A PHOTOGRAMMETRIC SYSTEM FOR 3D RECONSTRUCTION OF A SCOLIOTIC TORSO

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ABSTRACT

Scoliosis is a deformity of the human spine most commonly encountered with children. Its early detection is vital for the patient's treatment, so periodic examinations via X-rays are traditionally used to measure its progression. Since this can cause a significant dose of radiation leading to an increased risk of cancer, it is imperative to minimize the use of radiographs and introduce a non-invasive and radiation-free scoliosis detection methodology. Quantifying the scoliotic deformity of the torso surface is a valid alternative, because the internal spine curvature and the torso surface deformation are highly correlated. This work proposes a low-cost multi-camera photogrammetric system for the reconstruction of a torso surface with a sub-millimetre level accuracy, which will be suitable for the routine clinical monitoring of scoliosis with no harmful side effects. The paper first describes the system design for optimal accuracy. Secondly, it explains the system calibration in terms of the camera calibration, stability analysis, and establishing the exterior orientation parameters of the implemented cameras. Then, it covers the entire reconstruction procedure giving insights on the pattern projection, epipolar resampling, feature extraction, matching and tracking, intersection, and the final surface registration. The final accuracy is tested by evaluating the goodness of fit between the reconstructed surface and a more accurate surface that has been measured by a coordinate measuring machine.

INTRODUCTION

Scoliosis is a deformity in the human spine. A normal spine viewed from behind appears straight, while a scoliotic spine appears "S" or "C" shaped. A person is diagnosed with scoliosis once the spinal curvature is measured to be ten degrees or greater (Roach, 1999). The disease generally begins at the onset of puberty and progresses during the period of rapid growth, and thus it mostly affects growing children (Roach, 1999). Detecting scoliosis in its early stage is vital for its successful treatment. If it is left untreated, it can cause heart and lung problems (Wiegersma et al., 1998). The optimal treatment depends on its degree of progression. A curvature of 45 degrees or less can be treated conservatively with exercises or bracing. However, rapidly changing curvature or curvature exceeding 45 degrees may require surgery (Roach, 1999; Pinto et al., 1994).

The disease progression is monitored by periodic examinations and full-length standing spinal X-rays (Cailliet, 1975). In order to monitor the curve progression in growing individuals, serial radiographs need to be obtained as often as every three months for a period of time as long as five years (Reamy and Slakey, 2001). This may amount to a significant exposure to ionizing radiation and a potential risk of cancer (Levy et al., 1996). For this reason, it is imperative to minimize the use of radiographs and introduce a non-invasive and radiation-free scoliosis detection methodology. Magnetic resonance imaging (MRI) is a type of a radiation-free technology, however, it is very expensive and often unavailable (Peer et al., 1994). Moreover, the screening process is not suitable for the detection of scoliosis, because it is performed with the patient lying down instead of standing up, which neglects the effects of gravity.

In addition, the methods of monitoring scoliosis discussed so far produce 2D images and thus ignore the 3D nature of the spinal scoliotic deformity, which includes both lateral and rotational distortions. Furthermore, the rotational component of scoliosis is a key factor in the progression of the spinal curve. This and the fact that the internal spine curvature and the torso surface deformation are highly correlated, makes quantifying the scoliotic deformity of the torso surface a valid monitoring alternative. Some of the approaches of gathering torso surface information which have been used in the past include Moiré fringe topography, structured light, raster stereography, and laser scanning.

Moiré fringe topography is a method of obtaining a contour map of a 3D surface by utilizing a reference grating placed before a camera and a projection grating placed in front of a light source. After amplitude-modulating of the

projected light beam with the pitch of the grating, the phase of the spatial carrier is modulated by the shape of the object surface when the beam falls on the object surface. This method is capable of showing the level, presence, and direction of the deviation of scoliosis, however, it only considers the back of the person and not the whole torso (Takasaki, 1970).

The rasterstereography system employs the standard techniques of stereo photography except that one of the cameras is replaced with a projector, which projects a raster diapositive onto the surface of the back, and the camera records the pattern generated on the back from which 3D shape can be calculated (Dickman and Caspi, 2001). This is a simple and versatile alternative, however, high RMS error values of the surface reconstruction have been reported (Robu, 2006).

The idea behind a structured lighting system is that a known pattern is projected onto an object of interest, and the pattern is displaced according to the relief of the surface of the object. This pattern displacement is used to calculate the 3D coordinates of the object (Turner-Smith, 1988). The disadvantage of this methodology is that again only the back surface of the torso is mapped, and the accuracy of the 3D reconstruction is in the order of a few millimetres (Robu, 2006).

The most recent research in 3D radiation-free scoliosis evaluation has utilized laser scanning systems (Hill at al., 2002; Tardif et al., 2000). The primary limitation of the laser scanning systems is the scanning time required for acquisition of a full torso. A scan of relatively long duration may introduce 3D reconstruction errors due to the patient's breathing and movement. Photogrammetric systems, which are frequently used for surface reconstruction, do not have this motion problem (Mitchell, 1995). This study is thus motivated to investigate the potential for monitoring scoliosis using a photogrammetric system. The next two sections will briefly describe the proposed system design and methodology for the torso model generation, which will be followed by the experimental results and the conclusion.

