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# Accuracy and Difference Detection in Medical Applications of Photogrammetry

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## Accuracy and Difference Detection in Medical Applications of Photogrammetry

**Linking three-dimensional imaging to medical science:**

- **Accuracy, Precision, Calibration**
- **Surface Differences and Change Detection**
- **Getting started with hardware and software**

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## Speaker's interests:

- Medical measurement experience:
  - Dental – via microscope – detection of wear – using replicas
  - Scoliosis: automated back measurement by image correlation
  - Change detection in the dental and scoliosis applications.
- An interest in uses of medical measurement, including concerns about the effectiveness of medical photogrammetry in the digital imaging era, (co-chair of the medical measurement Working Group of Commission V of ISPRS, 1992-1996).
- Medical photogrammetry does not belong solely to photogrammetrists!



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## Medical measurement:

**Relevant characteristics of medical photogrammetry**

- Medical photogrammetry is in a class of close range photogrammetry with its own distinctive challenges and constraints because it has the crucial distinction that it involves living humans.
- Measurement of humans can be seen to include applications where the object of interest is not part of the live human because the challenge of photogrammetry involves an interaction with humans and a need to allow for them (e.g. analysis of a golf club swing). On the other hand, measurement of inert items, such as prostheses or parts removed from bodies, is not discussed here, as this does not involve human beings, and the photogrammetric considerations are not characterised by those involved in the study of live patients, even though the client may be a health practitioner.

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## Medical measurement continued

- It is necessary to be concerned about the humans'
  - health,
  - privacy
  - convenience and comfort - cameras are not intrusive! *The choice of cameras can influence accuracy*.
- Human beings, even when standing or sitting, continue to move continuously if almost imperceptibly, and so imaging needs to be both quick and finely synchronised. *Again this choice can influence accuracy*.



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## Medical measurement continued

- There are numerous **photographic** challenges with human objects, whether caused by the skin, with its low contrast and limited textural variation, or the eye, or by any body part, such as torso, limb or foot, which require all round coverage. *This can influence choice of measured points, whether targets or not* .

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## Medical measurement continued

- The **cost** of photogrammetric measurement usually needs to be kept low. The measurements are not normally crucial, and may often be dispensed with altogether, and replaced by a skilled surgeon, or with simple callipers if it becomes too expensive. Measurements intended for mass screening or anthropometric data collection need to have a low cost per measurement to make widespread implementation viable. It is ironic that in the field of medicine, which is typified by expensive, high technology equipment, that a significant advantage of photogrammetry can be its low cost. *Low cost can also influence accuracy*.



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## Medical measurement continued

Two very distinct groups of applications:

- A few uses are long-term, commercial, sophisticated, expensive, accurate. Mostly motion: gait (many reasons, including diabetes); also sport.
- Many other uses are for short term and non-commercial projects, and make use of photogrammetry's cheapness and flexibility. These uses can be contrasted with the few commercial uses of photogrammetry and the use of laser scanners and so on. Relative accuracies are NOT high, even though absolute accuracies may be very high.

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## Medical measurement continued

Uses in the second group:

- faces
- skin - ulcers
- dental – via replicas
- breasts
- feet and
- radiography

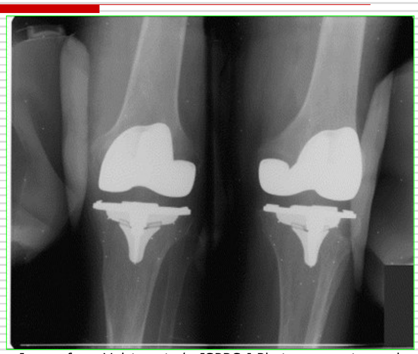

Image from Valstar *et al.*, ISPRS J Photogrammetry and Remote Sensing, 2002.



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## Medical measurement continued

Typical non-commercial medical photogrammetry:

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## A. Accuracy and Precision in Medical 3D

- Photogrammetry can be an accurate process. Indeed, if it is not accurate, it is not photogrammetry. It is simply amateur measurement, and it is not interesting or challenging…if it was easy, we would not be here?
- The photogrammetric process is subject to *many* sources of error, and computed results cannot be perfect, despite being capable of high accuracy if we need it.
- When high accuracy is wanted, we need to understand what can be done to achieve it – other than buying expensive software.
- But what about medical photogrammetry?



