spacing between targets of 10 pixels (with a 512x512 pixel array). There are 11 places on my initial trial where the targets are closer than this rather optimistic minimum spacing, and this was with a regularly shaped foot. Where the foot being measured had significant deformities there could be some dificulties in defining the shape with sufficient resolution.

3 In order to achieve the minimum target size noted above, then sperical targets would need to be 10mm in diameter. These would be dramatically large targets to place on the client's foot. They are likely to be as unhappy as I am at the prospect, and this is no way to introduce people to a new process (that they will probably be paying for!).

4 For the time being it seems that the cost of camera, frame grabber, and software is still notably higher than for a 70mm film camera (for example) and good tablet digitiser. Even now this extra cost needs to be balanced against the time saved. If a working system were to measure 100 feet in a year, and save 2 hours digitising on each one, then the annual savings over a photographic approach would be 200 hours of skilled time, plus the photographic processing costs. Over a 4 year 'life' the CCD system would save 800 skilled hours, plus processing, plus a 70mm camera tablet digitiser, less some reasonable share of the development costs of software to acquire the target coordinates. This equation can be evaluated for any particular place.

CONCLUSIONS

In the short term, in the situation here in New Zealand, CCD array cameras are not cost efficient. It seems to me inevitable that this will change, but I am not competent to predict that changeover with any degree of certainty, In the meantime our project will continue as planned.

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