PROPOSED SYSTEM DESIGN

In the proposed system, several low-cost amateur cameras are fixed on a metal arm (see

Figure 1). Four arms and four projectors are located around the torso (see

Figure 2). In this way, patients can easily get into position for data acquisition in this system design by rotating the corresponding arms (see

Figure 3). All cameras should operate simultaneously thus producing four scans, i.e. one scan from each arm. The entire surface is built up by combining the four pieces through utilizing the overlap between them.

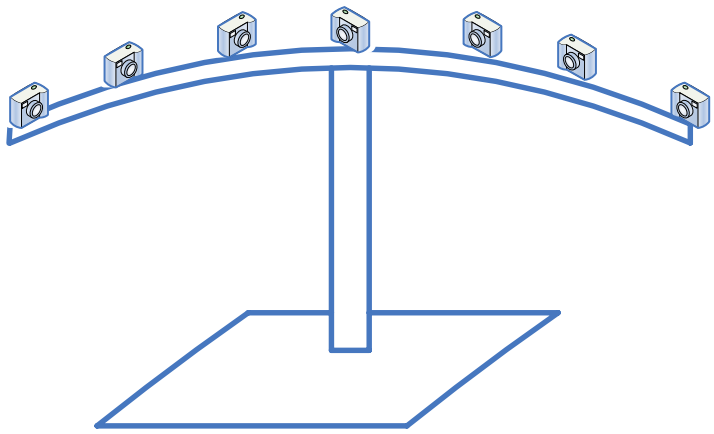


Figure 1. Cameras fixed on a metal arm.

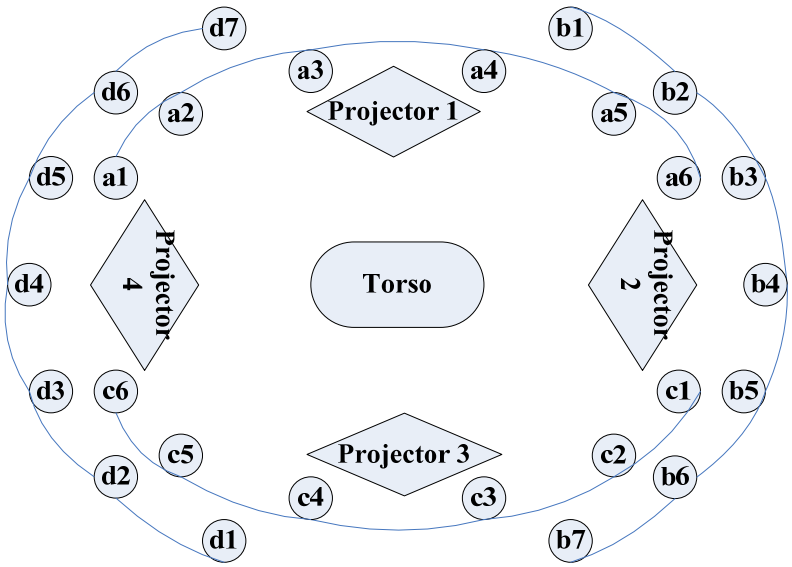


Figure 2. System design setup with cameras and projectors mounted on multiple metal arms around the torso.

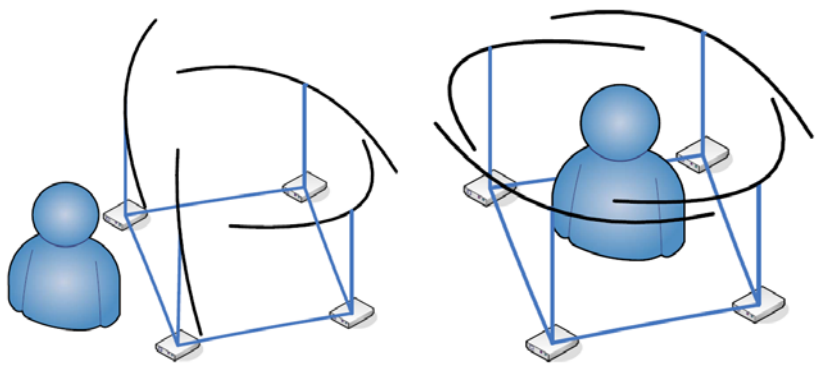


Figure 3. Patient entering the system for data acquisitioning.

System Calibration

The utilized cameras must be calibrated before use. The objective of the calibration process is to obtain the camera's internal characteristics (IOPs), which include the principal point coordinates, the principal distance, and the lens distortion parameters (Habib and Morgan, 2003). The cameras should also undergo a stability analysis procedure, which verifies that the estimated IOPs do not significantly change over time. This procedure is necessary, because the cameras are amateur ones, i.e. they are not specifically designed for metric applications (Habib and Morgan, 2005). The location and orientation, i.e. the exterior orientation parameters (EOPs), of each camera are obtained through a bundle adjustment procedure using a test field with known target points. Since the cameras are rigidly mounted on each metal arm, the relative EOPs of the exposure centres on each arm should stay the same over time. Thus, the bundle adjustment of each arm is only required to be done once.