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## A1. Issues

- What accuracy level has been achieved?
- How has the accuracy been estimated? (It may be estimated *a priori* (i.e. system design), and be wrong, or *a posteriori,* and still be wrong.
- Accuracy studies in medical photogrammetry are especially important because usually experience helps, but many of the projects are short term, using non-commercial equipment, relatively cheap, and so need to be tested or confirmed.

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## A1. Issues continued

**Overall issues:**

- What accuracy is needed for medical measurement? Is it realistic?
- Can you trust commercial software? Can you trust your own software?
- Does the software provide accuracy information?
- Does it help with design?
- Is its accuracy estimator in understandable terms?
- Can you trust results from test objects?
- Higher accuracy will cost more; what financial cost can be tolerated?
- What errors can be tolerated if it is necessary to reduce costs?
- Overall, does the measurements accuracy fit the purpose?
- What accuracy levels are achievable in medical photogrammetry?
- What are the accuracy challenges in medical photogrammetry?
- What are the advances in medical photogrammetry?

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## A1. Issues continued

- The topic of error statistics in photogrammetry is almost limitless. See: Cooper, M.A.R. & Cross, P.A., 1988. Statistical concepts and their application in photogrammetry and surveying. Photogrammetric Record, 12(71):637-663. .

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## A2. Quality Measures: general

Before we talk about medical photogrammetry, some general matters about accuracy:

- Error Types: Three groups:-

1. Measurement errors: randomly distributed, having equal likelihood of a positive or negative sign;
2. Systematic errors: caused by imperfections in the adopted value of a fixed quantity, or errors, omissions or other *inadequacies in the functional model*
3. Genuine mistakes, 'blunders' or 'gross errors' in the measurement and processing.



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## A2. Quality Measures: general continued

**Measures of quality: Accuracy, precision and reliability**

These terms may have different definitions in different scientific communities, and need to be defined:

***Accuracy*** can be defined as the difference between the determined quantity and the true value, and is generally the desired statistical indicator of the quality of results. However, accuracy can only be assessed by comparing computed values with "known" ones. If test objects or test points are available, then the achieved level of accuracy can be assessed. It is usually indicated by a root mean square error (rms) derived from the differences between the determined and true coordinates at the check points. ***Relative accuracy*** is the ratio of the parameter coordinate rms error to largest the span of the measurement.

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## A2. Quality Measures: general continued

***Precision*** (sometimes the word ***uncertainty*** is used) is derived most commonly in the solution during the least squares estimation of parameters. Precision describes the variability of a quantity, without regard to how close it is to the correct value, and is best indicated by a standard deviation for normally distributed errors. However, we generally deal with relative precision, the ratio of the mean target coordinate precision to the largest span of the measurement.



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## A2. Quality Measures: general continued

***Reliability*** relates to the ease with which gross errors, blunders or mistakes can be detected. Means of estimating and improving reliability are relatively complex and are not treated further here.

- Estimates of precision are important as a substitute for accuracy, because accuracy is usually not available unless there are test points, whereas precision has the advantage that it can be calculated without the availability of test points. However, it is an indicator of accuracy only in the absence of systematic errors. Because some systematic errors must be expected, a precision value may be an optimistic indicator of accuracy.

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## A3. System Design

**System Design: *a priori* accuracy estimation**

- It is obvious by now that a consequence of the existence of error sources is that each photogrammetric project has a design challenge to select:
  - the equipment: eliminate systematic errors in known parameters
  - the imaging configuration: the geometry of the intersecting rays, and specifically the angles between them
  - the measurement: the precision of the measurements of the (x,y) image coordinates on the image
  - the processing

  which will achieve the required accuracy, at minimum or acceptable cost.
- Planning the optimum camera configuration prior to a survey is a most difficult aspect.



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## A3. System Design continued

- Sometimes, experience can allow users to have confidence that accuracies will be achieved.
- Design can be aided by adopting standard or recommended procedures, and users should realise that many photogrammetric surveys are successfully executed, and are not prohibited by a need for design.
- In the simplest case, users can resort to rules-of-thumb: the object coordinate precision is indicated by the image precision multiplied by the scale number of the imagery, so that a 0.1 mm image measurement precision on a photograph at 1:100 scale could translate into about 10 mm precision on the object.
- Ideally, mathematical precision assessment will be utilised.

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## A3. System Design continued

The functional model describing the network is defined by equations relating any measured image coordinate ($y$) to the various required quantities ($x_1 \ldots x_m$), generally the coordinates of the points on the human object. The set of equations of the form:

$$y = f(x_1 \ldots x_m)$$

can be represented in matrix notation as:

$$\boldsymbol{Y} = \boldsymbol{AX} + \boldsymbol{C}$$

with coefficients *a* and constant terms c. The least squares solution for X is

$$\boldsymbol{X} = (\boldsymbol{A}^T\boldsymbol{A})^{-1}\boldsymbol{A}^T\boldsymbol{C}$$

If Σ represents an array of variances and covariances, then:

$$\boldsymbol{\Sigma}_X = (\boldsymbol{A}^T\boldsymbol{A})^{-1}\boldsymbol{A}^T\boldsymbol{\Sigma}_Y$$

We can play with various designs given by the ***A*** matrix and by variances in $\boldsymbol{\Sigma}_Y$.



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## A3. System Design continued

- A detailed study of mathematical network design is provided by Fraser, C.S., 1996. Chapter 9: Network Design, in Atkinson, K. B., 1996. Close Range Photogrammetry and Machine Vision, Whittles Publishing, Scotland (ISBN 1-870325-46-X), pp256-281.

- Note: Some writers talk about zero order design (the datum problem), first order design (the network choice), and so on, but it does not seem to be crucial and the terminology has not caught on.

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## A3. System Design continued

- It is necessary to recognise the benefits of a testing stage with new photogrammetric arrangements, primarily to test whether the accuracies of results meet requirements. Tests also serve to confirm other aspects of the solution. Accuracy confirmation can be done by using objects of known dimensions.



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## A4. On the job accuracy estimation:

**On the job accuracy estimation: *a posteriori*** accuracy estimation

- Achieved using

$$\boldsymbol{\Sigma}_X = (\boldsymbol{A}^T\boldsymbol{A})^{-1}\boldsymbol{A}^T\,\boldsymbol{\Sigma}_Y$$

where $\Sigma_Y$ is obtained using the real observations, not estimates of what they will be.

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## Note:

- ***Automating the design of photogrammetric networks is not yet feasible.***
- ***Software packages rarely offer even limited mathematical design assistance.***
- ***The capacity to critically assess the overall quality of the results is an important feature of photogrammetry software. Proficient software packages provide a set of precision estimates for each of the object space coordinates (i.e. X, Y and Z separately) for each of the points sought in the photogrammetric survey, and their covariance. Other software packages provide only rudimentary indicators of precision.***



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## A5. Improving accuracy

***Options in medical measurement practice:***

- Assume that we want low cost and moderate accuracy for a short term project.
- The aim is here is partly to list the range of error sources in photogrammetry and the relevant options in medical measurement.

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## A5. Improving accuracy continued

1. Improve the precision of the measurements of the image coordinates: use targets: *used when needed anyway, especially motion studies, but not in typical medical measurement*



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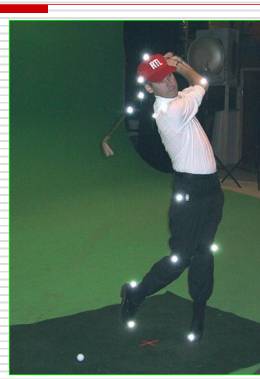
## A5. Improving accuracy continued

Reflective targets seen in dynamic human studies, from Qualisys.



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## A5. Improving accuracy continued

2. Improve target quality: use better and/or smaller targets: *may be able to select texturisation*



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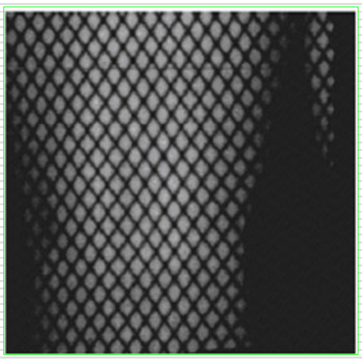
## A5. Improving accuracy continued

Human back texturised by casting a regular light pattern. The chosen pattern has the advantage that targets could be found.



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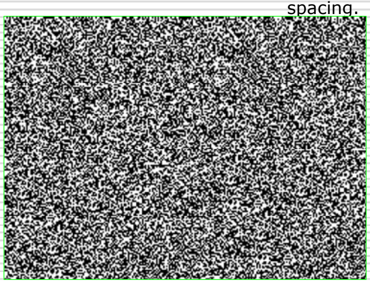
## A5. Improving accuracy continued

Random dot pattern as projected by D'Apuzzo for facial studies has the advantage that points are not likely to be confused with each other, automatic match precison can be high, and points can be chosen at any spacing.