Pattern Projection

The purpose of having projectors in the proposed system is to project a pattern onto the torso in order to provide artificial markers on its surface (see

Figure 4). This is necessary, because the torso surface is relatively homogeneous (see

Figure 5a) and with no artificial markers it would be impossible to identify conjugate points in the captured stereo-pairs. The projected pattern was generated by randomly arranging eleven unique 3x3 pixel sub-blocks (see

Figure 5b). However, to minimize any matching ambiguity, a sub-block was not repeated within a six-pixel radius. During the pattern projection, the lighting must be well managed to achieve optimal contrast of the artificial features on the surface of the subject.

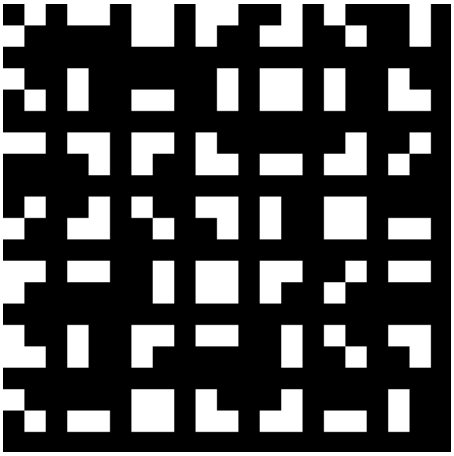


Figure 4. The designed pattern for projection.

(a) (b)

Figure 5. An example of a torso mannequin imaged with (b) and without (a) a projected pattern.

Balance Between Matching Reliability and Intersection Accuracy

To optimize the intersection accuracy, the baseline between two camera stations should be sufficiently large so that the intersection angle of the two light rays is as close to 90° as possible. This is referred to as a "large baseline" case, and this geometry usually involves significant relief displacement between the images. In automatic image matching, identification of conjugate points requires measuring the similarity of the area around a feature. However, due to the significant relief displacement between the images, the automated identification of conjugate points between the two images with a large baseline becomes problematic (Okutomi and Kanade, 1993; Molton et al., 2004). This is why the subject is simultaneously photographed using multiple cameras from different viewpoints that are close together, and the automatic matching is performed between the adjacent exposure stations with short baselines. After that, conjugate points are tracked through all the images, and every point is reconstructed using conjugate light ray intersection from multiple images. In this way, the procedure generates an accurate surface model by taking advantage of the reliable matching in images with short baselines and the reliable multiple light ray intersection from images with large baselines.

METHODOLOGY

By utilizing this system, the acquired data should be processed to generate a surface model of the entire torso. This is done by first generating epipolar stereo-pairs from the original images, performing feature detection on every image and then matching conjugate features in the corresponding image pairs. After that, the same matched features are tracked through all the overlapping images and used as tie points in a multiple light ray intersection. The resulted four surfaces from the four scanning arms are then registered in a common reference frame to produce the final 3D torso model. The proposed procedures for the 3D reconstruction described above are shown in

Figure 6 and further explained in the following sections.

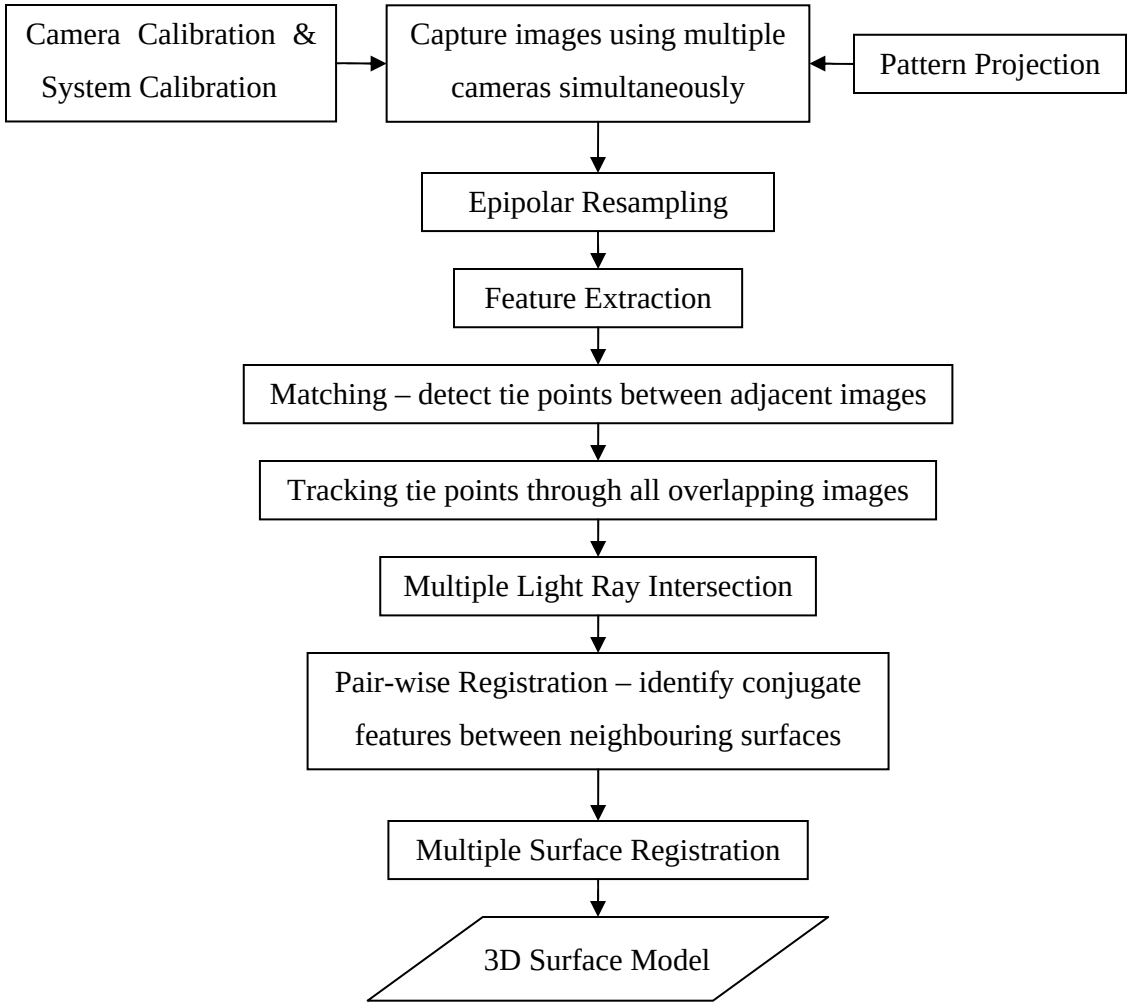


Figure 6. The proposed procedures for 3D surface reconstruction.

Epipolar Resampling

The acquired images must be pre-processed to ensure the reliability of the matching process. Adjacent image pairs are first resampled according to epipolar geometry. The primary objective of this procedure is to generate normalized image pairs where corresponding points appear on the same rows in the two images. The required information for the epipolar resampling includes the EOPs of the exposure camera stations and the IOPs of the involved cameras and is acquired from the system calibration (Morgan, 2004; Schenk, 1999).

Feature Extraction

The identification of surface features of interest is a prerequisite for image matching. In the proposed algorithm, these features are extracted using the Harris operator, which is an interest point detector (Harris and Stephens, 1988). Before the actual feature extraction (see

Figure 7a), users are also able to define a region of interest (ROI) in the images (see

Figure 7b) in order to speed up the process.

Figure 7c illustrates the extracted corner points on the torso mannequin.

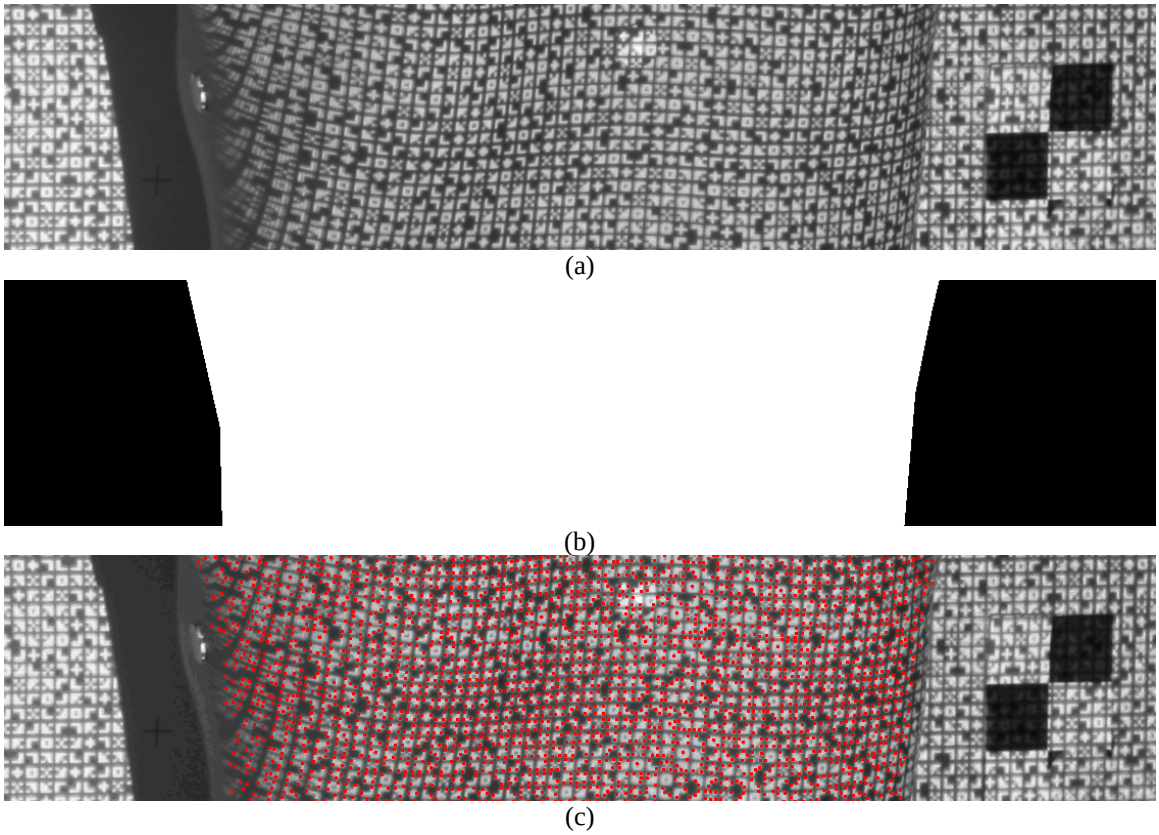
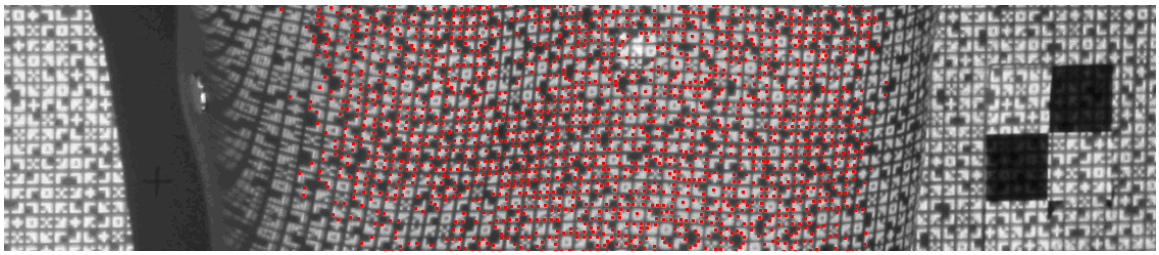