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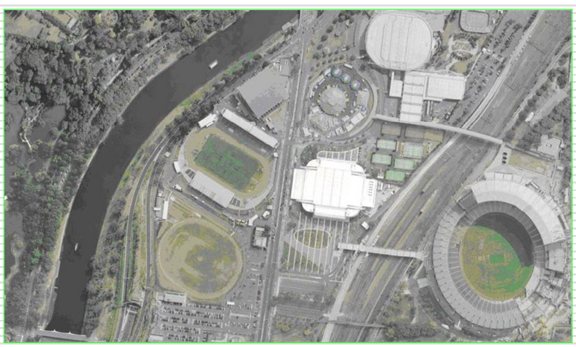
## A5. Improving accuracy continued

3.

Improve image resolution: but we can't compete with aerial cameras, which can go from this…



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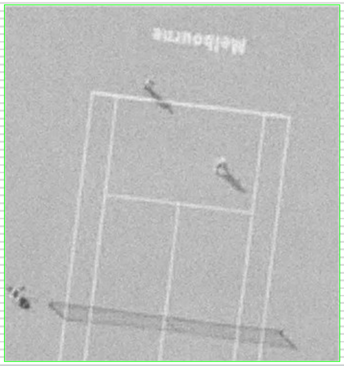
## A5. Improving accuracy continued

…to this





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## A5. Improving accuracy continued

4. Allow automated measurement of targets or automated matching: *currently used*

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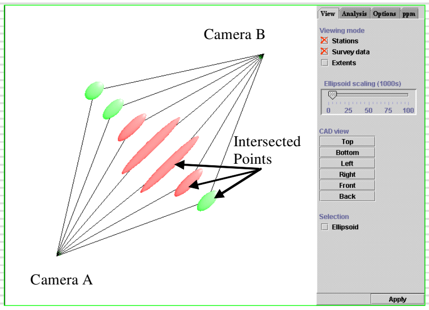
## A5. Improving accuracy continued

5. Improve the geometry of the intersecting rays: optimise the angles between them: *probably optimum in medical applications with small number of cameras*

Image courtesy: Best Practice for Non-contacting CMMs, Project 2.3.1/2/3 – Large Scale metrology, National Measurement System Programme for Length Metrology, University College London, *et al.* See http://www.ge.ucl.ac.uk/research/projects/dti.html



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## A5. Improving accuracy continued

6. Improve the precision of fixed quantities:
   - control point coordinates: *probably not significant for medical applications*
   - principal distance: *probably not very significant for medical applications*
   - pixel geometry of the digital sensor: *probably not significant for medical applications*
7. Increase the quantity of
   - observations on each point: *not sensible if automatic measurement*
   - points: *perhaps "hyper-redundancy", but high resolution already obtained*
   - cameras: *possible?*

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## A5. Improving accuracy continued

8. Overcome imperfections in the model by allowing for
   - a lack of flatness in the plane of the digital sensors or film:
   - for film distortion during wind-on or processing:
   - errors in the assumed position of the principal point:
   - errors in the assumed principal distance (focal length):
   - lens distortion: probably negligible for medical applications
   - non-perpendicularity between the sensor plane and the lens axis:
   - refraction: not significant at close ranges of medical applications
   - differential scale between the rows & columns in the sensor array
   - the angle between the rows and columns in the sensor array: not significant at close ranges of medical applications

*All probably insignificant for medical applications*



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## A5. Improving accuracy continued

9. Avoid gross errors due to:
   - wrongly identified and measured control points;
   - falsely matched points during automated point measurement;
   - using inappropriate units, for example: entering focal length in millimetres when metres are required.

*Should not be a significant improvement to accuracy and precision*

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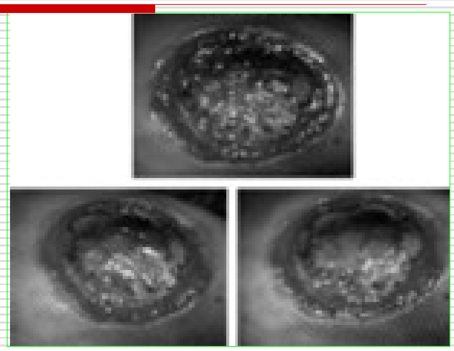
## A5. Improving accuracy continued

Differences in positions of highlights are visible in this set of three images taken from three different camera locations, in a photogrammetric measurement for the purpose of studying the healing of bedsores. From Malian *et al.*, (2005, Photogrammetric Record).