Figure 7. (a) An excerpt of an original image, (b) ROI mask for feature extraction, and (c) extracted corner points in the ROI.

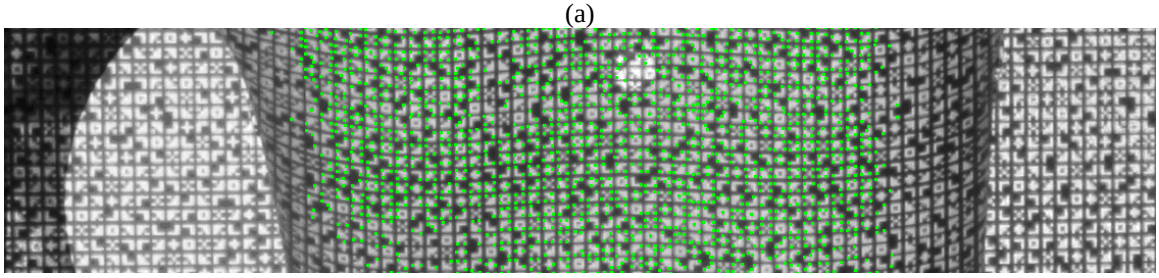
Image Matching

The choice of image matching procedure in the proposed system was the normalized cross correlation (NCC) method. NCC is an efficient technique for performing area based matching by locating the highest correlation of a feature from one image in a moving window in another image. Owing to the epipolar resampling, the search for conjugate points is performed along the corresponding row of interest. However, in order to handle the impact of potential errors from the IOPs and EOPs the search space across the epipolar line is wider than the size of the template.

Figure 8 shows the identified matching feature points in an example stereo-pair.



(a)



(b)

Figure 8. Detected conjugate corners in a stereo-pair.

Tracking

After image matching is performed for all stereo-pairs, feature tracking is done to identify the same features in all the images in which they appear. This is a prerequisite for the next procedure, i.e. the multiple light ray intersection.

Figure 9 shows an illustration of a feature being tracked in five consecutive images.

Figure 9. An example of a feature tracked in several consecutive images.

Intersection

The image coordinates of conjugate features are obtained through the matching and tracking procedures described above. Then, the collinearity equations are utilized to define the relationships between image and ground coordinates of the points. With the use of the IOPs of the involved camera, the EOPs of the involved images, and the image coordinates of the identified conjugate points, a least squares adjustment is then performed to determine the ground coordinates of the corresponding object points. The utilized multi-image intersection also improves the ability to detect blunders and inconsistencies among observations. Figure 10 shows the results of the reconstruction from one of the scanning arms.

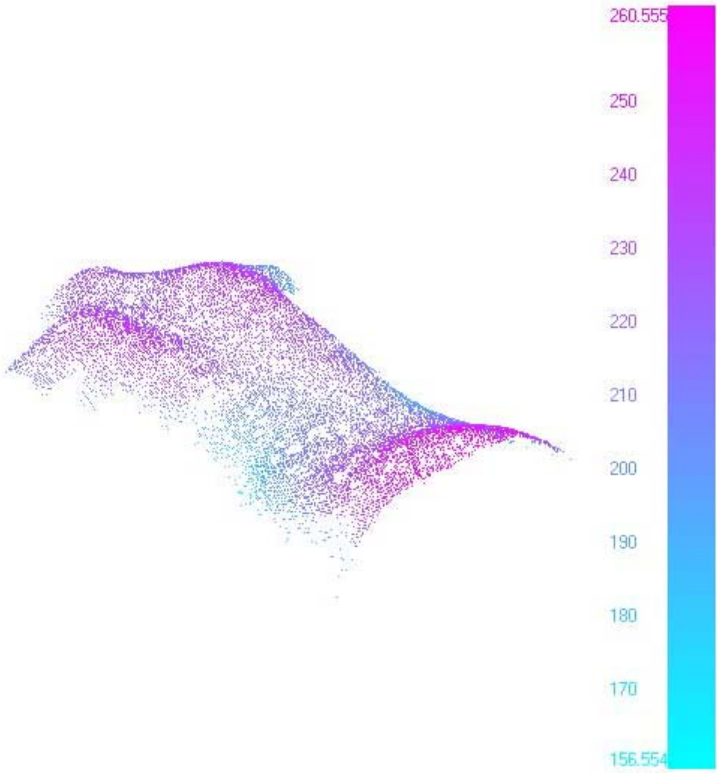


Figure 10. A reconstructed surface from one of the scanning arms in the proposed system.

Surface Registration

In the proposed system design, the torso surface is partially reconstructed by each scanning arm. The reconstructed pieces of the torso surface are then transformed and combined in the same reference frame. To effectively combine the reconstructed pieces, conjugate features in the overlapping areas between neighbouring surfaces must first be identified. This study takes neighbouring surfaces, and uses them in a pair-wise surface registration process. Following the pair-wise surface registration procedure, all the identified conjugate pairs are then used as inputs in an adjustment procedure for multiple surface registration. The multiple surface registration registers all the surfaces in a single reference frame.

Pair-wise Surface Registration

Habib et al. (2001) and Habib and Cheng (2006) developed an automated surface matching algorithm for registering 3D geographic datasets where there is a lack of an exact point to point correspondence. The algorithm is based on the Iterative Closest Patch (ICPatch) method, which establishes correspondence between two surfaces by identifying conjugate surface features and estimates parameters of the transformation function between two surfaces by minimizing the summation of normal distances between identified conjugate features. The features from one of the surfaces are 3D points, the features from the other surface are triangular patches, and the mathematical relationship between the reference frames of the two surfaces is described by a 3D similarity transformation. A coplanarity constraint (see Figure 11) is used as the similarity measure between the point-patch pairs, i.e. the enclosed volume of a transformed point and the corresponding patch is zero if the point and patch belong to the same plane. The average normal distance between the points and their corresponding patches serves as a check for the goodness of fit between the two surfaces after the registration. Figure 12 illustrates an example of the registration between the reconstructed surfaces of two scans.

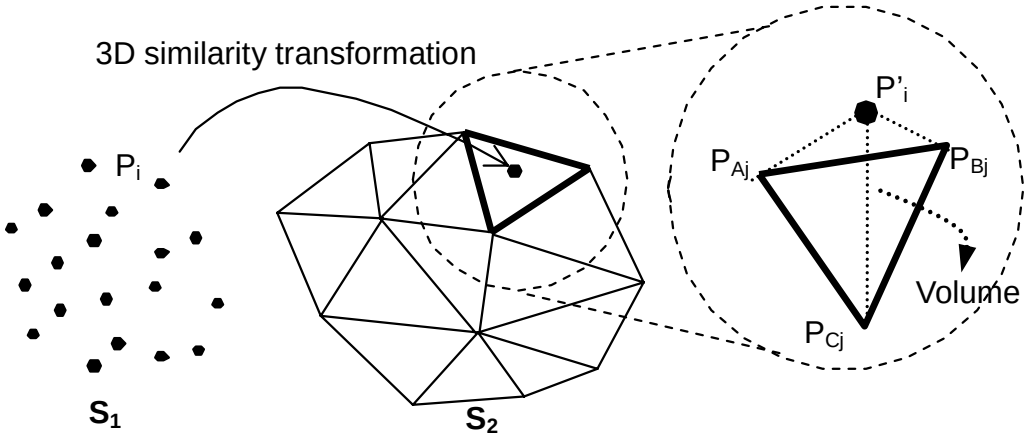


Figure 11. Similarity measure for relating conjugate primitives in two surface models (Cheng and Habib, 2007).