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## A5. Improving accuracy continued

10. Eliminate software errors - especially in derived quantities such as volumes
11. Allow for movement of the human object: *Synchronise cameras carefully*

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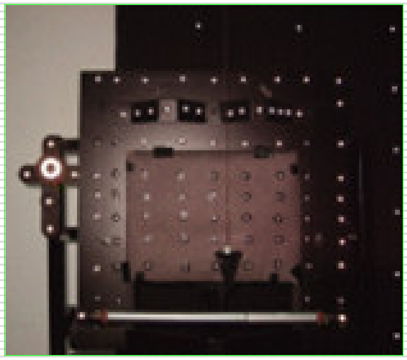
## A5. Improving accuracy continued

Simple camera synchronisation test, using a surveyor's plumb-bob, swung in front of the control frame. From Majid *et al.* (2005, Photogrammetric Record).





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## A6. Calibration

Systematic errors can be limited by calibrating the equipment and inserting the appropriate corrected values into the equations, for:

- Lens distortions
- principal distance
- differential scale between the rows and columns in the sensor array
- the angle between the rows and columns in the sensor array,

Self-calibration: systematic errors in the geometry can be incorporated into the functional equations if desired, and sought as unknown quantities in the solution.

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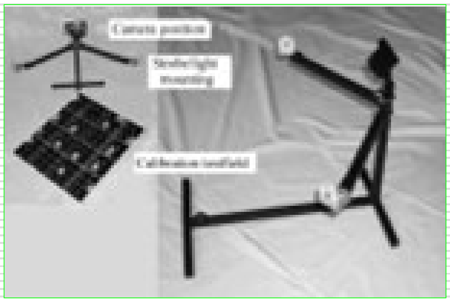
## A6. Calibration continued

Simple purpose built calibration frame used by Majid *et al.* (2005, Photogrammetric Record) in their facial studies which used both photogrammetry and scanning.





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## B. Surface Difference Detection

- A need exists for surface difference detection in medical measurement without the need for fixed reference points, because control points are so hard to use in medical applications.
- In the group of uses which included
  - faces
  - skin
  - dental
  - breasts
  - feet

The detection of change in the patient is usually a desirable outcome.

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## B1. Surface Difference Detection

- Methods for mathematical surface-to-surface alignment have been developing over the last decade, especially for automated inspection in manufacturing.
- In one group, techniques tend to be complex but versatile, coping with surfaces having a wide range of initial orientations. Such techniques typically involve minimization of separation vectors between points, the "iterative closest point" method.
- The techniques in the second group – discussed here- are generally simpler, being intended for comparative analysis of surfaces at different epochs *but in similar positions*, and are usually based on minimizing surface separation distances…
- and they can incorporate *difference detection*.



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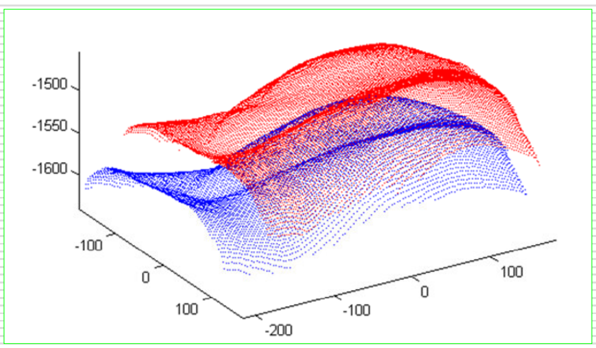
## B2. The Least Squares Approach



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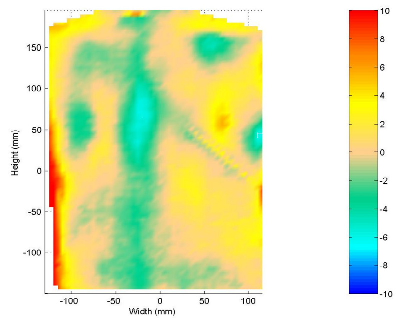
## B2. The Least Squares Approach continued

- Surface matching depends on the existence of regions which do not alter…but difference detection can be integrated into the mathematics of matching to exclude altered regions from matching.



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## B2. The Least Squares Approach continued

- In the least squares approach to surface matching, each surface model is assumed to be described by a set of Cartesian coordinate triplets, as a regular array of heights or an irregular network of points. The two sets of coordinates are assumed to represent the same surface measured at different times. The sum of the squares of the surface separations in the vertical direction at these points is minimized in the solution, and deformation information is gathered by assuming that separations which are significantly greater than a predefined quantity can be categorized as a change.

- Surface matching along these lines has been used for biomedical purposes: e.g. Karras & Petsa for monitoring the changing shapes of pregnant women's abdomens.

- It is tempting to rely upon commercially based program packages embedded in CAD/CAM programs. But the user is often unaware of the assumptions upon which they are based and, as a result, may draw erroneous conclusions under certain conditions.

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## B2. The Least Squares Approach continued

- The aim is to find that spatial relationship between the coordinate systems which would bring the surfaces into closest coincidence, as the solution minimizes the fit between the surfaces without an expectation that the discrepancies are zero. Once equations of this form have been written for all points in the second surface, corrections to the estimates are sought according to standard least squares estimation methods.
- Various transformation relationships may be employed in the solution, but the simple conformal transformation involving three shifts in X, Y and Z, three rotations about X, Y and Z and perhaps a scale factor.



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## B2. The Least Squares Approach continued

- Whether a surface matching solution converges to the correct solution depends primarily on the characteristics of the surfaces, the closeness of the initial estimates of the parameters which specify the transformation, and the method of calculating the surface gradients. Some surface shapes will be such that a best fit is difficult to define.
- An accurate solution depends on a strong matrix of coefficients of the unknown transformation parameters, and, as the crucial elements in the coefficients can be seen in the equations above to be the surface gradients, high accuracy demands that there are 'steep' gradients in the surfaces. If the initial parameter estimates are poor, the gradient used for the equation at any point needs to represent longer trends in the surface. The gradients, which have a crucial contribution to the successful least squares solution, must be estimated numerically, and some error must necessarily derive from the evaluation process.

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## B2. The Least Squares Approach continued

- If the above conditions can be met, least squares surface matching should achieve a positioning accuracy which is finer than the point spacing in the model because of the extensive redundancies in most solutions. Fortunately, the least squares theory provides for an estimate of the precision of the transformation parameters, based on the gradients and the residuals from the match.



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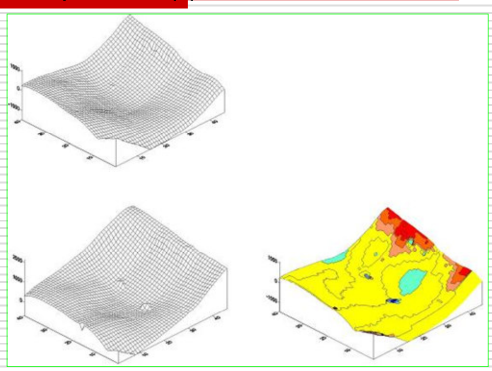
## B2. The Least Squares Approach continued

Incisal tooth pair and differences mapped after surface matching



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## C. Getting started with hardware/software

- So how does an interested user get started, if, as the following chapters suggest, measurement from imagery is the tool which can produce the three dimensional information that is required? The purchase of the camera is probably not a significant challenge. The main consideration is probably to purchase the most appropriate software required for the style of task, and to gain experience with it. Once the user has the images, it should be possible to simply try it.
- Medical photogrammetry does not belong solely to photogrammetrists!



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## C. Getting started continued

- Photogrammetric software which operates on an ordinary desktop computer is now widely available to help someone carry out all the photogrammetric procedures
  - select suitable image points or assist in their selection;
  - measure the image coordinates;
  - carry out the interior orientation;
  - carry out the exterior orientation;
  - calculate the object point coordinates; and
  - create the desired output for the client.

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## C. Getting started continued

- Prices vary, but much of it is affordable. Inexpensive but competent photogrammetric software on the market has made photogrammetry accessible to non-photogrammetrists over the last decade or two. Examples of software packages include
  - Australis (Photometrix),
  - Leica Photogrammetry Suite (Leica Geosystems),
  - iWitness (Photometrix),
  - PhotoModeler (PhotoModeler),
  - Rolleimetric (Photarc),
  - ShapeCapture (ShapeCapture) and
  - VirtuoZo (Supresoft)
- Hardware is cheap.



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## Conclusions

- Accuracy considerations are an essential aspect of all photogrammetry, but with medicals photogrammetry they need to be tempered by the limitations of the typical configurations and typical uses encountered in medical photogrammetry.
- Accuracy levels may be restricted; few advances are foreseeable.
- Comparative studies are so common in medical photogrammetry that the use of surface-to-surface registration may be beneficial.
- Software and hardware are so cheap and convenient that non-experts can easily attempt photogrammetry.