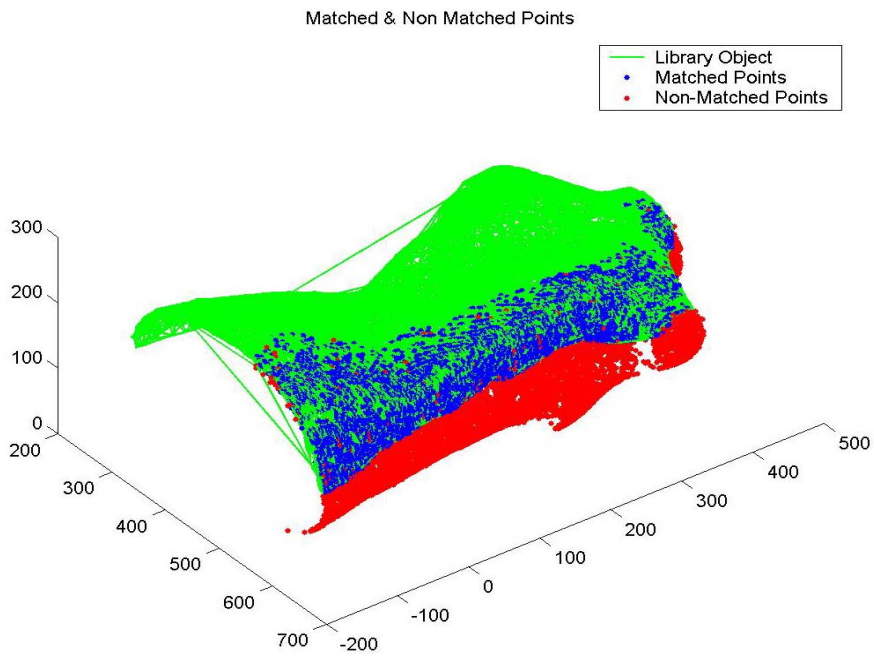


Figure 12. Pair-wise surface registration between two adjacent scans (green: the reconstructed surface of scan 1, blue: matched points from scan 4, red: non-matched points from scan 4).

Multiple Surface Registration

The four pieces of the torso can be integrated together by using the transformation parameters acquired from the pair-wise registration. However, the error associated with the transformation parameters propagates and the misclosure between the first and the last surfaces becomes unacceptable. To avoid this, a method for handling multiple surface registration was developed. A coordinate system of one of the scans is adopted as the reference frame, and the correspondence of the conjugate point-patch pairs in the overlapping areas of neighbouring surfaces is then utilized as the constraint in a least squares adjustment while all of the surfaces are processed simultaneously. The resulting 3D surface model is the output of the proposed system.

EXPERIMENTAL RESULTS

The objectives of the performed experiments were to test the feasibility and estimate the accuracy of the proposed system. When the necessary data was collected, one camera was utilized to simulate the proposed system in order to reconstruct the surface of a torso mannequin. The camera was placed in several stations to simulate each scan, and the images were taken sequentially. The baseline distances between the neighbouring exposure stations in each scan were approximately 0.8m. The distance between the projector and the mannequin was 1.7m. The camera was located along a semicircle path behind the projector and its distance to the subject was about 2.5m. After the data was processed, the resulted torso model was evaluated both qualitatively by examining the completeness of the reconstruction and quantitatively by first checking the goodness of fit in the multiple surface registration of the four scans and second by matching key features on the reconstructed torso model to "ground truth" acquired from a coordinate measuring machine.

In the first experiment the cross-section of the reconstructed torso (see Figure 13) visually shows that the four surfaces were combined well. The average normal distances between the matched point-patch pairs in the transformed scans were in the order of 0.5mm as seen in Table 1. The estimated RMS error between the reconstructed torso model and the coordinate measuring machine was 0.52 mm.

In order to test the repeatability of the system, a new dataset was collected four months later. This time, the average normal distance in the multiple surface registration of the four new scans was 0.8mm, and the RMS error was 0.58mm. The two torso models were then registered to each other and the average normal distance was 0.8mm, where 95% the points were matched.

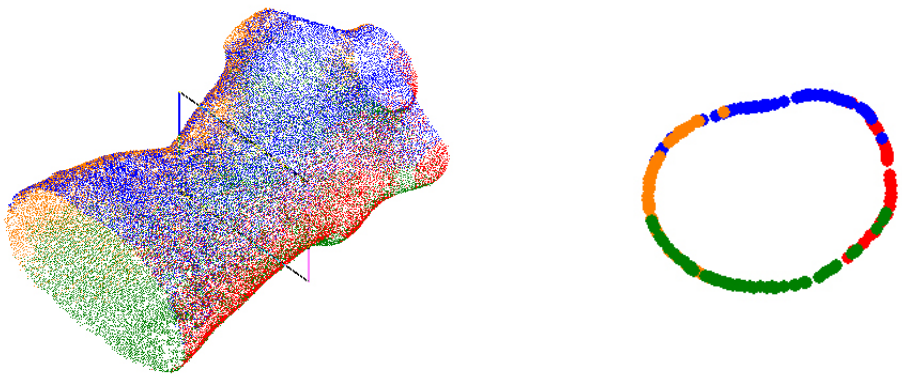


Figure 13. The reconstructed torso model (green: scan 1, orange: scan 2, blue: scan 3, and red: scan 4).

Table 1. Average normal distances between transformed scans using results from a four-scan system after multiple-surface registration

Surface Pair	Average Normal Distance (mm)
Scan 2 vs. Scan 1	0.504
Scan 3 vs. Scan 2	0.575
Scan 4 vs. Scan 3	0.466
Scan 4 vs. Scan 1	0.450

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This paper described the risks associated with scoliosis for growing children. Then it pointed out that the current methodologies for scoliosis assessment and monitoring employ X-ray imaging, which over time exposes the patients to a significant amount of ionizing radiation. Since there is a high correlation between the internal spine curvature and the torso surface deformation, quantifying the scoliotic deformity of the torso surface is an alternative method for scoliosis assessment and monitoring. This is why this research proposed a photogrammetric system as a radiation free replacement of X-ray imaging for providing 3D surface models of scoliotic torsos. The proposed system is based on a low-cost multiple-camera setup, and a pattern projection. The processing procedures include an epipolar transformation, feature detection, image matching, tracking, multiple light ray intersection, and surface registration. They are semi-automated, where the only manual involvement is to select a region of interest for the feature

extraction and matching. The performance of the proposed system was assessed using an artificial torso model, and the experimental results were encouraging, since the reconstruction exhibited sub-millimetre accuracy. Therefore the proposed system is sufficiently accurate for the clinical applications of scoliosis assessment and monitoring. Future work will include building a prototype of the proposed system, performing experiments on real subjects in a clinical environment, and getting involved in the actual analysis of the reconstructed torso for the purpose of monitoring the disease progression.

REFERENCES

Cailliet, R., 1975. Scoliosis: diagnosis and management, FA Davis, 15 (9): 53-54.

Cheng, R.W.T. & A.F. Habib, 2007. Stereo photogrammetry for generating and matching facial models, *Journal of Optical Engineering*, 46 (6): 067203.

Dickman, D. & O. Caspi, 2001. Diagnosis and monitoring of idiopathic scoliosis overview and technological advances, OrthoScan Technologies, Clinical Application Notes http://www.orthoscantech.com/diagnosis_pdf.pdf.

Habib, A., and R. Cheng, 2006. Surface matching strategy for quality control of LIDAR data, I*nnovations in 3D Geo Information Systems*, *Lecture Notes in Geo Information and Cartography*, pp. 67-83. Editors: Abdul-Rahman, A., Zlatanova, S., Coors, V., Springer.

Habib, A.F., Y.R. Lee, & M. Morgan, 2001. Surface matching and change detection using a Modified Hough Transformation for robust parameter estimation, *Photogrammetric Record*, 17 (98): 303-315.

Habib, A.F. & M.F. Morgan, 2003. Automatic calibration of low-cost digital cameras, *Journal of Optical Engineering*, 42 (4): 948-955.

Habib, A. & M. Morgan, 2005. Stability analysis and geometric calibration of off-the-shelf digital cameras, *Photogrammetric Engineering & Remote Sensing*, 71 (6): 733-741.

Harris, C. & M. Stephens, 1988. A combined corner and edge detector, *Proceedings of Alvey Vision Conference*, 15: 147-151.

Hill, D.L., D.C. Berg, V.J. Raso, E. Lou, N.G. Durdle, J.K. Mahood, & M.J. Moreau, 2002."valuation of a laser scanner for surface topography, *Stud. Health Technol. Inform*., 88: 90-94.

Levy, A.R., M.S. Goldberg, N.E. Mayo, J.A. Hanley, & B. Poitras, 1996. Reducing the lifetime risk of cancer from spinal radiographs among people with adolescent idiopathic scoliosis, *Spine*, 21 (13): 1540-1547.

Mitchell, H.L., 1995. Applications of digital photogrammetry to medical investigations, *ISPRS Journal of Photogrammetry and Remote Sensing*, 50 (3): 27-36.

Molton, N.D., A.J. Davison, & I.D. Reid, 2004. Locally planar patch features for real-time structure from motion, British Machine Vision Conference, 2004.

Morgan, M., 2004. Epipolar resampling of linear array scanner scenes, PhD Dissertation, University of Calgary, Calgary, Alberta, Canada.

Okutomi, M. & T. Kanade, 1993. A multiple-baseline stereo, *IEEE Transactions Pattern Analysis and Machine Intelligence*, 15 (4): 353-363.

Peer, S., M. Krismer, W. Judmaier, & W. Kerber, 1994. The value of MRI in the preoperative assessment of scoliosis, *Orthopade*, 23 (5): 318-322.

Pinto, W.C., O. Avanzi, & E. Dezen, 1994. Common sense in the management of adolescent idiopathic scoliosis, *Orthopedic Clinics of North America*, 25 (2): 215-223.

Reamy, B.V. & J.B. Slakey, 2001. Adolescent idiopathic scoliosis: review and current concepts, *Am. Fam. Physician*, 64 (1): 111-116.

Robu, D., 2006. Assessment of 3D reconstruction of scoliotic human torso using optical imaging techniques, MSc Dissertation, University of Calgary, Calgary, Alberta, Canada.

Roach, J.W., 1999. Adolescent idiopathic scoliosis, *Orthopedic Clinics of North America*, 30 (3): 353-365.

Schenk, T., 1999. *Digital Photogrammetry*, TerraScience, Laurelville, Ohio, 428.

Takasaki, H., 1970. Moiré topography, *Applied Optics*, 9 (6): 1467-1472.

Tardif, N., P. Poncet, J.L. Ronsky, J. Dansereau, & R.F. Zernicke, 2000. Evaluation of an integrated laser imaging/X-ray technique for torso asymmetry measurement in scoliosis, *Arch Physiol Biochem*, 108.

Turner-Smith, A.R., 1988. A television/computer three-dimensional surface shape measurement system, *Journal of Biomechanics*, 21 (6): 515-529.

Wiegersma, P.A., A. Hofman, & G.A. Zielhuis, 1998. The effect of school screening on surgery for adolescent idiopathic scoliosis, *European Journal of Public Health*, 8 (3): 237-240.